

Full length article



Transforming aquatic food systems through digital traceability: A review of global challenges and opportunities

Gisela Costa^{a,*}, Cristina Pita^{a,b}, Sofia Alexandre^c, Katina Roumbedakis^{b,d}, João Pontes^c, Michelle Hübel^e, Mafalda Rangel^c

^a Centre for Environmental and Marine Studies (CESAM), University of Aveiro, Aveiro, Portugal

^b Instituto de Investigaciones Marinas (IIM-CSIC), Vigo, Spain

^c Centre of Marine Sciences (CCMAR/CIMAR LA), Universidade do Algarve, Portugal

^d Centro de Investigación y Estudios Avanzados del Instituto Politécnico Nacional (Cinvestav-Mérida), Mérida, Mexico

^e GEOMAR Helmholtz-Zentrum für Ozeanforschung, Kiel, Germany

ARTICLE INFO

Keywords:

Technology
Fisheries
Aquaculture
Supply chain
Blockchain
Tracing
Tracking

ABSTRACT

Aquatic foods are among the most extensively traded food commodities globally, with increasingly complex supply chains and rising consumer demand for sustainable, ethically sourced, and legally compliant products. In this context traceability systems have emerged as vital tools for enhancing transparency, accountability, and resilience within these supply chains. This study presents a systematic review of the literature to identify key challenges and opportunities associated with the implementation of digital traceability systems in aquatic food supply chains. The review synthesizes evidence on diverse technologies, governance frameworks, and supply chain dynamics. The findings reveal that while technological innovation, such as blockchain and digital traceability platforms, show promising solutions for improving data management and efficiency, and enhance consumer trust, several barriers persist. These include high implementation and maintenance costs, technological barriers (e.g., complexity of data management and usability), stakeholder disinterest, unequal access to digital infrastructure, gaps in international cooperation and regulatory frameworks, and issues of system interoperability. Conversely, traceability presents multiple benefits, including enhanced supply chain efficiency, market access, stronger stakeholder collaboration, and alignment with consumer preferences for sustainable products. It also contributes to combating Illegal, Unreported, and Unregulated (IUU) fishing, enhancing fair labour practices, and promoting compliance with international standards. We conclude that inclusive, context-specific approaches (tailored to the diverse characteristics of fisheries, aquaculture, and small-scale operations) and cross-sector collaboration are essential to address the challenges inherent in globalized supply chains and realize the full potential of traceability systems in advancing more sustainable, transparent, and resilient aquatic food systems.

1. Introduction

Aquatic food products are one of the most extensively traded food commodities globally [1], accounting for 49% of all animal protein traded [2]. Global consumption of aquatic food has risen substantially, increasing from 9 kg per capita in 1961–20.7 kg in 2022, driven by an increase in production (mostly from aquaculture), international trade, economic development, and technological innovation [1]. In 2022, nearly 38% of the total aquatic food production was traded internationally, corresponding to 70 million tonnes and USD 192 billion in

trade value [1]. Amongst the most globally traded species are tuna, shrimp and salmon [3].

The globalization of aquatic foods trade – enabled by a reduction in transportation costs, improved logistics and enhanced storage and processing technology – has resulted in increasingly complex supply chains and intensified competition for access to high-value markets [1]. This transformation not only expanded the geographic reach of aquatic food systems but also fundamentally altered how these products are produced, distributed and valued across different regions [4]. The growing complexity arises from the growing number of supply chain nodes, i.e.,

* Corresponding author.

E-mail address: gsc@ua.pt (G. Costa).

<https://doi.org/10.1016/j.marpol.2026.107154>

Received 14 June 2025; Received in revised form 3 March 2026; Accepted 20 April 2026

Available online 25 April 2026

0308-597X/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

the various actors involved across stages of production, processing and distribution [5]. As these supply chains grow in complexity, ensuring traceability becomes more challenging due to the higher risk of information loss or manipulation [6]. These difficulties contribute to critical concerns, such as food safety, Illegal, Unreported and Unregulated (IUU) fishing, product fraud and human rights violations - issues that have resulted in increasing demands for transparency and traceability [7–10].

In response, regulatory frameworks for aquatic food traceability have started to develop to deal with the complexity of global aquatic food trade, harmonize information and promote interoperability [11]. For example, major aquatic food importers, such as the European Union (EU) or the United States of America (USA), have introduced legislation to enhance traceability and control. The EU first established general food traceability requirements in the 1990s, following public concerns regarding food safety (e.g., health crisis related to spread of bovine spongiform encephalopathy (BSE), commonly known as "mad cow disease") [12]. Since then, the EU has adopted regulations to prevent imports of aquatic food products with poor traceability or linked to IUU fishing (e.g., Council Regulations (EC) No 1005/2008¹; No 1224/2009²; No. 1379/2013³). More recently, the EU adopted Regulation (EU) 2023/2842⁴ on digital traceability, which entered into force on 9 January 2024. This regulation mandates that supply chain operators record and transmit traceability information digitally to the next actor in the supply chain. Its phased implementation begins in January 2026 for fresh and frozen products and extends to prepared and preserved products and algae from January 2029. In the USA, the Food and Drug Administration (FDA) implemented the Food Safety Modernization Act (FSMA) in 2011 to improve safety throughout supply chains. The FDA will introduce additional traceability requirements for aquatic food in 2026, to enable faster tracking and removal of contaminated products from store shelves [13]. Furthermore, the Seafood Import Monitoring Program (SIMP), mandates, from 2018, key data collection from importing countries [14]. Despite these efforts, standardized and widespread implementation of traceability systems and legislation remains limited in most countries [15].

Traceability systems are essential to foster transparent, accountable and responsible aquatic food supply chains. These systems improve data connectivity, enhance collaboration among supply chain actors and support better-informed decision-making [16]. Increasingly, digital traceability tools - including quick-response codes (QR codes), blockchain, radio frequency identification tags (RFID tags), among others - are being used to ensure data security and accessibility [2]. Nevertheless, traceability technology should be selected based on the specific characteristics of the aquatic food system, such as the type of data collected, production scale, infrastructure and management needs [15].

A key concern is that the push towards traceability may place a disproportionate burden in producers in the Global South [17–19]. A large share of internationally traded aquatic food originates from developing countries, many of which lack information, institutional capacity, infrastructure and the financial resources needed to meet the traceability standards demanded by high-income markets [17,18]. Still, downstream actors, such as retailers in developed economies (whose brands might be subjected to reputational risk) increasingly demand traceability from producers from these countries, including from

small-scale producers [17,18]. However, small-scale fisheries (SSF) - which are responsible for much of the aquatic food production in the Global South [19] - face significant challenges, including limited infrastructure at landing sites, poor connectivity, small catch volumes requiring aggregation, and lack of clear guidance on traceability requirements [17]. Therefore, to ensure that traceability contributes to sustainable and equitable governance of aquatic food systems, it is essential to understand its risks, incentives, drivers and benefits, and to design systems that allow the empowerment of fisheries, especially marginalized small-scale fisheries, in developing countries [19].

This systematic review of the literature aims to identify the key challenges and opportunities associated with aquatic food traceability across fisheries and aquaculture. To the best of our knowledge, no global review has been carried out to date focusing specifically on the challenges and opportunities of digital traceability in aquatic food systems. In addition to mapping the evolution of aquatic food traceability publications, this review also compares traceability technologies, certifications, geographical coverage, governance aspects, and operational differences across sectors, production systems scales.

2. Methodology

2.1. Search strategy and inclusion criteria

The comprehensive review of existing research involved systematically examining all databases available on Scopus and ISI Web of Science (WoS). To identify relevant publications, the search string "(blockchain OR traceab* OR transparen* OR trust) AND (seafood OR fisheries OR fishery OR aquaculture OR "aquatic food" OR "aquatic supply chain" OR "aquatic value chain" OR "fisher* value chain" OR "aquaculture value chain" OR "seafood value chain" OR "seafood supply chain" OR "fisher* supply chain" OR "aquaculture supply chain" OR "aquatic supply chain") AND (barrier OR problem OR challenge OR difficult* OR impediment OR obstacle OR struggle OR advers* OR hindrance OR opportunit* OR incentive OR benefi* OR motivation OR advantage)" was used. Titles and abstracts were scanned to identify articles potentially eligible for inclusion and the full text of the selected articles was then retrieved and read in full. We acknowledge that the adopted search strategy, based on a narrowly defined set of keywords, may have excluded studies addressing challenges and opportunities more implicitly.

Criteria for inclusion in the literature review were restricted to the following: (1) the article focused on digital traceability in aquatic food; (2) the article identified challenges or opportunities regarding the use of traceability; (3) the article was published in a peer-reviewed journal indexed in the databases up to August 2023.

The literature search was initiated in December 2022 and conducted progressively throughout the first half of 2023. Given the rapid pace of developments in digital traceability technologies, the search was extended to include studies published up to August 2023. This cut-off date reflects the period during which data retrieval and organization were completed.

In order to identify all available articles, the review question was intentionally left broad, and no restrictions were applied in terms of sector (fisheries and aquaculture sectors), geography or language, although the search terms were in English, due to all the databases searched being indexed and having titles and abstracts available in English. To ensure transparency and robustness, we conducted our systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [20]. PRISMA offers a checklist of essential elements that guide the reporting process. As outlined in Fig. 1, we structured the review in four distinct phases.

2.2. Data extraction and analysis

Qualitative data (i.e., excerpts from the integral publication text)

¹ Council Regulation (EC) No 1005/2008 of 29 September 2008 (<https://eur-lex.europa.eu/eli/reg/2008/1005/oj/eng>) [Accessed on 09 September 2024].

² Council Regulation (EC) No 1224/2009 of 20 November 2009 (<https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009R1224>) [Accessed on 09 September 2024].

³ Regulation (EU) No. 1379/2013 of 11 December 2013 (<https://eur-lex.europa.eu/eli/reg/2013/1379/oj/eng>).

⁴ Regulation (EU) 2023/2842 of the European Parliament and of the Council of 22 November 2023 (<https://eur-lex.europa.eu/eli/reg/2023/2842#ntr18-L-202302842EN.000101-E0018>) [Accessed on 09 September 2024].

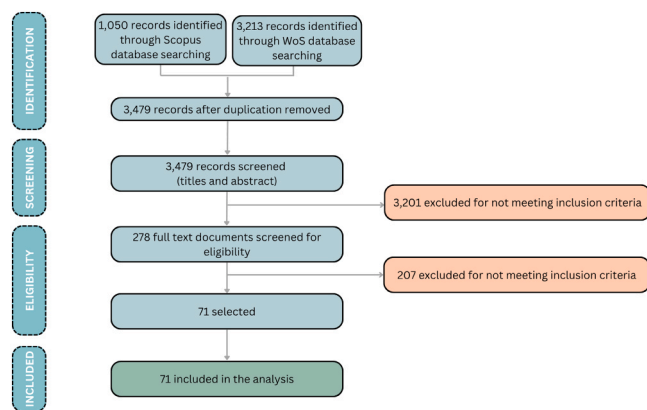


Fig. 1. Literature review flow diagram, according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA).

were retrieved from selected articles, namely the source (journal) and reference details, main aims of the article, topics covered, geographical scope, aquatic food sector covered (fisheries and/or aquaculture), technologies used, traceability challenges and opportunities, and other relevant topics (Table 1).

The coding process followed a thematic analysis approach [21], combining inductive reasoning, as themes were identified directly from the reviewed literature, and theoretical reasoning, as these themes were subsequently organized into analytical dimensions aligned with the PESTEL framework. The broader categories were informed by the PESTEL framework (political, economic, social, technological, environmental, and legal), a tool commonly used in strategic business management to identify factors that present threats and opportunities [22].

Challenges and opportunities identified in the literature were initially grouped into thematic clusters. A total of 22 such thematic groups were created. These were subsequently classified into "sub-categories", which were then grouped into broader categories to facilitate interpretation and synthesis of findings. Given the high volume and diversity of information, this hierarchical structure - moving from themes to sub-categories and then to categories - was necessary to have a clearer overall picture of the key dynamics in traceability implementation.

For this study, the PESTEL framework served as a theoretical guide to evaluate the challenges and opportunities of implementing traceability within an aquatic food system. The political and legal dimensions were merged into a single broader category called "governance". This category reflects the principles for good governance as outlined by the FAO, such as transparency, participation, and user empowerment [23]. It also includes elements of the governance system, such as sectoral policy objectives, compliance with legal frameworks, and fisheries management. All dimensions take into account the factors described in [22]: the economic dimension included growth rates, employment, interest rates, prices and markets; the social dimension covered society's characteristics, culture, values, norms and behaviours; the technological dimension referred to the development, use and evolution of technological solutions; and the environmental dimension addressed themes related with climate change and factors related with the natural environment.

We acknowledge that some challenges and opportunities may intersect more than one dimension, as factors influencing seafood traceability are often interdependent. Nevertheless, classifications were based on how each issue was predominantly characterized in the reviewed literature, following the main emphasis or mechanism described by authors.

Tables S1 and S2 of the Supplementary Material provide detailed descriptions of each theme and examples illustrating challenges and opportunities and how the information was coded under each theme and

Table 1 Information retrieved from the articles reviewed, description of the data collected, and analysis performed.

Type of information	Data collected	Data analysis
Challenges of aquatic food traceability	Text identifying challenges was retrieved from the articles	Challenges were identified from the literature, and each reviewed article was scanned for relevant mentions. When present, the corresponding text was extracted and coded as "present (=1)" (or "absent (=0)"; an "other" category captured challenges not listed initially. Challenges were organized into sub-categories based on thematic similarities and then grouped into broader categories through consensus. The analysis involved counting the number of articles mentioning each specific challenge. As articles could reference multiple challenges, the total number of mentions exceeds the total number of articles reviewed, therefore percentages for categories and sub-categories may sum more than 100%. The same process as described above for the challenges.
Opportunities of aquatic food traceability Geographic location	Text identifying opportunities was retrieved from the articles Text identifying the regions and country of the articles was retrieved from the articles	Data was classified into the following categories: <ul style="list-style-type: none"> • Asia; • Europe; • Africa; • Australia, as no other countries from Oceania were mentioned; • North America, since South America was not represented in the articles; • Several regions, applied when a single article referred to multiple distinct world regions; • No clear location, used when the article did not specify any identifiable geographical location. These categories were used to map the global distribution of case studies cited in the reviewed literature.
Traceability technology used	Text identifying the type of technology described was retrieved from the articles.	Information regarding the type of technology was classified into three categories: <ul style="list-style-type: none"> • Blockchain, when blockchain was explicitly mentioned as the traceability technology; • Other technologies, when technologies other than blockchain were referenced; • No clear technology, when it was not clear which technology was used.
Sector	The aquatic food sectors were identified.	Information on the aquatic food sector was classified into the following categories for analysis: <ul style="list-style-type: none"> • Fisheries, when the article specifically addressed this

(continued on next page)

Table 1 (continued)

Type of information	Data collected	Data analysis
		sector (includes small-scale fisheries); <ul style="list-style-type: none"> • Small-scale fisheries, when the article specifically addressed this sector (this category was analysed independently in certain parts of the study, due to the different nature of the sector with regards to digital traceability); • Aquaculture, when the article specifically addressed this sector (it was not broken down since there was only one article focusing on small-scale aquaculture); • Both, used when the article did not distinguish between fisheries and aquaculture, instead referring broadly to the aquatic food sector. These categories were used to identify sectoral differences in the challenges and opportunities associated with the implementation of traceability systems.
Date of publication	The year of the publication was retrieved.	The information was used to construct a timeline of aquatic food traceability advancements.

subsequently organized into subcategories and categories.

Each reviewed paper was analyzed in terms of its geographical scope, aquatic food sector, and technologies used, with the aim of identifying whether these characteristics shaped distinct descriptions of challenges and opportunities. To achieve this, papers were selected based on these characteristics and analyzed for both the frequency and the qualitative

descriptions of the challenges and opportunities identified (see Section 6).

3. Articles included in the review

The initial literature search yielded a total of 3479 potentially relevant articles. After screening title and abstract, and conducting a secondary review, 3201 were excluded for not meeting the inclusion criteria. In total, 71 articles met the criteria and were included in the review (Fig. 1).

Sections 3.1–3.3 provide a characterization of the reviewed literature according to three focuses: geographic distribution, traceability technologies, and aquatic food sectors represented. These descriptions establish the basis for subsequent analyses (Section 6), where challenges and opportunities are examined.

3.1. Geographic distribution of articles

Of the 71 articles included in the review (Fig. 2), 30% (n = 21) focused on Asia and 27% (n = 19) on Europe. Articles on digital traceability in these two regions were also among the earliest to be published [24–26], suggesting that traceability systems may have been more intensively explored and implemented in these contexts. North America and Australia were the focus of three articles each (4% each), while Africa was addressed in only two articles (3%). Notably, no peer-reviewed articles were found for South America, despite important traceability initiatives in the region, such as the Future of Fish (Peru and Chile), TrazApp (Peru), ShellCatch (Chile and Puerto Rico), and the Sustainable Shrimp Partnership (Ecuador) [27,28]. This could indicate a potential gap in published academic literature (while highlighting the relevance of including grey literature in future reviews of the challenges and opportunities of aquatic food traceability), but it may also reflect the limitations of the adopted search strategy rather than the absence of relevant work. A portion of the literature (23%, n = 16) covered multiple regions across different continents (Table S3, Supplementary Material).

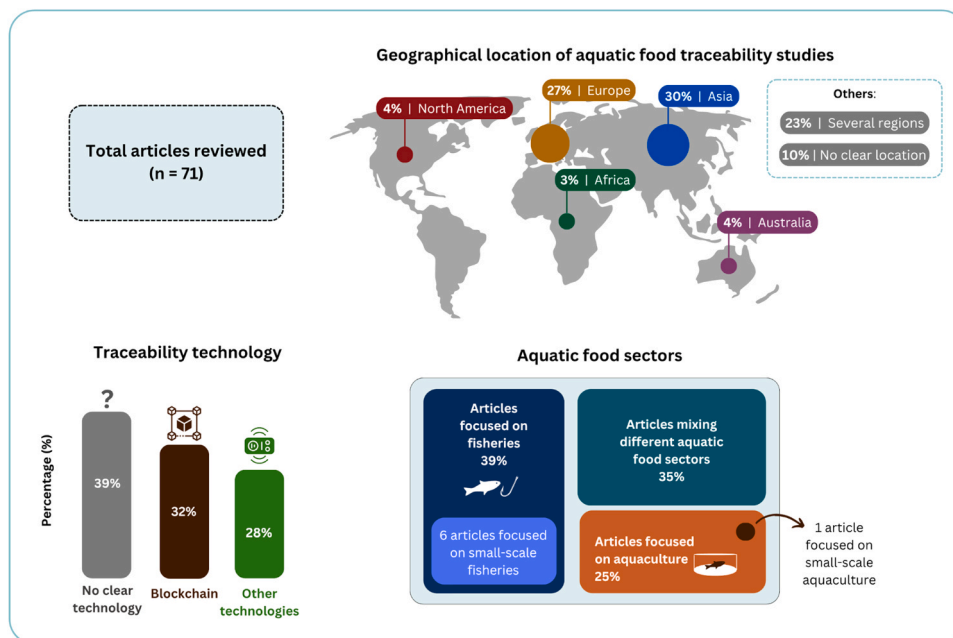


Fig. 2. Representation of some of the characteristics of the articles reviewed (n = 71). The map shows the geographical distribution of aquatic food traceability studies by region. The bar chart (bottom left) presents the proportion of studies by traceability technology, and the boxes (bottom right) indicates the distribution of reviewed articles across aquatic food sectors. Percentages indicate the proportion of the total (n total = 71) reviewed papers that refer to each category.

3.2. Traceability technologies focused on articles

Traceability technology was specified in 61% ($n = 43$) of the reviewed articles. Blockchain emerged as the most frequently cited technology (32%; $n = 23$), while a variety of other traceability tools were also mentioned - such as Vessel Monitoring Systems (VMS) and other satellite tracking systems, RFID technologies, browser services and apps, QR codes and other barcodes, Internet of Things (IoT), Artificial Intelligence (AI), among others. These were grouped under "Other Technologies" (28%, $n = 20$). Notably, 39% ($n = 28$) of articles did not specify the technology used.

These results indicate that blockchain is currently one of the most frequently studied digital technologies for enhancing aquatic food traceability, in the scientific literature reviewed. The fact that it is a decentralized ledger – i.e., no one authority manages the whole database – allows for tamper-proof data to be exchanged between stakeholders. Blockchain is considered an auditable and transparent traceability solution for aquatic food supply chains since information can always be verified and, according to specific blockchain permissions, be available for anyone to view the transactions [15,29]. These features ensure data security and prevent fraud, which aligns closely with the growing public demand in recent years for greater accountability across supply chains [29,30].

It is important to note that traceability systems often integrate multiple technologies simultaneously; for instance, blockchain-based systems may be used in combination with other technologies. See Table S4 and S5, in the Supplementary Material, for more information on the technologies mentioned in scientific articles.

3.3. Sectoral focus of articles

Most reviewed articles (39%, $n = 28$) addressed the fisheries sector. Within this sector, a smaller subset (8%, $n = 6$) explicitly focused on small-scale fisheries. Articles on aquaculture accounted for 25% ($n = 18$), including only one focused on small-scale aquaculture. Additionally, 35% ($n = 25$) of the reviewed literature broadly referred to both sectors, without distinguishing between fisheries and aquaculture. See Table S6 in the supplementary material provides more detailed information on which aquatic food sectors each reviewed article focused on.

Despite the limited representation of small-scale fisheries in the literature on digital traceability, their global importance is significant. The sector contributes approximately 40% of global catches, supports 90% of the total fisheries workforce, and sustains the livelihoods of 500 million people worldwide [1]. It is essential to account for small-scale fisheries when implementing digital traceability, to promote their inclusion in regional and international markets [1]. Digital solutions in general, and traceability in particular, should not be seen as incompatible with small-scale and/or data-poor fisheries. Instead, tailored solutions should be able to empower small-scale fisheries [31]. Similarly, small-scale aquaculture, while underrepresented in traceability research, is increasingly recognized for its role in global food security and rural development [32]. These specific contexts must be considered in the design and governance of aquatic food traceability systems, avoiding one-model-fits-all approaches.

3.4. Temporal trends and thematic evaluation of articles

Fig. 3 illustrates the publication trends up to August 2023. Aquatic food traceability has emerged as a research topic over the past two decades, with the first publication in 2004 and publication frequency increasing notably since 2020, with close to ten articles per year being released on this topic. Throughout this period, a shift in thematic trends seems to have emerged, and three interpretative periods were defined: 2004–2010; 2011–2018; and 2019–2023.

During the earliest period (2004–2010), aquatic food traceability was primarily discussed in the context of product mislabelling ensuring authenticity and food quality (e.g., [33]). Between 2011 and 2018, the focus expanded to include governance-related aspects, such as enhancing regulations and inspections and consumer empowerment (e.g., [34]). From 2019 onwards, the scope of traceability research broadened further, including traceability as a form of informational governance [19] and to strengthen supply chain relationships, investment decisions and corporate accountability [35]. Technological advancements have also shaped the field and, since 2019, blockchain-based traceability solutions have emerged as a dominant focus in the literature.

In general, traceability articles appear to have evolved to reflect the growing complexity of traceability as both a regulatory tool and a mechanism to demonstrate corporate responsibility. Key motivations for

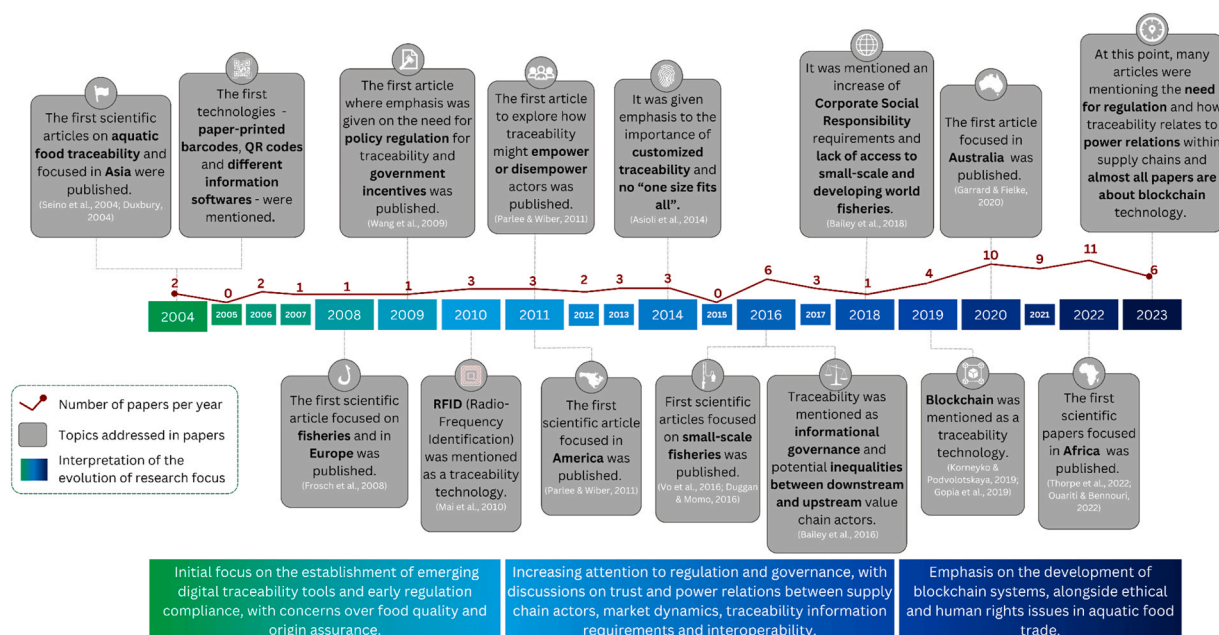


Fig. 3. Timeline of key developments in aquatic food traceability research (up to August 2023).

its adoption increasingly include brand reputation, and demonstrating corporate social responsibility, and adaptation to consumer expectations shifting towards ethical, environmental, and legal responsibility [15, 31].

4. Challenges in aquatic food traceability

The challenges identified in the literature on aquatic food traceability were grouped into five main categories, in descending order based on frequency of citations: technological, social, economic, governance and environmental (Fig. 4). These categories reflect the multidimensional nature of barriers to implementing effective traceability systems.

4.1. Technological challenges in traceability systems

Technological challenges were the most frequently discussed in the reviewed literature, encompassing a wide range of issues that were grouped into the sub-categories “Data collection and information sharing”, “Access to and use of technology”, and “Supply chain complexity”.

Under “Data collection and information sharing” three primary challenges emerged, including: “Increasing complexity of information needed”, which was cited in 28% of articles (n = 20) referring to the expanding scope of data needed for traceability, particularly in globalized supply chains [9,29,31,35–51], “Increasing amount of information required” reported in 21% of articles (n = 15) highlighting the burden placed on actors to record large volumes of detailed data [7,19,24,36,37, 42,43,48,52–58] and “Low interoperability of information systems” appeared in 20% of articles (n = 14) referring to challenges integrating data across different platforms and organizations [9,26,31,35,41,42,47, 57,59–64].

Adapting to modern technologies remains a significant challenge for

individuals working within aquatic food supply chains. Digital traceability systems require the electronic recording of each step in the supply chain, which in turn demands interoperability and compatibility across multiple operational nodes. This involves not only aligning the technological platforms used by different actors but also standardizing the type and volume of information to be collected, a particularly demanding task in highly complex and globalized aquatic food supply chains [19]. Several articles emphasized that interoperability issues are not solely technical but also linked to organizational, cultural, and relational dynamics within and between businesses (e.g., [41,42]). Therefore, the success of traceability depends on active collaboration among supply chain stakeholders to navigate the challenges these systems present [41,56]. Importantly, traceability systems are only as complex as they are designed to be, therefore much of the complexity in data collection and sharing can be thought of as a social and governance issue, rather than a technological one.

The second sub-category “Access to and use of technology” focused on challenges related to the use and availability of traceability tools, including: “Complexity of use” noted in 28% of articles (n = 20) where users experienced difficulties interacting with digital systems [9,29,31, 35–51]; the “Limited access to technology and/or familiarity with traceability” appeared in 25% of articles (n = 18), particularly in contexts with low digital capacity or limited training opportunities [29,36, 41,42,44,49,51,57,58,60–62,65–70]; and “Inefficiency of traceability tools” were reported in 11% of articles (n = 8) [9,25,26,35,54,61,65, 71].

The lack of understanding around traceability tools and technologies can hinder the engagement of additional supply chain actors and consumers [44]. Addressing these barriers requires the provision of enabling conditions that are often absent in aquatic food systems, including training programs, increasing qualified personnel and efforts to raise awareness about aquatic food traceability [49]. However, successful implementation does not depend solely on users adapting to new

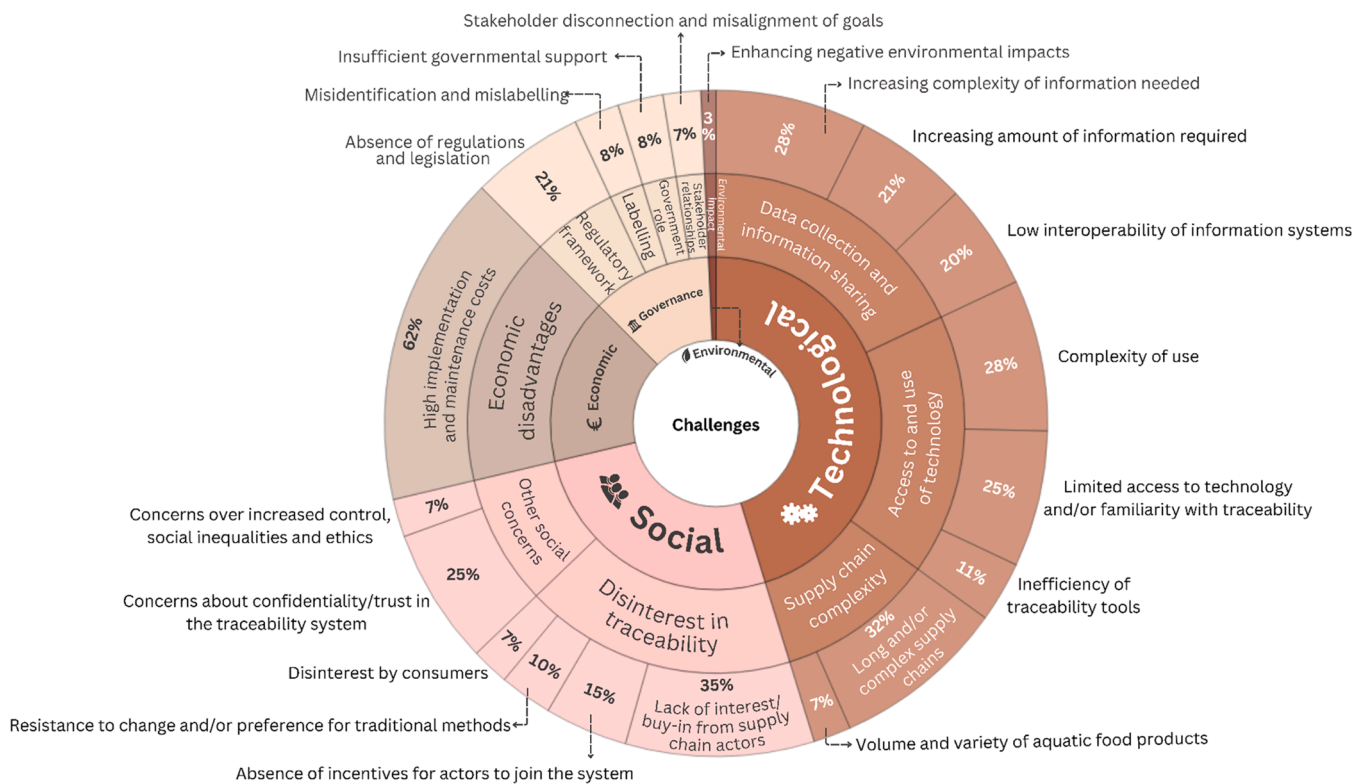


Fig. 4. Challenges to aquatic food traceability identified in the literature, organized into five main categories: technological, social, economic, governance, and environmental (inner circle), and their respective sub-categories (middle circle) and themes (outer circle). Percentages represent the proportion of reviewed papers mentioning each specific challenge.

technologies; technologies must also be tailored to meet the needs and their working conditions of users. Examples of inefficiencies in traceability systems reported in the literature include touch screens that are too small for operators to handle effectively [70], technology not suitable for the wet working conditions onboard fishing vessels [60] and even insufficient investment in context-appropriate technology, infrastructure and skilled operators, particularly in remote and resource-limited areas [26,35]. Although these adaptations require financial and time investments, they are essential to ensuring the effectiveness and long-term viability of traceability systems.

The last sub-category (“Supply chain complexity”) included challenges related to the structure and scale of aquatic food supply chains such as the “Long and/or complex supply chains” identified in 32% of articles (n = 23) and linked to increased data demands, stakeholder coordination, and traceability implementation costs [7,9,17,19,35–38,40,41,46,48,50,52,53,55–57,62,67,72–74] and the “Volume and variety of aquatic food products” noted in 7% of articles (n = 5) [17,31,73–75] which posed difficulties for system design and data standardization.

Although these aspects have operational implications and costs (e.g.: [9,73]), in the context of this review they were classified as a technological challenge. The literature indicates that the length, fragmentation, and diversity of aquatic food supply chains primarily hinder the development and interoperability of digital traceability systems, as well as the integration and management of heterogeneous data sources across multiple actors. These factors directly constrain the implementation of technological solutions for end-to-end traceability, thus justifying their inclusion under the technological dimension of the PESTEL framework.

Longer and more complex supply chains typically involve a greater number of actors, more varied data types, and higher risk of information loss or inconsistency [72]. Global trade further compounds these issues due to variability in national policies and traceability implementation capacities [19,50]. This added complexity increases the difficulty of tracing aquatic food effectively.

Although technological challenges were the most frequently reported in the literature, this category encompasses the greater number of distinct challenges, reflecting the wide diversity of distinct issues discussed within this category (Fig. 4). Technology is a central factor in traceability systems, which explains why it has been explored extensively in the literature and why technology challenges are reported in such a varied manner. The prevalence of these challenges should therefore be interpreted considering their scope and variability, rather than as an indication of severity alone.

4.2. Social challenges in traceability systems

Social challenges were grouped into two sub-categories: “Disinterest in traceability” and “Other social concerns”.

The first sub-category (“Disinterest in traceability”) included several recurring issues, with the most commonly cited being the “Lack of interest /buy-in from supply chain actors” mentioned in 35% of articles (n = 25) [9,17,24,26,29,34,36,37,39,41,42,44,48,49,53,61,64,68–70,76–80]. Related concerns include “Absence of incentives for actors to join the system” (35%, n = 11) [29,37,39,41,42,54,57,61,65,68,81] “Resistance to change and/or preference for traditional methods” (10%, n = 7) [41,57,63,65,70,80,82] and “Disinterest by consumers” (7%, n = 5) [29,42,48,78,83].

Many articles noted a lack of interest in adopting traceability systems, often without specifying underlying causes. Where explanations were provided, they included retailers favouring non-traceable products due to more consistent or abundant supply, lower costs, and reduced financial risks [17,70], low-income fishers’ unwillingness to absorb additional costs [61], and operational burdens such as separating lots, data entry and printing labels [36]. Reluctance to adopt new technologies also stems from concerns about changing established ways of operating and fears of sharing information, which could pose a competitive disadvantage [80]. Furthermore, some actors are sceptical

of the advantages of traceability technologies [39], suggesting that clearly communicating the advantages and benefits to each supply chain actor is critical for promoting uptake. By aligning traceability incentives with stakeholder interests, modernization efforts are more likely to be embraced.

The sub-category “Other social concerns” included broader concerns, particularly around “Concerns about confidentiality/trust in the traceability system” (25%, n = 18) [7,9,30,35,39,42,44,47,51,53,54,61,67,72,76,80,84] and perceived “Concerns over increased control, social inequalities and ethics” (7%, n = 5) [9,50,59,73,84].

While traceability systems have the potential to build trust and strengthen relationships within supply chains, this is not always the case. For instance, this complexity is illustrated in a study of migrant fishers in Thailand, where increased visibility through traceability systems did not lead to greater protection or empowerment [84]. Despite the digital monitoring, workers felt unable to report abuse due to their dependence on employers for legal status and mobility. The authors highlight that traceability systems can inadvertently reinforce existing power hierarchies. Traceability systems alone cannot be expected to address such social issues, as these are governance-related challenges that require careful consideration during the implementation of traceability systems.

Similarly, a lack of trust is often present at the outset of implementing traceability systems due to a history of competitive relationships within the aquatic food sector, where profits are frequently prioritized over collaboration [35]. Concerns around confidentiality are common, as sharing data may expose sensitive business information. For example, wholesalers may be reluctant to participate in traceability systems if doing so reveals their buyers to fishers or competitors, potentially threatening client relationships [80].

Power dynamics are another significant concern. While traceability systems can be seen as a competitive advantage by intermediaries, its implementation may further consolidate power imbalances between fishers and other supply chain actors, as well as between the global South (where aquatic food is largely sourced) and the global North (where traceability requirements and markets are concentrated) [59,62]. For instance, the EU relies heavily on aquatic food imports, and most originates in countries such as China, Morocco, Ecuador and Vietnam [85]. Consequently, the growing demand for traceability from the global North will intensify pressure on developing countries, particularly on downstream supply chain actors. It is expected that new regulations, such as Regulation (EU) No 2023/2842 mandating enhanced supply chain traceability, will further increase the demands on exporting countries in the global South. Although traceability measures aim to improve food safety, enhance control, combat IUU fishing, they may also drive-up cost and prices, shift market access dynamics and exacerbate existing power inequalities. For traceability to support equitable governance, it is essential to examine who bears the implementation costs, who controls the resulting data, and how systems can avoid reinforcing inequalities [19]. Addressing these concerns is key to ensuring that traceability contributes to meaningful and inclusive change rather than perpetuating existing disparities.

4.3. Economic challenges in traceability systems

The most frequently mentioned economic theme in the literature is the “High implementation and maintenance costs” of traceability, mentioned in 62% of articles (n = 44) [7,9,17,19,24,25,29,35–37,39,41–44,48–53,56,58–75,77,79,84,86]. Despite the widespread recognition of cost-related barriers, there is notable lack of concrete data in the literature on the actual financial costs associated with the implementation of traceability, resulting in limited transparency on this issue. The non-profit organization *Future of Fish* highlights this issue, identifying the absence of detailed data on costs - covering the costs involved in scoping, implementing, and using these systems - as a significant barrier to the adoption of traceability technology. In response, they

produced a comprehensive report [87] based on interviews with aquatic food companies and technology providers, outlining the financial breakdown of direct and indirect costs, including the extensive labour investment in terms of hours of labour, and revealing that implementing these systems can incur thousands of dollars. Improving standardized information on cost is essential for transparency, supporting informed decision-making and fostering the broader adoption of traceability technologies in the aquatic food sector. This issue could be addressed in supply chains where stakeholders are proactively engaged and supported, for example, governments could provide targeted financial support to ensure equitable access to traceability technologies.

4.4. Governance challenges in traceability systems

Governance-related challenges were grouped into several sub-categories, each representing a distinct issue affecting aquatic food traceability.

Under the “Regulatory framework” sub-category, the most frequently cited challenge was the “Absence of regulations and legislation” (21%, $n = 15$) [9,17,19,31,34,50,51,59,60,62–64,69,70,88]. A lack of regulatory requirements impedes the development and adoption of traceability systems [17]. Government support and regulation are critical for setting minimum information standards and addressing interoperability challenges across diverse supply chains.

The “Labelling” sub-category includes the challenge “Misidentification and mislabelling” (8%, $n = 6$) [19,47,58,67,73,74]. Even when regulations exist, the complex nature of aquatic food supply chains makes effective traceability difficult. Mislabelling - intentional or accidental - often occurs during product transfers between actors [58]. This underscores the need for stricter labelling standards and traceability systems capable of identifying inconsistencies throughout the supply chain.

Within the “Government role” sub-category, the challenge of “Insufficient governmental support” (8%, $n = 6$) [19,47,58,67,73] was cited. Often, retailers disclose information to consumers on a “need-to-know” basis, primarily to manage reputational risks [19]. Regulatory backing is essential to incentivize adoption, support capacity building, and enforce compliance.

The sub-category “Stakeholder relationships” includes the challenge “Stakeholder disconnection and misalignment of goals” (7%, $n = 5$) [35, 41,58,65,80]. The globalization and complexity of aquatic food supply chains often result in difficulties establishing cohesive relationships, as actors often have differing goals and interests. This challenge is shaped by inter- and intra-firm dynamics and power imbalances, particularly between upstream and downstream supply chain actors [35,58]. Addressing this issue requires building trust, fostering collaboration, and establishing consistent, shared goals, even across countries, to enable consistent regulatory implementation.

4.5. Environmental challenges in traceability systems

The environmental category consists of a single sub-category “Environmental impact”, which includes the least frequently mentioned challenge “Enhancing negative environmental impacts” (3%, $n = 2$) [9,73]. Although sparsely explored in the literature, this issue primarily relates to the energy consumption required for operating traceability systems. While the articles reviewed do not provide detailed data on energy use, it is known that certain digital technologies - especially blockchain - can be energy-intensive. However, energy demand varies depending on the algorithm used. For example, Practical Byzantine Fault Tolerance (PBFT), commonly employed in traceability databases, is considered energy-efficient compared to other algorithms [77, 89]. Of the two articles mentioning environmental impacts, one focuses on blockchain technology [9], while the other does not specify the technology used [73]. Consequently, the findings are somewhat inconclusive regarding the precise scale of environmental impacts. Further

research is needed to better understand and address potential environmental concerns associated with traceability systems.

5. Opportunities in aquatic food traceability

As with challenges, opportunities associated with traceability in aquatic food systems were grouped into five main categories, ranked by frequency of citations across the reviewed literature: governance, social, technological, environmental, and economic. These are followed by a set of cross-cutting opportunities that cut across all categories (Fig. 5). This categorization highlights the diverse and interconnected benefits that traceability systems can offer.

5.1. Governance opportunities in traceability systems

Opportunities in terms of governance were grouped into two sub-categories: “Enhanced management and compliance” and “Social responsibility”. The first encompasses three major themes, “Demonstrating compliance” (58%, $n = 42$) [9,10,19,29–31,35,36,38,39,43–48,50–52, 55–57,60,61,63,64,66–69,71,72,74,76–78,80,84,88,90–92], “Reducing illegal, unreported and unregulated (IUU) fishing” (38%, $n = 27$) [9,17, 19,31,39,42,43,47,53,56–59,61–64,67–69,74,76,81,84,88,90,91] and “Improving management and regulatory frameworks” (30%, $n = 22$) [9, 31,34,37,38,45–47,49–52,61,63,69,73,77,79,82,88,90,91].

Traceability systems can support aquatic food governance by embedding verifiable information throughout the supply chain. This information may serve as legal evidence to demonstrate the authenticity, legality, and sustainability of products, preventing those linked to IUU fishing, labour abuses, or environmental violations from entering key markets [10,84]. This is particularly advantageous for accessing markets such as the EU and USA, where growing requirements increasingly demand proof of legality and sustainability [76,84].

Technological advancements in traceability not only support regulatory compliance but can also potentially enhance the value of aquatic food products [31]. Traceability information can be used to improve internal management practices across aquatic food businesses, including inventory control, real-time decision-making in production practices, and consistent product quality [52]. In this way, traceability contributes to the transformation of the global aquatic food trade into a more transparent, reliable, accountable system adaptable to diverse entities and jurisdictions [64].

The second sub-category “Social responsibility”, includes two key opportunities: “Enhancing reputation, accountability and ethics” (19%, $n = 14$) [9,10,17,29,35,49,52,59,65,67,73,79,88,91] and “Empowering communities and improving relationships; fostering ownership pride” (11%, $n = 8$) [19,29,31,34,41,58,69,83]. Traceability systems can reinforce corporate social responsibility (CSR) by enabling aquatic food businesses to showcase their commitment to legal compliance and ethical sourcing, thereby enhancing brand reputation [29]. This is increasingly important given rising consumer and government scrutiny of aquatic food sustainability and social impacts.

Caution is needed as CSR claims may sometimes be driven more by maintaining legitimacy, image, and reputation, to meet consumers' growing awareness of the potential negative impacts of aquatic food production, than by genuine efforts to create equitable and inclusive supply chains [19].

Nonetheless, traceability can empower communities and supply chain actors. In an article it was observed that fishers felt a renewed sense of pride and ownership when receiving positive feedback from consumers [34]. In another study, suppliers used traceability tools to inform and educate customers about their products and practices, strengthening business identity [83].

Inclusive implementation of traceability is also crucial. It is important to engage communities to understand their needs and tailor solutions that work for them, regardless of their position in the supply chain, rather than imposing one-size-fits-all systems [41]. When traceability is

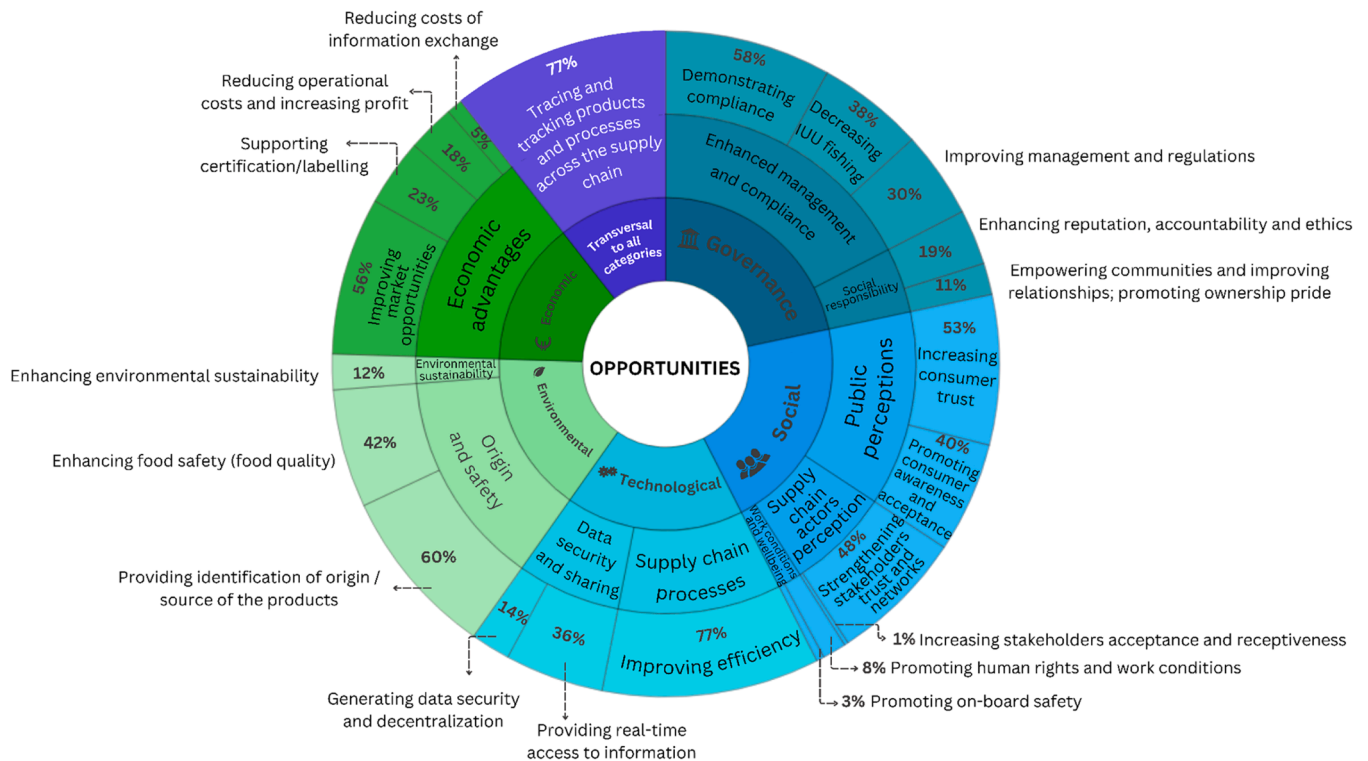


Fig. 5. Opportunities for aquatic food traceability identified in the literature, organized into five main categories: governance, economic, social, technological, environmental and transversal to all categories (inner circle), and their respective sub-categories (middle circle) and themes (outer circle). Percentages represent the proportion of reviewed papers mentioning each specific opportunity.

introduced as a regulatory requirement, policymakers should ensure the system is flexible and adaptable to avoid imposing a disproportionate burden on specific groups. Collaboration and adaptability are essential to foster an inclusive, effective system that benefits all supply chain actors and promotes greater transparency.

5.2. Social opportunities in traceability systems

Social opportunities associated with aquatic food traceability fall under three main themes: “Public perceptions”, “Supply chain actors’ perceptions” and “Work conditions and wellbeing”.

A significant portion of the literature highlights the role of traceability in improving “Public perceptions” especially “Increasing consumer trust” (53%, $n = 38$) [9,10,17,19,25,29,34,36,40,44–48,51,52,54–56,62,63,66–71,73,77,78,82,83,88,90,91,93–95] and “Promoting consumer awareness and acceptance” (40%, $n = 28$) [9,10,17,24,25,29,31,35,37,39,44,46,59,60,62,66–69,71,73,79,80,82,83,86,94,95].

Traceability systems ensure quality and safety of products, provide verifiable information about the product’s origin and its journey through the supply chain, which can foster consumer confidence and enhance the value of products [44,68]. However, consumer responses to traceability are not uniform. Traceability might appeal primarily to consumers, more conscious of aquatic food quality, sustainability, or ethical sourcing, which are willing to pay a premium for these products [96]. The impact of traceability on aquatic food pricing and consumer willingness to pay remains underexplored in the literature. Making traceability a legal requirement may shift broader cultural norms, enhancing trust and confidence in aquatic food products and fostering more informed, responsible consumption.

Under the sub-category “Supply chain actors’ perception”, a main opportunity emerged “Strengthening stakeholders trust and networks” (48%, $n = 34$) [9,10,24,29,30,35,39–41,45–48,51,54,56–58,62,67,69,71,74,76,77,81–83,88,90–93,95]. It also includes “Increasing stakeholders’ acceptance and receptiveness” ($N = 1$) [80]. For instance,

compatibility with fishing operations, aquaculture farms, or restaurant management systems can facilitate the adoption of this technology. Trust and transparency, fostered through traceability tools, can enhance cooperation and facilitate information sharing across aquatic food supply chains [10]. However, trust is not automatically created through digital tools alone; it must often be built through collaborative, co-designed implementation processes [76]. In fragmented and globalized aquatic food supply chains, achieving such co-creation can be difficult, but inclusive stakeholder engagement and government dialogue may enhance system legitimacy and effectiveness.

Lastly, the social sub-category “Work conditions and wellbeing” highlights “Promoting human rights and work conditions” (8%, $n = 6$) [9,57,61,81,84,88] and, “Promoting on-board safety” (3%, $n = 2$) [1,61,88]. Labour rights abuses, including forced labour and exploitation of migrants, women, and children, remain widespread in the aquatic food sector [1]. Traceability systems can support ethical sourcing by verifying origin and production practices and preventing products associated with illegal or abusive practices from entering markets [84]. They can also help generate data on working conditions, promote fair trade certification, and encourage accountability [9]. However, questions remain about data integrity and oversight, including: Who ensures the accuracy of reported labour conditions? and how can systems avoid overlooking or misrepresenting key social indicators?

5.3. Technological opportunities in traceability systems

Technological opportunities in aquatic food traceability were grouped into two sub-categories: “Supply chain processes” and “Data security and sharing”.

“Improving efficiency” (77%, $n = 55$), part of first sub-category, was the most frequently cited opportunity for digital traceability in aquatic food systems [7,9,10,17,19,26,29–31,34–39,41–45,47,48,50–58,60–64,67,69–72,74,75,77–82,88,90–94]. Digital traceability systems streamline workflows, replacing outdated paper-based methods, reducing

documentation burdens, improving accuracy across transactions. For example, automated systems can eliminate manual catch reporting and facilitate real-time payments, enhancing operational performance across the supply chain [9,58,61]. Over time, this translates to improvements in quality control and document handling [38].

In the second sub-category, key opportunities included “Providing real-time access to information” (36%, n = 25) [10,24,25,29,30,35,36,43,45–47,50–52,54–56,67,69,71,73,77,84,90,91] and “Generating data security and decentralization”, mentioned in 10 articles (14%) [10,47,50,62,63,69,77,88,91,93], which enables easy continuous tracking of product movement within the supply chain and supports timely decision-making [35], and “Generating data security and decentralization” (14%, n = 10) [10,47,50,62,63,69,77,88,91,93]. These features help prevent data manipulation and increase trust across supply chain actors [10,69].

Together, these technological innovations support greater transparency, responsiveness, and reliability, pointing to a continued shift away from manual systems toward fully digital, integrated traceability solutions.

5.4. Environmental opportunities in traceability systems

Environmental opportunities linked to traceability were grouped into two sub-categories: “Origin and safety” and “Environmental sustainability”.

In the “Origin and safety” sub-category, key opportunities include: “Providing identification of origin / source of the products” (60%, n = 43) systems [7,9,10,17,19,24,25,29,30,34,35,37,39,40,43–47,53–57,62–64,66,67,69,71,73–75,77,78,81,83,88,90,91,93,95] and “Enhancing food safety and quality” (42%, n = 30) [7,9,10,19,35,37,38,40,44,45,47,49–51,57,58,61,63,65,66,68,69,73,77,79,81,86,88,91,93]. Traceability systems enable detailed documentation of the origin of the product, whether wild-caught or farmed. This improved product authenticity, allows for the verification of the production area and capture method, and strengthens consumer trust [66,67]. Traceability also facilitates the identification of food safety issues, for instance, in the event of contamination along the supply chain, allowing for a more accurate assessment of risks and enabling quicker actions to address issues [29,44].

An opportunity “Enhancing environmental sustainability” (12%, n = 9) [9,19,35,57,63,73,77,88,94] is included in under the “Environmental sustainability” sub-category. Traceability systems can track the carbon footprint of a product, reduce food waste by facilitating redistribution of surplus, and increase transparency regarding sustainable practices throughout the supply chain [77,88].

5.5. Economic opportunities in traceability systems

Economics opportunities of traceability include “Economic advantages”, which includes four key opportunities, namely, “Improving market opportunities” (56%, n = 40) [10,17,19,25,31,34–39,41,44,45,49,52–54,57,58,60–62,65–67,69,71,73,77–81,83,90–94], “Supporting certification/labelling” (23%, n = 17) [10,17,19,31,34,35,37,39,43,44,50,56,69,73,74,77,90] “Reducing operational costs and increasing profit” (18%, n = 12) [31,38,52,55,58,61,63,67,81,84,90,91] and “Reducing costs of information exchange” (5%, n = 4) [10,35,51,62].

Traceability systems enable product differentiation and visibility, boosting consumer interest and enhancing market competitiveness [10,25]. Informed consumers are often willing to pay a higher price for traceable, high-quality aquatic food, incentivizing supply chain operators to maintain traceability practices [25]. Traceability is a requirement to prevent mislabelling [10] and to support sustainability certification in fisheries and aquaculture, which is increasingly required for access to premium markets [10,17,37]. Beyond market access, traceability can reduce operational and communication costs and improve supply chain efficiency [10], though quantitative evidence on these cost savings

remains limited in the literature. In some cases, traceability has also been linked to improved labour outcomes, such as regularized payments for migrant workers [84].

These incentives suggest potential for broader socioeconomic benefits, and future research could explore which specific economic benefits most effectively drive stakeholders’ adoption of traceability in aquatic food supply chains, and whether motivations differ by type of stakeholders (e.g., producers, processors, retailers, or small vs large scale operators).

5.6. Opportunities transversal to all categories

The opportunity “Tracing and tracking products and processes across the supply chain” is categorized as transversal, as it intersects with all categories: governance, social, technological, environmental, and economic. Not surprisingly, it is also an opportunity most frequently cited in the literature (77%, n = 55) [7,9,10,17,19,24,25,29,30,34–39,42,45–48,50–58,60–64,67,69–75,78,80,83,84,86,88,90–95,97]. Although this opportunity might seem redundant given that the purpose of traceability is to track and trace, many articles emphasized the specific benefits of improved traceability mechanisms. These include enhanced communication between different actors in the supply chain [45], real-time quality control and corrective actions [53], and more transparent, community-based supply chains, as demonstrated in the “Fishadelphia” community-supported fishery initiative [83]. These examples highlight how robust traceability systems can create ripple effects across multiple dimensions, significantly improving aquatic food tracking and tracing, and reinforcing their role as a foundational tool for more transparent, responsive, and inclusive aquatic food systems.

6. Challenges and opportunities of traceability systems by focus

The distribution of challenges and opportunities in the reviewed literature reveals a few differences across aquatic food sectors, geographic regions, and types of technology. Examining these characteristics helps to understand how contextual factors shape the implementation and effectiveness of traceability systems. The following subsections highlight the most recurrent challenges and opportunities within each focus, illustrating how sectoral, regional, and technological characteristics influence the development and uptake of traceability in aquatic food value chains.

6.1. Challenges to traceability across aquatic food sectors

Traceability challenges identified in the reviewed literature were analysed according to the aquatic food sector they addressed: all fisheries and all aquaculture, and small-scale fisheries separately (Fig. 6). To isolate sector-specific insights, articles that merged multiple aquatic

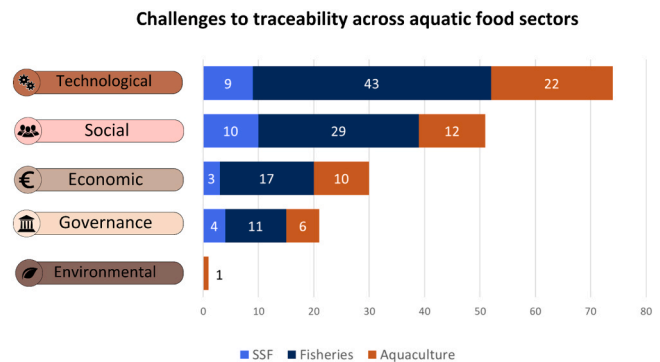


Fig. 6. Number of references mentioning traceability challenges across aquatic food sectors - fisheries and aquaculture in general, and small-scale fisheries - within each category (n = 46). SSF = small-scale fisheries.

food sectors were excluded, resulting in a final dataset of 46 articles. The only article addressing small-scale aquaculture was grouped with the other aquaculture articles. Fig. 6 presents the total number of mentions for each challenge category by sector.

Technological challenges were the most frequently mentioned across the fisheries and aquaculture sectors overall. The order of challenge categories was generally consistent across these two sectors, suggesting that the aquatic food industry faces broadly similar traceability obstacles regardless of the production systems. However, this trend did not hold for small-scale fisheries, where social challenges appeared more prominently.

Articles specifically focused on small-scale fisheries were underrepresented ($n = 6$) limiting the strength of conclusions. The most frequently mentioned challenges in this sector included: “Lack of interest/buy-in from supply chain actors”, “Absence of incentives for actors to join the system”, “Concerns about confidentiality/trust in the traceability system” and “Limited access to technology and/or familiarity with traceability”. Despite their recurrence, these challenges were not typically linked to unique characteristics of the small-scale fisheries sector in the reviewed articles.

One surprisingly underexplored issue was the challenge “Volume and variety of aquatic food products”, which is often cited as a problem for the small-scale fisheries sector. Small-scale fisheries typically involve small volumes of diverse catches difficult to trace to individual vessels and are usually aggregated during processing [17]. This issue may also extend to small-scale aquaculture, where inconsistent production volumes have been reported as a barrier to accessing broader markets [73].

Interestingly, most articles focused on traceability of small-scale fisheries ($n = 4$) targeted tuna fisheries [17,61,76,81]. This interest in tuna may be due to it being one of the most widely traded aquatic products globally, making it the subject of international regulation [98]. The traceability of tuna is particularly important for compliance with export requirements for major markets such as the EU [74].

Another recurring theme in the small-scale fisheries literature was the pressure exerted by global North markets and dominant retailers on producers in the global South. Two articles [17,81] highlighted compliance challenges related to stringent requirements imposed by the USA or EU. These cases illustrate a mismatch between those incurring the costs of traceability and those benefiting from it. Therefore, it is necessary that traceability systems and associate regulations (e.g., Regulation (EU) No 2023/2842) account for the unique characteristics and constraints of small-scale fisheries and aquaculture to ensure equitable and effective compliance.

It is important to note that the reviewed literature did not systematically distinguish between marine and freshwater systems within aquatic food sectors. As a result, this study could not assess potential differences in traceability challenges and opportunities between these environments. However, these differences are significant and deserve further attention. For instance, a large share of freshwater fisheries production remains unreported or unidentified by species, although reporting rates vary geographically - from as low as 10% in Europe to over 60% in some Asian countries [1]. The majority of freshwater production takes place in developing regions, particularly in Asia and Africa, which together account for over 90% of global freshwater catches. In these areas, producers encounter considerable challenges in monitoring fisheries that are geographically scattered, operationally complex, and demanding in terms of resources [1]. These characteristics may make the implementation of traceability systems in freshwater systems particularly challenging. Future research should therefore examine how traceability systems can be adapted to the specific operational and institutional contexts of marine and freshwater production.

6.2. Traceability opportunities across aquatic food sectors

Fig. 7 illustrates how traceability-related opportunities differ across the aquatic food sectors - fisheries (including small-scale fisheries),

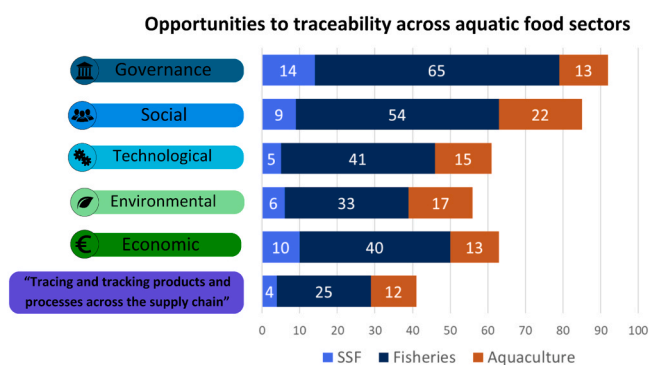


Fig. 7. Number of references mentioning opportunities for traceability across aquatic food sectors - fisheries and aquaculture in general, and small-scale fisheries - within each category ($n = 46$). SSF = small-scale fisheries.

aquaculture, and small-scale fisheries) based on 46 articles that focus on one of these sectors. A single article addressed small-scale aquaculture and was grouped with other aquaculture articles due to limited representativeness.

In fisheries and small-scale fisheries, governance-related opportunities are most frequently cited, particularly concerning the prevention of IUU fishing, a complex challenge involving jurisdictional fragmentation and regulatory gaps across maritime zones. In response, FAO developed a document identifying Critical Tracking Events (CTEs) and Key Data Elements (KDEs) across all supply chain steps, along with their respective data sources [1]. This framework aims to leverage traceability systems to address compliance, including targeting IUU fishing.

For small-scale fisheries, economic opportunities rank second, with the most cited being "Improving market opportunities". Small-scale fisheries could gain great opportunities by complying with export requirements in high-value markets, such as the EU and USA [80], and the use of these tools, can enable access to aquatic food markets that would otherwise remain out of reach [61]. However, equitable access remains a concern, as the implementation of traceability systems could exacerbate the marginalization of communities with limited financial or influential power in the international aquatic food market [19]. Nonetheless, when implemented inclusively, considering access and governance issues, unique market opportunities could be unlocked for small-scale fisheries, as the sector can align with consumer demand for sustainable, premium aquatic food and promote fairer supply chains.

In the fisheries sector, social opportunities rank second, especially "Increasing consumer trust" and "Strengthening stakeholder trust and networks". Fisheries supply chains involve complex networks with multiple intermediaries and traceability supports transparency in these complex supply chains, contributing to foster trust among consumers and stakeholders alike [17,74].

For aquaculture, the most cited opportunity falls under the social category, particularly "Increasing consumer trust". By improving transparency and information, traceability can counter negative consumer perceptions of aquaculture, particularly regarding the quality of fish feed [45,78]. Environmental opportunities rank second, with key opportunities including "Tracing and tracking products and processes across the supply chain", "Providing identification of origin/source of the products" and "Enhancing food safety (food quality)". These align with consumer concerns and further highlight the role of traceability in strengthening credibility and quality assurance of aquaculture products.

6.3. Challenges to traceability across geographic locations

The traceability challenges reported in the reviewed literature vary according to the geographical focus of the articles (Fig. 8). To isolate location-specific patterns, articles that combined multiple regions ($n = 16$) or did not specify a geographic location ($n = 7$) were excluded,

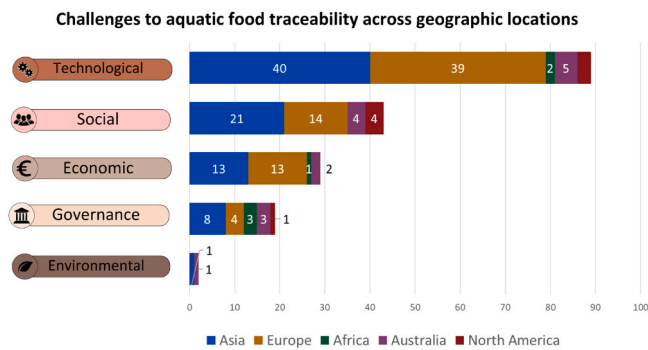


Fig. 8. Number of references mentioning challenges related to aquatic food traceability in different geographic locations, within each category (n = 48).

resulting in a final sample of 48 articles considered in this section.

Social and technological challenges are most frequently mentioned in articles from North America and Australia, while governance challenges dominate in African-focused literature. In contrast, articles based in Europe and Asia predominantly emphasize technological challenges. Notably, environmental challenges were only reported in articles focused on Africa and Asia.

As highlighted previously, power asymmetries between actors in the global North and producers in the global South are a recurring concern. Several articles emphasized the fact that traceability requirements disproportionately burden producers in the South [19,61]. These dynamics often exacerbate existing inequities and raise questions about the fairness and feasibility of implementing universal traceability standards. While broad continental trends are observable, some traceability challenges are more closely tied to specific national or local contexts. For instance, some studies have noted that remote areas often face great difficulties in accessing infrastructure or skilled human capital for implementing traceability [29,35]. Similarly, regulations can introduce unintended traceability challenges. For example, the introduction of yellowfin tuna stock rebuilding programs and quotas in the Indian Ocean after 2016 led to the incentive to mislabel over-quota catches as alternative species [74]. These examples highlight that while certain challenges are influenced by specific conditions, broader systemic issues such as inequalities in power dynamics and regulatory complexities remain key obstacles to achieving effective and equitable traceability in global aquatic food supply chains.

6.4. Traceability opportunities across geographic locations

Traceability-related opportunities were also examined by location. Of the reviewed studies, 48 articles were included in this analysis, excluding those that combined multiple regions (n = 16) or did not specify a location (n = 7).

As shown in Fig. 9, regional trends were subtle but notable. Articles focused on Asia, Africa, Australia, and North America tended to emphasize governance and social opportunities. In contrast, European articles focused more on the utilitarian advantage of traceability, particularly “Tracing and tracking products and processes across the supply chain”. This variation may reflect different regional priorities. In the global South, where regulatory systems and market access challenges are more pronounced, traceability offers opportunities to improve governance, transparency, and inclusion. In Europe, where regulatory frameworks and infrastructure are more established, the focus shifts to process efficiency and quality assurance.

Notably, human rights protections and the working conditions of migrant workers emerged as key themes in two Asian-focused articles [9,84]. While these issues are global, the emphasis in the Asian context reflects the region’s dominant role in the aquatic food sector. As of 2022, Asia accounted for 70% of the global aquatic animal output, 91.4% of

Opportunities to aquatic food traceability across geographic locations

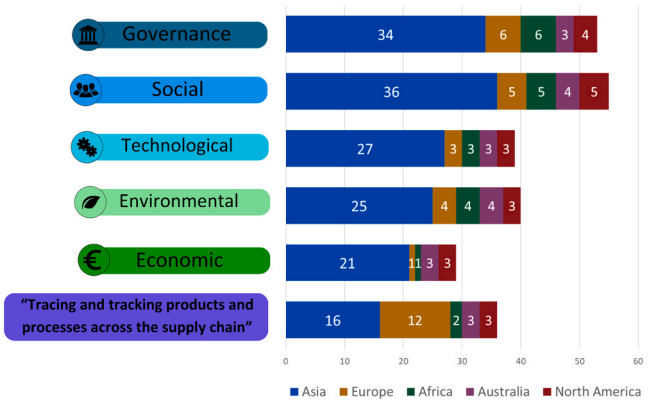


Fig. 9. Number of references mentioning opportunities related to aquatic food traceability in different geographical locations, within each category (n = 48).

the total aquaculture production, and hosted the world’s largest fishing fleet. The region is also a leader in aquatic food consumption and exports [1]. Asian articles have also been contributing with important insights into aquatic food traceability for a slightly longer period (as shown in Fig. 3), offering valuable insights into implementation practices, challenges, and innovation. A more balanced representation of regional studies would further enhance understanding of how traceability systems function across diverse governance, economic, and social settings.

6.5. Challenges to traceability across technologies

Traceability challenges were also analysed in relation to the types of technologies discussed in the reviewed articles (Fig. 10). Articles that did not specify a particular technology (n = 28) were excluded, leaving 43 articles for analysis in this section. Technologies were grouped into two categories: blockchain-based systems and other technologies (e.g., barcodes, RFID, QR codes, cloud-based platforms, and databases).

Across both groups, technological challenges were the most frequently mentioned, followed by social, economic and governance, and finally environmental challenges. This ranking mirrors the general patterns observed across all reviewed articles (Fig. 6), suggesting that traceability systems face broadly similar barriers regardless of the technology employed.

Despite social challenges being discussed more frequently in articles focused on blockchain, few articles establish a direct link between these challenges and the technology itself. Some have noted that limited previously reported successful experiences with blockchain led to scepticism and reluctance among many supply chain actors to invest in its implementation [29]. Others observed that many pilot projects on

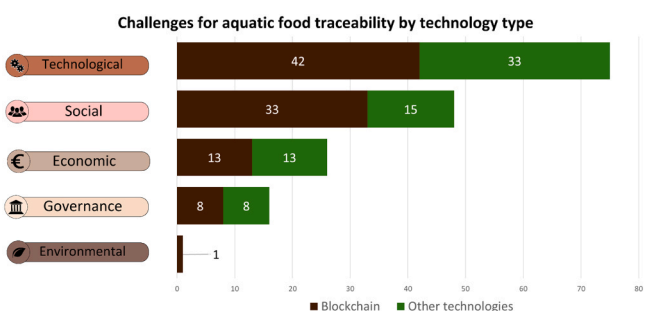


Fig. 10. Number of references mentioning challenges for aquatic food traceability by technology type - for blockchain and other technologies (e.g., barcodes, RFID, QR codes, cloud-based platforms, and databases) - within each category (n = 43).

blockchain traceability failed due to a lack of incentives, especially for producers, which they suggest could be mitigated through targeted financial support [57].

Stakeholder resistance to blockchain adoption was also linked to transparency concerns. Because blockchain systems can reveal sensitive trade and pricing data, certain actors - particularly intermediaries - have resisted its use to protect strategic information [80].

Despite blockchain being a relatively new technology, economic challenges associated with the costs of implementation, integration with other technologies (such as RFID tags or IoT devices) and maintenance were rarely described. Nevertheless, the lack of knowledge surrounding these systems likely imply costs that cannot be overlooked [64]. It is important to recognize that these more expensive technologies may be less accessible in less economically developed contexts, particularly in the Global South, where financial and infrastructural constraints further limit the feasibility of adopting advanced digital systems. It is essential to carefully assess whether blockchain technology is the right tool for a specific aquatic food system before pursuing its implementation [15].

6.6. Traceability opportunities across technologies

Traceability opportunities linked to specific technologies were analysed in 43 articles, excluding those that did not specify a technological approach ($n = 28$). As shown in Fig. 11, the most frequently mentioned opportunities relate to social and governance benefits. However, technological opportunities - particularly in articles focused on blockchain - are also prominent.

Blockchain, in particular, is highlighted for its ability to enhance data security and process integrity. For example, data recorded on a blockchain platform is immutable, creating an irreversible timeline [29], which is an effective tool against aquatic food fraud. In addition to its tamper-proof nature [30], blockchain also enables automated compliance through smart contracts - self-executing programs that streamline supply chain transactions - further enhancing traceability efficiency [56].

The most frequently cited opportunity across blockchain-related articles is “Improving efficiency”. However, efficiency gains - such as real-time data access and streamlined documentation - are also enabled by other digital technologies, suggesting these benefits are not exclusive to blockchain. The degree of automation and functionality can vary significantly depending on the technological tools deployed.

Further research is needed to assess different technologies in aquatic food traceability systems, including the cost-effectiveness and performance of blockchain versus alternative technologies. Such work could help identify which features are most critical to achieving traceability goals and which technologies best deliver them across different aquatic

food supply chain contexts.

7. Recommendations for stakeholder engagement in aquatic food traceability

The results of this review point to the need for coordinated governance approaches that translate traceability ambitions into inclusive and implementable policies. Because the challenges and opportunities identified are deeply interconnected, policy responses must be designed to align incentives and clarify the roles of key actors across the supply chain.

Governments should lead in developing coherent policy frameworks that promote interoperability and data standardization, while ensuring proportionality, so that compliance requirements match stakeholder capacity. In doing so, regulatory design should align with international traceability standards - such as those advanced by the Global Dialogue on Seafood Traceability (GDST) and endorsed by the FAO [99,100] - to ensure global coherence and compatibility. Regulatory instruments should be accompanied by financial and technical support to enable adoption among all types of stakeholders, including small-scale businesses and producers. National authorities could further promote uptake through incentives (such as subsidies for digital infrastructure, capacity building around technologies, or market recognition initiatives) to offset the high upfront costs of implementation and lack of buy-in of supply chain actors. Governments should also parallelly implement feedback mechanisms to capture stakeholder perspectives and facilitate joint and explanatory sessions that clarify traceability systems and related administrative obligations. Furthermore, governments must promote consumer awareness by endorsing education campaigns on the value of traceability, sustainability, and informed seafood choices, ultimately stimulating market demand for traceable products.

Producers are not only implementers but also key enablers of traceability. They can take active roles by participating in co-design and pilot initiatives to test context-appropriate tools, adopting simple digital record-keeping systems to build data consistency, and organizing collectively through cooperatives or associations to share costs and strengthen bargaining power. By engaging in training and digital literacy programs, producers can enhance their capacity to manage traceability systems effectively and use traceability data to demonstrate good practices, improve brand reputation, and access higher-value markets. Active participation in policy dialogues is also essential to ensure that regulations and technological solutions reflect the realities and constraints of production on the ground. However, these actions require coordinated support, adapted resources, and genuine interest from other stakeholders (such as governments, industry, NGOs) to foster the collaborative environments needed for such initiatives to succeed.

Industry actors (including processors, importers, or retailers), hold a pivotal responsibility for ensuring transparency and fairness along the supply chain. They must actively facilitate data sharing and traceability compliance. Their role extends beyond technological adoption to connecting directly with producers, returning value to traceable products through fair pricing, long-term partnerships, and recognition of sustainable practices. Industry actors should also ensure an equitable distribution of costs and benefits, acknowledging that smaller operators often face disproportionate burdens. Meaningful engagement with governments through regular feedback and participation in policy consultations is essential to ensure that regulations are both practical and effective. Finally, industry actors should take part in collaborative strategies that build trust, improve interoperability, and promote responsible sourcing across the sector.

NGOs can act as intermediaries by facilitating stakeholder dialogue, building capacity, and ensuring that traceability efforts incorporate social and ethical dimensions, including labour rights, gender equity, and community participation. They also have an important advocacy role, influencing policy agendas, promoting accountability, and raising public awareness about the social and environmental implications of

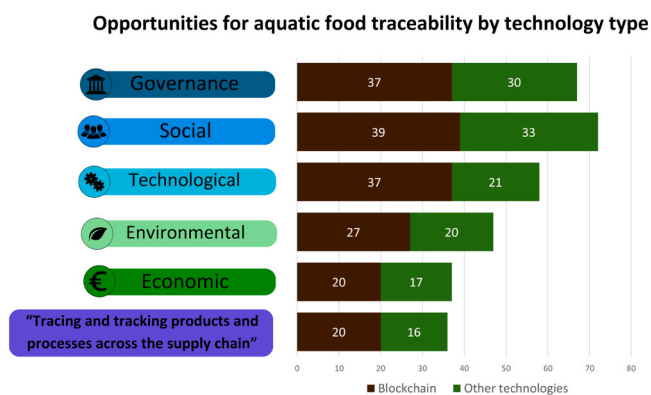


Fig. 11. Number of references mentioning opportunities for aquatic food traceability by technology type - for blockchain and other technologies e.g., barcodes, RFID, QR codes, cloud-based platforms, and databases - within each category ($n = 43$).

seafood production and trade. In addition, their efforts to harmonize standards and bridge data and capacity gaps between the global North and South are critical to achieving equitable and effective traceability implementation.

Researchers and innovation actors have a complementary role in assessing the design, implementation, performance, cost-effectiveness, and social impacts analysis of traceability tools, providing evidence to guide adaptive policy. Further collaboration between academia, governments, and industry can foster learning networks and support scaling of successful pilots.

While recognizing that the feasibility and implementation challenges differ across regions and governance context, we believe that, taken together, these governance actions and stakeholder collaborations can help move digital traceability from a compliance-oriented tool toward a transformative mechanism that fosters transparency, accountability, and equity across global aquatic food systems.

8. Conclusion

This systematic literature review highlights the complex landscape of challenges and opportunities associated with traceability systems in global aquatic food supply chains. While emerging technologies, such as blockchain, offer promising solutions for enhancing transparency, accountability and data security, their widespread adoption remains constrained by potential high costs, limited technical capacity, interoperability issues, the complexity of aquatic food supply chains, social resistance, and other governance and regulatory challenges. Despite these barriers, the benefits presented by aquatic food traceability systems are substantial and transformative. Traceability can expand market access, improve supply chain efficiency, enhance product quality, and strengthen consumer trust. Additionally, it can also promote social justice by increasing visibility into labour conditions, reducing exploitation, and supporting fair trade practices.

Addressing traceability challenges and capitalizing on the opportunities it provides requires context-specific approaches that considers the diversity and scale of aquatic food businesses, geographic region, and stakeholder capacities. The aquatic food sector is highly diverse, with significant variation in stakeholder capacities, regional governance structures, and supply chain complexity. One-size-fits-all solutions are unlikely to succeed. Instead, traceability initiatives should prioritize inclusive design, equitable cost-sharing, and regulatory frameworks tailored to local realities, particularly for small-scale fisheries and producers in the global South.

Looking ahead, future research should address key knowledge gaps, such as the cost-effectiveness of various technologies and traceability methods, the specific challenges faced by small-scale fisheries, and the needs of underrepresented regions like South America. As traceability systems evolve and gain momentum - playing an increasingly critical role in regulatory compliance and corporate reputation - efforts should prioritize inclusivity and adapt technologies to context-specific realities. Comparative analyses of traceability models can help inform implementation strategies tailored to diverse settings. Moreover, more empirical research is needed to understand how digital traceability systems can be scaled and sustained in resource-limited contexts without reinforcing existing inequalities.

In practical terms, the findings of this review suggest several policy and governance priorities. Governments should focus on creating enabling regulatory environments that align with international standards, provide targeted support for small-scale producers, and promote consumer awareness of traceability and sustainability. Industry actors must ensure transparency, equitable data sharing, and fair distribution of costs and benefits. NGOs can play crucial advocacy and capacity-building roles to promote inclusivity and accountability across supply chains. Collaborative and multi-stakeholder approaches are therefore essential to ensure that digital traceability advances both market efficiency and social equity.

Ultimately, traceability is more than a technological tool, it is a governance mechanism capable of driving aquatic food system change. By addressing implementation challenges and leveraging the opportunities presented, traceability can support the transition to more sustainable, equitable, transparent, and resilient aquatic food systems. Achieving this vision will require international cooperation, inclusive policy-making, and a commitment to innovation across the sector.

CRediT authorship contribution statement

Mafalda Rangel: Writing – review & editing, Supervision, Methodology. **Michelle Hübel:** Writing – review & editing. **João Pontes:** Writing – review & editing. **Katina Roumbedakis:** Writing – review & editing, Methodology. **Sofia Alexandre:** Writing – review & editing, Methodology, Investigation. **Cristina Pita:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Gisela Costa:** Writing – original draft, Methodology, Investigation, Conceptualization.

Acknowledgements

The authors would like to acknowledge the financial contribution of the Horizon Europe project SEA2SEE (Innovative blockchain traceability technology and stakeholders' engagement strategy for boosting sustainable seafood visibility, social acceptance and consumption in Europe) (Grant Agreement No. 101060564) and national funds through FCT – Fundação para a Ciência e a Tecnologia I.P. to CESAM under the project/grant UID/50006 + LA/P/0094/2020, CCMAR through projects UIDB/04326/2020 (DOI:10.54499/UIDB/04326/2020) and LA/P/0101/2020 (DOI:10.54499/LA/P/0101/2020), and to CP under project Ref.2020.02510.CEECIND/CP1589/CT0018. FCT/MCTES (<https://doi.org/10.54499/2020.02510.CEECIND/CP1589/CT0018>).

Author Statements

We, the authors (Gisela Costa, Cristina Pita, Sofia Alexandre, Katina Roumbedakis, João Pontes, Michelle Hübel, and Mafalda Rangel) confirm that:

- This manuscript is original, has not been published before, and is not under consideration for publication elsewhere.
- This study received financial support from the Horizon Europe project SEA2SEE (Grant Agreement No. 101060564), and national funds through FCT – Fundação para a Ciência e a Tecnologia I.P. to CESAM (UID/50006 + LA/P/0094/2020), CCMAR (projects UIDB/04326/2020, DOI:10.54499/UIDB/04326/2020, and LA/P/0101/2020, DOI:10.54499/LA/P/0101/2020), and to CP under project Ref. 2020.02510.CEECIND/CP1589/CT0018 (FCT/MCTES, DOI:10.54499/2020.02510.CEECIND/CP1589/CT0018).
- The authors declare no conflicts of interest.
- Ethical approval was not required for this research.
- All authors have read and approved the manuscript in its current form and agree with its submission to Marine Policy.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.marpol.2026.107154](https://doi.org/10.1016/j.marpol.2026.107154).

Data availability

Data will be made available on request.

References

- [1] FAO, State World Fish. Aquac. 2024 Blue Transform. Action. Rome (2024), <https://doi.org/10.4060/cd0683en>.
- [2] FAO, *The State of World Fisheries and Aquaculture 2022 - Towards Blue Transformation*. Rome, FAO, 2022, <https://doi.org/10.4060/cc0461en>.
- [3] A. Lem, M. Castro de Souza, and W. Griffin, "The importance of international trade for fisheries and aquaculture. Trade policy briefs products," Rome, 2023. doi: 10.4060/cc9061en.
- [4] J.L. Anderson, F. Asche, T. Garlock, Globalization and commoditization: the transformation of the seafood market, *J. Commod. Mark.* 12 (2018) 2–8, <https://doi.org/10.1016/j.jcomm.2017.12.004>.
- [5] M. Fox, M. Mitchell, M. Dean, C. Elliott, K. Campbell, The seafood supply chain from a fraudulent perspective, *Food Secur* 10 (4) (2018) 939–963, <https://doi.org/10.1007/s12571-018-0826-z>.
- [6] C.R. Hopkins, S.I. Roberts, A.J. Caveen, C. Graham, N.M. Burns, Improved traceability in seafood supply chains is achievable by minimising vulnerable nodes in processing and distribution networks, *Mar. Policy* 159 (2024) 105910, <https://doi.org/10.1016/j.marpol.2023.105910>.
- [7] Z. Du, Z. Wu, B. Wen, K. Xiao, R. Su, Traceability of animal products based on a blockchain consensus mechanism, *IOP Conf. Ser. Earth Environ. Sci.* 559 (Sep. 2020) 012032, <https://doi.org/10.1088/1755-1315/559/1/012032>.
- [8] S.G. Lewis, M. Boyle, The expanding role of traceability in seafood: tools and key initiatives, *J. Food Sci.* 82 (S1) (Aug. 2017) A13–A21, <https://doi.org/10.1111/1750-3841.13743>.
- [9] N. Tsolakis, D. Niedenzu, M. Simonetto, M. Dora, M. Kumar, Supply network design to address United nations sustainable development goals: a case study of blockchain implementation in Thai fish industry, *J. Bus. Res.* 131 (2021) 495–519, <https://doi.org/10.1016/j.jbusres.2020.08.003>.
- [10] Y. Zhang, Y. Liu, Z. Jiong, Z. Xiaoshuan, B. Li, E. Chen, Development and assessment of blockchain-IoT-based traceability system for frozen aquatic product, *J. Food Process Eng.* 44 (Feb. 2021), <https://doi.org/10.1111/jfpe.13669>.
- [11] M. Borit, P. Olsen, *Seaf. Trace Syst. gap Anal. inconsistencies Stand. norms* (2016).
- [12] A. Arizeno, C. Coff, D. Barling, The European union and the regulation of food traceability: from risk management to informed choice? in: C. Coff, D. Barling, M. Korhals, T. Nielsen (Eds.), *Ethical Traceability and Communicating Food* Springer Netherlands, Dordrecht, 2008, pp. 23–42, https://doi.org/10.1007/978-1-4020-8524-6_2.
- [13] Food and Drug Administration USA, "Food Safety Modernization Act (FSMA)," <https://www.fda.gov/food/guidance-regulation-food-and-dietary-supplements/food-safety-modernization-act-fsma>. Accessed: Feb. 05, 2025. [Online]. Available: <https://www.fda.gov/food/guidance-regulation-food-and-dietary-supplements/food-safety-modernization-act-fsma>.
- [14] NOAA Fisheries, "Seafood Import Monitoring Program." Accessed: Feb. 05, 2025. [Online]. Available: (<https://www.fisheries.noaa.gov/international/international-affairs/seafood-import-monitoring-program>).
- [15] F. Blaha, K. Katafono, *Blockchain application in seafood value chains*, *FAO Fish. Aquac. Circ. (C1207)* (2020) 1–43.
- [16] R.C. Subramaniam, et al., The socio-ecological resilience and sustainability implications of seafood supply chain disruption, *Rev. Fish. Biol. Fish.* 33 (4) (2023) 1129–1154, <https://doi.org/10.1007/s11160-023-09788-1>.
- [17] D.E. Duggan, M. Kochen, Small in scale but big in potential: opportunities and challenges for fisheries certification of Indonesian small-scale tuna fisheries, *Mar. Policy* 67 (2016) 30–39, <https://doi.org/10.1016/j.marpol.2016.01.008>.
- [18] C. Pita, A. Ford, Sustainable seafood and small-scale fisheries: improving retail procurement, 2023 International Institute Environment Development (IIED). Accessed (Feb. 05, 2025). (<https://www.iied.org/21306iied>) ([Online]. Available).
- [19] M. Bailey, S.R. Bush, A. Miller, M. Kochen, The role of traceability in transforming seafood governance in the global South, *Curr. Opin. Environ. Sustain* 18 (2016) 25–32, <https://doi.org/10.1016/j.cosust.2015.06.004>.
- [20] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, *Ann. Intern Med* 151 (4) (Aug. 2009) 264–269, <https://doi.org/10.7326/0003-4819-151-4-200908180-00135>.
- [21] V. Braun, V. Clarke, Using thematic analysis in psychology, *Qual. Res Psychol.* 3 (2) (Jan. 2006) 77–101, <https://doi.org/10.1191/1478088706qp063oa>.
- [22] F.T. Rothaermel, *Strategic management*, McGraw-Hill Education, 2015. (<https://books.google.pt/books?id=yPwMrgEACAAJ>) ([Online]. Available).
- [23] C. Breuil and Y. Yvergniaux, "Good governance of marine fisheries: concepts and intervention framework of the SmartFish Programme," 2014. Accessed: Feb. 09, 2025. [Online]. Available: <https://openknowledge.fao.org/handle/20.500.14283/bs229e>.
- [24] D.K. Guntuku, A.S. Kuna, D. Boyanapalle, B. Venkataraman, ITC AQUA CHOUPAL MODEL: An ICT based traceability mechanism for solving Indian shrimp export-oriented problems. *Computers in Agriculture and Natural Resources*, 4th World Congress Conference, Proceedings of the 24-26 July 2006 (Orlando, Florida USA) Publication Date 24 July 2006, ASABE, St. Joseph, MI, 2006, <https://doi.org/10.13031/2013.21926>.
- [25] K. Seino, et al., Development of the traceability system which secures the safety of fishery products using the QR code and a digital signature, *Oceans'04 MTS/IEEE Techno-Ocean* (IEEE Cat. No. 04CH37600) (2004) 476–481, <https://doi.org/10.1109/OCEANS.2004.1402962>.
- [26] G. Senneker, E. Forås, K.M. Fremme, Challenges regarding implementation of electronic chain traceability, *Br. Food J.* 109 (10) (Jan. 2007) 805–818, <https://doi.org/10.1108/00070700710821340>.
- [27] M. Borit, P. Olsen, Beyond regulatory compliance – seafood traceability benefits and success cases, *FAO Fish. Aquac. Circ. No. 1197* (2020) 52, <https://doi.org/10.4060/ca9550en>.
- [28] WWF Peru, "Toward traceability throughout the whole production chain - Fact sheet." Accessed: Feb. 01, 2025. [Online]. Available: https://wwflac.awsassets.panda.org/downloads/factsheet_traceability_2019_v2_5_1_1.pdf.
- [29] Y.-T. Lin, D. Pyke, R. Clarke, and A. Corporandy, *Bumble Bee and Blockchain*. London, 2023. doi: 10.4135/9781529619091.
- [30] A.E.C. Mondragon, C.E.C. Mondragon, E.S. Coronado, Feasibility of internet of things and agnostic blockchain technology solutions: a case in the fisheries supply chain, 2020 IEEE 7th Int. Conf. Ind. Eng. Appl. (ICIEA) (2020) 504–508, <https://doi.org/10.1109/ICIEA49774.2020.9102080>.
- [31] J. Penca, Mainstreaming sustainable consumption of seafood through enhanced mandatory food labeling, *Front Mar. Sci.* 7 (2020), <https://doi.org/10.3389/fmars.2020.598682>.
- [32] M.G. Bondad-Reantaso, P.B. Bueno, H. Demaine, T. Pongthanapanich, Development of an indicator system for measuring the contribution of small-scale aquaculture to sustainable rural development, *Meas. Contrib. small-Scale Aquac. Assess. FAO Fish. Aquac. Tech. Pap.* 534 (2009) 161–179.
- [33] J.G. da Cunha, M.A. Massola, A.M. Saraiva, V.L. Lobão, Continental malacoculture chain modeling and traceability requirements. *Computers in Agriculture and Natural Resources*, 4th World Congress Conference, Proceedings of the 24-26 July 2006 (Orlando, Florida USA) Publication Date 24 July 2006, ASABE, St. Joseph, MI, 2006, <https://doi.org/10.13031/2013.21923>.
- [34] C.E. Parlee, M.G. Wiber, Who is governing food systems? Power and legal pluralism in lobster traceability, *J. Leg. Plur. Unoff. Law* 43 (64) (Jan. 2011) 121–148, <https://doi.org/10.1080/07329113.2011.10756672>.
- [35] T. Bhatt, et al., Project to develop an interoperable seafood traceability technology architecture: issues brief, *Compr. Rev. Food Sci. Food Saf.* 15 (2) (Mar. 2016) 392–429, <https://doi.org/10.1111/1541-4337.12187>.
- [36] D. Asioli, A. Boecker, M. Canavari, Perceived traceability costs and benefits in the Italian fisheries supply chain, *Int. J. Food Syst. Dyn.* 2 (4) (2011) 340–356, <https://doi.org/10.18461/ijfsd.v2i4.242>.
- [37] K.T.P. Dong, Y. Saito, N.T.N. Hoa, T.Y. Dan, T. Matsuishi, Pressure–state–response of traceability implementation in seafood-exporting countries: evidence from Vietnamese shrimp products, *Aquac. Int.* 27 (5) (2019) 1209–1229, <https://doi.org/10.1007/s10499-019-00378-2>.
- [38] K.A.-M. Donnelly, P. Olsen, Catch to landing traceability and the effects of implementation – a case study from the Norwegian white fish sector, *Food Control* 27 (1) (2012) 228–233, <https://doi.org/10.1016/j.foodcont.2012.03.021>.
- [39] K.A.-M. Donnelly, M. Thakur, J. Sakai, Following the mackerel – cost and benefits of improved information exchange in food supply chains, *Food Control* 33 (1) (2013) 25–31, <https://doi.org/10.1016/j.foodcont.2013.01.021>.
- [40] N. Elfiana, I. Sulaiman, Yusriana, Traceability system for lobsters supply chain: a review finding and method, *IOP Conf. Ser. Earth Environ. Sci.* 1116 (1) (2022) 012010, <https://doi.org/10.1088/1755-1315/1116/1/012010>.
- [41] M. Gooch, B. Dent, G. Sylvia, C. Cusack, Rollout strategy to implement interoperable traceability in the seafood industry, *J. Food Sci.* 82 (S1) (Aug. 2017) A45–A57, <https://doi.org/10.1111/1750-3841.13744>.
- [42] M.J. Hardt, K. Flett, C.J. Howell, Current barriers to large-scale interoperability of traceability technology in the seafood sector, *J. Food Sci.* 82 (S1) (Aug. 2017) A3–A12, <https://doi.org/10.1111/1750-3841.13796>.
- [43] K.M. Karlsen, B. Dreyer, P. Olsen, E.O. Elvevoll, Granularity and its role in implementation of seafood traceability, *J. Food Eng.* 112 (1) (2012) 78–85, <https://doi.org/10.1016/j.jfoodeng.2012.03.025>.
- [44] T. (Jiun-Shen) Lee, M. Hsu, A.M. Dadura, K. Ganesh, TRIZ application in marketing model to solve operational problems for Taiwanese aquatic products with food traceability systems, *Benchmark. Int. J.* 20 (5) (Jan. 2013) 625–646, <https://doi.org/10.1108/BJJ-01-2012-0001>.
- [45] L. Qi, J. Zhang, M. Xu, Z. Fu, W. Chen, X. Zhang, Developing WSN-based traceability system for recirculation aquaculture, *Math. Comput. Model* 53 (11) (2011) 2162–2172, <https://doi.org/10.1016/j.mcm.2010.08.023>.
- [46] J. Oliveira, et al., Traceability system for quality monitoring in the fishery and aquaculture value chain, *J. Agric. Food Res* 5 (2021) 100169, <https://doi.org/10.1016/j.jafr.2021.100169>.
- [47] P.K. Patro, R. Jayaraman, K. Salah, I. Yaqoob, Blockchain-based traceability for the fishery supply chain, *IEEE Access* 10 (2022) 81134–81154, <https://doi.org/10.1109/ACCESS.2022.3196162>.
- [48] L.F. Rahman, L. Alam, M. Marufuzzaman, U.R. Sumaila, Traceability of sustainability and safety in fishery supply chain management systems using radio frequency identification technology, *Foods* 10 (10) (2021), <https://doi.org/10.3390/foods10102265>.
- [49] F. Wang, Z. Fu, W. Mu, L. Moga, Z. Xiaoshuan, Adoption of traceability system in Chinese fishery process enterprises: difficulties, incentives and performance, *J. Food Agric. Environ.* 7 (Apr. 2009).
- [50] J. Zhang, T. Bhatt, A guidance document on the best practices in food traceability, *Compr. Rev. Food Sci. Food Saf.* 13 (5) (Sep. 2014) 1074–1103, <https://doi.org/10.1111/1541-4337.12103>.
- [51] H. Zhang, F. Gui, The application and research of new digital technology in marine aquaculture, *J. Mar. Sci. Eng.* 11 (2) (2023), <https://doi.org/10.3390/jmse11020401>.

- [52] D. Asioli, A. Boecker, M. Canavari, On the linkages between traceability levels and expected and actual traceability costs and benefits in the Italian fishery supply chain, *Food Control* 46 (2014) 10–17, <https://doi.org/10.1016/j.foodcont.2014.04.048>.
- [53] K.A.-M. Donnelly, K.M. Karlson, Lessons from two case studies of implementing traceability in the dried salted fish industry, *J. Aquat. Food Prod. Technol.* 19 (1) (Jan. 2010) 38–47, <https://doi.org/10.1080/10498850903430813>.
- [54] R. Garrard, S. Fielke, Blockchain for trustworthy provenances: a case study in the Australian aquaculture industry, *Technol. Soc.* 62 (2020) 101298, <https://doi.org/10.1016/j.techsoc.2020.101298>.
- [55] K. Gopi, D. Mazumder, J. Sammut, N. Saintilan, Determining the provenance and authenticity of seafood: a review of current methodologies, *Trends Food Sci. Technol.* 91 (2019) 294–304, <https://doi.org/10.1016/j.tifs.2019.07.010>.
- [56] S. Jiang, Truls Bakkejord Ræder, Experience on using archimate models for modelling blockchain-enhanced value chains. Proceedings of the 26th International Conference on Evaluation and Assessment in Software Engineering, in EASE '22, Association for Computing Machinery, New York, NY, USA, 2022, pp. 375–382, <https://doi.org/10.1145/3530019.3531346>.
- [57] F. Tolentino-Zondervan, P.T.A. Ngoc, J.L. Roskam, Use cases and future prospects of blockchain applications in global fishery and aquaculture value chains, *Aquaculture* 565 (2023) 739158, <https://doi.org/10.1016/j.aquaculture.2022.739158>.
- [58] V.D. Vo, N. Mainetti, P. Fenies, Traceability and transaction governance: a transaction cost analysis in seafood supply chain, *Supply Chain Forum. Int. J.* 17 (3) (Jul. 2016) 125–135, <https://doi.org/10.1080/16258312.2016.1188588>.
- [59] M. Bailey, H. Packer, L. Schiller, M. Tlusty, W. Swartz, The role of corporate social responsibility in creating a Seussian world of seafood sustainability, *Fish Fish* 19 (5) (Sep. 2018) 782–790, <https://doi.org/10.1111/faf.12289>.
- [60] L. Dediú, L.M. Moga, V. Cristea, The barriers for the adoption of traceability systems by Romanian fish farms, *Aquac. Aquar. Conserv. & Legis.* 9 (6) (2016) 1323–1330.
- [61] A. Grantham, Ma.R. Pandan, S. Roxas, B. Hitchcock, Overcoming catch data collection challenges and traceability implementation barriers in a sustainable, small-scale fishery, *Sustainability* 14 (3) (2022), <https://doi.org/10.3390/su14031179>.
- [62] O. Houghton, C. Campbell, G. Howe, T.H. Walcott, Evaluating the integration of blockchain technologies in supply chain management: a case study of sustainable fishing, 2022 Int. Conf. Comput. Netw. Telecommun. & Eng. Sci. Appl. (Conte) (2022) 51–56, <https://doi.org/10.1109/CoNTESA57046.2022.10011252>.
- [63] S. Ismail, H. Reza, K. Salameh, H. Kashani Zadeh, F. Vasefi, Toward an intelligent blockchain IoT-enabled fish supply chain: a review and conceptual framework, *Sensors* 23 (11) (2023), <https://doi.org/10.3390/s23115136>.
- [64] O. Korneyko, A. Podvolotskaya, S. Street, Assessment of the blockchain capabilities to combat the global trade in 'falsified' and 'illegal' fish products, *J. Eng. Appl. Sci.* 14 (10) (2019) 3310–3315.
- [65] A. Jose, S. Prasannavenkatesan, Traceability adoption in dry fish supply chain SMEs in India: exploring awareness, benefits, drivers and barriers, *Sadhana* 48 (1) (2023) 19, <https://doi.org/10.1007/s12046-023-02077-4>.
- [66] H. Metref, D. Calvo-Dopico, Señalización de la calidad y análisis de los beneficios asociados a la trazabilidad. Análisis del mercado del atún en España, ITEA-Inf. óN. Técnica Econ. ómica Agrar. 112 (2016) 421–437, <https://doi.org/10.12706/itea.2016.026>.
- [67] T. Sengupta, G. Narayanamurthy, R. Moser, V. Pereira, D. Bhattacharjee, Disruptive technologies for achieving supply chain resilience in COVID-19 era: an implementation case study of satellite imagery and blockchain technologies in fish supply chain, *Inf. Syst. Front.* 24 (4) (2022) 1107–1123, <https://doi.org/10.1007/s10796-021-10228-3>.
- [68] D. Suh, R. Pomeroy, Evaluation of seafood traceability system in Korea: demand-oriented analysis, *Ital. J. Food Saf.* 9 (3) (Nov. 2020), <https://doi.org/10.4081/ijfs.2020.9021>.
- [69] U. Tokkozhina, A.L. Martins, J.C. Ferreira, A. Casaca, Traceable distribution of fish products: state of the art of blockchain technology applications to fish supply chains, in: A.L. Martins, J.C. Ferreira, A. Kocian, U. Tokkozhina (Eds.), *Intelligent Transport Systems*, Springer Nature Switzerland, Cham, 2023, pp. 89–100, https://doi.org/10.1007/978-3-031-30855-0_6.
- [70] X. Zhang, J. Feng, M. Xu, J. Hu, Modeling traceability information and functionality requirement in export-oriented tilapia chain, *J. Sci. Food Agric.* 91 (7) (May 2011) 1316–1325, <https://doi.org/10.1002/jsfa.4320>.
- [71] A. Parreño-Marchante, A. Alvarez-Melcon, M. Trebar, P. Filippin, Advanced traceability system in aquaculture supply chain, *J. Food Eng.* 122 (2014) 99–109, <https://doi.org/10.1016/j.jfoodeng.2013.09.007>.
- [72] E.A. Jaya, M.Z.C. Candra, T.D. Ferindra, Development of blockchain-based traceability system for fishery products, 2021 Int. Conf. Data Softw. Eng. (ICoDSE) (2021) 1–6, <https://doi.org/10.1109/ICoDSE53690.2021.9648448>.
- [73] P. Schrobback, J. Rolfe, S. Rust, S. Ugalde, Challenges and opportunities of aquaculture supply chains: case study of oysters in Australia, *Ocean Coast Manag* 215 (2021) 105966, <https://doi.org/10.1016/j.ocecoaman.2021.105966>.
- [74] A. Thorpe, O. Hermansen, I. Pollard, J. Isaksen, P. Failler, G. Touron-Gardic, Unpacking the tuna traceability mosaic – EU SFPAs and the tuna value chain, *Mar. Policy* 139 (2022) 105037, <https://doi.org/10.1016/j.marpol.2022.105037>.
- [75] S. Frosch, M. Randrup, M. Thorup Frederiksen, Opportunities for the herring industry to optimize operations through information recording, effective traceability systems, and use of advanced data analysis, *J. Aquat. Food Prod. Technol.* 17 (4) (Oct. 2008) 387–403, <https://doi.org/10.1080/10498850802369179>.
- [76] A.A.A.S.K. Djelantik, S.R. Bush, “Assembling tuna traceability in Indonesia,” *Geoforum* 116 (2020) 172–179, <https://doi.org/10.1016/j.geoforum.2020.07.017>.
- [77] L. Hang, I. Ullah, D.-H. Kim, A secure fish farm platform based on blockchain for agriculture data integrity, *Comput. Electron. Agric.* 170 (2020) 105251, <https://doi.org/10.1016/j.compag.2020.105251>.
- [78] I. Islam, M. Nielsen, B. Badiuzzaman, B. Schulze-Ehlers, Knowledge transfer from experienced to emerging aquaculture industries in developing countries: the case of shrimp and pangasius in Bangladesh, *J. Appl. Aquac.* 33 (2) (Apr. 2021) 73–95, <https://doi.org/10.1080/10454438.2020.1716914>.
- [79] N. Mai, S. Gretar Bogason, S. Arason, S. Víkingur Árnason, T. Geir Matthíasson, Benefits of traceability in fish supply chains – case studies, *Br. Food J.* 112 (9) (Jan. 2010) 976–1002, <https://doi.org/10.1108/00070701011074354>.
- [80] B.S. Thompson, S. Rust, Blocking blockchain: examining the social, cultural, and institutional factors causing innovation resistance to digital technology in seafood supply chains, *Technol. Soc.* 73 (2023) 102235, <https://doi.org/10.1016/j.techsoc.2023.102235>.
- [81] A. Shamsuzzoha, J. Marttila, P. Helo, Blockchain-enabled traceability system for the sustainable seafood industry, *Technol. Anal. Strateg. Manag* (2023) 1–15, <https://doi.org/10.1080/09537325.2023.2233632>.
- [82] R.K. Haraldsdóttir, Á.D. Óladóttir, “Knowledge management and traceability of decisions for value creation in a family firm.” *Proceedings of the European Conference on Knowledge Management, ECKM, 2021*, pp. 335–344.
- [83] G. Cumming, K. Hunter-Thomson, T. Young, Local food 2.0: how do regional, intermediated, food value chains affect stakeholder learning? A case study of a community-supported fishery (CSF) program, *J. Environ. Stud. Sci.* 10 (1) (2020) 68–82, <https://doi.org/10.1007/s13412-019-00577-6>.
- [84] A. Kadfak, M. Widengård, From fish to fishworker traceability in Thai fisheries reform, *Environ. Plan E Nat. Space* 6 (2) (Jun. 2022) 1322–1342, <https://doi.org/10.1177/25148486221104992>.
- [85] T. and E. C. for F. European Commission: Scientific, R. Prellezo, J. Guillen, M. Tardy Martorell, J. Virtanen, and E. Sabatella, *The 2023 annual economic report on the EU fishing fleet (STECF 23-07)*. Publications Office of the European Union, 2023. doi: 10.2760/423534.
- [86] D. Duxbury, Traceability of seafood products, *Food Technol.* 58 (Jan. 2004) 60.
- [87] Future of Fish, “Costs for Traceability Technology Implementation.” Accessed: Jul. 09, 2024. [Online]. Available: <https://www.futureoffish.org/toolkits/understanding-costs-for-traceability-technology-implementation/>.
- [88] O.P.Z. Ouairi, J. Bennouri, Blockchain technology in sustainable supply chain management: from theoretical expectations to application perspective. Case of the fisheries sector, 2022 14th Int. Colloq. Logist. Supply Chain Manag. (LOGISTIQUA) (2022) 1–6, <https://doi.org/10.1109/LOGISTIQUA55056.2022.9938085>.
- [89] X. Zheng, W. Feng, Research on practical byzantine fault tolerant consensus algorithm based on blockchain, *J. Phys. Conf. Ser.* 1802 (3) (2021) 032022, <https://doi.org/10.1088/1742-6596/1802/3/032022>.
- [90] S.R. Bush, et al., Private provision of public information in tuna fisheries, *Mar. Policy* 77 (2017) 130–135, <https://doi.org/10.1016/j.marpol.2016.12.019>.
- [91] O. Iermakova, I. Sedikova, A. Dashian, Prospects of implementation of blockchain technology into aquaculture sector of Ukraine, *Econ. Ecol. Socium* 6 (2022) 29–37, <https://doi.org/10.31520/2616-7107/2022.6.2.3>.
- [92] B. Jäger, A. Mishra, IoT platform for seafood farmers and consumers, *Sensors* 20 (15) (2020), <https://doi.org/10.3390/s20154230>.
- [93] I. Afrianto, T. Djatna, Y. Arkeman, I. Hermedi, I.S. Sitanggang, Block chain technology architecture for supply chain traceability of fisheries products in Indonesia: future challenge, *J. Eng. Sci. Technol.* 15 (2020) 41–49.
- [94] A. Corallo, M.E. Latino, M. Menegoli, M. Cataldo, L. Mancarella, Application of technological system based on processes modelling and analysis: a case study in Italian aquaculture company, *IOP Conf. Ser. Mater. Sci. Eng.* 521 (1) (2019) 012010, <https://doi.org/10.1088/1757-899X/521/1/012010>.
- [95] A.P. Marchante, A.Á. Melcón, M. Trebar, A. Grah, P. Filippin, Improvement of traceability processes in the farmed fish supply chain, in: Z. Zhang, R. Zhang, J. Zhang (Eds.), *LISS 2012*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 1065–1070, https://doi.org/10.1007/978-3-642-32054-5_150.
- [96] R. Vriezen, M. Plishka, J. Cranfield, Consumer willingness to pay for traceable food products: a scoping review, *Br. Food J.* 125 (5) (Jan. 2023) 1631–1665, <https://doi.org/10.1108/BFJ-01-2022-0085>.
- [97] G.J. da Cunha, A.M. de, A. Massola, A.M. Saraiva, V.L. Lobão, Continental malacoculture chain modeling and traceability requirements. Computers in Agriculture and Natural Resources, 4th World Congress Conference, Proceedings of the 24-26 July 2006 (Orlando, Florida USA) Publication Date 24 July 2006, ASABE, St. Joseph, MI, 2006, <https://doi.org/10.13031/2013.21923>.
- [98] P. Guillotreau, D. Squires, J. Sun, G.A. Compeán, Local, regional and global markets: what drives the tuna fisheries? *Rev. Fish. Biol. Fish.* 27 (4) (2017) 909–929, <https://doi.org/10.1007/s11160-016-9456-8>.
- [99] F. Blaha, A. Vincent, Y. Piedrahita, Guidance document: advancing end-to-end traceability – critical tracking events and key data elements along capture fisheries and aquaculture value chains, FAO, 2023, <https://doi.org/10.4060/cc5484en>.
- [100] Global Dialogue on Seafood Traceability, “The Standard.” Accessed: Nov. 15, 2025. [Online]. Available: (<https://thegdst.org/resources/standard/>).