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Towards inclusive digital traceability in fisheries: Expert perspectives and the European Union regulatory framework

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ABSTRACT

With the globalization of aquatic food markets and rising legislative demands, traceability systems are gaining traction both as tools for tracking products, as well as potential levers for improving management, equity, and social responsibility across supply chains. However, their current implementation in fisheries often reinforces existing power imbalances, raises concerns about unequal burdens on supply chain actors, exposes interoperability challenges and the existent restricted information flows to consumers. To better understand digital traceability dynamics in fisheries, experts from a range of sectors (including the fishing industry, research and technology) were interviewed (n = 43) to identify key incentives and barriers about these systems. The study proposes a conceptual framework linking influencing factors (drivers, challenges, and solutions) to key dimensions of digital traceability systems, including governance, costs, data ownership, and technology use. Findings reveal that economic factors dominate both as primary drivers and as barriers to adoption of digital traceability. While stakeholders recognize benefits such as improved market access or enhanced consumer trust, they also highlight implementation and maintenance costs as continuous major challenges, particularly for small-scale fisheries and businesses. Experts also emphasize the importance of developing context-specific and interoperable solutions, supported by adequate financial and technical assistance. Additionally, regulation can be a powerful catalyst for the adoption of digital traceability in fisheries, but to be effective, it must go beyond just aiming for legal compliance to also foster inclusivity, resilience, and shared responsibility across fisheries value chains.

1. Introduction

The current globalized aquatic food trade system plays a crucial role in employment, food supply, revenue generation, and overall economic growth and development. In 2022, the European Union (EU) was the world's largest single market for aquatic animal products (with intra-EU trade also playing an important role) followed by the United States of America (USA), as the largest individual importing country, and China [1]

For the fisheries sector, international trade remains a cornerstone of global economic interconnection and food security strategies [2] However, the sector continues to face challenges related to data quality, often resulting from limited national surveys, unreported transshipments at sea, inadequate vessel and fisher registration systems, and the persistent issue of illegal, unreported, and unregulated (IUU) fishing [1] Moreover, supply chains have become increasingly complex due to advances in technology, logistics, and storage conditions, increasing difficulties in tracking the products. This limited availability of reliable information hampers sectoral development and undermines effective fisheries resource management [1] [3],

Digital traceability is one of the key innovations in sustainable fisheries trade and value chains [1], aiming at ensuring product quality, sustainability, and legality. The EU General Food Law defines traceability as "the ability to trace and follow a food, feed, food-producing animal, or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing, and distribution" [4] For the purposes of this study, we adopt the EU definition while acknowledging, as noted by Islam and Cullen [5], that multiple interpretations of traceability exist.

When discussing traceability an important distinction needs to be

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made between internal and external traceability. The concept of internal traceability, introduced by Moe [6], focuses on a specific stage within the supply chain and refers to the ability to track a product batch and its history within a single link of the production process. The sequential transfer of this information between different supply chain actors enables external traceability (or end-to-end traceability), which connects multiple organizations across the supply chain [5,6].

Traceability can serve the interests of various stakeholders, including consumers, businesses, public authorities, and the scientific community [6], with the potential of bringing several positive changes across the fisheries supply chain, including the access to higher-value markets [7], and the improvement of consumer trust [8,9].

To address the complexity of aquatic food supply chains and the lack of harmonization in related data, regulatory frameworks to improve transparency and traceability have begun to emerge worldwide [10] - for example, in the USA with the Food Safety Modernization Act and the Seafood Import Monitoring Program, which strengthen food safety and ensure the legality and transparency of seafood imports [11,12]. China has also implemented measures that appear to focus primarily on food quality and public health, such as the Food Safety Law of the People's Republic of China (2015) [13] Additionally, some private and regional initiatives in China are emerging to provide consumers with greater traceability information regarding fisheries sustainability [13]. In the EU several laws have been shaping what is mandatory since the beginning of the 21st century (Fig. 1). The most directly related to aquatic food traceability and supply chain regulation are Articles 58 of Council Regulation (EC) No. 1224/2009 and its most recent update with the digitalization of information mandated by Article 58 of Regulation (EU) 2023/2842. The mandatory use of the CATCH electronic system (Articles 12a-e of Regulation (EU) 2023/2842) represents a significant step toward the digitalization of information. In this context, it is important to distinguish between catch certification, which serves as a control tool to verify legal origin and combat IUU fishing, and traceability systems, which focus on tracking the product's movement through the supply chain. While CATCH is not *per se* a traceability system, its role in digitalizing catch documentation is central to the broader EU objective of ensuring a transparent and legally compliant aquatic food trade [14]. Despite this digital shift, the EU regulations are limited to a 'one-step back'-'one-step forward' approach, rather than a full end-to-end traceability solution, with data only accessible to authorities upon request.

Although EU Regulation 2023/2842 governs digital traceability within the EU market, the EU aquatic food system is deeply globalized. Aquatic foods are among the most extensively traded food commodities worldwide, with approximately 38% of global production entering international trade in 2022 [1,15]. The EU is the world's largest net importer of fishery and aquaculture products, with a self-sufficiency rate of only 38,1% in 2023 [15]. In 2024, extra-EU imports totaled EUR 29, 87 billion and 5,95 million tonnes, sourced primarily from Norway, Ecuador, Morocco, and the United Kingdom [15]. Major imported species such as salmon, warmwater shrimps, tuna, and Alaska pollock therefore move across multiple jurisdictions before reaching EU consumers [16]. As a result, traceability systems intended to serve the EU market necessarily implicate non-EU actors throughout the supply chain.

Recent developments illustrate how traceability and catch documentation have become central instruments of trade. Following Brexit, the United Kingdom, as a third country, aligned its seafood export documentation with the EU's strengthened IUU import requirements, which took effect in January 2026 and mandate more detailed catch certificates, processing statements and non-manipulation documents [17]. In parallel, following Russia's invasion of Ukraine, fisheries were targeted by EU sanctions for the first time. In June 2026, the European Commission proposed 21st sanctions package introduced substantial restrictions on imports of certain Russian fish products and a complete ban on others, including cod [18]. These measures responded, in part, to evidence that Russian seafood was being routed through third-countries for processing before entering the EU market, prompting the European Council to remove both duty-free and most-favored-nation treatment for Russian fishery products. This further reinforces the importance of traceability for verifying both the origin of catches and the location of processing [19,20]. The United States had already adopted the same approach in December 2023, maintaining import prohibitions on seafood harvested in Russian waters or by Russian-flagged vessels even when processed in third-countries [21]. Taken together, these developments demonstrate that digital traceability and catch documentation have evolved beyond fisheries management tools into critical instruments of market access, trade enforcement, and security policy.

1.1. Related work

Research on digital traceability in fisheries and aquatic food supply chains has expanded rapidly in recent years, with several review papers beginning to consolidate the evidence. For example, Cromwell et al. (2025) [22] reviewed digital technologies supporting traceability and transparency in global fish supply chains, while Macusi et al. [23] reviewed drivers of and barriers to traceability adoption. Building on this growing body of work, Costa et al. (2026) carried out a systematic review synthesising the global challenges and opportunities of digital traceability across aquatic food supply chains [16]. This review informed the conceptual framework adopted in this study (Section 2.1), identified recurring challenges to traceability implementation, including high implementation and maintenance costs, limited interoperability between systems, and stakeholder resistance. It also highlighted key incentives for adoption, such as improved access to high-value markets, regulatory compliance, consumer trust, and enhanced supply chain efficiency. The present study complements this literature review by providing empirical evidence from experts involved in the design, implementation, and use of digital traceability systems. Whereas the review synthesized evidence from published literature, this study examines how challenges and opportunities are perceived in practice by those directly engaged with traceability systems.

Prior studies, synthesized recently across European and non-European contexts [16], have identified several recurring challenges to digital traceability adoption (most notably high implementation and maintenance costs, limited interoperability between systems, and stakeholder resistance) alongside key incentives such as access to high-value markets, regulatory compliance, consumer trust, and improved supply chain efficiency. Despite all the benefits digital traceability can bring to the fisheries food sector, concerns around inequality also arise. Traceability systems may reinforce or even exacerbate existing power imbalances, both between fishers and other actors in the supply chain, and between the global South (where most aquatic foods are sourced) and the global North (where traceability standards and aquatic food markets are concentrated) [7,24].

Despite a considerable amount of research, existing studies on fisheries digital traceability often lack cross-dimensional integration. For instance, some focus primarily on the technical definitions and characteristics of traceability systems [25–27], while others examine drivers and barriers in specific regional or small-business contexts [28,29]. While the literature has made important advances in each of these areas individually [16], what remains less explored is how the technical, economic, and governance aspects interact in practice, and how practitioners involved in designing, implementing, and using traceability systems perceive these interactions. This perspective is particularly relevant as mandatory frameworks such as EU Regulation 2023/2842 take effect, requiring supply chain actors to navigate these interactions in real implementation contexts.

This study addresses this gap by developing a conceptual framework that maps the four key dimensions of fisheries digital traceability and their interactions, drawing on semi-structured interviews with 43 experts across the global fisheries supply chain. The framework is intended to support the design of more sustainable and effective digital

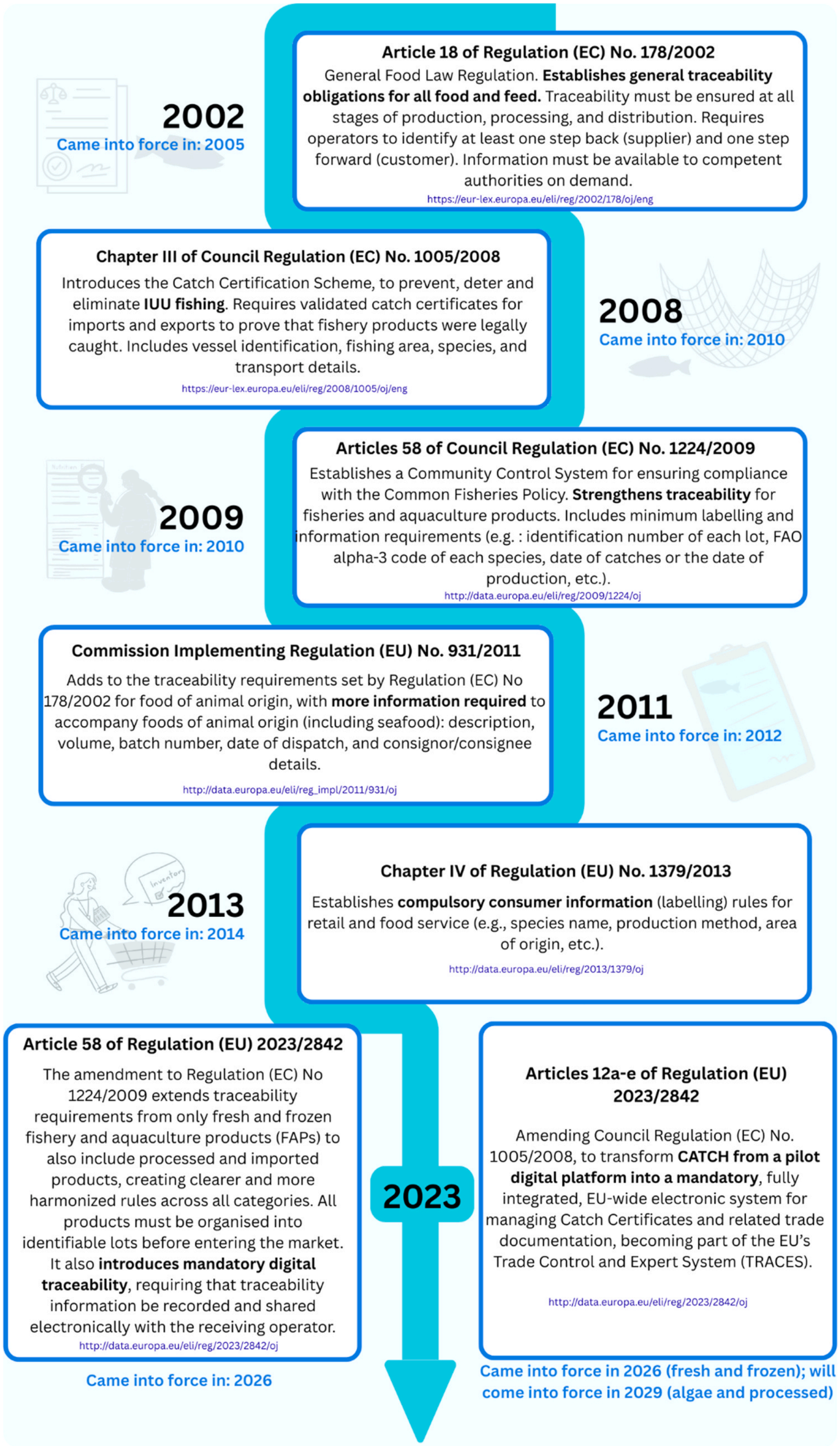

Fig. 1. Timeline of EU regulations and regulatory tools related to fisheries traceability.

traceability strategies, with particular attention to the European Union regulatory context.

2. Methodology

2.1. Building the conceptual framework

This study developed a conceptual framework for digital traceability based on two main sources. First, we adapted Jose and Prasanna-venkatesan (2023) [30] model of drivers and barriers. In our approach, “perceived benefits” are considered active drivers that encourage adoption, while also identifying specific solutions to mitigate the negative impact of challenges. Second, we used Islam and Cullen (2021) [5] to define the four principles related to the technical and operational structure of the system: Why, Who, Where, and How. We were particularly interested in the “How” but, while these authors focus on a technical perspective, we expanded this dimension to include economic and governance aspects, informed by Costa et al [16]. . From this combined evidence, four key dimensions were identified: data governance, decision-making, cost management and technology used. Definitions of each dimension are provided in Section 3.1.

This framework identifies key dimensions and influencing factors for fisheries digital traceability. Next, we used this framework to design a set of questions for expert interviews, with the objective of identifying their views on the most prominent influencing factors and on how these dimensions could be developed to enhance efficiency and success of digital traceability systems in fisheries. The objective is to offer diverse perspectives on key dimensions and influencing elements, thereby contributing to the development of a more robust and better prepared digital traceability system within fisheries.

2.2. Data collection

To gain practical insights into these dynamics, this study draws on 43 semi-structured interviews with experts across various segments of the fisheries supply chain (such as professionals from fisheries, transformation, commerce, non-profit organizations, etc) from around the world, utilizing a flexible protocol to explore experts' perspectives on (1) the primary factors influencing a traceability system, including challenges, solutions, and drivers, and (2) the best practices for each key dimension of a traceability system. The focus of the questions was on external traceability. The expertise of the people interviewed, and time constraints related with the semi-structured nature of the interview, resulted in experts elaborating freely on certain topics and not on all questions. Consequently, not all questions were answered by every expert, and the total number of responses varies for different questions. Accordingly, in the results section (Tables 1 and 2), "n total" refers to the total number of experts who addressed a given topic, while "n" indicates how many of those experts mentioned a specific factor or theme within that topic.

Interviews were conducted online between January and May 2025, with each interview lasting approximately one hour. Experts were initially selected based on their professional background and experience related to fisheries traceability. At the end of the interview, experts were asked to recommend other relevant experts to contact. This snowball sampling [31] approach enabled the inclusion of a diverse range of voices with knowledge and experience with traceability systems. No restrictions were placed on the geographical location of experts.

Pending consent, interviews were audio-recorded and transcribed for analysis. All transcripts were anonymized during processing. This study was conducted in accordance with General Data Protection Regulation, and all experts provided informed consent (following process nº CEUAlg Pn°144 /2025).

Table 1
Insights gathered from expert’s views regarding the drivers for digital traceability in fisheries. Note: n total = total number of experts who addressed this topic; number of replies = experts who mentioned the specific factor. Totals vary across topics since not every expert addressed every theme (see Section 2.2).

Driver	Key insights	(n total = 26)
Meeting consumer demands	There is an increasing consumer awareness and interest in trust and transparency regarding their choices. As people prioritize ethical and sustainable products, the ability to provide trustworthy data has become a driver for traceability.	n = 11
Managing reputational risks	This concerns particularly large companies and brands with a public-facing image. Traceability acts as a crucial tool for protecting a brand's value and addressing potential scandals related to food safety, illegal fishing, or human rights violations.	n = 10
Complying with legal requirements	While it's a slow-moving process, regulations are becoming more comprehensive and stringent. Complying with legal requirements is seen as a major driver for traceability, often a foundational, non-negotiable motivation for businesses.	n = 10
Gaining market access	Gaining market access is fundamental for traceability, particularly for companies that want to export to high-value markets (such as the USA, EU or Japan).	n = 9
Addressing sustainability concerns	This has been fueled by a growing public demand for ethical and environmentally responsible products. Non-governmental organizations (NGOs) have been needg for transparency, and businesses are now taking the lead, driven by the need to meet targets and consumer expectations.	n = 9
Securing investor funding	Securing investor funding is a major driver for traceability, as private funders and corporate investors increasingly demand transparency and accountability.	n = 3
Ensuring quality and healthy fishery products	Ensuring quality and healthy fishery products is fundamental, as it provides a verifiable way for businesses to guarantee product safety and quality to consumers.	n = 2
Securing competitive advantage	Traceability allows businesses to get ahead of the competition and establish themselves in high-end markets by guaranteeing the quality and origin of their products.	n = 2
Responding to societal pressure	This pressure stems from a broader public discourse (and not directly from consumers) about the need for a more sustainable and ethical society. As issues like climate change become more prominent, companies feel compelled to demonstrate their commitment to sustainability.	n = 1

2.3. Data analysis

The interviews were analyzed using a Thematic Analysis Approach [32], a flexible and interpretative way to analyze the data. The thematic analysis employed a theoretical approach, structuring data around interview questions with the aim to broaden the conceptual framework's highlighted subjects. Responses with similar meanings were grouped into categories, allowing the identification of key themes and the most frequently mentioned issues across experts. To structure the diverse range of challenges and solutions identified by experts, the PESTEL (Political, Economic, Social, Technological, Environmental, and Legal) [33] was applied as an interpretive tool rather than as an objective classification. We acknowledge that many themes traverse more than one PESTEL dimension, as the factors influencing fisheries traceability are often interdependent, therefore, each theme was assigned to the

Table 2
Insights gathered from expert's views regarding the most mentioned challenges for digital traceability in fisheries. Note: n total = total number of experts who addressed this topic; number of replies = experts who mentioned the specific factor. Totals vary across topics since not every expert addressed every theme (see Section 2.2).

Challenge	Key insights	n total = 43
Interest in maintaining the opacity of business information	Resistance largely reflects attempts to conceal fraud, protect competitive interests, and avoid regulatory or reputational risks.	n = 22
Low interoperability of information systems	Low interoperability in fisheries traceability stems from fragmented systems, inconsistent legal requirements, and a lack of shared standards and coordination across actors and jurisdictions.	n = 19
High implementation and maintenance costs	High implementation and maintenance costs, combined with uncertain return on investment, discourage investment in fisheries traceability systems.	n = 19

dimension that most directly reflected its dominant theme. For example, where an expert framed a barrier primarily in terms of financial burden, it was coded as "Economic", even if the issue also included governance or technological implications. This interpretive logic aims to acknowledge the multidimensional nature of the themes.

The MAXQDA 24 Analytics Pro software was used to support the organization and visualization of the data.

3. Results and discussion

3.1. Conceptualization of digital traceability systems and framework development

The key dimensions of traceability systems in fisheries were defined according to the following dimensions and related literature:

Decision-making: It is crucial to establish clear and inclusive decision-making processes when developing information systems for traceability [34]. The authors emphasize that for decisions to be effective and sustainable, stakeholders must first "decide how to decide". This involves establishing rules and ensuring adequate resources to address issues such as noncompliance, ambiguity, or illegality. With this dimension we aim to include broader questions of system management, specifically, who should oversee the traceability system and which actors should be involved in its governance and operation. In other words, this dimension focuses on the procedural and institutional arrangements that shape the traceability system itself: the actors, authorities, and participation structures that determine how the system is designed, managed, and adapted over time.

Data Governance: Several unresolved questions remain crucial for the effective implementation of electronic catch documentation and traceability (eCDT) systems, including who owns the system and its data, who has access to that data, and under what conditions [34]. Without stakeholder alignment on these fundamental issues, traceability systems risk becoming mere data collection tools, ineffective at driving meaningful change. Whereas decision-making concerns the procedural arrangements that shape the system, data governance concerns the substantive rules applied to the data itself: what data exists, how it is structured, stored, shared, and protected, and who is accountable for its quality and integrity.

Cost management: The financial burden of implementing and maintaining digital traceability systems is widely recognized as a major challenge [35,36]. As Bailey et al [37]. note, it is critical to determine who bears the financial responsibility for supporting systems that facilitate information flow within and beyond global value chains.

Technologies used: Technology is a central component of any digital traceability system. To design systems that are both efficient and fit-for-purpose, it is essential to understand the available technological options and their capabilities [38].

Fig. 2A. presents an overview of how the above defined key dimensions shape a traceability system and how the influencing factors are interconnected.

3.2. Characterization of experts interviewed

Experts were professionally active in a variety of fisheries sectors, most working in non-profit organizations (NPOs) and based in the EU. Fig. 3 illustrates the geographical distribution and professional sector of the experts who took part in the interviews.

Experts indicated extensive experience working with the fisheries sector (average of 17.7 years) and with traceability (average of 11.3 years). Most (77%) had direct contact with digital traceability systems and technologies, while 23% reported indirect contact - either by following relevant regulations or by representing other businesses in the sector. The nature of the experts' experience and involvement with traceability and information systems was highly diverse, encompassing various roles across the fisheries value chain, such as supporting communities and stakeholders in implementing traceability systems, designing digital and technological traceability solutions or developing logistical solutions for fishery businesses.

It is important to note that the expert sample is objectively skewed toward a certain profile, namely EU-based professionals working in NPOs (see Table S1, Supplementary Material, for a full cross-tabulation of professional sector and geographic origin). It is also worth noting that two experts based in Europe and working in consultancy mentioned that they are working across African and Asian regions as well. As such, the geographic distribution described reflects each expert's primary base rather than the full scope of their professional experience. This was not intentional but resulted from the snowball sampling approach and the study's focus on EU traceability regulations. Findings should therefore be approached with this framing in mind. Future work would benefit from including more producers, policymakers, and other relevant actors from different regions of the world to incorporate additional perspectives.

3.3. Drivers for digital traceability implementation

Experts identified several reasons driving the need for digital traceability in the fisheries sector (Table 1).

3.3.1. Meeting consumer demand

Among the three most frequently mentioned drivers, there was consistent emphasis on the critical role of meeting consumer demands. Experts noted that providing information not only satisfies consumer curiosity but also significantly enhances the value of the product. However, a key question arises: to what extent are consumers willing to pay a premium for detailed information about fishery products? Findings from Govzman et al [39]. show that cost is the primary barrier for consumers in Europe, the USA, Canada, Australia, and New Zealand. Given that price is a central factor for many consumers, price increases associated with traceability may limit uptake in the general market. Instead, traceability might result in premium products that could thrive in niche markets (such as fine dining restaurants), where customers are willing to pay more for quality and provenance. Whether the economic benefits of traceability outweigh its costs, the market capacity for such products, and the long-term sustainability of these initiatives remain open questions that require further research across different fisheries supply chains.

3.3.2. Manage reputational risk

According to Bailey et al [37]. , in business-to-business (B2B; which

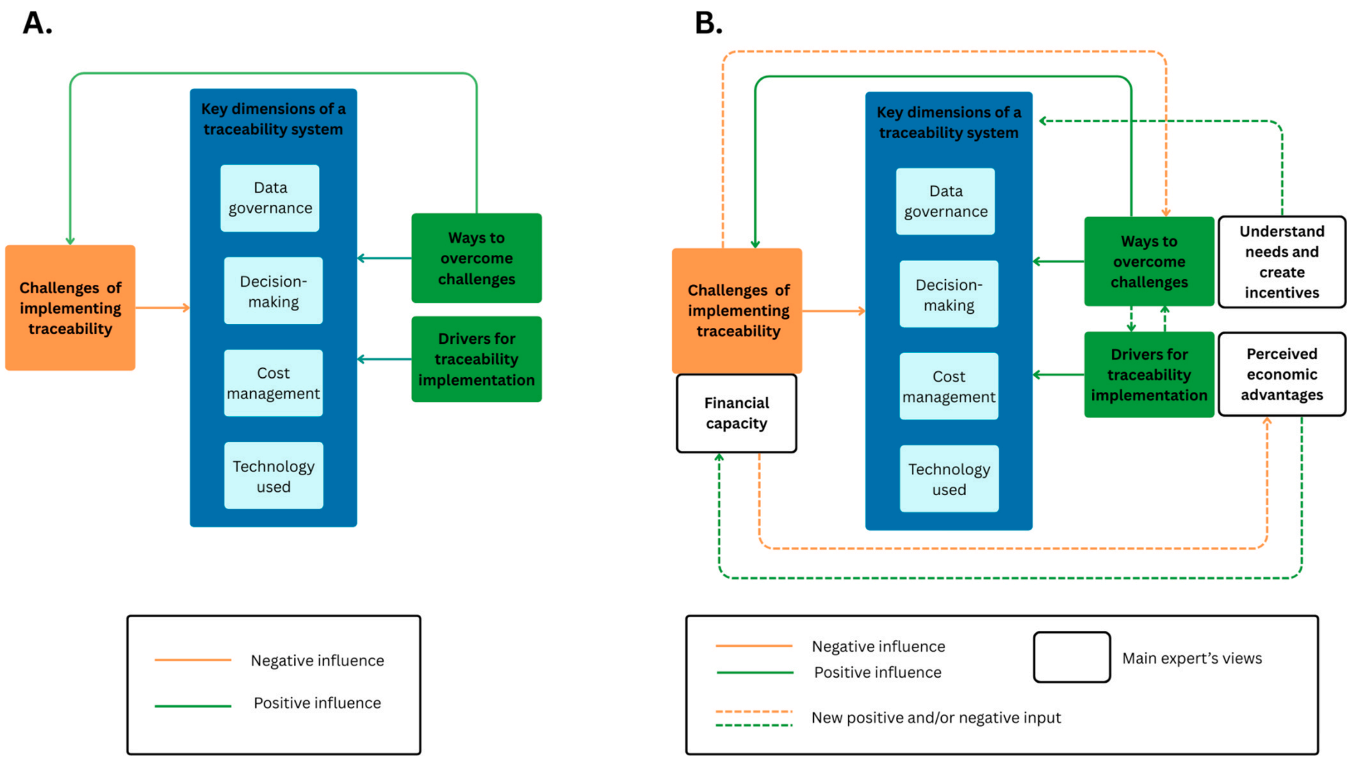

Fig. 2. Framework on how different factors influence a digital traceability system in fisheries, and the key dimensions that compose them: A - before including expert' perspective; B - after including experts' perspectives.

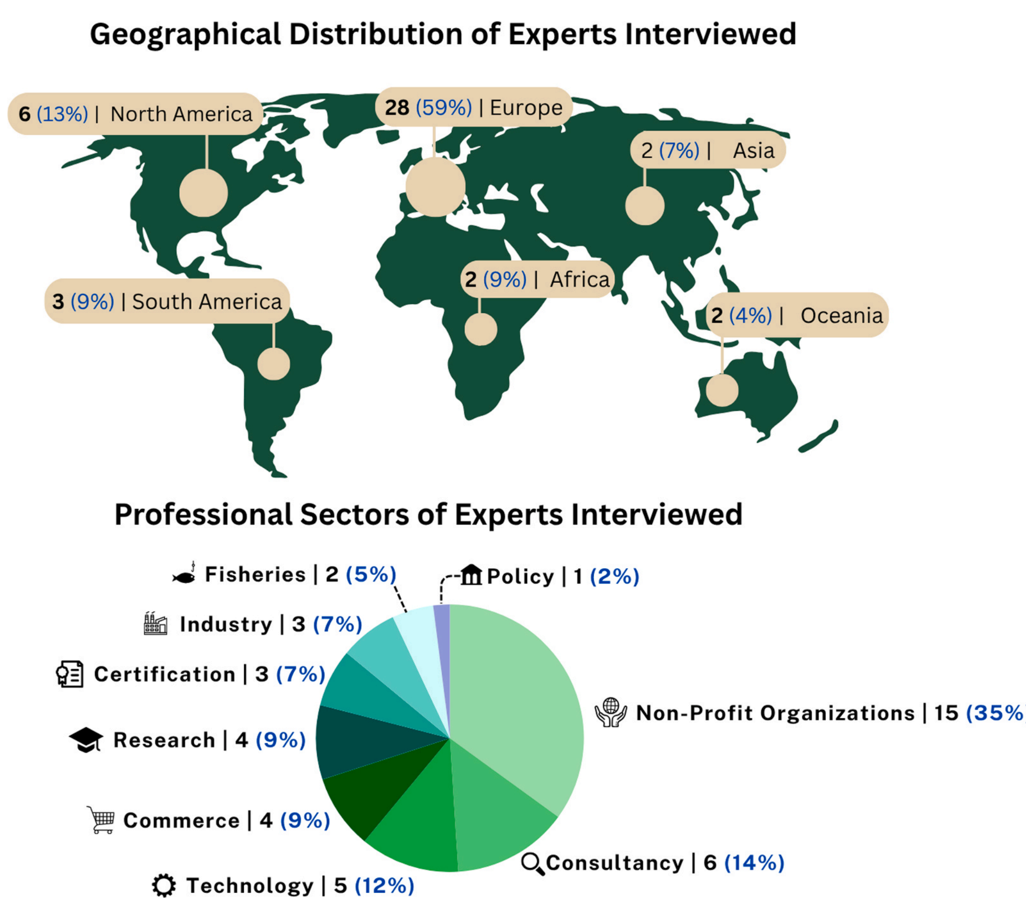

Fig. 3. Characterization of experts interviewed (n = 43).

can be compared with internal traceability) traceability, information flows traditionally served to enhance efficiency and mitigate reputational risk. For example, it can bolster food safety, expedite recalls, and lead to extended shelf life, which in turn commands higher prices for premium products. More recently, this expanded to consumer-facing traceability (CFT) systems (or B2C; business to consumer), which share information with consumers or civil society. The study mentions that the retail sector is particularly vulnerable to reputational damage, a concern also strongly emphasized by experts in this study. Companies are driven by the notion that a stained reputation can lead to significant financial losses. According to experts, implementing traceability not only demonstrates compliance with evolving social and environmental standards, but also provides the verifiable data needed to reassure consumers, investors, and even NGOs, thereby supporting consumer trust as a key market asset. However, as Bailey et al [37]. mention, businesses are using traceability to manage reputational risk by controlling the flow of information on a "need-to-know" basis, prioritizing information control over full transparency and challenging the notion of information democratization. One expert cautioned that excessive transparency, without adequate contextual understanding, could expose companies to reputational attacks, as illustrated below: *"It's dangerous to have too much transparency because you have people who are not reasonable at all in NGOs and they attack where it works. You give information, then they attack you because you have given information. So in some cases, we wonder if it is good to give information because then you expose your flank to attacks."*

3.3.3. Comply with legal requirements

Experts noted that compliance with regulations is another significant driver for traceability, as bodies such as the U.S. Food and Drug Administration, the EU, and the FAO are increasingly mandating digital traceability for fisheries. They mentioned that while this is a gradual process, these regulations are becoming more comprehensive and stringent. However, a critical challenge arises from the differing capacities of nations to enact and enforce these systems. As Bailey et al [37]. noted, institutional inertia in many centralized states can result in rigid governments that struggle to respond quickly to legal requirements imposed by other country legislators, potentially limiting opportunities in global supply chain markets. This underscores how, despite growing international pressure, the implementation of these regulations is often hindered by national capabilities.

All these drivers (but also others, such as securing competitive advantage or investor funding or gaining market access) are directly connected with perceived economic advantages that can potentially be gained with the implementation of a digital traceability system in fisheries.

3.4. Challenges of implementing digital traceability

Experts identified a widely diverse set of challenges for the adoption of digital traceability systems in fisheries, summarized in Table 2 (for more detailed information consult Table S2, Supplementary Materials). Three challenges stand out and will be discussed in detail: the interest in maintaining opacity in business information (mentioned by 22 experts), the low interoperability of information systems (mentioned by 19 experts), and the high implementation and maintenance costs (also mentioned by 19 experts).

3.4.1. Interest in maintaining the opacity of business information

Many experts shared that some resistance to sharing information may stem from fraudulent practices and illegal activity, such as restaurants marketing fishery products as entirely local or small-scale while sourcing most products from wholesalers. This aligns with the broader literature on aquatic food fraud, which highlights how complex and opaque supply chains facilitate economically motivated deception, including species substitution, misrepresentation of origin, and chain-of-custody abuse [40]. Consequently, businesses may avoid traceability to evade scrutiny that could damage sales and corporate reputation. In fisheries, uncovering IUU activities faces resistance because transparency can expose human rights violations (including forced labor) and the capture of unauthorized species. Fox et al [40]. emphasize that fraud is frequently linked to these broader ethical abuses, making transparency a significant operational risk for some actors.

Additionally, some experts (n = 4) highlighted that fishers often keep fishing grounds confidential to protect productive areas from competitors, a challenge rooted in distrust among supply chain actors. Furthermore, general distrust in authorities (n = 3) drives privacy concerns. Experts reported that fishers fear catch data will be used for arbitrary fines. This mistrust is worsened in places where corruption is prevalent, as some authorities reportedly extort bribes to overlook irregularities and may oppose digital traceability because it creates a digital audit trail that prevents such bribery. Grant et al [41]. argue that mandatory traceability systems, when used as anti-corruption tools, are themselves vulnerable to corruption, particularly because authorities may retain control over data entry, verification, and monitoring processes. Although neither voluntary nor mandatory traceability systems are designed to address corruption per se, this highlights a critical governance challenge in fisheries: information sharing does not automatically result in fair or consistent enforcement. Instead, increased transparency can, in some contexts, enable selective punishment or discretionary enforcement. These dynamics help explain why fishers may distrust authorities and resist data sharing. Ensuring fair, accountable, and transparent fisheries governance is therefore a fundamental precondition for the effective and equitable implementation of innovative digital traceability systems.

Finally, experts from the industry (n = 4) worried that consumers or NGOs might misinterpret transparent data. For instance, misunderstanding handling procedures or catch dates could lead to skepticism regarding freshness. Bailey et al [37]. note that while consumer-facing traceability is marketed as empowering, it exposes businesses to reputational risk if information is taken out of context. Experts added that visible catch dates could harm competitive advantage by leading consumers to reject older, yet perfectly safe, products in favor of newer stock.

3.4.2. Low interoperability of information systems

Many experts expressed concerns regarding the lack of communication between different digital traceability systems. They highlighted the need for standardized data languages - interoperability - to reduce user confusion and enable effective information exchange. This challenge is compounded by differing legal requirements across countries, which complicates international fisheries supply chains. Three experts pointed to the Global Dialog on Seafood Traceability (GDST) as a potential solution. This non-profit provides an international platform for establishing a common language, defining minimum data elements and technical formats for exchange [42]. In contrast, some experts (n = 3) noted that many businesses continue to develop their own tailored solutions, which further complicates the harmonization of information. Achieving effective information exchange between public and private actors remains a highly complex task requiring global consensus on standards.

Literature consistently identifies interoperability as a primary challenge in aquatic food traceability [16]. The interview findings confirm that these hurdles are not just technical; they are deeply rooted in organizational practices, governance, and the absence of shared data agreements [43,44]. Ultimately, improving interoperability requires technical alignment combined with coordination, trust, and consensus-building across multiple jurisdictions [45].

3.4.3. High implementation and maintenance costs

Beyond the initial expenses of purchasing technologies and training operators, companies face ongoing maintenance, including system updates, data storage, and technical oversight. Some experts emphasize that these costs disproportionately burden smaller businesses with limited capital. In non-mandatory contexts, experts (n = 4) stress that long-term financial sustainability and return on investment must be proven before launch.

Some experts (n = 3) also point to the fact that traceability is frequently perceived as a business risk because the market is often unwilling to pay a premium for traceable products, discouraging investment. Given this, we argue for greater transparency regarding actual costs, as limited public data currently hinders informed decision-making. Existing estimates suggest expenses can reach several thousand dollars [46].

3.5. Interactions between challenges

Several connections emerged between the different challenges identified by the experts. The links shown in Fig. 4 were drawn directly from the interviews, where experts described how one challenge influenced or depended on another; they therefore reflect expert-articulated relationships. In some cases, certain challenges appeared to be determined by other challenges ("depends on"), while in other cases challenges seemed to exert an influence ("affect") on other challenges. These connections are shown in Fig. 4.

Most notably, financial demands underpin nearly all other barriers. The ability to invest and the expected economic return are the primary hurdles to implementation. Logistical and technical challenges are also deeply interconnected. Digital traceability necessitates advanced machinery and the physical separation of catches, which is logistically complex. Furthermore, it requires specialized personnel to manage unfamiliar technologies. These requirements simultaneously stem from and exacerbate financial constraints, as they demand continual investment in training and upgrades while straining existing budgets.

3.6. Ways to overcome challenges

Experts were also consulted regarding potential ways to overcome the challenges of implementing digital traceability in fisheries. Several ideas were identified and categorized into the same themes as the challenges - Political, Economic, Social, Technological, and Legal. While the primary challenges identified are often economic and technological/logistical, the most prominent solution appears to be political in nature. There was no answer related to the "Environmental" type (Fig. 5) (For more detail see also Table S3, Supplementary Materials).

A majority of experts (n = 27) emphasized that successful digital traceability depends on context-specific solutions and clear stakeholder incentives. The role of "champions" (organizations like NGOs or government authorities pushing for traceability) is crucial, as their direct engagement with stakeholders ensures a smoother transition and helps in understanding people's concerns and needs. This interaction allows for the development of technologies that are better adapted to local realities, not only in terms of logistics but also operational costs, directly addressing the main economic and technological challenges. Experts suggested that co-designing systems, identifying key data elements, and mapping product flows, promote higher adoption and functionality.

Furthermore, experts emphasized that incentives must be tailored to each specific case and context. They argued that stakeholders need to see traceability as a value-add for their operations. These incentives are crucial for ensuring the creation and maintenance of high-quality data

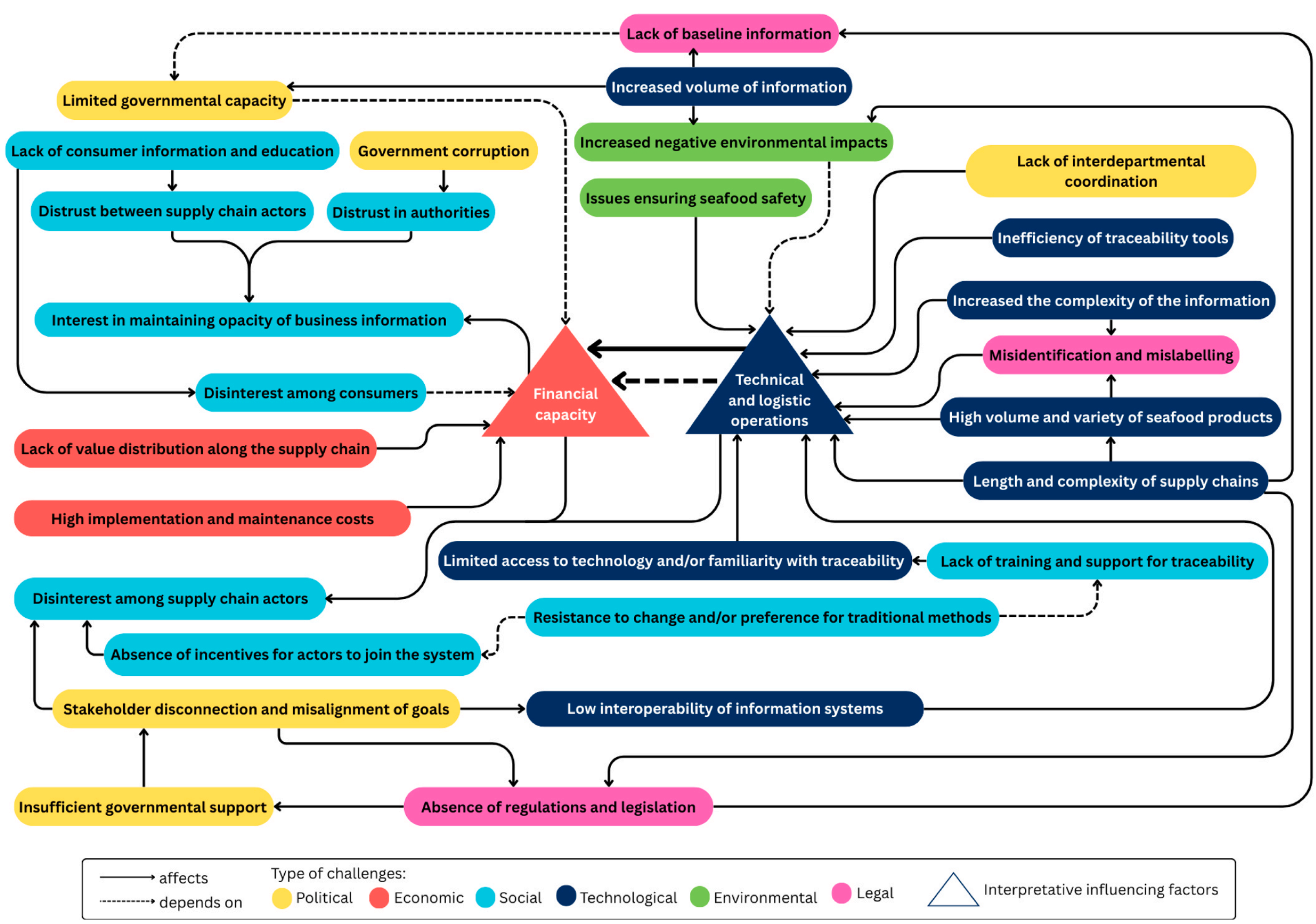

Fig. 4. Connections between challenges as identified by experts during interviews.

Fig. 5. Strategies to overcome the primary challenges of implementing digital traceability in fisheries (n total = 39). Note: n total = total number of experts who addressed this topic; n = experts who mentioned the specific factor. Totals vary across topics since not every expert addressed every theme (see Section 2.2.

throughout the supply chain. Incentives can be financial, such as providing budgets to cover the costs of implementing digital technology, or they can involve improving the management efficiency of fishing or business operations to increase profits. They can also include capacity building, which involves providing training and coaching in areas like human rights, codes of conduct, finance, and digital literacy. Lewis and Boyle [47] also noticed that there is no "one-size-fits-all" approach to traceability, since there can be different data collection needs (dictated by a company's infrastructure), and that the financial incentive (the Return on Investment (ROI)) will vary from one stakeholder to the next. This supports your argument that incentives must be tailored, as a financial model that works for a large business might not provide the same value to a small-scale fishery.

Inquired experts also highlighted again the unique challenges faced by small-scale fisheries and small businesses. The link between political solutions and financial/technological impact highlights a critical debate over governance: whether these systems and incentives should be managed by the government, private entities, or through collaborative models. This issue is explored further in the following section.

3.7. Key dimensions of a traceability system

3.7.1. Management and decision-making responsibilities

When asked who should manage traceability (n = 20) - essentially, who should oversee and make decisions regarding a digital traceability system, most experts (n = 15) advocated for a participatory process. This inclusive approach facilitates the development of comprehensive tools, maintains motivation, and aligns goals to improve connectivity - a challenge mentioned by experts during interviews regarding the new EU regulations on digital traceability.

Experts noted that involving stakeholders increases success rates by addressing ground-level concerns rather than relying on purely top-down mandates. While this may not always mean full co-management, it necessitates active involvement, as Leslie and Lugo-Mulligan [34] confirm that stakeholder alignment is essential for the impact of traceability initiatives.

Others suggested that governmental agencies (n = 3) are best suited for oversight due to their perceived impartiality and resource capacity, while some (n = 4) also argued that the ideal manager depends on specific business models and technological drivers. Additionally, two interviewees acknowledged that the private sector should manage its own internal systems.

The new EU regulation (Regulation (EU) 2023/2842), which introduces mandatory digital traceability requirements for fisheries products, is not a prescriptive rule and when interviewing the policy official, it became clear that there was a strong effort to engage directly with industry actors and Member State representatives, through visits and open discussions, to ensure that the implementation process is as smooth and inclusive as possible. This approach fosters stakeholder involvement, but it is essential that these administrative efforts impact the effective implementation of traceability, rather than being merely a consultative exercise to satisfy procedural requirements. Still, throughout the interviews, some experts mentioned that their national authorities had not yet provided clear guidance on the new EU rules. The presence of informed personnel on the ground, or the organization of clarification sessions, was identified as a factor to support businesses and supply chain actors in adapting to the new requirements and in understanding what resources and assistance may be available to them.

3.7.2. Cost management

When discussing who should fund digital traceability (n = 33), many experts (n = 10) suggested that governments should provide incentives to cover or initiate the funding**.** Some believe this is a governmental responsibility to promote transparency, while others assert that if traceability is legally mandated, Member States must provide support. Within the EU, experts suggested the European Commission should provide initial funding since the return on investment is often unclear. These incentives are viewed as a transitional step toward the economic self-sufficiency of supply chain actors. In the case of the EU, there are indeed some funds or programs that can be leveraged to help with control, data collection, digital tools, innovation, or capacity building, such as the European Maritime, Fisheries and Aquaculture Fund (EMFAF) [48]. There can also be national or regional public investment, for example, in Germany, the European Maritime and Fisheries Fund - EMFF (predecessor of EMFAF) funded projects to standardize digital control systems and databases for aquatic food traceability and inspections, paying for digital tools, exchange platforms, and training inspectors under a €364 thousand project [49]. Naturally, there is public funding outside the EU, for example, the Government of Canada and the Province of New Brunswick announced over $38 million in funding for innovation and technology in aquatic food sectors, including equipment, data collection technologies, and quality systems [50]. Beyond public funding, some experts (n = 2) proposed that philanthropy or private investors should support implementation. For example, the Walton Family Foundation has funded traceability projects through partnerships like SALT [51].

Regarding running costs, experts offered diverse views, suggesting the private sector (n = 6), consumers (n = 4), or collaborative stakeholder efforts (n = 4) should bear the burden. A subset (n = 3) noted that the solution is context-dependent, relying on the specific political setting and the resources available to each actor.

Similarly to the views expressed by experts, Leslie and Lugo-Mulligan [34] confirm that multiple financial mechanisms can sustain traceability. They emphasize that systems must remain accessible to small-scale fisheries and that the benefits should outweigh costs. Interestingly, they argue that by systematically recording financial data, traceability can actually foster financial autonomy for small-scale fishers, potentially improving their access to formal bank loans by providing verifiable revenue records.

3.7.3. *Technology used*

When questioned about the best technology for a digital fisheries traceability system, experts provided two main perspectives. Some recommended specific technological tools, while others emphasized that the crucial factor was the inherent characteristics of the technologies and methods used, rather than their specific form (Table 3).

The most frequently cited response was "context-dependent technological solutions". While this may seem vague, they acknowledge the importance of offering supply chain participants the flexibility to adapt traceability in a manner that suits their individual needs. The EU regulation regarding aquatic food digital traceability (Regulation (EU) 2023/2842) aligns with this view and it does not prescribe a specific technology for traceability.

We argue that although this approach appears ideal, it is also crucial to consider interoperable methods. The current EU regulation does require a minimum traceability information that has to be made available, but it overlooks international standards as the GDST, endorsed even by FAO [52]. We believe this is a missed opportunity for achieving consistent data collection and transfer within the EU.

3.7.4. *Data governance*

Data governance questions are essential when discussing digital traceability because they determine who controls, accesses, and benefits from data across complex supply chains [53]. The prevailing view among experts is that data collectors should own their own data (Table 4), reasoning that user ownership boosts motivation, balances power structures, and upholds the rights of those generating the information.

Under the EU General Data Protection Regulation (GDPR), it is imperative that traceability data protects personal identities. While Regulation (EU) 2023/2842 collects identifying data like vessel names or trip IDs, this must not be made public. The Commission and Member States share a joint responsibility to ensure cross-border data exchanges do not violate privacy rights.

Despite these safeguards, most experts (n = 27) stressed that commercially sensitive information (such as specific fishing grounds or client lists) must remain private to protect competitive advantages. To address this, experts proposed displaying only anonymized or aggregated data or providing details to authorities only upon request. Conversely, some experts (n = 7) argued that aggregated data should be public to promote transparency, while others (n = 6) advocated for tiered access: detailed data for enforcement authorities and confidential data for businesses.

While "maintaining opacity" was cited as a major challenge, expert solutions (such as protecting business privacy while ensuring compliance) are seen as necessary for stakeholder buy-in. These goals can be met through permissioned blockchain systems that restrict data access to authorized users, allowing companies to retain control over who can view specific information [54]. For example, IBM's Food Trust platform operates as a permissioned blockchain in which access to data is role-based, meaning that supply chain actors can share selected agri-food information (from fishery to retail) without exposing commercially sensitive details to all participants, while still enabling traceability and accountability across the chain [55]

Finally, although meeting consumer demand is a key driver for traceability, experts under-emphasized B2C transparency in favor of protecting competitiveness. B2C enhancement could include providing more precise catch or production areas (beyond broad FAO zones), and aggregated intermediary chain data accompanied by timestamps - not compromising businesses or fisheries from a competitive standpoint. Importantly, this information should also be made available in restaurants and food service establishments, where, contrary to retail settings, consumers might have even less access to information about the origin of the product. For instance, a study by Oceana found that 98% of 69 bluefin tuna dishes tested in Brussels restaurants were in fact another fish species [56]. Evidence suggests that aquatic food fraud has declined as a result of robust EU policy interventions [57,58]. Improving regulatory control could aid consumers to make better-informed and more sustainable choices, while also strengthening trust and market integrity across the entire fisheries supply chain.

Table 3
Experts (n total = 37) answers on the ideal technologies to use in a fisheries traceability system. Note: n total = total number of experts who addressed this topic; n = experts who mentioned the specific factor. Totals vary across topics since not every expert addressed every theme (see Section 2.2).

Specific technologies/methods mentioned	Technologies' characteristics
Smartphone applications (n = 13)	Context-dependent technological solution (n = 16)
Blockchain (n = 11)	Use technology already available (n = 10)
Quick response code (QR Code) (n = 11)	Interoperable systems with Critical Tracking Events (n = 4)
Artificial Intelligence (n = 8)	Technologies offline compatible (n = 3)
Vessel Monitoring System (VMS) (n = 3)	Technologies compatible with working conditions at sea (n = 2)
Cameras on board (n = 2)	Good storage capacity (n = 1)
Application Programming Interfaces (APIs) (n = 2)	
Smart scales (n = 1)	
Digital logbooks (n = 1)	
Satellites onboard (n = 1)	
Internet of Things (IoT) (n = 1)	
Global Positioning System (GPS) (n = 1)	
Barcodes (n = 1)	

3.8. *Framework refinement through expert perspectives*

While the theoretical framework we developed to define the key dimensions and factors influencing digital traceability in aquatic food systems (Fig. 2A) established a foundational structure to analyse these systems, the subsequent refinement based on expert perspectives (Fig. 5B) provides a more nuanced understanding of the systemic drivers within the fisheries sector.

Financial capacity and return on investment emerged as the key influencing factors in fisheries food digital traceability. As previously noted, the cost of implementing traceability has been the most frequently identified challenge in the literature on digital traceability in aquatic food systems [16]. Moreover, it reflects a broader trend, as surveys of conservation practitioners similarly identify high upfront and ongoing costs as the most commonly reported barriers to adopting new technologies [59].

We argue that the challenges of implementing digital traceability in fisheries can negatively affect both the drivers of traceability adoption and the solutions to overcome these same challenges. For instance, Asioli et al [60]. found that a firm's financial capacity (often linked to its size) correlates with both the expected and realized benefits of traceability. Smaller companies tend to anticipate greater gains from traceability systems, but in practice, they benefit less after implementation. This suggests that smaller or less-resourced businesses struggle to

Table 4
Experts answer about fisheries digital traceability data ownership. Note: n total = total number of experts who addressed this topic; n = experts who mentioned the specific factor. Totals vary across topics since not every expert addressed every theme (see Section 2.2).

Who should own traceability data? (n total = 27)
Data collectors (n = 19)
The government (n = 7)
Context-dependent solutions (n = 3)
Who should have access to traceability data? (n = 34)
Business or sensitive information should be kept private (n = 27)
Aggregated data should be made public (n = 7)
Different levels of access should be given to different stakeholders (n = 6)
Data collectors should have access to their own data (n = 5)
Data collectors should be able to choose who to share their data with (n = 4)
Full access should be provided to scientists (n = 1)
All data should be made public (n = 1)

convert expectations into tangible outcomes. Building on this, broader reviews of fisheries traceability indicate that challenges such as high implementation costs, limited infrastructure, and inadequate institutional support not only deter initial adoption but also weaken key economic drivers (like return on investment or market premiums) that would otherwise encourage uptake [23].

Research indicates a reciprocal, rather than linear, relationship between the drivers and challenges of traceability. The current study demonstrates that recognizing economic benefits can transform barriers into enablers, illustrating that finding solutions to traceability issues (like clarifying system needs) allows for the creation of targeted incentives that boost stakeholder engagement [34]. Conversely, drivers like legal compliance can catalyze the development of more interoperable technical solutions [52].

While ideal dimensions for digital fisheries traceability often focus on participatory and inclusive decision-making, experts stress that effective solutions must be context specific. This underscores the importance of avoiding "one-size-fits-all" mandates in favor of engaging local communities to understand their unique realities [44]. Beyond the general need for context, specific progress requires increasing the engagement of fishery stakeholders in discussions, strengthening governmental financial and technical support for implementation, developing more interoperable technologies and regulation, allowing sensitive or personal information to be kept private, and providing data collectors ownership rights to their data.

Future research could explore these relationships using statistical analysis to assess the significance of correlations between factors. This study was limited to a qualitative and interpretive analysis of expert responses.

Achieving full external traceability may be unrealistic given the complexity of fisheries supply chains and the varying capacities of actors at multiple levels. It was noted by an expert that in other industries, traceability is not necessarily promoted as fully end-to-end; instead, it is openly acknowledged that only a certain percentage of a product, for example a certain percentage is traceable:

> *"If you need 100% traceability, and that's the only way to get sustainable outcomes, that's one answer, but I don't believe that's necessary. Within forestry and electricity for instance, we're actually quite comfortable with the fact that (…) that 20% of this product has come from sustainable sources or renewable sources. (…) And you could say over time you want to try and ramp that number up. (…) I think that's why we're not seeing it in place. If we all accepted that there's a degree of uncertainty (which is there already) (…) if we made that more explicit…"*

This more flexible perspective is supported by the World Resources Institute [61], which, while prioritizing full traceability, advocates for increased transparency even when data is limited. Similarly, research into green electricity traceability by Yu et al [62]. proposes using "approximate traceability queries" to improve data reliability, effectively allowing for a margin of error.

While disclosing incomplete traceability data carries the risk of being misinterpreted by the public, normalizing this level of transparency could shift perceptions. By making these limitations explicit, the industry can demonstrate that a genuine, measured effort toward sustainability is a sign of responsibility, rather than a failure to achieve perfection.

4. Conclusions

This study addressed an important knowledge gap by examining the technical, economic, and governance dimensions of fisheries digital traceability in an integrated way, while exploring how practitioners perceive their interactions during real-world implementation. Drawing on 43 expert interviews structured around an integrative conceptual framework, our findings show that these dimensions are interconnected. Financial capacity and expected return on investment emerged as cross-cutting determinants shaping both technical and governance challenges. Moreover, the relationship between drivers and barriers was not linear but reciprocal. Strong drivers can help overcome challenges and turn barriers into enablers, whereas persistent constraints, such as inadequate financial capacity, can weaken these same drivers, reduce the effectiveness of solutions and slow adoption.

Digital traceability systems play a vital role in ensuring fishery products' quality and safety, preventing IUU fishing, and supporting sustainable management of marine resources. Yet, their implementation remains shaped by economic hurdles. The perceived benefits of traceability often relate to financial gains (enhanced consumer trust, access to premium markets, and added product value) while the principal barriers are similarly economic (including high implementation and maintenance costs and limited financial capacity) particularly among small-scale fisheries and small businesses.

These findings highlight the need for technologies that are both cost-effective and contextually adapted to different operational realities. Moreover, interoperability and the technical literacy of users are essential components of successful traceability systems and should be central considerations in their design. Although achieving uniform traceability regulations across diverse fisheries contexts (such as those within the European Union) remains challenging, the EU's new Regulation (EU) 2023/2842 represents an important step forward by emphasizing (B2B) traceability and digitalization.

Recent events reinforce this point, the tightening of EU import controls, the United Kingdom's alignment with those requirements, and the use of catch documentation to enforce sanctions on products originating from Russian all indicate that traceability has become a strategic instrument of international trade and security policy rather than a mere compliance obligation. This evolving context makes the development of cost-effective, interoperable, and equitable systems all the more urgent.

These findings both corroborate and extend the existing literature. They are consistent with syntheses identifying cost and limited interoperability as some of the dominant barriers to aquatic food traceability

[16,23,60]. At the same time, the study advances this body of work in two respects. First, it operationalises and extends the technical framings of Jose and Prasannavenkatesan (2023) [30] and Islam and Cullen (2021) [5] by embedding drivers and solutions, as well as economic and governance considerations alongside the technical ones. Second, by foregrounding the perspective of the practitioners who design, fund, and operate these systems, it complements review-based accounts with an implementation-grounded understanding of how governance arrangements, financing responsibilities, and technological choices interact. This practitioner lens is particularly timely as Regulation (EU) 2023/2842 moves from adoption into phased implementation.

To foster equitable and effective implementation, we recommend:

- Developing inclusive, interoperable, and context-sensitive solutions co-designed with diverse stakeholders;
- Providing governmental or institutional support for initial investments and capacity building;
- Increasing transparency about traceability costs and return on investment to inform decision-making;
- Ensuring data collectors retain ownership of their data, while protecting sensitive business and personal information;
- Disclosing aggregated traceability data to the public to enhance trust, accountability, and perceptions of sustainability within the fisheries sector.

Although regulations may prove to be the most effective driver of systemic change, it should not be regarded merely as a compliance tool. Instead, it represents an opportunity to foster fairness, resilience, and shared responsibility across fisheries value chains, while simultaneously generating economic benefits for fishery businesses. Ultimately, when thoughtfully designed and equitably implemented, digital traceability has the potential to become a transformative tool for fisheries, supporting sustainability, strengthening governance, and creating long-term value across fisheries value chains.

CRediT authorship contribution statement

Gisela Costa: Writing – original draft, Methodology, Investigation, Conceptualization. **Mafalda Rangel:** Writing – review & editing, Supervision, Methodology. **Cristina Pita:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2026.107265.

Data availability

Data will be made available on request.

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