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Digital technologies for traceability and transparency in the global fish supply chains: A systematic review and future directions

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ABSTRACT

Ensuring sustainability and ethical practices in global fish supply chains requires robust implementation of digital technologies that conform to traceability and transparency policies in the fisheries industry. This paper provides an in-depth review of 27 impactful studies published from 2008 to 2024, examining how digital technologies enhance fish supply chain traceability to inform effective global fisheries policies. The review identifies three key research streams: (1) enabling technologies such as blockchain and Internet of Things; (2) critical traceability parameters for transparency, including fraud prevention and consumer trust; and (3) sustainability benefits, such as enhanced regulatory compliance and cold-chain efficiency. By mapping gaps in current research, this study establishes a future research and policy agenda and underscores the transformative potential of digital innovations in sustainable fish supply chain governance. Policymakers are encouraged to utilise these technologies to create strong frameworks that ensure transparent data sharing and compliance verification among all supply chain participants in order to address illegal, unreported, and unregulated fishing, promote sustainability, and safeguard human rights in fisheries. Although the focus of this paper is on fish supply chains, findings and recommendations may apply to traceability and transparency in other supply chains aiming for sustainable operations.

1. Introduction

Sustainable Development Goal (SDG) 14 commits the global community to regulate fishing practices, end overfishing, eliminate illegal, unreported, and unregulated (IUU) fishing, and promote science-based management to restore fish stocks to sustainable levels [1]. Despite these ambitions, the target remains unmet as fisheries worldwide face persistent challenges. Improving fisheries supply chain policies and governance at national, regional, and international levels is seen as critical, with transparency in decision-making and implementation recognised as a key part of the solution [2,3]. Transparency and traceability not only strengthen accountability but also support effective fisheries policies and governance. The Aarhus Convention underscores three pillars of transparency: access to information, public participation in decision-making, and access to justice [4]. These principles serve as a foundation for global environmental governance and fisheries management.

Efforts to enhance transparency and traceability often focus on Regional Fisheries Management Organisations (RFMOs), which oversee highly migratory and shared fish stocks [5]. The 1995 United Nations Fish Stocks Agreement (UNFSA) emphasises openness in RFMO decision-making and encourages participation from intergovernmental and non-governmental organisations [1]. While progress has been made, gaps remain in understanding how increased transparency impacts fisheries policies and governance performance. This calls for continued efforts to align transparency initiatives with effective, sustainable management practices. Fishery Improvement Projects (FIPs), for instance, aim to transition fisheries from unsustainable to sustainable practices by addressing environmental and management challenges through collaborative, time-bound plans involving multiple stakeholders [see 6]. As FIP products align with the responsible procurement policies of certain companies, incorporating traceability practices has become essential to ensure proper identification and support for improvement claims [7]. To meet this demand, more projects are now

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exploring ways to integrate traceability goals into their work plans. Although there has been growing research interest in transparency, including RFMO transparency, limited comprehensive studies on the technology gap that could positively facilitate the connections between increased openness and fisheries policies and governance performance exist.

Traceability—the ability to track and monitor food, feed and ingredients throughout every stage of production, processing, and distribution [8]—has emerged as a pivotal strategic tool in addressing the growing ecological and social challenges faced by supply chains in various industries, including food, extractive, and textile sectors. Within the global fish industry—a sector characterised by its vast network of artisanal fishers, smallholder fish farmers, aggregators, processors, exporters, importers, wholesalers, retailers, restaurants, and consumers—traceability enabled by digital technologies has the potential to revolutionise and give meaning to transparency, governance, and sustainability policies. The need to integrate traceability practices into fishery improvement projects has been highlighted as an important activity to ensure that companies operating within the global fisheries supply chain adhere to responsible procurement policies [7]. Traceability tools and information serve various purposes across different actors in the fisheries supply chain [9] For those involved upstream, these tools are used to uphold claims about the quality and integrity of fish products and on the consumer end, play a role in educating customers about the origins and details of fish products, as well as ensuring adherence to due diligence requirements [7].

Digital technologies for traceability are understood to massively enhance stakeholders' ability to 'identify and trace the history, distribution, location and application of products, parts, materials, and services as well as to 'verify historical information and localise parts, materials and products across the supply chain employing documented recorded identification' [see 10]. These technologies foster accountability and reduce operational inefficiencies as well as inform global fisheries supply chain policies. Despite its importance, the literature on digital technologies for traceability in the fish industry remains fragmented. This is particularly concerning given the unique complexities of global seafood supply chains, where a fish harvested in one part of the world may change hands multiple times, traverse thousands of miles, and undergo extensive processing before reaching its ultimate consumers – thousands of miles away. Noting the inherent lack of transparency and unfairness of global supply chain management, traceability has been connected with supply chain governance as a critical quality management component [11] anchored by modern digital technologies. Garcia-Torres, Albareda, Rey-Garcia and Seuring [10], observe that traceability is a notable strategic tool for managing complexity and uncertainty in global supply chains across many industries. Seafood is a typical global commodity with a complex network of businesses engaged at the local, regional, national, and international levels.

As at March 2025, the most recent comprehensive data on global fisheries and aquaculture production is from 2022, as reported in the Food and Agriculture Organization's (FAO) 2024 edition of *The State of World Fisheries and Aquaculture*. According to the United Nations FAO, global fisheries and aquaculture production reached a record high in 2022. The total first-sale value of this production was estimated at USD 452 billion, comprising USD 157 billion for capture fisheries and USD 296 billion for aquaculture [12]. International trade of fisheries and aquaculture products has also seen significant growth. In 2022, the value of global exports of aquatic products reached USD 195 billion, accounting for over 9 % of total agricultural trade (excluding forestry) and about 1 % of total merchandise trade in 2022 [12]. However, this is a complex and opaque network [13–15] plagued by significant challenges, including IUU fishing activities, human rights abuses, and product fraud. These issues erode consumer trust, jeopardise sustainability, and amplify the urgent need for transparency.

As a direct reflection of the nature of the global fish industry, information is maintained in silos by separate supply chain actors, making it difficult to trace a seafood product fully or effectively as it moves along the chain. This obscured nature of supply chains creates challenges in the monitoring of whether actors follow recognised legal and ethical standards. IUU is a global concern as it has a negative effect on sustainable fish stocks. While the extent of current IUU activities globally is difficult to estimate, a study by Agnew, Pearce, Pramod, Peatman, Watson, Beddington and Pitcher [16] provides a glimpse of the extent of the problem globally. According to this study, which involved analysis of IUU activities in 54 countries and on the high seas, the total value of IUU losses worldwide is between USD 10 and USD 23.5 billion annually, representing between 11 and 26 million tonnes [16]. This accounts for approximately 15 % of total catches annually [14,15]. A 2018 report from Greenpeace, "Misery at Sea", highlighted some of the documented human rights abuses in fisheries [17]. As a result of these reported illegal and unethical practices, the global seafood industry is saddled with unprecedented criticism and declining trust among consumers [14]. The FAO indicates that global marine fishery resources have declined - the proportion of fishery stocks within biologically sustainable levels decreased from 90 % in 1974 to 62.3 % in 2021, which is 2.3 % lower than in 2019, with maximally sustainably fished stocks at 50.5 % (57.3 % in 2019) [12, 13, see also 18]. However, the problem is not simply consumption but waste, as up to 30 %-35 % of the global fisheries and aquaculture production is either lost or wasted every year within supply chains [19,20].

Addressing these challenges requires innovative digital solutions that not only track the movement of physical goods but also enable seamless data sharing among stakeholders. These distinctive features of the global fish supply chains accentuate the applicability of relevant digitally enabled technologies for traceability in such an industry. In this way, digital technologies for traceability could transform a complex global fish supply chain to achieve supply chain transparency and sustainability [21]. In recent decades, the use of data and digital technologies to drive efficiency and innovation in many agricultural industry sectors has become apparent. Still, seafood needs to catch up in this regard. While physical seafood goods are being transferred through global supply chains, the related data is not being shared in any significant way. This lack of data comes at a cost. Without relevant data and insights based on digitally enabled technologies for traceability, fish stocks cannot be adequately managed, supply chain efficiencies cannot be substantially improved, and cold-chain and logistics services cannot be easily coordinated. Without digital technologies for traceability in the global fish supply chains, the world's growing population, projected to reach almost 10 billion (9.7 billion) in 2050 [22], could inevitably collapse the seafood ecosystem.

To address this gap, this paper presents a systematic review of 27 impactful studies published between 2008 and 2024, focusing on digital technologies for traceability in the global fish supply chain. The systematic review, of studies published up to April 2024, employed guidelines set out in the preferred reporting items for systematic review and meta-analysis framework [23]. The search, synthesis, and conceptualisation of data followed the three macro stages proposed by Tranfield, Denyer and Smart [24], which involve formulating the review question to select relevant papers, searching for other potential articles, and analysing accepted papers for data extraction. This study contributes to the literature by offering a comprehensive analysis of how digital technologies can address critical challenges in the fish supply chain, providing actionable insights for researchers, policymakers, and industry stakeholders. By highlighting the transformative potential of digital traceability, this paper underscores the urgency of adopting innovative solutions to ensure the sustainability and resilience of global seafood supply chains.

As the novel systematic review undertaken on digital technologies for traceability in the global fish industry, this paper provides original insights into digital technologies for traceability research by revealing three key research streams: (1) technological enablers of traceability and transparency, (2) critical parameters necessary for achieving transparency, and (3) the sustainability benefits enabled by digital traceability. By synthesizing findings from these studies, this paper not only maps the current state of research but also establishes a forward-looking agenda to guide future investigations and practical applications in the field. Following the introduction section, the methods employed for the systematic review covering search strategy, study selection and data extraction are summarised. The following section presents the results that cover key characteristics of case studies applying digital solutions to implement traceability and transparency in fish supply chains (FSC); technological enablers of traceability and transparency in FSC(s); traceability parameters to promote transparency in FSCs and the benefits of digital traceability for the sustainability of FSCs are presented. This is followed by the discussion section, and the final section presents the conclusion.

2. Methods

2.1. Structure of the review

In terms of structure, this systematic review employed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines [23]. In addition, the search, synthesis, and conceptualisation of data followed the three macro stages proposed by Tranfield, Denyer and Smart [24] (Table 1). Thereby, the first step involved the formulation of the review question and the criteria for the study (to select the correct papers). The second step involved searching for other potential articles. The last step involves analysing the selected studies for data extraction and discussion.

2.2. Search strategy

The studies used in this systematic review were identified by searching Scopus, Web of Science, and Google Scholar databases. No minimum time limit was applied in the search, to access all possible documented literature on the subject area due to the relatively recent application and adoption of digital technologies to promote transparency and traceability in fish supply chains.

Table 1
Review protocol.

Macro stages	Steps	Details
Planning the review	Review question formulation Review protocol for the location of studies	– established review questions based on the aim of the study – developed search terms and strings – search on Scopus, Web of Science, and manual search on Google/ Google Scholar – search fields: title, abstract and keywords – search language limited to English – search without a minimum period (date of search – April 2024) – should be peer-reviewed
Conducting the review	Evaluation and selection of studies Analysis and synthesis	– screening (titles, abstracts/ keywords, and full-text articles) – read the full paper – google spreadsheet to extract data based on the results of the research questions – content analysis based on literature review by crossing data from different technologies, discussions, and authors
Reporting and Dissemination	Presentation of results	– answer the review question from what is known in the literature – highlight the relevant points and gaps

The search focused on articles written in English; it was not limited to studies published in indexed Journals but also unpublished articles/reports that demonstrated the use of digital technologies in promoting transparency and visibility in fish supply chains. The inclusion of articles in non-indexed journals and combining other databases with mainstream scientific databases has been advanced to achieve better search results that improve the reliability of the collected data and ensure that critical literature is not missed [25–27]. Commentaries, editorials, manuals, and conceptual studies were disregarded. The search syntax used included the following terms referring to fish supply chain and traceability or transparency: (fish supply chain, fish value chain, fish supply network, fish industry, seafood industry, seafood supply chain, traceability, transparency, visibility in the fish supply chain, sustainability of fish supply chains; food supply chains, agri-food supply chain); combined with technology-related terms (digital innovation(s), digital technology, sensors, wireless sensor network (WSN), blockchain, radio frequency identification (RFID), and IoT).

2.3. Study selection

After removing duplicates, the initial selection of relevant studies was initially based on title and abstract screening to ascertain the existence of transparency or traceability and fish supply chain and technology-related keywords (Fig. 1). A full paper reading was carried out by applying more stringent inclusion criteria. Thereby, studies that used one or a combination of digital technologies or solutions to enable traceability or transparency in fish supply chains were retained to constitute the systematic review. Furthermore, a study had to demonstrate technology validation (case study) or at least proof of the concept and focus on at least one supply chain actor, i.e., primary producers, processors, distributors, the food service sector, and consumers.

2.4. Data extraction

A data extraction sheet was designed based on the reviewed studies, particularly digital innovations in fish supply chains and traceability. We systematically recorded and coded all necessary data from the studies, including study characteristics usually reported in systematic reviews. We extracted information related to the type of technological innovations, the purpose of innovation, the level of integration of technologies, the stage of the supply chain where technologies are adopted, the fish sector, fish/seafood product type, country, year of study, and nature of the study. Regarding transparency, traceability, and sustainability of fish supply chains, we extracted data on the key benefits of enabling traceability and transparency parameters, implications for supply chain sustainability, and challenges and risks associated with adopting digital innovations. These elements enabled the formulation of a complete narrative of an overview of the selected studies concerning characteristics, application of digital innovations to promote transparency, benefits and risks and implications for fish supply chain sustainability.

3. Results

3.1. Study characteristics

As Fig. 1 shows, our search initially identified 520 studies of potential interest. However, after full article screening, including removing duplicates, 27 studies were selected and classified based on the technology family and technologies integration deployed to implement the traceability system (Table 2). The studies in this review were published from 2008 onwards, either as a case study, pilot study, or proof of concept demonstrating the potential of the innovation to enable traceability and transparency in the fish supply chain. Broadly, several studies focused on aquaculture (9) and marine catch or fisheries (11). Among advanced countries, most of the studies (7) were conducted in

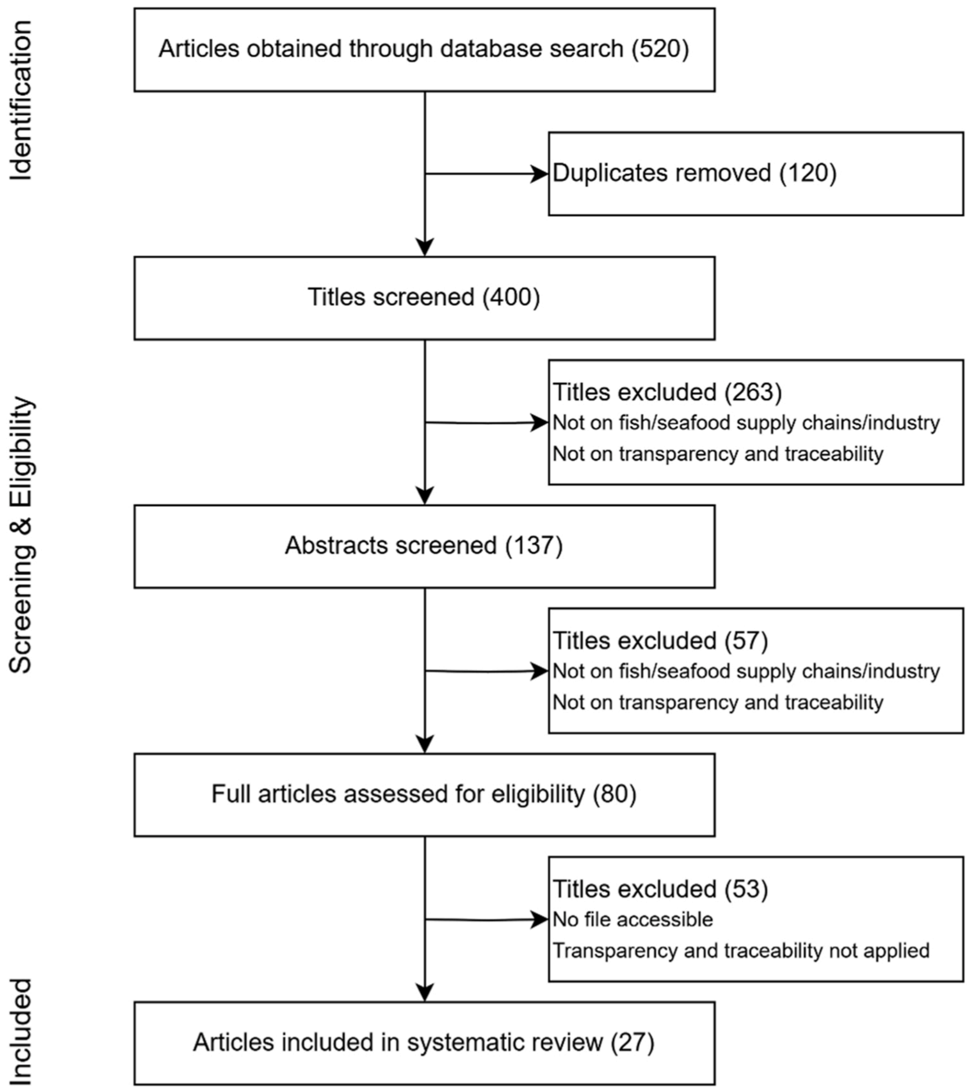

Fig. 1. A flow chart of the search and study selection procedure.

Europe (Spain, Slovenia, Sweden, and Norway, Italy). This could be due to the EU food traceability Regulation (EC) No. 178/2002 (2002), which came into force in 2005 as part of the EU General Food Law [28]. In middle and low-income countries, China had the most (5) studies than any Asian country - all the studies focused on traceability and transparency in aquaculture. One study (each) originated from Fiji and Iceland, and there was one proof of concept study by a blockchain traceability organisation (Fishcoin).

Of the studies, sixteen implemented innovative solutions that provide traceability data along all stages of the FSC (depending on the chain length). Of which, eight covered traceability information, including farmer/fisher details, breeding/hatchery data, farming data (pond/tank/cage information, water quality, feeding and medicine data), catch data and equipment used, discharge and landing data, processing, inventory and sales data, transportation data (all stages), and retail data [14,18,29–34]. Furthermore, five studies implemented traceability solutions for the entire chain but did not collect information on the sources of fingerlings [35–37] or the fisher [38,39]. The remaining studies deployed innovative solutions at the processing, packaging, storage, and distribution stages of the FSCs. These studies focused mainly on monitoring temperature, humidity, and product freshness to improve traceability and transparency in cold-chain logistics; processed frozen Tilapia [40,41], fresh chilled Cod [42], South African fresh Hake [43], and fresh Piran sea bass [44]. At the same time, three of these studies focused on integrating real-time temperature and humidity monitoring data into existing traceability data [41,43,44]. At the same time, other studies focused on predicting product freshness and shelf life [40] and establishing criteria for temperature alerts in cold-chain logistics at the organisation level [42].

However, four studies investigated how technological innovations deployed to enhance traceability and transparency can create value for supply chain actors, especially fishers [18,31,37]. While studies by Jæger and Mishra [37] and Fishcoin [18] examined how seafood traceability at the primary production level can generate direct value for seafood farmers, the study by Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31] analysed direct and indirect data monetisation on a blockchain platform. Where fisherfolks are incentivised to capture verified catch data which is then sold to third parties such as retailers and final buyers, or institutions (like banks, NGOs, and government agencies) access the data free of charge in exchange for providing services like loans, credits and training to the fisher.

3.2. Technological enablers of traceability and transparency in FSCs

Digital innovations enabling traceability and promoting transparency in FSC can broadly be categorised into identification technologies, sensing technologies, IoT and data management technologies. Table 3 summarises the primary technology applications used,

Table 2
Overview of key characteristics of case studies applying digital solutions to implement traceability and transparency in FSC.

Authors	Country	Fish sector	Stage of FSC	Type of fish	Key data element (KDE) collected to enable traceability and transparency	Objective
Grantham, Pandan, Roxas and Hitchcock [45]	Philippines	Marine Catch	Fishers and processors	All major tuna species for export	Data on catch data and Fisher details	To develop and deploy digital, democratized data capture methods
Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29]	Spain and Slovenia	Aquaculture	All stages of FSC (including breeding)	Fresh sea bream and sea bass	Breeding and farming operations (receiving of juveniles at the farm, movement of fish between cages, feed, and medication, number of dead fish, net replacement, cage number and a batch of fish in a cage and others); harvesting and transportation data; processing stage - order information, fish type, weight, inventory data; temperature and humidity monitoring (during transportation, processing, packaging, storage)	A traceability system architecture based on web services, which integrate traceability data with environmental data
Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44]	Slovenia	Aquaculture	Processing, shipping, wholesale /distribution, retail & consumer	Fresh Piran sea bass	Farm operations records - from breeding to harvest. Processing data (orders, weighing, sorting, packaging fish into boxes) Cold-chain monitoring RFID-TL to the box (ambient temperature and fish temperature)	Temperature monitoring traceability system (at the box level) in a fresh fish supply chain
Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43]	Spain	Marine catch	Processing, shipping, wholesale /distribution, and retail	South African fresh hake	Temperature, relative humidity and time data, traceability data (such as origin, species type, and capture data). It also provides information on product freshness or lifetime	Validation of real-time traceability and online monitoring of fresh fish logistic cold-chain
Ringsberg and Mirzabeiki [34]	Sweden	Marine catch	Fisher, processors, wholesalers' retailers and consumers	Fresh Cod (whole & filleted)	Fisher details: fishing activity (vessel ID & name, date of catch, net weight of the catch, species name, fishing location, type of fishing gear, catch discharged date, & landing site). Processing data (date/time of fish arrival, date & type of processing, fish box ID, location of boxes; time/date of shipping). Retail data (time/date of arrival of filleted fish boxes, boxes location; sales information); Restaurants (traceability information is in plain text on the menu)	Explore the potential effects of implementing the Electronic Product Code Information Service (EPCIS) standard and RFID to enable fish traceability
Yu-Chia, An-Pin and Chun-Hung [30]	Taiwan	Aquaculture	Fish farmer; Live fish centre (storage /sales) & restaurants	Live fish products (Cobia and Grouper)	Farm records (origin of fish larva, feeding and drug data); third-party inspection records (test of residues of chemical and drugs); Live fish centre - sales and inventory data (the origin of fish, the time of arrival, storage tank ID, water quality in the tanks, feeding activity); traceability information via web service /internet	Adoption of RFID for traceability system in a live fish supply chain traceability
Qi, Zhang, Xu, Fu, Chen and Zhang [33]	China	Aquaculture (recirculation)	Farmers	Fresh fish	Farming data (pond information - source of fingerlings, feeding records, disease treatment records, fish quantity); water quality data (water temperature, salinity, dissolved oxygen, and pH value); batch and identification management, sale data	Developed a wireless sensor network to monitor water quality in recirculation aquaculture
Thakur and Ringsberg [39]	Sweden and Iceland	Marine catch	From catch to restaurant /retail	Fresh fish	Catch data, storage, transportation, and distribution data. Traces the product through the supply chain from Fisher to the retail/restaurants	Developed and evaluated an electronic traceability system based on the EPCIS standard by enabling automatic data capture for the fish traceability system
Tingman, Jian and Xiaoshuan [40]	China	Aquaculture	storage and distribution	Processed fresh tilapia (frozen)	Temperature monitoring (ambient temperature and temperature of frozen fish)	Evaluating fish product quality (frozen tilapia fillet) to predict shelf life through monitoring temperature changes

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Table 2 (*continued*)

Authors	Country	Fish sector	Stage of FSC	Type of fish	Key data element (KDE) collected to enable traceability and transparency	Objective
Zhang, Liu, Mu, Moga and Zhang [41]	China	Aquaculture	storage and distribution	Processed Chilled Tilapia	RFID tag integrated with GPS and mobile communication used for temperature management with traceability of Chilled Tilapia	Development of a temperature-managed traceability system
Hafliðason, Ólafsdóttir, Bogason and Stefánsson [42]	Iceland	Marine catch	Processing and packaging (storage and shipment)	Fresh, chilled Cod	Temperature monitoring data (ambient temperature and temperature of fish)	Use WSN application in logistic and temperature mapping in cod supply chains and establish criteria for temperature alerts
Zhang, Wang, Yan, Glamuzina and Zhang [36]	China	Aquaculture	Farm, processing, packaging, storage, transportation	Chinese sturgeon	Farm data, time of catch, weight, temperature, and respiratory data (obtained by wireless sensors for online monitoring), processing data (batch ID, time of processing), retailer (time of sale), inspection data, and fresh sensory index	Developed an intelligent traceability platform based on the Hazard Analysis and Critical Control Point (system and integrated wireless monitoring and quality control models to improve transparency in the transportation of waterless fish
Cook [14]	Fiji	Marine catch	Fisher to the final consumer	Tuna (fresh and frozen)	Data on the catch (species, weight, catch zone); fishing vessel information; details of crew	Application of blockchain technology for seafood traceability (specifically, tuna caught in a Fijian longline fishery) to help stop illegal, unreported, and unregulated fishing, unsustainable fishing practices
Fishcoin [18]		Fisheries and aquaculture	All stages of the FSC (from catch to the consumer)	All types of fish and seafood	Catch data: **s**pecies, time, and location of catch - (including FAO zone, country of catch, region, management authority); landing date; vessel information (including captain name, homeport); fishing method; the total weight of catch; certification. Processing data: **s**pecie (s) name, date and time received, location received (weight, batch id.), dates & time shipped (name of processor/packing plant, pallet id., and supplier/customer). Distribution**:** product name, weight, container/seal No., pallet id., batch/serial No., dispatch date, receiving date, transport company details. Temperature and time profile information collected during transit/shipment (all stages)	A decentralised data ecosystem that uses blockchain technology to serve as both a mechanism and incentive structure to collect and share traceability data. The system incentivises data exchange between actors (using the Fishcoin token)
Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31]	Philippines	Marine catch (artisanal handline tuna fishing)	Fisher	Tuna (yellowfin, skipjack, and frigate tuna)	Fisher data (name, fishing license); fishing information (type of fishing vessel, registration no., fishing gear, location, type of fish); sales information (sales price, buyer identity, quantity of fish sold and purchase receipts)	Blockchain-enabled application incentivises fisherfolks to capture verified catch and trade data through data monetisation. The data is sold to third parties (i.e., retailers /final buyers) and indirect monetisation (institutions can access the data for free in exchange for services such as micro-finance to fisher folks)
Zhang, Liu, Jiong, Zhang, Li and Chen [35]	China	Aquaculture	All stages of the supply chain	Frozen Turbot	Farming data (pond ID., location, name of farmer/aquaculture company, number of staff, fish species, water quality); processing and packaging data (factory ID, time of processing, operating temperature, truck id, place of departure, transport time); quality inspection data; distribution data (cold-chain or logistic provider (name & truck id), time of departure, place of departure, temperature (ambient and relative temperature), location tracker, vibration, abnormal temperature and heat alert); retail (ambient temperature and relative humidity, location, time of sales)	Novel frozen aquatic product traceability system (BIOT-TS) based on blockchain, and the Internet of Things (IoT) improves weak security, performance, and centralised data management in cold-chain traceability systems
Provenance [32]	Indonesia	Marine catch (artisanal pole	Fisher to the consumer	Fresh Tuna (Skipjack/ Yellowfin)	Fisher attributes, data on fishing activities (location of catch, quantity of catch, fish specifies and	Explore how new technologies could form the basis for an open system for traceability that

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Table 2 (*continued*)

Authors	Country	Fish sector	Stage of FSC	Type of fish	Key data element (KDE) collected to enable traceability and transparency	Objective
		line/handline fishing)			batch ID) and data on certification scheme(s)	empowers consumers demanding transparency for food
Jæger and Mishra [37]	Norway	Aquaculture	Farmers & consumers	Fresh fish	Fish farmer data (production facilities and operational data); fish crate and fish data (containing all information related to the fish, including crate ID) A standard reading device reads the label and transmits it to the EPCIS database	Investigate how the IoT platform can be used to implement seafood traceability at the farmer level and how the system can be used to generate value for farmers (being the source of both the fish and reliable, high-quality information related to the fish)
Grecuccio, Giusto, Fiori and Rebaudengo [38]	Italy	Marine catch	Fisher & consumer	Fresh fish and seafood products	Fishing activity data (fishing location and vessel route), landing data - and batch ID for each type of fish are written into an RFID tag. Sales data, transportation data (truck delivery route, onboard temperature monitoring, and completion of delivery data) retailers can share the information with the customers through a QR code tagged to the product to access the information stored in the blockchain	The study focuses on cold-chain monitoring during logistics operations. It uses blockchain and IoT devices to tackle food integrity and safety in fish traceability, enabling the sharing of information with the final consumer without needing to depend on a centralised trust authority

categorised by the leading technology domain and the level of integration. The most common identification, location, and sensing technologies employed in FSC include Radio Frequency Identification and data capture - RFID (sensing tags, monitors, readers, and scanners), time-temperature and humidity sensors, barcodes, QR codes, WSN, Near Field Communication (NFC), and Global Positioning Systems (GPS). Regarding database repositories, servers, and data management platforms, the most widely considered technologies were blockchain and EPCIS. While mobile applications, GPRS, web-based services, and combinations of sensors for data collection and exchange were typical in IoT solutions.

Technologies that enable traceability and promote transparency within FSCs must be able to collect information and data in the whole supply chain. More importantly, the technologies must allow data to be collected automatically as part of the processes along the supply chain and make the information available to actors and stakeholders within the chain, including consumers, in real-time. To this end, RFID and sensor technologies provide the base for developing digitally enabled traceability systems – internal traceability within fish sector organisations and the supply chains. Sensor devices embedded in the fish supply chain infrastructure can collect, process, analyse, and store data. Developing technologies like 2D barcodes, QR codes, RFID, and WSN is a critical factor in the new electronic traceability system in fish and seafood supply chains, leading to new opportunities to improve safety and enhance supply chain and process transparency.

The most common demonstration study examined was the integration of RFID and WSN for electronic traceability and condition monitoring (Table 3). Yu-Chia, An-Pin and Chun-Hung [30] investigated an RFID-enabled traceability system for live fish supply by integrating RFID sensor tag applications with barcodes. The sensors collect information on farming activities, conditions, and automatic transporting processes. The traceability information is exchanged with customers through barcodes linked to web-based services containing information about the fish. Other studies investigated the integration of RFID with temperature sensors, WSNs, barcodes, QR codes, and traceability databases for temperature monitoring in the intercontinental fresh fish logistic [43], monitoring the temperature and humidity of fish products – during processing, storage, and transportation conditions [40,41,44]; and monitoring water quality in recirculation aquaculture [33].

Although RFID and sensing technologies can capture data, process, store and share with supply chain actors and stakeholders, including consumers, in real-time, this requires data to be of high-quality and accessed securely, limiting access to only relevant actors and consumers [46]. Blockchain technology, a decentralised ledger system that allows cryptographed transactions in blocks, has gained attraction in food supply chains due to its advanced traceability capabilities to increase food safety, and ability to allow high-quality data to be shared in a secure and trusted manner and thereby increase consumer trust [47,48]. In the fish and seafood supply chains, blockchain has been combined with sensing and identification technologies to help stop illegal, unreported, and unregulated fishing (IUUF), unsustainable fishing practices and human rights abuses in the tuna industry and to provide open seafood traceability that empowers consumers demanding transparency for food [18,31,32].

The decentralised capability of blockchain technology has been explored with mobile applications and IoT to provide seafood traceability solutions that both serve as a mechanism for quality data capturing and incentivising data exchanged between actors [18] and for direct and indirect monetisation of verified data captured by fisherfolks, thereby creating value for fishers [31]. In addition, value creation empowers and strengthens the competitive power of the fishers while addressing the asymmetry in cost versus revenue that hampers traditional food supply chains [37]. Besides, blockchain and IoT technologies were used to tackle food integrity and food safety in cold-chain logistics and fish traceability systems that enable sharing of information with the final consumer without depending on a centralised trust authority [35,38]; and to improve weak security performance, inefficient centralised data management in cold-chain traceability systems [35].

However, achieving an electronic traceability system in fish supply chains requires integrating technologies. We argue that the level of integration of technologies is critical in achieving a certain level of traceability and transparency in the supply chains. We have defined and categorised this level of traceability into three (3) standards: High, Medium and Low (Table 3). The justification for categorising the levels of traceability is based on the extent to which technologies are integrated to achieve the desired traceability outcomes and promote transparency. For instance, a high level of traceability means that digital traceability can provide comprehensive information about the fish product, including, fishing, farming and catch information (origin and identification), processing, storage, and distribution. Importantly, it enables both internal and external traceability of critical data elements (Table 2) and other information about the history of the fish product, as

Table 3
Main technology applications and nature of integration.

Technology family & domain	Main technologies	Integration of technologies	Application area	Level of traceability*	Reference
Identification and sensors	NFC or RFID	Smartphone-based app, NFC cards, or RFID tags and Transponders	Traceability	Medium	Grantham, Pandan, Roxas and Hitchcock [45]
Identification and sensors	RFID, WSN & EPCIS	RFID and WSN, 2-D barcodes, web-based services and EPCIS	Traceability and cold-chain monitoring	High	Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29]
Identification and sensors	RFID	RFID - temperature loggers (RFID-TL); RFID tag and QR code; RFID reader and traceability server	Traceability and Cold-chain monitoring	High	Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44]
Identification and sensors	RFID	RFID smart tags & time-temperature and humidity sensors	Traceability, cold-chain monitoring, shell life prediction and quality monitoring	High	Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43]
Identification and data management platform	RFID and EPCIS	EPCIS, QR Code and RFID tags	Traceability of fresh fish	High	Ringsberg and Mirzabeiki [34]
Identification	RFID	RFID tags and barcode	Traceability of live fish	Medium	Yu-Chia, An-Pin and Chun-Hung [30]
Identification and sensors	WSN	WSN (sensor nodes); wireless handsets with an RFID module and RFID tags	Traceability and quality monitoring (water quality)	Medium	Qi, Zhang, Xu, Fu, Chen and Zhang [33]
Identification and data management platform	RFID and EPCIS	RFID tags, RFID readers, EPCIS	Traceability of fresh fish	Medium	Thakur and Ringsberg [39]
Identification and sensing technologies	RFID	RFID temperature recorder & RFID reader	Shell life prediction and quality monitoring	Low	Tingman, Jian and Xiaoshuan [40]
Identification and location	RFID & GPS	RFID with temperature sensor tags, GPS, GPRS, wireless network, Internet	Cold-chain monitoring	Medium	Zhang, Liu, Mu, Moga and Zhang [41]
Sensors	WSN	WSN, temperature sensor recorders and data loggers	Cold-chain monitoring	Low	Hafliðason, Ólafsdóttir, Bogason and Stefánsson [42]
Identification and sensors	WSN & RFID	WSN, RFID tag, RFID & QR Code, WIFI, Internet and 3 G/GPRS and EPCIS server	Traceability and quality monitoring of waterless live fish	High	Zhang, Wang, Yan, Glamuzina and Zhang [36]
Data management platform	Blockchain	Blockchain, RFID tags, sensors QR code and RFID scanners, Internet, mobile app (TraSeable), server	Traceability of fresh fish	High	Cook [14]
Data management platform	Blockchain	Blockchain, IoT, sensors and mobile technology	Traceability (creates value for actors) and quality monitoring	High	Fishcoin [18]
Data management platform	Blockchain	Blockchain, Streamer network, mobile application, Internet, GPS	Traceability system to create value for fishers	High	Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31]
Data management platform and sensors	Blockchain and IoT	Blockchain and IoT, multi-sensors, QR code, RFID, WIFI, GPS, NFC recorders and WSN	Traceability, cold-chain monitoring, shell life prediction and quality monitoring	High	Zhang, Liu, Jiong, Zhang, Li and Chen [35]
Identification and data management platform	Blockchain and mobile technologies	Mobile, blockchain, QR code and RFID smart tags and NFC smart stickers, Internet	Traceability	High	Provenance [32]
Identification and data management platform	IoT and blockchain	IoT platform with EPCIS, ERP, CRM, and Blockchain, Internet, Barcode, QR code or RFID tag	Traceability system to create value for the fishers	High	Jæger and Mishra [37]
Data management, location, and identification	IoT and blockchain	Blockchain, temperature monitoring sensors, GPS, mobile network, RFID tags, QR code	Traceability, cold-chain, and quality monitoring	High	Grecuccio, Giusto, Fiori and Rebaudengo [38]

* The level of traceability is based on how the technologies have been integrated to achieve the intended traceability outcome and how that promotes transparency parameters. A **High level** of traceability means that digital traceability can provide information about the fishing, farming and catch information (origin and identification), processing, storage, and distribution; enables internal and external traceability of critical data elements and other information about the history of the fish product, integrate traceability system with product quality/freshness monitoring; and consumers can access traceability information. **Medium-level** traceability – collect information on catch/farming conditions and harvest, enabling internal and external traceability. **A low level** of traceability is where the system only focuses on processing, storage, or distribution stages of the FSCs, or focuses on product quality monitoring during transit and needs to provide catch/farming information or the information available to consumers and external stakeholders.

well as quality monitoring of the fish product (product quality and freshness) and consumers' access to traceability information. A medium level of traceability means that the integration of digital technologies collects information on catch or farming conditions and harvest (product origin and identification), enabling internal and external traceability, but the scope of information is less comprehensive compared to the high-level. For example, it may not offer the same level of transparency to consumers such as product quality, freshness and so on. A low level of traceability is where the digital integration system only focuses on the processing, storage, or distribution stages of the FSCs, or focuses on product quality monitoring during transit and needs to provide catch/farming information or the information available to consumers and external stakeholders.

Within both the policy and practice arena, we argue that establishing a clear level of traceability would be critical not only in harnessing public and private sector investments in digital technologies to enhance traceability and transparency in fish supply chains but will also ensure consistency in transparency, data sharing among stakeholders, and monitoring and enforcement. We present two best practice pilot case studies to demonstrate the integration of technologies that can be used in the different stages of the supply chains and the level of traceability achieved. The first case study focuses on aquaculture and involves the development of a novel frozen aquatic product traceability system, BIoT-TS, based on blockchain and IoT and covers all stages of the FSC [35]. The second case study focuses on marine catch and explores the potential effects of implementing the EPCIS standard and the use of RFID to enable fish traceability along the entire product supply chain [34].

3.2.1. Case study 1: digital technologies integration and traceability in aquaculture

The case study draws on the work of Zhang, Liu, Jiong, Zhang, Li and Chen [35]. They developed a novel frozen aquatic product traceability system (BIoT-TS) that is based on blockchain and the Internet of things (IoT) as the main technologies. The system was implemented, deployed, and applied at Lin Ju aquatic enterprise (Chain, Shandong Province, Yantai City), and evaluated using frozen turbot (*Scophthalmus maximus*) product supply chains that are circulated and sold under the background of e-commerce cold-chain logistics. The case study demonstrated the highest number of digital technologies integration (eight different technologies - Table 4) with at least four technologies integrated at each stage of the supply chain ensuring high level of traceability in terms of data collection, quality control and monitoring, and sharing of data between stakeholders resulting in both internal and external traceability. The case study meets all the five key traceability parameters (see Table 5 and discussed in 3.3) that we have defined as a requirement for any digital traceability system to promote transparency in FSCs. The strength of this system lies in the level of integration of technologies and the data collected at the different stages of the aquaculture production system - from the farm to the consumer, making it particularly suitable for multi-stages tracking management of cold-chain logistics from production, logistics, and circulation to sales. Table 4 summarises the integrated technologies, data collected and parameters that are used in every stage of the BIoT-TS system.

The BIoT-TS system consists of two sub-systems: the blockchain subsystem that is in charge of the audit for data manipulation of on-chain transactions and storage as well as quality tracing transactions and the IoT sub-system that utilizes the multi-sensors in every section during the different logistics scenarios, which is in charge of monitoring and harvesting the logistics information. The IoT subsystem includes three tiers: the multi-sensors monitoring tier, the data communication and processing tier, and the application and representation tier. Through those three tiers, the sensitive monitoring data are distributed, acquired, fused, compressed, processed, analysed, and finally represented in the application tier. This process is facilitated by the design and implementation of the systems' interoperable functions, and real-time tracking information that is transparently shared in the logistic links of production, circulation, consumption, and authority inspection.

Information about aquaculture production, processing, quality inspections and regulations from government authorities and trade associations, cold-chain logistics, distribution and retailers as indicated in Table 4, are collected through IoT and stored on blockchain technology. By leveraging decentralised data management, smart contracts, and consensus mechanisms, traceability information can be securely partitioned and encrypted. This approach facilitates effective government oversight and allows consumers to access historical data for verification purposes. Thus, the system provides the advantages of reliable, and tamper-proofing when compared with traditional tracking technology [35]. Within the blockchain storage system, there are specific nodes for the aquaculture enterprise, cold-chain logistics companies, distributors and retailers and government supervision. The distributed yet integrated nature of nodes makes it easier to identify and locate quality problems. The nodes that cause the problems are directly identified through tracing operations and sharing strategies, which greatly diminishes the cost of responsibility discovery and improves the efficiency of problem discovery. In addition, it also can precisely trace the main responsibility, identify potential risks, assess the degree of hazards, and share regulatory information. Therefore, a more reliable tracing platform is integrated, constructed, and applied, allowing all stakeholders and actors along the supply chain to adopt and ensure transparency across the value chain.

Moreover, having such highly integrated technologies comes with benefits at all stages of the aquaculture supply chain. At the production stage, collecting essential traceability information about the aquatic production process and conditions —including water quality, drug residues, species information, and location is crucial for enhancing the quality and safety of aquaculture. This information not only influences consumers' purchasing intentions but also establishes an effective mechanism for tracing aquatic food sources. The level of information collected and integration of the technologies from the production level to factory processing increase the influences of the aquatic food brand, optimise transaction processing based on accurate product identification, and reduce costs and wastes of aquatic food production. While at the same time improving accuracy for aquatic food quality control and with clear responsibilities when problems occur thereby reducing the

Table 4
The technologies and parameters that are used in every stage of BIoT-TS.

Stages of Turbot Supply Chain	Information Technology	Data Collected	Monitoring Parameters	Tracking Process
Aquaculture production	Lora, Zigbee, NB-IoT, RFID	Farming data (pond ID., location, name of farmer/ aquaculture company, number of staff, fish species, water quality	Dissolved oxygen, pH, salinity, ammonia, temperature, nitrogen, drug residue	Aquaculture water quality monitoring and drug residue checking, upload to BIoT-TS
Processing (aquatic food)	Wi-Fi, RFID, Zigbee, NFC	Processing and packaging data (factory ID, time of processing, production batch, packaging requirement, operating temperature, truck ID, place of departure, transport time	Temperature, abnormal operations, humidity, disinfection levels	Precisely monitor the temperature, humidity, disinfection status, and upload to BIoT-TS
Quality inspection (government regulators /trade associations)	4 G, Wi-Fi, RFID	Processing factory ID, packaging approval, quality inspection data and packaging	TVB-N, histamine, metals, hazardous substances (Malachite green, chloramphenicol, nitrofurans, etc.)	Take representative samples, automatic rapid detection, wireless on-chain
Cold-chain logistics	4 G, NB-IoT, Zigbee, NFC, GPS	Cold-chain or logistic provider (name & truck id), time of departure, place of departure, duration, and temperature changes	Abnormal door open/close events of a refrigerated truck, temperature, relative humidity, logistic positions, the integrity of package, vibration (acceleration) and heat alert	Finish the logistics ambient parameters on-chain process, and abnormal ambient fluctuations in transport are also uploading to BIoT-TS
Distribution/ retailers	Wi-Fi, RFID, Zigbee	Distributor/retailer company name, product details, warehousing time, allocation situation, storehouse length of time, order correlation, place of departure, and delivery time	The authenticity of label information, batch information, cross-sale information, dispatch information, temperature, destination code	Temporary storage management, outbound collection, cross-sale checking
Point of sale/ consumers	Wi-Fi, NFC, RFID	Confirmation of receipt, real-time queries, query time, and location of query	QR code, location, queried quality result, sale time, and the concerned feedback information	Quality traceability query, upload the quality feedback, early warning information prompt

Table 5
Critical parameters to achieve traceability and transparency in FSC.

Traceability and transparency parameters	Critical indicators for achieving transparency	Reference
Product identification (Include origin)	• Details of the fish farmer/fisher and fishing vessel name, port number/name. • The origin of the fish larva/fingerlings and the fish type (scientific or trade names). • Location and origin of catch/ pond. • Catch data/harvest (date, time weight, quantity). • Aquaculture production conditions (e.g., water quality, feed, diseases, and medication records). • Lot/batch reference – tags or ID (ponds/ cages/tanks, crates, boxes, bins).	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Thakur and Ringsberg [39], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44], Grantham, Pandan, Roxas and Hitchcock [45], Visser and Hanich [60]
Ability to reduce or prevent product substitution and mislabelling	• Reduces product substitution, fraud, and counterfeiting risks through product tagging and tracking. • Downstream actors are incentivised to minimise product fraud by exchanging data for tokens (paid by the downstream actors). • Allows information/ data to be authenticated by other chain actors. • Promote security, confidentiality, and robustness of information transactions. • The system can be interrogated to flag where fraud has occurred. • Record information in near real-time and make it accessible to other chain actors, making it difficult to alter.	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44], Visser and Hanich [60]
Promote and improve food safety and health risk	• Product quality can be monitored as time/ temperature/humidity profiles during transit or bacterial count as the seafood travels along supply chains. • Product quality information is accessible to all chain actors and consumers. • Integrate product identification, history, and traceability data with temperature/ humidity monitoring data (product quality and freshness). • Monitor product quality during production –e.g., managing diseases, feeds, medicines and monitoring effluents and water quality. • Product historical records can be audited instantly to identify fraud patterns to avoid risk quickly, and regulatory authorities can deal with fraud instances quickly. • Product quality-related information is securely stored.	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Thakur and Ringsberg [39], Tingman, Jian and Xiaoshuan [40], Zhang, Liu, Mu, Moga and Zhang [41], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44]
Improve or increase consumer choice /information/ confidence and trust	• Provide consumers with information about the product history (i.e., breeding, feeds, pond information, medicines usage, water temperature/quality, and catch information) through QR codes, barcodes or NFC stickers labels on fish boxes or packaging. • Customers can access the tracing server to check the validity and traceability information. • The customers can verify a complete story of the fish product and check if any violation of the cold-chain parameters has occurred. • Traceability information is provided in plain text on the processed fish packaged/menus (i.e. restaurants/food service). • Enhances the reliability of traceability queries and safeguards consumers' rights and interests.	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Zhang, Liu, Mu, Moga and Zhang [41], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44]
Improves internal and external traceability & visibility	• Improve internal traceability and visibility for all actors connected in the chain from the catch to the retailer - all processes from aquaculture activities, catching, landing, processing, transportation, storage, and sales data are collected automatically in real-time. • Consumers can access traceability information, including the origin and location of the catch, via NFC smart stickers, barcodes, and QR codes,	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Zhang, Liu, Mu, Moga and Zhang [41], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and

(continued on next page)

Table 5 (*continued*)

Traceability and transparency parameters	Critical indicators for achieving transparency	Reference
	thereby improving transparency and visibility into the product's traceability. • Improves internal transparency and visibility concerning the product quality through the time-temperature/ humidity and location monitoring systems – internal actors can monitor or verify the state of the product quality. • Consumers and retailers can access the product's time-temperature/ humidity and location information while in transit and, therefore, can better manage shelf life. • Regulatory authorities and other third-party stakeholders can access traceability information (catch, landing date/ time, sales information from processing, whole-sales, and retails). • Traceability information is provided in plain text on the packaged or the menu at restaurants. • Integrating product quality (freshness) information with traceability data and makes this available to all internal actors. • All actors can query and retrieve information from a centralised repository system and add data to maintain and build the "story of the fish" and view the history of the products they are handling. • Ensures collection of quality traceability data by rewarding and incentivising actors (fisherfolks, processors, wholesalers, distributors, retailers etc.). • External traceability partners - governments, regulators and customers can query safety and quality information about the fish product. • Ensures the information is stored securely and cannot be altered by other users. • Regulatory authorities can provide quality inspection information on the product on the traceability system.	Kovačič [44], Visser and Hanich [60]

errors of mislabelling. As the product moves from the processing factories to the distribution and retail stage, critical quality and monitoring data with product identification information result in optimising the productivity of the product receiving and distributing process improves the efficiency of the temporary inventory management and increases the pick rates. At the point of sale, the traceability information is made available through a barcode which enhances the purchase confidence for consumers; improves the fast recalling and timely feedback and reliability of traceability queries as well as safeguards consumers' rights and interests.

3.2.2. *Case study 2: digital technologies integration and traceability in marine catch supply chain*

The second case study focuses on traceability within marine catch supply chains and draws on the pilot study by Ringsberg and Mirzabeiki [34] who explored the potential effects of logistics operations of implementing EPCIS standard and radio frequency identification (RFID) technology to enable food traceability. The pilot case study was implemented in Swedish fresh cod supply chain. The supply chain is strictly regulated by governmental authorities through fishery control. However, the use of non-automated techniques, such as handwritten stickers and documents, for information transfer between supply chain actors leads to challenges in meeting legal food traceability requirements and inefficiencies in logistics operations. The implementation of the EPCIS standard provides benefits in information management and data exchange to accomplish upstream and downstream food traceability while the RFID technology enables automatic capture of data. Compared to case study 1, this case demonstrates less integration of technologies – three systems consisting of EPCIS, Barcode and RFID tags, with EPCIS being the main data management platform while the RFID tags are used for data capture and transfer of data. The simple integration of the three systems, however, enabled collection of critical data across the cod supply chain: producer (fisher), processor, wholesaler, retailer and consumer to enable full traceability and transparency within the chain.

At the primary production stage, information about the fisher and fishing activities (including fishers name and business address, vessel ID & name, date of catch, net weight of the catch, species name, fishing location, type of fishing gear, catch discharged date, & landing site) are collected and stored on the EPCIS system. This detailed information is then processed into either RFID-labelled fish boxes (with unique Global Returnable Asset Identifier: GRAI number) and cardboard boxes (with unique Serialised Global Trade Item Number: SGTIN) for unique identification of transport units. The traceability of the supply chain starts with the scanning of the GRAI number of all RFID-tagged fish boxes dedicated to one fishing activity at the producer. Once the boxes are scanned by the fisher, it is reported as an EPCIS object event, which then links electronic product code data to the GRAI number, time/date and location) of each fish box to pre-reported information stored at governmental authorities about the upcoming fishing activity. The landing activity starts when the fish boxes are moved from the fishing vessel onto the quay. During transport, each fish box is then scanned to report the landing activity as an EPCIS transaction event, and a "landing declaration" is sent to the governmental authorities. Landed fish boxes are then sold by the fisher to either a processor or a wholesaler according to sales agreements.

Fish boxes that arrive at the processor and the wholesaler are reported as EPCIS transaction events according to transfer operations and sales agreements of fresh-caught fish. The sale of fish boxes is characterised by submission of conveyance and deductive bills to governmental authorities. Processing of fresh fish starts once the incoming fish boxes are scanned (GRAI number). The scanning provides processing data (date/time of fish arrival, date & type of processing, fish box ID, location of boxes; time/date of shipping) which is then reported as an EPCIS transaction event. Once the fresh code is processed into fillets, they are packaged into cardboard boxes and labelled with unique stickers including an RFID tag and printed product information. This is reported as an EPCIS aggregation event including information about time/date of filleting, location and unique identity (i.e. SGTIN) of each cardboard box. Once the card boxes are labelled and reported, they are then stored. Any shipments of cardboard boxes of filleted fish from storage facilities are made according to sales agreements between the processor and wholesaler. The shipments are reported as EPCIS transaction events, and as conveyance and deductive bills sent by the processor to governmental authorities. In the EPCIS transaction event, information about time/date of dispatch, the location and unique identity (i.e. SGTIN) of each cardboard box is reported.

At the wholesale stage, any incoming fish boxes and cardboard boxes are scanned and reported as EPCIS transaction events before they go into storage. Any shipment of cardboard and fish boxes from the storage is made according to sales agreements between the wholesaler and retailers and reported as EPCIS transaction events and as "delivery notes" sent by the wholesalers to governmental authorities. At the retailer, the identification number (i.e. the SGTIN and GRAI number) of each box received is scanned and reported as an EPCIS transaction event, transferring information about time/date of arrival of filleted fish boxes, box location and sales information. In the event where the retailer is a store, fish fillets are sold to end consumers in wrap-up paper labelled with a sticker, including a barcode and traceability information in plain text and the sale is reported as EPCIS aggregate event. Where the retailer is a restaurant, the fish is sold to end consumers as a component in meals, which is reported as an EPCIS quantity event and the traceability information is provided in plain text on the menu.

The case shows that it is possible to achieve a high level of traceability and transparency within marine catch fish supply chains, using EPCIS and RFID technologies. The fundamental principle of food traceability is efficient tracking and tracing of unique logistical physical units in a way that enables monitoring of products and components to preserve food safety, quality and sustainability, which this case study demonstrates. The practical implication of this case study shows that regulatory requirements on food traceability place responsibility on companies by authorities. The case study shows that the physical movement or the information flow linked to a traceable resource unit of goods between supply chain actors is critical to achieving both internal and external traceability.

3.3. Traceability parameters to promote transparency in FSCs

Technologically enabled traceability systems are critical to achieving transparency in FSCs; they must collect data on the product history, condition of production, and product quality and share data with internal and external stakeholders. According to Future of Fish [49], an entire chain end-to-end digital traceability requires the performance of at least five core traceability technology functions: vessel-dock capture, product data pairing, internal traceability, supply chain visibility, and data verification [see also 50]. Based on the two pilot case studies and the studies reviewed, we identified five critical parameters that full-chain digital traceability should achieve to promote transparency: product origin and identification, reduction or prevention of product fraud, promotion of health and safety, improvement in consumer trust and confidence, and improvement in internal and external visibility (Table 5).

3.3.1. Product origin and identification

An important traceability indicator is the ability of the traceability systems to provide information about the product origin, production condition and product history (how the product has been handled through the chain). Consumers are increasingly concerned about where their fish product comes from and often demand the provenance of the product they buy. This traceability parameter was implemented in aquaculture and marine catch and is traceable in all stages of the supply chains as evidenced in the two case studies. In the case of a marine catch, RFID technology (tags, labels, sensors), mobile app and GPS and vessel tracking systems were used to capture key data elements on the location and origin of catch (including FAO sub-region/area), vessel details, catch information – date, time, weight, type of fish – scientific and trade name [14,18,31,32,34,38,43] details of fishers [14,18,31,32,34]; and landing site and discharge date [18,34,38]. The digital traceability system must capture information on the fishing method and gear used [14,18,31], giving visibility into the sustainable fishing practices used to catch the fish.

Similarly, digital traceability systems implemented in aquaculture must provide information on product origin, identification, and history. Within aquaculture, traceability systems based on RFID, WSN, 2D barcodes, web-based services and EPCIS were implemented to capture data on the origin of the fish larva/fingerlings, fish type (scientific or trade names), location of ponds/cages, movement of fish between cages, and details of the fish farmer [29,30,33,35]. Further, the conditions under which the fish is farmed are essential to ensure the health and safety of the fish, consumers, and product quality. Therefore, the traceability system must provide traceable information concerning feeding records, disease management, and the medication used [29,30,33] and water quality – test of chemical and drug residues [30,33,35]. Importantly, integrating third-party inspection data on affluent and water quality of the fishponds/tank into the traceability system, as demonstrated in case study 1 [35], and by Yu-Chia, An-Pin and Chun-Hung [30] and Zhang, Wang, Yan, Glamuzina and Zhang [36], will enable transparency in the production condition and integrity of the quality of the fish product.

RFID ID numbers, tags, and barcodes for lot/batch identification ensure that information collected during fishing and aquaculture production is automatically shared with sales companies/buyers, processors and retailers and can be traced to the fish farmer, vessel, or vessel fisher. Furthermore, at each stage of the chain, actors can add other information (such as date/ time of arrival at the processing plant, temperature during transit, processing and storage temperature, and location of the product) to the lot/batch (linked to the origin and identification information). Lots/batches at the processing and retail can subsequently be merged and identified with a new batch/lot reference (but containing the exact traceability information) as demonstrated in the two case studies. Therefore, at local, regional, national, and global levels, policy initiatives must strengthen the integration of technologies that provide strong capabilities for capturing key data elements for product origin and identification in order to achieve the Global Dialogue on Seafood Traceability (GDST) standard for end-to-end seafood traceability.

3.3.2. Reduction or prevention of product fraud

The fishing, aquaculture, and seafood supply chains are often challenged with a need for more trust along various stages of the supply chains [51]. Product fraud – substitution and mislabelling are a widespread phenomenon within fish value chains; between 2007 and 2013 alone, more than twenty cases of mislabelled fish and seafood products were reported in Europe and North America [52]. A full digital traceability system can improve trust among supply chain actors and stakeholders by reducing or preventing product fraud. Automatic availability of information from the farm/net to the plate increases transparency [51,53,54]. Of the studies reviewed, fourteen of the studies implemented solutions to reduce or prevent product mislabelling, substitution and counterfeiting risks through product tagging and tracking. The physical attachment of production and catch data captured at the source to the product (through a barcode, RFID tags or chips, QR code, or alphanumeric code) is essential to preserve data integrity as it journeys with the product through the supply chain. Adding key data elements at each stage as the product moves through the supply chain eliminates the challenge of data attrition and familiarity with internal traceability as demonstrated in both case studies. Thus, the system maintains and builds the "story of the fish", and actors can view the history and handling of their products. Thus, provides a single source of truth for traceability from producer to consumer [14,18,29,32,34–38,44].

Recording information in real-time or near real-time and accessible to other actors makes altering it difficult. As shown in case study 1, blockchain-centric traceability systems allow information/data to be verified and authenticated by other actors in the chain. Storing all transactions in a decentralised manner enables the detection of product substitution easily, as the system can be periodically or automatically interrogated to identify or flag where errors or fraud might have occurred [35,37,38]. The immutability and consistency of data promote the security, confidentiality, and robustness of information transactions. However, even with the most secure platforms like blockchain, product substitution and mislabelling can still occur – particularly in lengthy and complex supply chains like the tuna industry without the participation of downstream actors [14].

Cook [14] found that blockchain traceability increased transparency in the internal supply chain of the Fiji tuna industry. However, tracing the tuna beyond international importers or distributors took much work, especially at the retail level, where the tuna was processed into steak. The participation of downstream actors is needed to maintain and ensure the traceability of the product [14,32]. Product fraud in the seafood industry is prevalent downstream of the supply chains [52,55–59]. Therefore, digital traceability solutions that incentivise downstream actors to minimise product fraud whereby they pay for the traceability data captured at source and through the supply chain have the most significant potential to promote transparency and eliminate product fraud [18,31,37].

3.3.3. Promotion of food safety and reduction of health risks and engender consumer trust and confidence

When exposed to the elements, seafood and fish products can quickly lose their quality and freshness, posing safety and health risks to consumers and increasing consumers' demand to know the state of the freshness of the fish or seafood product. A full-chain digital traceability system must promote food safety and health risks of the fish product in question by integrating production condition and identification, and other traceability data with temperature/humidity, freshness, or bacterial count monitoring as the seafood travels along supply chains to protect the consumers from the consumption of unsafe foods [18,29,33,35,36,38,40,43,44]. Consumers can access information about the product history (i.e., breeding, feeds, pond information, medicines usage, water quality, and catch information) and quality and freshness through QR codes, barcodes or NFC stickers labels on fish boxes or packaging [18,29,32–38,41,44]. However, more importantly, consumer confidence and trust are enhanced if consumers can access the traceability server to check the validity and authenticity of the traceability information and check if any violation of the cold-chain parameters has occurred [38,41]. While allowing consumers to access traceability information promotes transparency and increases trust and consumer confidence about the provenance of the seafood, the traceability and product quality-related information must be securely stored [18,32,35,36,38]. A real benefit of having traceability is that a product's historical records can be audited instantly to identify fraud patterns to avoid risk, and regulatory authorities can rapidly deal with fraud instances.

3.3.4. Improvements in internal and external traceability and visibility

A digital traceability system that promotes transparency in FSC should achieve internal traceability and visibility within the supply chain and external traceability and visibility of the supply chain [50]. Internal traceability technologies enable a company or supply actors to track and preserve information on individual batches or units as the units are processed within the company facility [29,30,33,36,41,43,44]. However, as the unit or batch is passed on to other external traceability partners or actors within the supply chain (e.g., producers, processors, wholesalers, retailers) who perform the process, that affects ownership, physical movement, position, or position condition of the traceability unit, Full-chain digital traceability should improve internal and external traceability and visibility for all actors connected in the chain. All production processes from aquaculture activities [29,33,44], catching, landing, processing, transportation, storage, and sales data [14,18,29–32,36–38,41,43] are collected automatically in real time. However, commitment from trading partners to share KDE tracked with the product with trading partners [14,18,31,38] is essential to achieve full transparency and visibility of the supply chain that goes beyond the minimum "one up one down" scheme required by regulators [37,46,50,53].

Besides, digital traceability solutions must improve internal and external transparency and visibility concerning product quality through time-temperature/humidity and location monitoring; allowing partners to monitor or verify the state of product quality [29,33,35,36,38,41–44]. Partners can also query and retrieve information from a centralised repository system and add data to maintain and build the "story of the fish" and view the history of the products they handle [14,29,43]. At the same time, internal traceability solves most of the food industry's food safety, quality, and recall needs [50]. External visibility is enhanced when governments, regulators, third-party stakeholders, and customers can access traceability information, including the catch's origin and location, and can query safety and quality information about the fish product [14,18,29,38,41].

3.4. The benefits of digital traceability for the sustainability of FSCs

A complete chain digital traceability system promotes transparency and visibility in supply chains and enables the supply chains' sustainability. From the studies reviewed, nine sustainability indicators were identified because of implementing an electronic traceability system that can promote the sustainability of the fish supply chains and benefit the actors in the chain (Table 6). Depending on the nature of integration – i.e., integrating traceability data with product quality and freshness monitoring, and the length of the chain, the majority of the studies reviewed promote five sustainability indicators: Improves chain or network efficiency; improves chain communication, optimisation and integration; improves regulatory and legislative compliance; enhances cold-chain optimisation/product quality and freshness; and efficient management of recalls. Five studies showed the potential to promote supply chain sustainability by dealing with IUUF, and improving environmental stewardship/sustainability. Four studies tackled the issue of social inequality in fisheries - dealing with modern slavery and human rights abuses and improving fisher/farmers' income.

3.4.1. Chain or network efficiency improvement and transactional cost reduction

Automating the process of collecting traceability and environmental information from the farm through transport, processing and storing as the product moves through the supply chain eliminates manual and paper-based data capture. Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29] reported total time-savings of 95.13 % and 89 % in two case studies relating to work activities - reading labels, filling paper forms, and filling Excel sheets. At the same time, Ringsberg and Mirzabeiki [34] reported labour cost savings equivalent to one month of a full-time job at the wholesale level. Collecting logistic data through RFID allows real-time sharing of logistic processes and data among actors. Thereby reducing labour costs [34,44] due to a decrease in the time allocated to capture and transfer information between different processes and actors [34,43,44]; improving the efficiency of daily workflows and pond management by integrating safety and water quality monitoring information with feeding and disease management data reduces workload and cost [30,33,35,36]. Moreover, it reduces costs of labelling and re-labelling of goods in primary production and identification and reporting of goods in storage operations – i.e., reusable RFID tags instead of non-reusable stickers [29,34,35,38,39,41].

However, an increase in time was found in some cases during the movement and loading of goods at the producer, processor, and

Table 6
The benefits of digital traceability for the sustainability of FSC.

FSC Sustainability indicators	Benefits to actors	Reference
Improves chain or network efficiency and reduces transactional cost	• Reduction of inventory losses and management costs. • Dynamic planning of logistics. • Reduces workload and lower labour cost. • Reduces the cost of information sharing and exchange. • Increased efficiency of product flows.	Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Grecuccio, Giusto, Fiori and Rebaudengo [38], Thakur and Ringsberg [39], Tingman, Jian and Xiaoshuan [40], Zhang, Liu, Mu, Moga and Zhang [41], Hafliðason, Ólafsdóttir, Bogason and Stefánsson [42], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44], Grantham, Pandan, Roxas and Hitchcock [45]
Improves chain communication and integration	• External partners can access data in a standardised format enabling logistics and chain integration and information exchange. • Extend information visibility and exchange possibilities. • Improves communication between customers and the company.	Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37], Thakur and Ringsberg [39], Tingman, Jian and Xiaoshuan [40], Zhang, Liu, Mu, Moga and Zhang [41], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44], Grantham, Pandan, Roxas and Hitchcock [45]
Improves regulatory and legislative compliance	• To improve the implementation of traceability regulations, companies can provide an audit trail of the supply chain process. • Improves data sharing to fulfil regulatory requirements and help the government estimate the size of the fish stock. • Avoid risks and allow regulatory authorities to identify and address those risks quickly.	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Yu-Chia, An-Pin and Chun-Hung [30], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Jæger and Mishra [37]
Effective cold-chain monitoring and optimisation	• Reduces time and labour cost – removes the need for manual physical inspection and recording of time-temperature data. • Temperature/humidity alert system. • Improves product quality and freshness. • Better data for real-time decision-making.	Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Grecuccio, Giusto, Fiori and Rebaudengo [38], Tingman, Jian and Xiaoshuan [40], Zhang, Liu, Mu, Moga and Zhang [41], Hafliðason, Ólafsdóttir, Bogason and Stefánsson [42], Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43], Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44]
Improves processes and efficient management of recalls	• Better inventory and stock management. • Improves yields, inventory, and stock management at production (sustainable fishing). • Positive economic effects of increased sales for all actors. • Ability to deal with recalls in a faster and more efficient manner. • Reduces severe or frequent recalls. • Provide valuable information in legal trials - food safety issues or issues related to the shipment insurance.	Cook [14], Fishcoin [18], Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Qi, Zhang, Xu, Fu, Chen and Zhang [33], Ringsberg and Mirzabeiki [34], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Zhang, Wang, Yan, Glamuzina and Zhang [36], Grecuccio, Giusto, Fiori and Rebaudengo [38], Thakur and Ringsberg [39]
Deals with Illegal, Unregulated and Unreported fishing	• Better visibility about the origin, identification, and location of catch. • It reduces IUUF, helps with stock management, and enables sustainable fishing practices.	Fishcoin [18], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Grecuccio, Giusto, Fiori and Rebaudengo [38], Grantham, Pandan, Roxas and Hitchcock [45]
Improves environmental stewardship/ sustainability	• Improves the reputation of actors and premium price for promoting sustainable fishing practices and better management of fish stocks. • Farmers improve their reputation through monitoring and reporting on quality water and effluents. • Enables removal of unethically or illegally sourced products by allowing improved targeted market advantage through informed purchasing.	Cook [14], Fishcoin [18], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Provenance [32], Zhang, Liu, Jiong, Zhang, Li and Chen [35], Grantham, Pandan, Roxas and Hitchcock [45]
Able to deal with modern slavery and human rights abuses.	• Improve the reputation of companies of the ethical production process /ethical product. • Improve the working condition of farmers/ fisherfolks.	Cook [14], Fishcoin [18], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31]
Improves fisher/ farmers income	• The monetisation of data generated by fisher and fish farmers. • Fisherfolks earn higher revenue for catch with verified provenance.	Fishcoin [18], Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31], Jæger and Mishra [37], Grantham, Pandan, Roxas and Hitchcock [45]

(continued on next page)

Table 6 (*continued*)

FSC Sustainability indicators	Benefits to actors	Reference
	• More equitable distribution of supply chain benefits.	

wholesaler because the forklift used to transport fish boxes needed to travel slower to ensure the readability of RFID tags by the RFID scanner [34]. Stock information in real-time eliminates the need to read individual boxes of fish and, therefore, provides a more efficient way of preparing orders, which reduces the cost of the sorting process by electronic manipulation of orders [29,34,35]. Besides, the automatic collection and sharing of data leads to dynamic logistics planning, increases product flow efficiency, and reduces the cost of information exchange, especially where other actors in the chain validate data [18, 38].

3.4.2. Chain communication and integration improvement

Digital traceability allows the automatic recording of information from farm to retail via RFID tags, labels/tags, and sensors to improve chain communication and network optimisation and integration as all aspects of the supply chain are integrated into an intelligent traceability system [14,36]. Especially with regards to blockchain-centric traceability system, chain integration is improved as actors provide instant and real-time communication to all members whenever information about the transaction is added or altered [14], and the data validation process improves communication between actors and optimised integration of the network [18,31,32,37]. Moreover, storing data in standardised EPC global or EPCIS format ensures that external partners in the chain can easily access data enabling logistics and chain integration and information sharing [29,34,39,43,44]. Capturing and sharing information in a standardised format extends information visibility between actors; and sharing information with consumers through the F2F web page or web services [29,33,36,39]. Thereby improving communication between customers and the company.

3.4.3. Cold-chain monitoring and optimisation

Temperature is an essential factor affecting the shelf life of perishable products, including fish and seafood [53]. Effective cold-chain management of fish and seafood products, integrated with digital traceability systems, is essential to meet consumer and regulatory agencies' increasing quality and safety demands. Traditionally, temperature monitoring of chilled fish and cold fish has been accomplished using thermometers and compact temperature loggers [61]. These involve manual inspection and recording temperature readings in refrigerators, trucks, containers, or boxes, making them inconvenient and increasing labour costs. RFID with temperature sensors or data loggers can automatically record time-temperature/humidity information at regular intervals without physical inspections of thermometers. Therefore, RFID sensor tags provide cost-effective solutions for cold-chain optimisation and improve temperature management [53]. Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29] implemented a novel traceability system architecture based on web services and integrated RFID temperature sensors and data loggers to collect environmental information alongside traceability data.

Linking the temperature and humidity conditions from the farm to the consumer with traceability data improves cold-chain optimisation to reduce cost and time. Trebar, Lotrič, Fonda, Pleteršek and Kovačič [44], using Ultra High-Frequency semi-passive RFID data loggers, provided a temperature monitoring solution in the new Piran Sea bass supply chain as part of the traceability system (at the box level). The RFID data loggers were placed inside the box to measure the temperature of the fish and the ambient temperature. Monitoring of product quality data during processing, transportation and storage improves quality freshness [34, 44] not only for the processed frozen or chilled fish products but also in the monitoring of quality and freshness in live fish transport from farm level to retail and restaurants [30]; and in preserving and monitoring product inherent freshness and quality in transporting waterless live fish [36].

During transportation and product moving, failure may occur with refrigeration units, inevitably causing losses – reducing the quality of frozen and chilled fish/seafood products. Combining a time-temperature traceability system with communication technologies like GPS, mobile communication provides real-time monitoring, tracking, and tracing, thereby optimising cold-chain management [35,36,38,40,41,43]. Using a combination of RFID tags, GPS and mobile communication, Zhang, Liu, Mu, Moga and Zhang [41] developed a temperature-managed traceability system that provides product quality evaluation and assurance systems and uses E-mail XML technologies to send real-time information to drivers and managers and customers during storage and transportation of chilled tilapia [41].

While RFID data loggers with WSN were used to map temperature in cold chains to determine criteria for alerts and warning systems in cod supply chains [42], RFID temperature tags, GPS, and mobile network applications were used to monitor temperature and to provide heat alerts in a blockchain cold chain monitoring system [38]. Similarly, Abad, Palacio, Nuin, Zárate, Juarros, Gómez and Marco [43] developed and validated the application of RFID smart tags for real-time online cold-chain monitoring of a fresh fish logistic chain from South Africa to Europe. The measured environmental values (temperature and relative humidity data) were integrated with important traceability data such as origin, species, and capture data. The real-time environmental information received from sensor tags can be used to estimate product freshness or lifetime/predict the shelf life of fish products [40,41,43]. Tingman, Jian and Xiaoshuan [40] predicted the shelf life of frozen Tilapia fillets by using RFID tags to monitor temperature changes in a refrigerated van and analyse the effect of temperature profiles on quality.

Time-temperature alert systems that document any disruption in the cold-chain and make information visible through online decision support enable faster and better decision-making that improves product quality and freshness and reduces the high risk of spoilage or losses [38, 41–43]. Such optimisation of cold-chain monitoring through real-time automatic data collection, analysis and sharing data between actors provides an effective chilled management tool that reduces distribution risks and optimises the distribution of quality products.

3.4.4. Processes improvement and efficient management of recalls

To achieve sustainability of fish supply chains, automation of data collection as part of the work process from production activities to distribution is essential. Implementing a digital traceability system can help improve the work process, enabling flexibility and responsiveness during recalls [29]. In terms of recalls, implementing digital traceability systems reduces recall frequency and scope, resulting in savings, for example, labour cost and reduced reliability and claims lawsuits. For instance, the RFID-based traceability system can provide time-temperature data as evidence of compliance and product handling conditions and lead to efficient handling of issues compared to paper-based systems [62].

Digitalising records and information helps improve inventory and stock management in factories, distribution, and retail [32]. Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29] found there was a reduced time (90–96 %) in processes (identifying goods in storage and registers and systems used for business management), the introduction of an electronic system allows access to traceability information in real-time and manages product recalls in a faster and more efficient manner – product tagging and tracing [see also 14, 18, 33, 35, 36, 38]. Implementation of digital traceability systems was found to improve processes relating to inventory and stock management, control-purchase orders, improved processing, collecting orders, sorting fish, packaging and labelling, preparation of orders, and documentation generation [29,32–34,39]; improve yields and inventory control/stock management at production and ensure sustainable fishing [14,31,32,36]. This leads to positive economic effects of increased sales and purchasing activities for all supply chain actors because of reliable traceability information [34]. The provision of master data also increases the opportunity for producers to sell their goods on the open market through internet auctions or directly to international partners [34].

3.4.5. Dealing with IUUF and environmental stewardship improvement

IUUF, coupled with mislabelling and product substitution, poses the most significant threat and challenge to fisheries and the sustainability of fish supply chains. However, implementing a full-chain electronic traceability system can help deal with the threat posed by IUUF. In a pilot study that implemented a blockchain traceability system that integrated RFID tags, sensors, QR codes and a mobile app (TraSeable) in the Fijian tuna industry showed that automatically collecting catch data (time, date, location, quantity, species type caught) and tagging and tracing same along with the tuna deals with the issues of IUUF [14,60]. Similarly, Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31] and Grecuccio, Giusto, Fiori and Rebaudengo [38] used blockchain, mobile applications, GPS, RFID tags and QR codes to monitor boats and vessels' location, catch activities and catch data and routes of travel at sea to help to prevent IUUF. Automatically loading catch data together with Marine Stewardship Council certification on the blockchain helps improve stock management and enable sustainable fishing practices and environmental sustainability [18,31,32]. Cook [14] reported that automatically collecting catch data (time, date, location, quantity, species type caught) and tagging and tracing same along with the tuna deals with the issues of IUUF [14,60]. Similarly, Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31] and Grecuccio, Giusto, Fiori and Rebaudengo [38] used blockchain, mobile applications, GPS, RFID tags and QR codes to monitor boats and vessels' location, catch activities and catch data and routes of travel at sea to help to prevent IUUF. Automatically loading catch data together with Marine Stewardship Council certification on the blockchain helps improve stock management and enable sustainable fishing practices and environmental sustainability [18,31,32].

Furthermore, using blockchain technology to manage catch data and other traceability information potentially enables the removal of unethical or illegally sourced products, as fish product information on the system must be verified by others in the network [14,18,31]. Collecting timely and accurate data on catches is critical to reducing IUUF; to this end, Provenance [32] and Fishcoin [18] pilot studies that reward efforts for data gathering by fishers provide a better option for preventing IUUF and ensuring sustainable stock management of fish. This creates premium prices for fishers already using sustainable techniques such as pole and line and handline fishing but not reporting catches [32].

3.4.6. Dealing with modern slavery and improving fish farmer's income and livelihoods

Digital traceability solutions can achieve true sustainability if they can deal with modern slavery and human rights abuses in fisheries and supply chains and improve the working conditions of fisherfolks and fish farmers [45]. The traceability system developed and piloted by WWF demonstrated [14] the potential of digital technologies to stop modern forms of slavery in fisheries – (crew working conditions and safety and threats to licensing revenues) [60]. Although the piloted projects by Marttila, Nousiainen, Sheppard, Malka and Karjalainen [31] and Fishcoin [18] do not directly deal with the issues of modern slavery in the fishing industry, monetisation of traceability data that offer direct payments to fisherfolks based on the data that they generate have enormous potential to improve their incomes levels, livelihoods and provide access to loans which they can use to expand their operations [37]. Additionally, the traceability system creates higher value for the fisherfolks for every catch with verified provenance [14,18,31,37]. Thus, bringing equity into the distribution of supply chain benefits. Such digital traceability also improves the reputation of companies for ethical production processes/ products. This has critical policy implications to ensure economic and social equity through their value chains

4. Discussion and conclusion

4.1. Discussion of findings

This review identified five critical parameters that are necessary to promote transparency in a full-chain digitalised traceability system: provide information about the product history (identification and origin, condition of production), prevent, or reduce fraud, product quality (promote health and safety), improve consumer trust and confidence, improve internal and external visibility [49,50]. Sterling and Chiasson [63] argued that effective traceability enables "…identify[ing] the origin of the product and sources of input materials, as well as the ability to conduct backward and forward tracking using recorded information to determine the specific location and life history of the product" ([63] p.7). Thus, accessing all information throughout the product's life cycle should be possible using recorded identifications [64]. This review has revealed that an effective digitalised traceability system engenders several benefits for seafood supply chain ecosystems. These include supply chain or network efficiency improvement and transactional cost reduction, chain communication and integration improvement, cold-chain monitoring and optimisation, process improvement and efficient management of recalls, IUU and environmental stewardship improvement, and dealing with modern slavery and improving fish farmers' income and livelihoods.

As argued by Sterling and Chiasson [63] and others, an effective traceability system yields sustainability benefits to businesses through the ability to validate sustainability claims, quality assurance, continuous improvements, supply chain efficiencies, increase access to new markets and customers, enable value capture by being able to trace products to the source as well as risk mitigation [63,65]. To governments and policymakers, 'bait to plate' a fully digitalised seafood traceability, is critical to strengthening sustainable fisheries practices, improving fish stock management, combating IUU fishing, and seafood fraud, dealing with modern slavery and ensuring food security [31,63,66]. Bailey, Bush, Miller and Kochen [66] argued that while historically, business-to-business traceability promotes the coordination of value chain activities and managing reputational risks, "the future value of traceability lies in how to design and organise systems in such a way that information flows can be harnessed to improve global seafood governance" ([66], p.25). Traceability information improves regulation, particularly consumer-facing traceability systems improves sustainable seafood governance [66].

Seafood value chains – from "bait to plate" model form a complex value chain in global trade [65], and most of the seafood is sourced from the global South [66]. The global seafood trade involves seafood products often travelling long distances across multiple ports, changing hands among brokers, wholesalers, processors, and retailers [63,67]. This review has shown that digital traceability solutions have enormous potential to promote transparency and equity and improve livelihoods and sustainability in an opaque industry and supply chains like global fish. However, the adoption of digital technologies comes with numerous challenges: accessibility, availability of local suppliers and technicians or lack of experienced partners, cost of implementation, data management (interoperability), data access and lack of data privacy (who controls the data that is generated), lack of adequate infrastructure - internet coverage, and environmental factors [29,50,68].

Digital technologies like RFID and WSN are readily available and widely deployed at various scales in aquaculture, marine catch, and fish supply chains. However, this requires investment in new technologies which comes with costs. Initial costs of implementation including procumbent of the hardware and the equipment and costs associated with maintenance of the system are outside the means of the typical small-scale fishers or fish farmers [34,35,44,45]. For instance, labelling fish boxes with RFID tags is expensive due to physical conditions, with high initial set-up costs for the producers and all supply chain actors. Parreño-Marchante, Alvarez-Melcon, Trebar and Filippin [29] reported that investments in new technologies, like more wide-screen handheld readers and higher protection for RFID terminals due to offshore environments, increase costs.

Although the cost of RFID technology has fallen in the last decades, it is more expensive compared with labelling techniques - stickers and QR barcode technology, which provide effective tracking and monitoring, high fault tolerance, significant information content, convenient usage, and minimum tracing cost [35]. RFID tags' expense prohibits smaller fishing industry operators, particularly those in the global South, from participating in traceability schemes [60]. Notwithstanding, the high cost associated with the adoption of the technology, it has been noted that deploying reusable RFID data loggers and embedding RFID and WSN with other technologies like temperature recording and monitoring systems lower costs on equipment, making integrated systems cost-effective compared with traditional temperature sensors and data loggers [41,44].

While several pilot projects/studies [14,18,31,32,35,37,38] and conceptual studies have [47,68,69] demonstrated the enormous potential of using blockchain technology or integrating blockchain with other digital traceability technologies to ensure transparency and sustainability in fish supply chains, the cost of implementation, running and maintaining the systems have always been the most significant barrier [68]. For example, pilot projects in the tuna industry reveal that the technology is costly to implement and requires expertise and technological infrastructure, which are not readily available in the production areas in the global South, and the cost of storing data on the smart contract is expensive [14,31]. The WWF-piloted blockchain technology project in the Pacific tuna industry involves individually tagging the tuna once it is caught. This is an additional step for the fishing vessel crew and is something that fishing companies must introduce into their workflow, and crew members must be incentivised, which comes at a cost [14]. In this case, data monetisation that incentivises small and micro-scale artisan fishers and allows them to collect traceability data that meets international standards by using low-cost solutions such as a mobile app at the harvesting stage provides the best solution [18,37]. While such incentives through low-cost technology such as mobile apps improve the accessibility of the technology and allow fisherfolks to be included in the traceability system, they do not own, have access to and, or control over the data set.

Besides the affordability of digital traceability technologies, the availability of local suppliers, technicians, and expertise, especially in the global South, hinders the deployment and adoption of digital traceability technologies. Cook [14] reported that a lack of available local expertise and suppliers resulted in a lack of support for the supply, implementation, and maintenance of the RFID equipment, including the tags and sensors. However, the adoption of low-cost solutions that are built on the use of smartphones to capture data (like the mobile app "Tracey") does not require technicians to operate effectively [31].

Environmental conditions such as temperature, humidity, water/moisture, and conductive materials (like metals) and structure of the processing plant were found to affect the reliability, stable connections, and readability of NFC cards /RFID tags at different stages of the supply chains [29,42,44]. At the box level, using WSN sensors to measure temperature presented some challenges – opening of packages and the environmental conditions in the boxes limit the transmitting range. To reduce environmental barriers, especially within processing plants and logistics stages, the use of laminated tags, multiple antennas, and dense reader mode features of modern readers. The use of amplitude and phase demodulation to eliminate communication holes through automatic "in-phase" and "quadrature" (I/Q) selection frequencies has been recommended [34,44]. At high seas, lack of internet access on board fishing vessels and sea platforms (on-growing farms) where cages are kept can result in data loss. Some NFC cards and RFID tags are not designed to withstand the wet working conditions of the fishing vessel and were often unreadable or otherwise damaged by bad weather conditions at high seas [45].

The technical infrastructure to maintain near real-time data transfers (e.g., in blockchain) can be challenging. Sending and receiving data at high seas depends on satellite communication systems, which are expensive to install and may not be "feasible in small-scale fisheries or fisheries with limited financial resources" [51]. The cost of transmission could still be high and available bandwidth could be too small to support transmission demand. Thus, data cannot automatically be registered once the fish has been caught, even in blockchain technology that allows caught fish to be tagged and data transmitted and recorded as digital assets [14,29].

Again, differences exist in technological advancement between the global South and global North, with an estimated 95 % of global seafood coming from the global South countries, which poses a possible logistical hurdle in the implementation and operation of traceability systems. Much of the traceability processes in the global South (if any) remain heavily paper-based, with Government agencies (like fishery ministries), private fishing companies and third-sector organisations working with fisherfolks. Therefore, for traceability and transparency to work, digitalisation of the processes along the supply chains would be required, in addition to interoperability of information systems implemented in these countries. Resource deficiencies, including funding and capacity issues, pose a challenge for implementing digital traceability solutions in the global South. Further, knowledge gaps of what full-chain traceability is and what full-chain digital traceability does impact its adoption, especially in the South global context. Especially where there are poorly demonstrated incentives for creating buy-in to the value full-chain digital traceability can offer [50].

Interoperability, data management, and data security challenge achieving traceability and transparency in the global seafood supply chains [50,68]. Hardt, Flett and Howell [50] observed that interoperability is critical for full-chain digital traceability. However, it must be more present in the seafood industry (ibid, p.4). For any digital technologies to be fully interoperable and achieve transparency in traceability, the system must have the capacity to share data using a standard data format and interpret and understand the shared data. This is only achievable in some of the systems reviewed. For example, RFID technology produces high data volume; it is time-dependent and changes dynamically, increasing the complexity of data management [29]. Therefore, integrating RFID into blockchain technology, although, enables automation and passive data collection, is not ideal for implementation on blockchain because of the extensive data set that it generates and blockchain technology requires independent verification and validation points [31,50]. To achieve full-chain digital traceability, there is the need to have complete data alignment among firms and actors within the specific ecosystems; this will ensure the involvement of all stakeholders and enable value capture for stakeholders [47,70]. As argued by Sterling and Chiasson [63], traceability does not guarantee that a product can be traced in the entire value chain, as seen in the WWF piloted project on Tuna where it was difficult to trace the downstream – during secondary processing and retail levels. Thus, disparate systems used to manage information at the individual business level throughout the supply chain must be interoperable and comply with open standards of traceability systems such as meeting the Global Dialogue for Seafood Traceability standards or frameworks.

Again, the adoption of digital traceability systems is not immune to fraud, and data security always is a challenge. For instance, the increasing adoption of RFID technology poses security and privacy risk challenges that can affect companies and government processes, and even individual customers involved in the deployment of the system [53]. The RFID system is prone to security attacks because the information that it contains (in the tags/readers) can be read. Beyond the tags and readers that can be comprised (tag counterfeit, unauthorised access to tag memory), the associated software networks and databases that support traceability systems are also prone to security risks [53,71,72]. Notwithstanding, the implementation of advanced encryption standards for the authentication of readers helps to secure tags and prevent tag forgery thereby dealing with security and privacy concerns.

Moreover, the data security and reliability of data captured and provided throughout the supply chain are essential to achieve transparency. To this end, a digital traceability system built on a blockchain platform data management system dramatically improves security by suppressing counterfeit operations. It uses asymmetric cryptography technology to encrypt each transactional data information [36]. Using verifiers or validators to verify each catch information, trade data provided by the fisher, and validation throughout the supply chain improves data accuracy, reliability, and trust [35,47]. However, in the WWF pilot study, downstream actors' cooperation is critical for adopting blockchain technology. Without agreement among all parties to maintain traceability or without appropriate incentives to engage in the process effectively, it is difficult, if not impossible, to achieve "Bait to Plate" transparency [14,31]. Outside upstream processes (primary production and processing), it is extremely difficult to verify whether fish and seafood products are labelled correctly after secondary processing (into different product categories such as steaks, fillets, loins, and minced meat) by downstream actors [60]. Majority of fish and seafood products fraud and mislabelling occurs at the downstream of the fisheries supply chains [73]. In this regard integrating digital technologies with DNA technology will ensure transparency within global fish supply chains.

Furthermore, to ensure equity in a fully digitalised traceability system, the issue of who has access to, and who owns and controls the data is very critical. In a truly equitable and transparent traceability system, all stakeholders, including fisherfolks, must have access to and own the traceability data generated by each actor within the system and across the value chain. However, equity challenges exist [74], especially in the case of a marine catch, where most small-scale fishers responsible for generating the harvest data need access to or own the traceability system even when data collection is incentivised. For instance, the Fishcoin system allows fishers and farmers worldwide to record their harvest data within mFish app; the data is only stored locally on the user's device (e.g., within mFish or other digital logbooks) at the point of the data captured. Once the data have been validated on intelligent contract by the receiver and the data producer receives tokens in their wallets, the data is registered on the blockchain. The fisher no longer has access to that data [18].

Where discrete asset ownership is implemented, each asset is assigned to an entity. The ownership of that data resides with those who generate the data, who have the power to turn on or turn off specific input fields depending on the stage of the process and who will be viewing the record; permission to access information is only granted at the asset ownership level [14]. In a decentralised ledger and blockchain system like the "Tracey app" piloted in the Philippines, the data owner decides who can access the data, the period, and the subscription fee. The data owner is not pressured to open access [31]. Similarly, Jæger and Mishra [37] reported that on a piloted distributed IoT application on the blockchain, each actor generates their data and owns the data, thus allowing the owner control over that data. While decentralised and discrete data ownership offers control and privacy; accessibility is an issue. This can result in an excessive exercise of power and control, leading to 'data asymmetry' [47]. This defeats the purpose of full-scale transparency in a digitalised traceability system and, therefore, the sustainability of fish supply chains [69]. However, Schmidt and Wagner [75] used transactional theory to understand how blockchain might influence supply chain relations and argued that the consensus-based record validation process limits opportunistic behaviour and the impact of environmental and behavioural uncertainty. However, an important question remains: who benefits from the digitalised system and who loses?

4.2. Policy implications of the findings

Taking cognisance of the fact that extant research on digital technologies for traceability in the global fish industry prior to this study existed either in silos or fragmented, this paper highlights the distinctive features of the different research streams devoted to how digital technologies promote traceability and transparency in the global fish supply chains. The systematic review revealed three main research streams on digital technologies for traceability in the global fish industry. The first strand of literature centred on the key technological enablers of traceability and transparency in fish supply chains. In the second strand, the research stream on critical traceability parameters needed to achieve transparency specific to fish supply chains was highlighted. Finally, five distinctive major benefits of digital traceability for the sustainability of fish supply chains were identified and accordingly classified. These are 1) improvements in global fish supply chain or network efficiency; 2) improvements in fish supply chain communication, optimisation, and integration; 3) improvements in regulatory and legislative compliance within the global fish supply chain industry; 4) enhancements of cold-chain optimisation/product quality and freshness; and 5) efficiency in the management of recalls.

These insights based on the findings have policy implications by informing practical applications of global fisheries supply chain policies, regulations, and governance objectives, which are mainly legal (compulsory) requirements. Firstly, digital tools like blockchain and electronic logbooks can enhance traceability, ensuring compliance with sustainable fishing practices outlined in the FAO Code of Conduct for Responsible Fisheries. In addition, technologies such as vessel monitoring systems (VMS) and satellite tracking can help enforce the Port State Measures Agreement (PSMA) by identifying and blocking illegally caught fish from entering ports. Similarly, while real-time data collection and sharing platforms can support transparency in decision-making processes for Regional Fisheries Management Organisations (RFMOs), as mandated by the UNFSA, digitalisation of catch reporting and quota management systems can improve compliance with the Common Fisheries Policy of the European Union regulations, promoting sustainable fisheries management.

The findings further have a bearing on facilitating the attainment of the GDST and Sustainable Development Goal (SDG) 14. Interoperable digital traceability systems can ensure the accurate tracking of seafood products across supply chains, supporting GDST standards and Technologies like AI-driven predictive models and IoT devices can aid in restoring fish stocks and combating IUU fishing, aligning with SDG 14 targets. By integrating these technologies, fisheries governance can become more transparent, efficient, and aligned with global sustainability goals including the objectives of the International Labour Organization (ILO) Work in Fishing Convention (C188). Indeed, digital platforms can monitor and ensure decent working conditions for fishers, addressing labour rights issues in the fisheries sector.

Beyond direct policy implications of the existing global fisheries supply chain policies, regulations, governance conventions and treaties, it has general implications for traceability and transparency enhancement, monitoring and enforcement improvement, streamlining data collection and analysis, supporting sustainable practices, empowering stakeholders and fostering collaboration. Despite the likely cascading effects of these policies on the general well-being of the industry, policy implications relating to supporting sustainable practices and empowering stakeholders could have direct profit-maximising effects that will consolidate private interests. For instance, private operators that draw on digital tools to optimise fishing operations, reducing bycatch and minimising the environmental impact of fishing could invariably enhance their sustainability credentials and build a competitive brand in the global fisheries market. Secondly, adopting predictive models powered by AI, assist in forecasting fish stock levels, enabling sustainable harvesting, could also have lower operational cost implications for private fishing companies in the industry. There are also the potential implications for enhanced corporate citizenship credence through digital inclusion that ensure that small-scale fishers and communities benefit from technological advancements.

4.3. Conclusion

The study advances the understanding of digital technologies for global supply chain transparency research by revealing evidence-driven insights on the three main streams of digital technologies for transparency in the extant literature, providing a nuanced and holistic perspective on the discipline, and motivating further research paths to potential novel empirical studies. We recommend that future research focus on cost-effectiveness, long-term sustainability, and practicability for adopting the deployed digital technologies among small-scale fishers and farmers in the global South.

The findings of this study highlight the critical role digital technologies play in fostering traceability and transparency within global fish supply chains. This has significant implications for marine policy, particularly in addressing illegal, unreported, and unregulated fishing, promoting sustainability, and safeguarding human rights in fisheries. Policymakers are urged to leverage these technologies to establish robust frameworks that mandate transparent data sharing and compliance verification across all supply chain actors. Additionally, policy measures should incentivise the adoption of technologies like blockchain and IoT, which not only enhance traceability but also foster consumer trust and improve governance. By aligning technological advancements with comprehensive regulatory policies, governments and international bodies can ensure the long-term resilience and equity of global fish supply chains, promoting ecological balance and ethical practices.

CRediT authorship contribution statement

Cromwell Jonas: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Turkson Charles:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Dora Manoj:** Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Yamoah Fred Amofa:** Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

We have nothing to declare

Data availability

Data will be made available on request.

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