Aquaculture International (2025) 33:397
https://doi.org/10.1007/s10499-025-02069-7

REVIEW

Understanding the application of digital technologies in aquaculture supply chains through a systematic literature review

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Received: 7 March 2025 / Accepted: 27 May 2025 / Published online: 14 June 2025

Abstract

The study conducts a systematic literature review of the application of digital technologies in aquaculture supply chains (ASC) to identify key research clusters, examine collaborative efforts in the field, and highlight emerging knowledge themes. The methodology comprises a database search in Scopus and Web of Science over a 5-year period (2019–2023) following the PRISMA framework. Bibliometric analysis using Biblioshiny reveals that "Climate Change," "Aquaculture", "Sustainability", and "Food Security" were dominant keywords in this field. Notably, the Sustainability cluster exhibits the highest Callon Centrality (2.819) and Callon Density (63.378), underscoring significant research focus on integrating digital technologies to enhance sustainability in ASC. Hungary emerges as the country with the strongest international research collaboration. However, we identified weak collaboration between African nations and the global research community. Five primary research themes were identified; these include the role of digital technologies in ASC optimization, the disruption of fisheries supply chains due to the COVID-19 pandemic and the mitigating role of digital innovations, the contribution of digital technologies to reducing food waste and advancing the circular economy, the impact of climate change on fishes, and the challenges and opportunities in applying digital solutions within ASC. Despite persistent challenges—such as limited transmission bandwidth, network delays, and issues with low-power, long-range communication—significant opportunities exist to overcome these barriers through technological advances and stronger global research collaboration. Such progress is vital to transforming ASC into a more sustainable and competitive system. The study provides actionable insights for stakeholders while laying a foundation for future research and governance in this evolving field.

Keywords Aquaculture · Artificial intelligence · Digital technologies · Climate change · Fisheries · Supply chains · Sustainability

Handling Editor: Chao Zhou

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Introduction

Aquaculture encompasses the cultivation of fishes, molluscs, shellfish, and aquatic plants (Kaleem et al. 2021). However, fish continues to serve as a significant protein source and a highly nutritious food that is consumed in homes all over the world (FAO 2022; Ntiri et al. 2022; Biazi and Marques 2023). However, as the world's population grows, so will fish consumption, which is anticipated to be propelled by factors such as increasing incomes, urbanization, enhancements in post-harvest methods, and shifting dietary preferences, causing fish consumption to exceed the oceans' and seas' actual production capacity (FAO 2022; Biazi and Marques 2023).

Aquaculture supply chains (ASC) encompass the processes involved in producing and distributing aquaculture products, spanning from farm to fork. Typically, the ASC comprises a network of interconnected activities, including hatchery, production, processing, exporting, distribution, transportation, and more, all collaborating to deliver fish products to customers (Mangano et al. 2022). Nonetheless, supply chain management (SCM) embodies the array of tasks carried out within an organization to enhance the management of its supply chain (Li et al. 2005; Ayoubi and Radmehr 2023). Efficient SCM brings about benefits such as heightened sales, reduced costs, and maximized profits (Ayoubi and Radmehr 2023; Sitek and Wikarek 2014; Banaeian et al. 2015). SCM is thus considered a critical factor for improving business performance, achieving a competitive advantage, and increasing the sustainability of the supply chain (SC).

However, the COVID-19 pandemic delivered a systemic shock impacting every aspect of the global food system, including aquatic food (Biazi and Marques 2023; Liverpool-Tasie et al. 2021; Bassett et al. 2022) and reduced levels of production (Bennett et al. 2020; Campbell et al. 2021). Additionally, technological constraints in business tools and the absence of strong systems and sensors capable of monitoring animal physiological traits and environmental conditions pose challenges for the aquaculture sector in maintaining high-quality, sustainable food production. The majority of aquaculture farms still rely on manual data collection by human operators over prolonged periods. Thus, the operator's experience informs management and decision-making, which may be adversely impacted by human subjectivity (Biazi and Marques 2023).

The realization of fisheries' triple-bottom-line objectives—economic, social, and environmental—is contingent upon sustainable fish and seafood production (Tolentino-Zondervan and Zondervan 2022). In response, there has been a notable increase in the adoption of digital technologies in fisheries in recent years (Yang et al. 2021; Schöggl et al. 2023). To address farming challenges, improve efficiency, and state-of-the-art fisheries facilities, emerging digital technologies such as the Internet of Things (IoT), big data, cloud computing, artificial intelligence (AI), and blockchain are progressively being utilized in aquaculture (Zhang and Gui 2023). By utilizing the capabilities of cutting-edge technology applications, digitalization is anticipated to completely change SC operations from end to end (Tsolakis et al. 2023).

Numerous studies have explored fisheries and associated digital techniques across various countries (Jeebhay et al. 2004; Jayathilakan et al. 2012; Bjørndal et al. 2016; Liu et al. 2022). However, prior research (Hald and Kinra 2019; Pournader et al. 2020; Dutta et al. 2020) conducted systematic literature reviews alongside bibliometric analyses on the utilization of digital technologies such as BT in supply chains, discussing emerging themes in SC, transportation, and logistics. The authors (Latino et al. 2022) performed a bibliometric analysis on agricultural digitalization, while Rowan (2023) discussed the role played by digital technologies in facilitating and enhancing fisheries and ASC. Additionally, other researchers conducted systematic literature reviews and bibliometric analyses on studies concerning the intersection of digital technologies and fisheries supply chains, but there is a lack of research on the emergence of knowledge themes in this field (Wang et al. 2021; Manoj et al. 2022; SiouNing et al. 2023).

To address this gap, this study conducts an in-depth analysis of the utilization of digital technologies in ASC through an emergence of knowledge themes using recent studies from 2019 to 2023. Thus, this study provides a fresh outlook and offers significant contributions as one of the initial endeavors to investigate the implementation of digital technologies in ASC. This study identifies influential journals, articles, authors, affiliations, and countries based on a systematic review of existing studies and bibliometric analysis. Furthermore, it analyzes the conceptual, intellectual, and social frameworks of the research to explore the emergence of knowledge themes in this field from a comprehensive dataset of literature indexed in two databases from 2019 to 2023. This provides new insights on the state of the art in the digitalization of ASC and sets the stage for future research directions. Hence, the following research questions were addressed:

RQ1: What are the research trends on the nexus of application of digital technologies in ASC?
RQ2: What are the research clusters in digital technologies and ASC?
RQ3: How have collaborative efforts shaped research in digital technologies application in ASC?
RQ4: What are the emerging knowledge themes in literature in the application of digital technologies in ASC?

Materials and methods

Database search

A database search was conducted on the utilization of digital technologies in ASC, encompassing both Scopus and Web of Science (WOS) databases from 2019 to 2023. A total of 587 documents were identified through this search. The selection of Scopus and WOS Core Collection databases was based on their renowned reputation for indexing high-quality publications. These databases boast the most extensive compilation of citation sources and thousands of peer-reviewed journals across various disciplines (Vrchota et al. 2020). Additionally, both databases are frequently utilized for scientific mappings in diverse fields, whether for individual studies, comparison, or database construction (Aria and Cuccurullo 2017, Rodríguez-Soler et al. 2020; Aria and Cuccurullo 2022). Given the swift evolution of digital technologies in ASC, a 5-year timeframe (2019–2023) was chosen to concentrate on the latest advancements, offering a timely and pertinent analysis for the study. Also, the selection of this timeframe was motivated by the sudden onset of the COVID-19 pandemic, which disrupted food supply chains, including aquaculture, and posed challenges to global food security.

Documents inclusion and exclusion criteria

The methodology employed in this study hinges on a systematic literature review (SLR), adhering to the PRISMA approach. Before commencing the SLR, a review protocol was established, drawing from the guidelines outlined by Page et al. (2020) and Yépez-Ponce et al. (2023), to ensure a transparent, rigorous, and exhaustive research process that basically included four steps: formulating the keywords, conducting a preliminary search in the chosen databases, setting the eligibility criteria for selection of documents, and selecting the relevant documents based on the eligibility criteria. The eligibility criteria (EC) are EC1—publication year (2019–2023), EC2—document type (articles, reviews, and conference papers), EC3—access type (open access), and EC4—language (English). The EC is outlined in Table 1.

The search keywords used as search criteria to identify articles from Scopus databases were Scopus: Application AND of AND Digital AND Technologies AND in AND Aquaculture AND Supply AND Chains while the search string for WOS database was TS = (application of digital technologies in aquaculture). A total of 1164 documents were returned from the preliminary search in the database (Scopus = 612; WOS = 553). However, based on the eligibility criteria earlier set, 587 documents were finally identified from both databases (Scopus = 282; WOS = 305). Figure 1 describes the SLR process leading to the selection of the final 46 documents included in the study for performing the bibliometric analysis and the qualitative synthesis in the study.

Data pre-processing

The metadata of the 587 documents obtained from a database search in both Scopus and WOS were first imported into Biblioshiny and saved as separate excel files, which were later imported into R Studio and converted into an R bibliographic data frame using bibliometrix. Thereafter, both datasets were combined, and five duplicates were removed after combining both Scopus and WOS datasets, leaving 582 objects (articles); these combined data were saved as a separate excel file towards the selection of the final 46 articles that were included in the systematic review.

Software package used

The bibliometric analysis was conducted using the open-source R software, using the Biblioshiny tool provided by the bibliometrix package.

Table 1 Criteria for article inclusion

Inclusion criteria	Inclusion criteria
• Focus on keywords such as aquaculture, adoption of digital technologies in ASC, sustainability, supply chain management, and level of implementation of digital technologies • Focus on fisheries • Peer-reviewed articles with open access • Articles published in English language • Articles that include original results of primary studies, systematic literature reviews, and conference papers	
Exclusion criteria	
• Articles that do not discuss at least one of the keywords • Articles not exploring fish farmers • Book chapters and editorials	

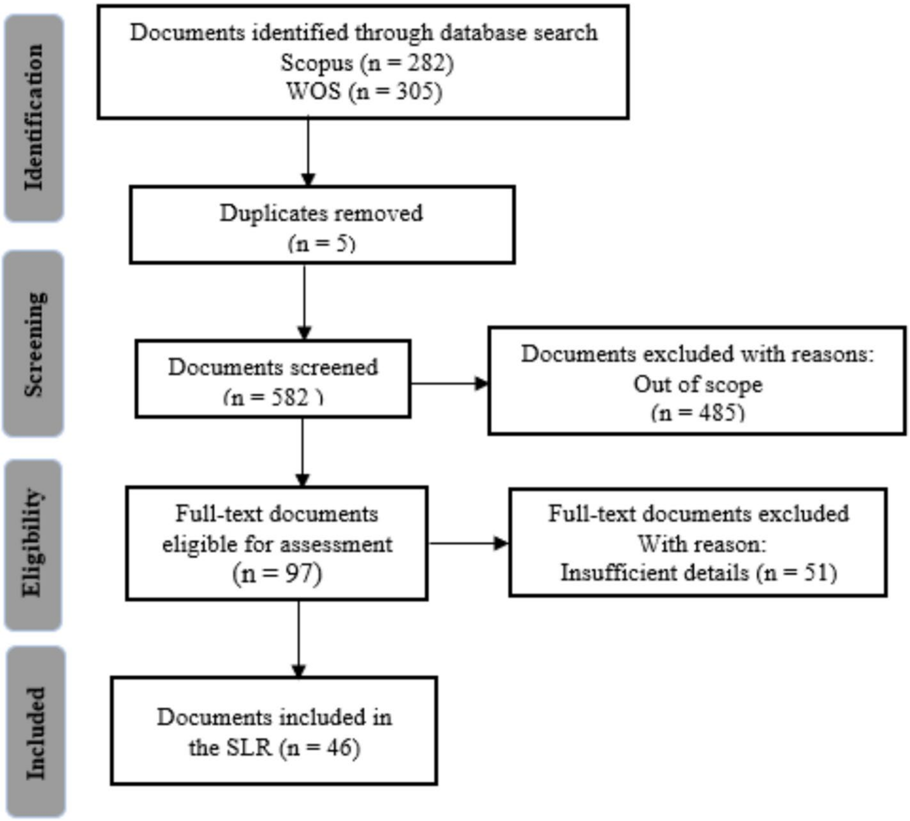

Fig. 1 The systematic literature review process according to PRISMA guidelines

Results and discussion

An analysis of the meta-data of the final 46 articles included in this study was done to show the statistics relating to yearly publications, productive source titles, authors, and countries. Also, prolific affiliations and collaborations, including most globally cited documents and references spectroscopy, were examined. Furthermore, the conceptual, intellectual, and social structures of the datasets were analyzed to answer the research questions posed in the study. A summary of the main information describing the meta-data is provided in the supplemental results.

RQ1: What are the research trends on the nexus of the application of digital technologies in ASC?

Annual publication distribution

Figure 2 illustrates the annual distribution of the 46 documents published from 2019 to 2023 regarding the application of digital technologies in ASC research. It indicates a rise in the frequency of documents published annually, with the count increasing from 1 article (Stafford 2019) in 2019 to 6 articles in 2020 (Vrchota et al. 2020; Rogerson and Parry 2020; Morato et al. 2020; Li et al. 2020a; Freitas et al. 2020; Rowan and Galanakis 2020). However, there was a slight dip in the number of publications (five articles in 2021) (Jahanbakht et al. 2021; Pylianidis et al. 2021; Tsolakis et al. 2021; Ruiz-Salmón et al. 2021; Longo et al. 2023). This decline may be attributed to the emergence of the COVID-19 pandemic, which prompted various responses such as lockdown, travel restrictions, and school closures worldwide in 2020, followed by a gradual reopening of economies around late 2020. Subsequently, from 2022 to 2023, the number of documents surged again, with over a 200% increase compared to 2021, comprising 16 articles published in 2022 and 18 articles in 2023.

Productive authors

The top 10 most productive authors in Table 2 include Rowan, N. taking the lead with 4 articles, followed by Rejeb, A. and Rejeb, K. with 3 articles each. The remaining authors, Apolloni, A., Dora, M., Iranmanesh, M., Jagtaap, S., Kumar, M., Pakseresht, A., and Tsolakis, N. have 2 articles each. These top 10 authors published 14 articles (30.44%) of the total 46 articles found in the domain from 2019 to 2023.

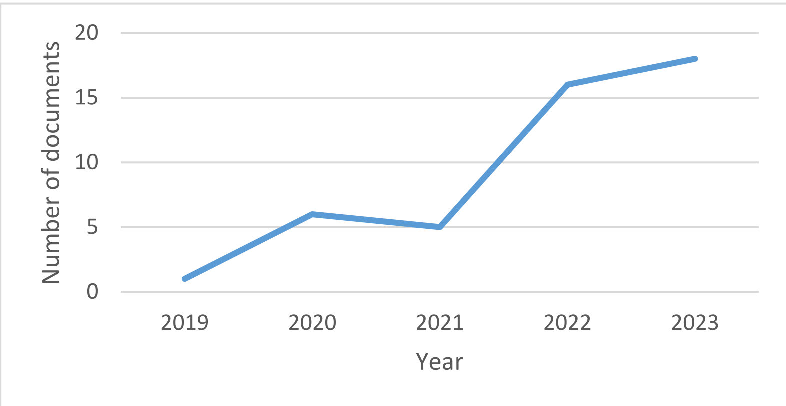

Fig. 2 Year-wise distribution of documents in the application of digital technologies in ASC

Table 2 Productive authors in application of digital technologies in ASC research

S/n	Authors	Number of articles
1	Rowan, N	4
2	Rejeb, A	3
3	Rejeb, K	3
4	Apolloni, A	2
5	Dora, M	2
6	Iranmanesh, M	2
7	Jagtaap, S	2
8	Kumar, M	2
9	Pakseresht, A	2
10	Tsolakis, N	2

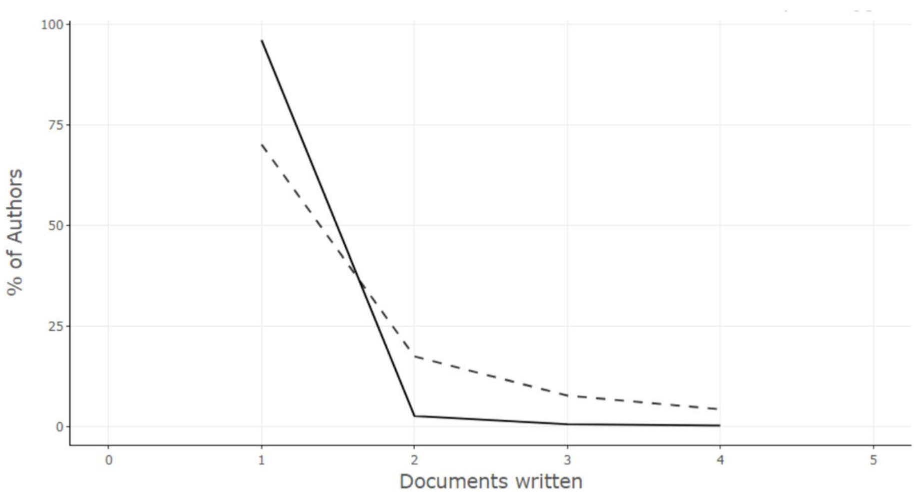

Fig. 3 Author productivity and Lotka's law dynamics in the application of digital technologies in the ASC field

Table 3 Percentage distribution of documents written by authors in the application of digital technologies in the ASC domain

Documents written	Number of authors	Percentage of authors (%)
1	281	96.23
2	8	2.73
3	2	0.70
4	1	0.34

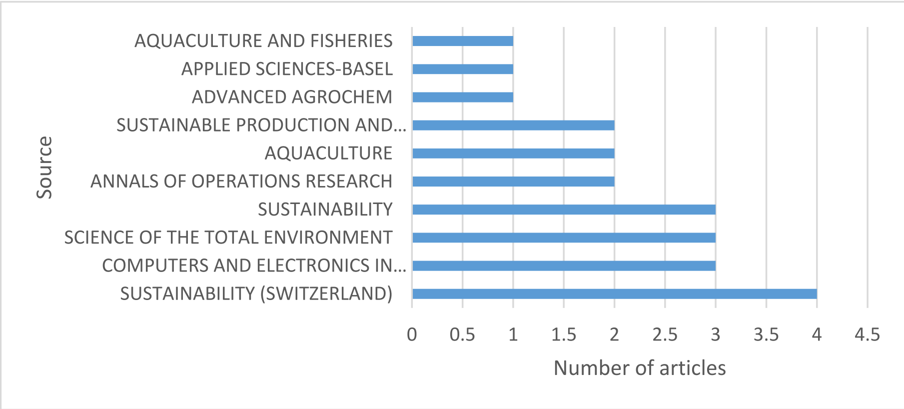

Fig. 4 Top source titles in the application of digital technologies in ASC research

Table 4 Prolific affiliations in ASC research

S/n	Affiliation	Number of articles
1	China Agricultural University	5
2	University of Cambridge	4
3	Brunel University London	3
4	Instituto Español De Oceanografía	3
5	University of Engineering and Technology Lahore	3
6	Bioscience Research Institute, Chongqing University	2
7	Chongqing University	2
8	Cranfield University	2
9	Dalhousie University	2
10	La Trobe University	2

Author productivity analysis using Lotka's law

Lotka's law is a bibliometric concept utilized for assessing the productivity of an author on the basis of the distribution of the documents authored (Sahu and Jena 2022). In Fig. 3, the dashed lines represent authors with fewer documents or lesser activity in the research field under consideration in this study, whereas the solid lines indicate productive authors that have contributed substantially to the literature or have a significant proportion of documents in a research domain. Most authors, specifically 281 authors (96.23%) as stated in Table 3, have authored only one document in this research field. Eight authors (2.73%) have authored two documents, two authors (0.70%) have authored three documents, while only one author (0.34%) has authored four documents. Consequently, this distribution aligns with Lotka's law that suggests a smaller proportion of authors produce the bulk of the documents, while a greater proportion produce fewer documents (Kawamura et al. 2000).

Productive source titles

The top 10 source titles in the research field shown in Fig. 4 include *Sustainability (Switzerland)* being the top contributor with 4 articles; *Computers and Electronics in Agriculture*, *Science of the Total Environment*, and *Sustainability* have 3 articles each. Others in the top 10 ranking include *Annals of Operation Research*, *Aquaculture*, and *Sustainable Production* and *Consumption* with 2 articles each, while *Advanced Agrochem*, *Applied Sciences-Basel*, and *Aquaculture and Fisheries* have published 1 article each. These top 10 source titles have contributed 22 (47.83%) articles in the total set.

Prolific affiliations

Among the top ten prolific institutions in Table 4, China Agricultural University emerges as the most prolific, with 5 articles. This was followed by the University of Cambridge (4 articles), Brunel University London, Instituto Español De Oceanografía, and the University of Engineering and Technology Lahore, which have 3 articles each. Bioscience Research Institute, Chongqing University, Cranfield University, Dalhousie University, and La Trobe University have 2 articles each. The analysis of the top affiliations by geographical region showed that out of the 28 articles published by these top 10 most productive affiliations, 42.86% of these articles have an affiliation to Asia, the European region (42.86%), and North America (7.14%) while the remaining 7.14% is from Oceania.

Productive countries

The top ten countries with the highest productivity in the domain, as shown in Fig. 5, include the UK, which takes the lead with 14 articles, followed by China, Italy, Canada, Hungary, India, Sweden, the USA, Australia, and Germany, with 5, 5, 4, 3, 3, 3, 3, 2, and 2 articles, respectively.

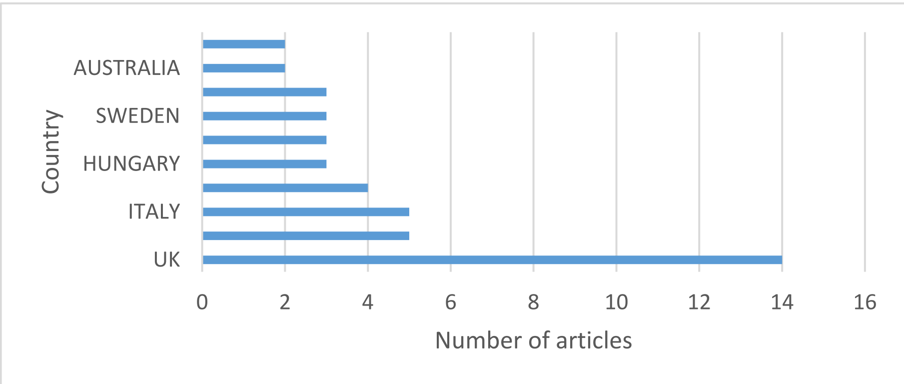

Fig. 5 Most productive countries in the application of digital technologies in ASC research

Table 5 Highly global cited documents in digital technologies and ASC research field

References	Total citations (TC)	TC per year	Normalized TC
Rogerson and Parry 2020)	213	42.60	1.77
Misra et al. 2022)	183	61.00	7.73
Jahanbakht et al. 2021)	176	44.00	1.70
Rowan 2023)	175	35.00	1.45
Pylianidis et al. 2021)	129	32.25	1.24
Tsolakis et al. 2021)	115	28.75	1.11
Morato et al. 2020)	96	19.20	0.80
Li et al. 2020a)	95	19.00	0/79
Vrchota et al. 2020)	79	15.80	0.65
Freitas et al. 2020)	66	13.20	0.55

Table 6 Average citations per year in the application of digital technologies in ASC research

Year	Mean TC/ document	*N*	Mean TC/year	Citable years
2019	8	1	1.33	6
2020	120.67	6	24.13	5
2021	103.8	5	25.95	4
2022	23.69	16	7.90	3
2023	9	18	4.50	2

Top globally cited documents

The most cited documents offer comprehensive insights into the impact and geographical reach of research publications, as indicated by cumulative citations per annum and normalized citations, highlighting the continued influence and relevance of these publications within the scientific community (Delcea et al. 2023). The most globally cited document is "Blockchain:case studies in food supply chain visibility" by Rogerson and Parry (2020), with 213 citations, as shown in Table 5. According to Wang et al. (2019), authors with significant citation counts demonstrate the adaptability, significant impact factor, and robustness of knowledge dissemination stemming from their publications.

In this study, Rogerson and Parry (2020) hold the highest total citations, TC =213, TCY =42.60 with a NTC =1.77, as depicted in Table 1. Conversely, Misra et al. (2022) exhibit a lower total citation count (TC =183), but with a higher TCY of 61.00 and NCT of 7.73. The publication year of the document is crucial in determining the NTC, as indicated in Table 1. To calculate the NTC value, the TC is divided by the mean number of citations/documents extracted from the dataset for the respective year of publication (Delcea et al. 2023). In the case of Rogerson and Parry, published in 2020, the average citations per document are 120.67, as shown in Table 6. Therefore, dividing the TC of Rogerson and Parry (2020), 213 citations, by 120.67 yields an NTC value of 1.73. Consequently, the document by Rogerson and Parry (2020) has accrued approximately 1.73 times additional citations compared to the mean TC received by other documents included in the dataset for the year 2020.

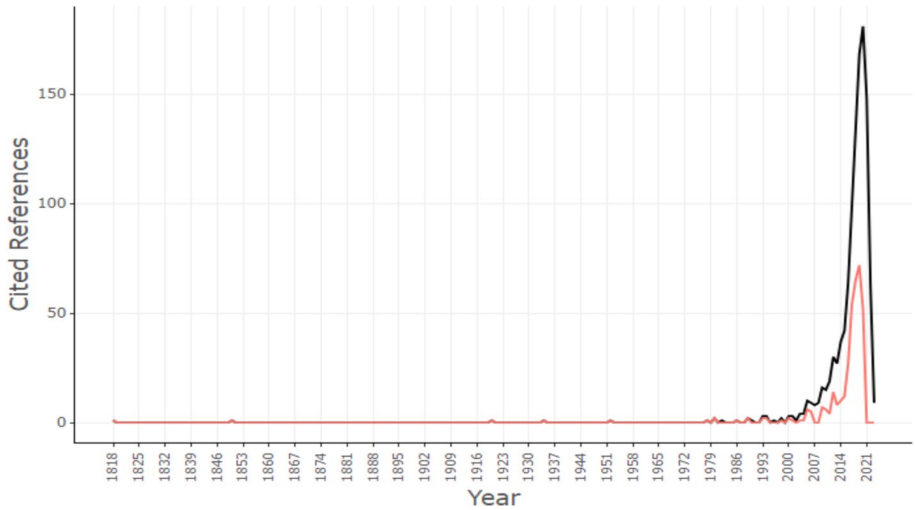

Fig. 6 Reference spectroscopy in digital technologies ASC research field

Most cited references

Bornmann and Marx (2013) introduced a unique and innovative method of cited reference analysis known as reference publication year spectroscopy (RPYS) (Marx et al. 2014; Haunschild and Bornmann 2022), which provides a visual illustration of the RPYS plotted against the total number of cited references, revealing initial peaks indicative of historical origins. RPYS demonstrates a notable evolution in citations over time, displaying stable intervals alongside periods of exceptional growth (Delcea et al. 2023). In Fig. 6, citations were sparse from the early nineteenth century to the late twentieth century, but they began to increase in the early twenty-first century, initially experiencing slight growth followed by intermittent fluctuations. From 2014, the number of citations rose steadily, reaching its peak in 2020. However, there has been a significant decline in recent years, starting from 2021, despite the considerable research activities ongoing in the twenty-first century. This decline may be attributed to a shift in research relevance and/or areas of interest.

RQ2. What are the research clusters in digital technologies and ASC?

To address RQ2, both the conceptual and intellectual structures of the 46 papers selected for final inclusion in the SLR were explored.

Conceptual structure

Co-word networks serve to elucidate the conceptual structure by revealing connections between concepts through term co-occurrences. They are utilized to comprehend the themes studied by academics and pinpoint the most significant and current concerns. Conceptual structure analysis is commonly employed for this purpose. In addition to keywords, Bibliometrix can analyze terms from article titles and abstracts using network analysis,

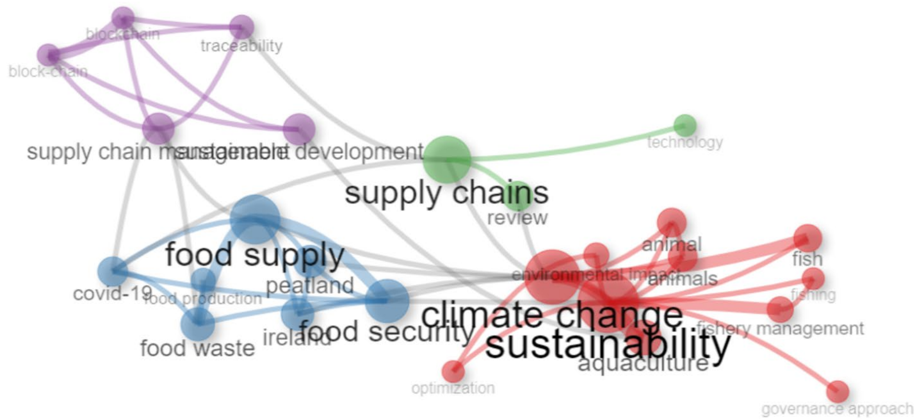

Fig. 7 Network visualization of co-occurrence of keywords in the application of digital technologies in ASC research

correspondence analysis (CA), or multiple correspondence analysis (MCA) to plot the conceptual structure in two dimensions (Aria and Cuccurullo 2017). In this study, both network and factorial approaches were considered for analyzing the conceptual structure to address RQ1.

Co-word analysis through keyword co-occurrences

Thematic clusters or collections of words that are frequently related to one another in documents can be found using co-word analysis. This can offer a summary of a field's primary themes or subdomains. Furthermore, terms with a lot of citations may point to subjects that have a lot of significance and relevance for the scientific community (Delcea et al. 2023). Hence, the frequently occurring keywords have been identified to frame a conceptual map of the application of digital technologies in ASC research in Fig. 7. The co-occurrence of keywords in the application of digital technologies in ASC research from 2019 to 2023 in Fig. 7 indicates that there are four clusters containing 26 keywords, and cluster 1 is the largest and contains the highest number of keywords (11).Sustainability is ranked as the

Table 7 Description of the co-occurrence network in the application of digital technologies in the ASC research domain

Cluster	Number of keywords	Keywords
1 (red color)	11	climate change, aquaculture, sustainability, environmental impact, fish, fishery management, optimization, animal, animals, fishing, governance approach
2 (blue color)	7	food supply, food security, covid-19, food waste, Ireland, food production, peatland
3 (green color)	3	supply chains, technology, review
4 (purple color)	5	supply chain management, sustainable development, traceability, block-chain, blockchain

Fig. 8 Word cloud of the common keywords in the application of digital technologies in ASC research (2019–2023)

leading keyword, followed by climate change and food supply, with a PageRank of 0.113, 0.098, and 0.062, respectively, thus indicating their significant relevance to the research. A detailed description of the four clusters in Fig. 7 is provided in Table 7.

The word cloud showcased in Fig. 8 provides a visual representation of the most encountered words, showcasing the frequency of each word's occurrence in articles. Larger words within the word cloud indicate higher frequency within the observed documents, while smaller words represent lesser frequency. This relationship allows for an understanding of how frequently each keyword is utilized (Prabakusuma et al. 2023). It is evident that

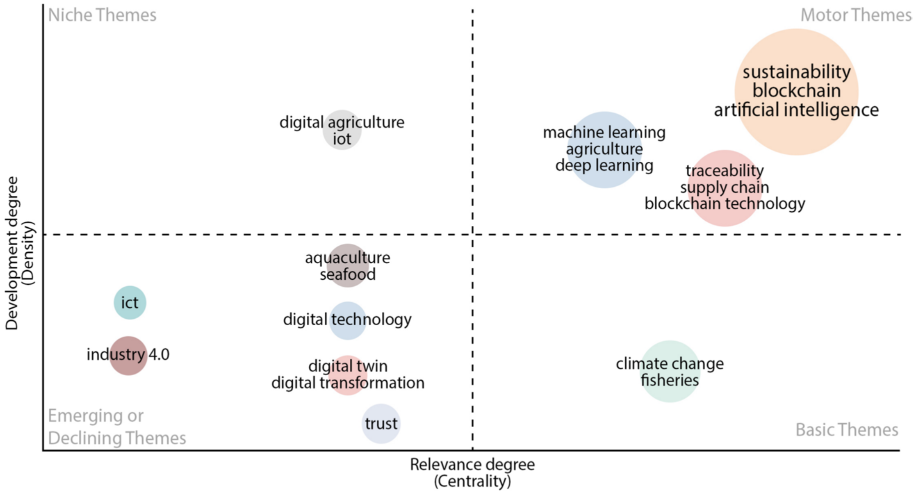

Fig. 9 Thematic map based on Callon's measure of centrality and density of keywords co-occurrence in the application of digital technologies in ASC research

climate change, aquaculture, sustainability, food supply, supply chain management, supply chains, food security, sustainable development, covid-19, and environmental impact were the top ten most frequent keywords with a frequency of 9, 8, 8, 6, 6, 6, 5, 5, 4, and 4 respectively. The word cloud highlights a significant focus on keywords such as “climate change” and “sustainability” and further exemplifies their relevance in the ASC field.

Conceptual thematic map

Using the author’s keyword clusters that are regarded as themes, these themes are mapped in a two-dimensional diagram by which these themes can be analyzed, based on the quadrant where these themes were placed (Fig. 9). To optimize the readability and interpretation of Fig. 9, we implemented two key adjustments—label simplification (all cluster labels were restricted to a maximum of three words to reduce visual clutter) and spatial reorganization. In the emerging–declining themes quadrant, overlapping clusters were systematically repositioned to resolve occlusion issues that initially rendered clusters illegible.

The motor themes are the first quadrant (upper-right) and measure density; the internal associations between the keywords provide a measure of the themes’ level of development (Siccardi and Villa 2023). As a result, the themes are significant and well-developed for the field of study (Aria et al. 2020, 2022). The basic themes are the second quadrant (lower-right) and is a measure of centrality, showing the themes’ relevance as determined by the external associations between the keywords (Siccardi and Villa 2023). These themes are significant for a domain and deal with broad issues that are relevant to many studies within the field. The third quadrant is on the upper-left and contains niche themes that are very specialized and characterized by high-density internal links but low centrality (unimportant external links), i.e., highly developed and isolated themes, though their significance for the field is limited. The fourth quadrant (lower-left) is made up of emerging/declining themes with low density and centrality, themes that are marginal and also poorly developed (Aria et al. 2020, 2022; Cobo et al. 2011).

The thematic map in Fig. 9 contains 11 clusters (with 34 words) which are clearly described in Table 8. Motor themes represent well-established, highly developed research areas that continue to propel research forward within the field, demonstrating significant potential for future advancement and innovation. Figure 9 reveals that motor themes in the present study are sustainability, circular economy, traceability, and food security. A closer look at the cluster network of the motor themes also reveals themes such as food safety, food waste, valorisation, COVID-19, supply chain, and fish supply networks. All of these themes emphasize the significance of the application of digital technologies in optimizing ASC processes. Basic themes in Fig. 9 encompass topics related to climate change and fisheries. This implies that existing research has explored this subject extensively, yet opportunities remain for substantial theoretical and methodological advancement. Hence, future studies should focus on climate change effects on aquatic ecosystems. Empirical studies demonstrate significant disruptions to fisheries productivity and species distribution (Ruiz-Salmón et al. 2020), including projected habitat loss for deep-sea organisms (Morato et al. 2020). While these changes develop gradually, their combined effects will match other major environmental threats, potentially collapsing marine trophic structures and global seafood networks. The niche themes contain digital agriculture and IoT. Although these themes are highly developed, implying their relevance to diverse fields, they, however, have limited significance in this study. On the other hand, aquaculture, seafood, digital technology, trust, Industry 4.0, digital twin, digital transformation, and ICT unfold as emerging/

Table 8 Description of the thematic map in ASC research

Occurrences	Keywords	Cluster	Cluster label
5	traceability	1	Traceability
4	supply chain	1	Traceability
3	blockchain technology	1	Traceability
2	eco-efficiency	1	Traceability
2	fish supply networks	1	Traceability
5	machine learning	2	Machine learning
4	agriculture	2	Machine learning
2	deep learning	2	Machine learning
2	farming	2	Machine learning
3	digital twin	3	Digital twin
2	digital transformation	3	Digital twin
2	ict	4	ICT
16	sustainability	5	Sustainability
9	blockchain	5	Sustainability
8	artificial intelligence	5	Sustainability
5	big data	5	Sustainability
5	covid-19	5	Sustainability
4	food security	5	Sustainability
4	internet of things	5	Sustainability
3	food supply chain	5	Sustainability
2	agri-food	5	Sustainability
2	circular economy	5	Sustainability
2	digital	5	Sustainability
2	food waste	5	Sustainability
2	valorization	5	Sustainability
3	aquaculture	6	Aquaculture
2	seafood	6	Aquaculture
2	industry 4.0	7	Industry 4.0
2	digital agriculture	8	Digital agriculture
2	iot	8	Digital agriculture
3	climate change	9	Climate change
3	fisheries	9	Climate change
2	digital technology	10	Digital technology
3	trust	11	Trust

declining themes which may indicate either a mature and highly saturated studied subject or alternatively, a promising avenue for potential innovation and thematic expansion. Further discussions on these themes are provided in the "RQ3: What are the emerging knowledge themes in literature in the application of digital technologies in ASC?" section of this study.

The Callon's measure of centrality and density indicates that cluster sustainability leads with Callon Centrality (2.819), Callon Density (63.378), Rank Centrality (11), Rank Density (11), and Cluster Frequency (64). This is followed by cluster traceability with Callon Centrality (1.086), Callon Density (53.666), Rank Centrality (10), Rank Density (8), and Cluster Frequency (16); cluster climate change with Callon Centrality (0.5), Callon Density (38.888), Rank Centrality (9), Rank Density (2), and Cluster Frequency (6); and cluster machine learning with Callon Centrality (0.404), Callon Density (61.875), Rank Centrality (8), Rank Density (9), and Cluster Frequency (13), indicating that these clusters are not only highly important but also central to the application of digital technologies in the ASC research field.

Factorial analysis

The bibliometrix-R tool enables factorial analysis to determine the conceptual structure of bibliometric data. This is achieved by conducting either CA or MCA, which helps depict the conceptual framework of the field. Additionally, K-means clustering is employed to identify clustered documents that share common concepts. The outcomes are then represented on a two-dimensional map (Aria and Cuccurullo 2017). Specifically, the MCA technique was utilized in this study to examine the associations among categorical variables, such as the study's keywords, through a factorial analysis of mixed data (FAMD). By employing this technique, relationships among categories can be identified and visualized (Delcea et al. 2023). A factorial map is used in Fig. 10 to display the keywords that have contributed the most.

In Fig. 10, it was observed that the prominent keywords in the first quadrant are "supply chains," "decision making," "sustainable development," "aquaculture," "fish," "sustainability," "article," "climate change," "food supply," "life cycle," "United States," and "agriculture," The first quadrant focuses on articles that explored "aquaculture supply chains," "sustainability in aquaculture supply chains," "addressing food supply and food safety in aquaculture supply chains," "climate-triggered shifts in the suitable environment of deep sea fishes," "life cycle assessment of fish," and "agriculture and food supply in the United States." The keywords in the first quadrant illustrate the benefits of a sustainable ASC—in protecting the oceans and supporting economies.

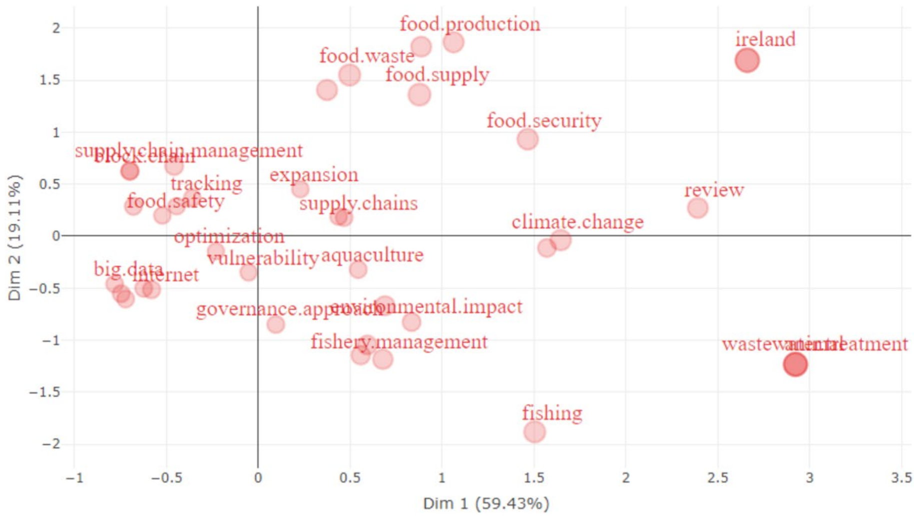

Fig. 10 Factorial analysis word map of the application of digital technologies in ASC research (2019–2023)

In the second quadrant, keywords like "food security," "review," "metabolism," "human," "nonhuman," "procedures," "human," and "soil" are prevalent. The second quadrant clearly indicates the focus of research on food security toward addressing a key target (zero-hunger) of the United Nations Agenda 2030 on Sustainable Development. *The prevalent keywords in the third quadrant are "technology," "innovation," "supply chain management," and "blockchain." Studies in this quadrant may address "technology and innovation in SCM" and "application of blockchain in SCM,"* thereby indicating the relevance of blockchain in increasing trust, traceability, and transparency in the supply chain. Finally, in the fourth quadrant, keywords such as *"technologies," "biomass," "big data," "internet," "model," "quality," "identification," "performance," "design," "information," "prediction," "challenges," and "precision agriculture"* were conspicuous. Articles in this quadrant were distinguished by *"use of technologies such as big data for information management," "design of models for prediction," "identification of biomass," and the "use of the internet to improve performance."* This quadrant solidifies the diverse benefits of the application of digital technologies.

Table 9 Most contributing documents in the application of digital technologies in ASC research

References	Dimension 1	Dimension 2	Contributions	Total citations	Cluster
(Misra et al. 2022)	− 0.22	0.04	1.1	183	1
(Rowan and Galanakis 2020)	0.88	1.07	54.56	175	1
(Pylianidis et al. 2021)	− 0.37	− 0.2	4.33	129	1
(Morato et al. 2020)	− 0.01	− 0.12	0.48	96	1
(Vrchota et al. 2020)	− 0.22	− 0.2	2.46	79	1
(Freitas et al. 2020)	− 0.1	− 0.19	1.36	66	1
(Ruiz-Salmón et al. 2021)	1.09	− 0.89	52.1	56	1
(Rejeb et al. 2022b)	− 0.27	− 0.11	1.99	39	1
(Munir et al. 2022)	− 0.33	0.19	3.58	30	1
(Rejeb et al. 2022a)	0.08	0.49	8.02	16	1
(Ojo et al. 2022)	− 0.16	− 0.09	0.85	15	1
(Bassett et al. 2022)	− 0.19	0.14	1.42	13	1
(Pakseresht et al. 2022)	− 0.13	0.34	4.17	12	1
(Yang et al. 2023a)	− 0.15	0.19	1.62	12	1
(Pakseresht et al. 2023)	− 0.33	0.32	5.72	9	1
(Alobid et al. 2022)	− 0.24	− 0.17	2.24	9	1
(Stafford 2019)	0.15	− 0.37	5.04	8	1
(Longo et al. 2023)	− 0.2	0.12	1.37	5	1
(Onyeaka et al. 2023)	0	0.18	1.05	5	1
(Zhang and Gui 2023)	− 0.22	− 0.21	2.45	4	1
(Lan et al. 2023)	− 0.18	− 0.1	1	4	1
(O'Neill et al. 2022)	1.31	0.06	37.88	2	1
(Jolly et al. 2023)	− 0.07	− 0.2	1.37	2	1
(Mileti et al. 2023)	− 0.15	0.15	1.21	2	1
(Cooke et al. 2023)	− 0.02	− 0.14	0.65	2	1
(Ogunji and Wuertz 2023)	0.11	− 0.19	1.42	1	1
(Zhang et al. 2023)	− 0.06	− 0.12	0.56	0	1

Also in Fig. 10, one cluster emerged containing 27 documents; however, only four documents ((Rowan and Galanakis 2020; Rejeb et al. 2022a; Onyeaka et al. 2023), and (O'Neill et al. 2022)) rank with the highest contributions because they also fall under the positive quadrants of both dimensions, as shown in Table 9. The aggregation of documents into a single cluster implies a shared characteristic or likeness among the documents within the analyzed context. Words with analogous coordinates within this framework are inclined to share similar relationships or patterns in the scrutinized data. The positive or negative values along either dimension denote the direction of the relationship (Delcea et al. 2023).

The four most contributing documents ((Rowan and Galanakis 2020; Rejeb et al. 2022a; Onyeaka et al. 2023) and (O'Neill et al. 2022)) identified provide deeper reflection on the implications of our results for advancing the field. The study (Rowan and Galanakis 2020) re-conceptualizes the COVID-19 pandemic as more than a crisis but positions it as a driver for transforming food systems in ways that align with sustainability goals, thereby offering actionable insights that equip stakeholders (businesses, policymakers, and researchers) with strategies to foster a more resilient, equitable, and sustainable food systems. Furthermore, (Rejeb et al. 2022a) significantly advances food supply chain studies, synthesizing pandemic-induced disruptions, proposing evidence-based solutions, and outlining a forward-looking research agenda. It serves as a bridge between theory and practice, advocating for adaptive technologies driven by FSC models capable of weathering future shocks. On the other hand, by integrating perspectives from AI, Environmental Science, and Economics, Onyeaka et al. (2023) establishes a framework for resource-efficient and inclusive food systems, and O'Neill et al. (2022) advocates that future research should prioritize overcoming implementation barriers such as data limitations and outdated infrastructure while extending AI-driven innovations to underserved regions. Additionally, this study pioneers interdisciplinary convergence, linking aquaculture sustainability, microbial ecology, and biotechnology to address systemic challenges in food production.

Intellectual structure

The intellectual framework is employed to delineate both the co-citation network and the historiography in this study. However, the present study specifically conducts a

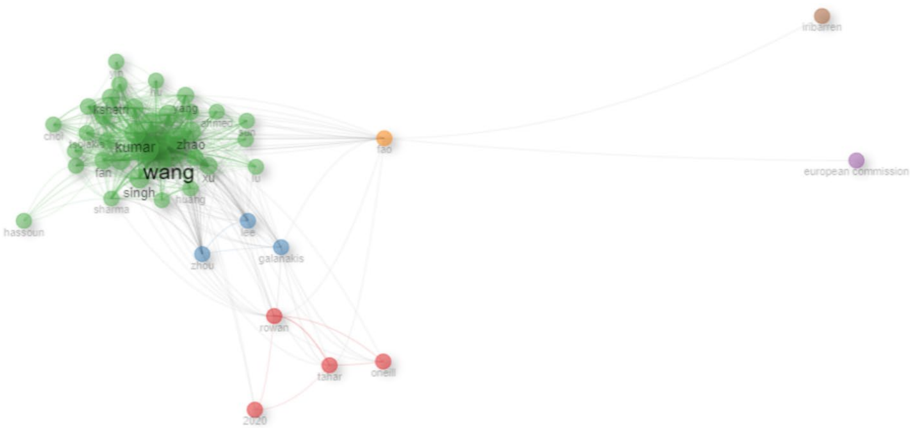

Fig. 11 Co-citation network of the application of digital technologies in ASC research (2019–2023)

co-citation network analysis, which is a citation analysis method that unveils the framework of a particular research domain by examining the connections between the nodes (such as authors, articles, and journals). The links between nodes, referred to as edges, can be interpreted differently based on the network type, including co-citation, direct citation, and bibliographic coupling. Several dimensions are instrumental in interpreting co-citation networks, including "node centrality and peripherality," "proximity and distance," "tie strength," "clusters," and "bridging contributions" (Aria and Cuccurullo 2022). Co-citation network clusters are also formed based on their closeness, but the factor of their proximity is co-citations instead of co-authors.

Figure 11 shows relations between cited-reference works (nodes) based on authors of the 46 articles in the application of digital technologies and aquaculture SC research. The co-citation network comprises 6 clusters and 46 items. Cluster 1 (red color), cluster 2 (blue color), cluster 3 (green color), cluster 4 (purple color), cluster 5 (orange color), and cluster 6 (brown color) contain 4, 3, 36, 1, 1, and 1 authors, respectively. The earliest cited authors in their respective clusters in Fig. 12 are Rowan, N.; Galanakis, C.; Wang, Y.; European Commission; FAO; and Iribarren.

RQ3: How have collaborative efforts shaped research in digital technologies application in ASC?

To address RQ2, we examined the social structure of the 46 documents. The social structure encompasses collaboration networks, elucidating the relationships between authors, affiliations, and countries within a particular research field. This highlights networks of researchers and international partnerships (Kilicoglu and Mehmetcik 2021).

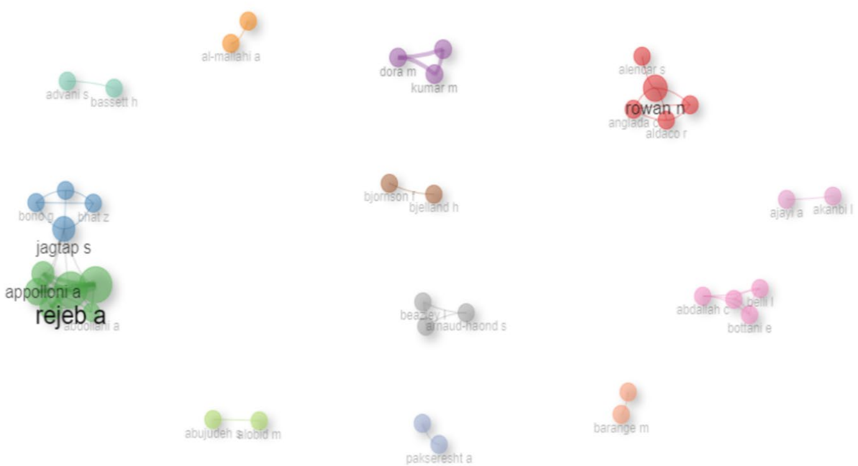

Fig. 12 Authors' collaboration network in digital technologies and ASC research

Authors' collaboration

The authors' collaboration network in Fig. 12 shows that out of the 292 authors that have been identified in the study, there are 13 clusters comprising 39 authors that have collaborated with each other. Each node in the network represents an author. Cluster 1 (red color) is the largest, thus containing the highest number of authors (13), followed by cluster 2 (blue color) with 8 authors and cluster 5 (orange color) with 6 authors; next is cluster 3 (green color), cluster 6 (brown color), and cluster 8 (grey color) which contains 3 authors each, while cluster 4 (purple color), cluster 7 (pink color), and cluster 9 (lemon color)are the smallest, with the least authors (2 each). Large clusters indicate maximum closeness between the authors based on collaboration, while isolated authors from the same cluster indicate less closeness and low collaboration; these studies are mostly single-authored.

Collaborations exist among different researchers in this field, cutting across different disciplines, territories, and affiliations. The most collaborative authors identified in the collaboration network are as follows: Rejeb, A. (cluster 3); Rejeb, K. (cluster 3); Rowan, N. (cluster 1); Jagtap, S. (cluster 2); Iranmanesh, M. (cluster 3); Anglada, C. (cluster 1); Aldaco, R. (cluster 1); Almeida, C. (cluster 1); Appolloni, A. (cluster 3); and Abdallah, C. (cluster 7). These authors as illustrated in Table 10 hold PageRanks of 0.038, 0.038, 0.036, 0.030, 0.029, 0.026, 0.026, 0.026, 0.025, and 0.025, respectively, establishing them as the top ten most collaborative authors in the research domain.

As highlighted by Prabakusuma et al. (2023) and Cancino et al. (2017 and 2020), these leading collaborative authors possess the largest node size within the co-authorship collaboration network, indicating significant contributions, substantial citation frequencies, and extensive connections with other authors in the domain. Moreover, in the contemporary era, authors are increasingly regarded as proficient researchers, especially in the field of aquaculture sciences that engage in multifaceted scientific endeavors that encompass interactions with diverse research sponsors, institutions, collaborators, publishers, industries, and peers. They are also involved in the registration and commercialization of their patents, inventions, intellectual property rights, and discoveries (Prabakusuma et al. 2023; Perkmann et al. 2013; Kosmützky and W¨ohlert 2021; Neema and Chandrashekar 2021; Joffre et al. 2017). Consequently, in the evolution of academic research, the influence of prominent authors is paramount in shaping as well as defining the collaboration network, driving shifts in scientific perspectives, and facilitating a global dissemination of intellectual knowledge (Prabakusuma et al. 2023; Cancino et al. 2017, 2020).

Table 10 The most collaborative authors in ASC research and their PageRanks

S/n	Authors	PageRanks
1	Rejeb, A	0.038
2	Rejeb, K	0.038
3	Rowan, N	0.036
4	Jagtap, S	0.030
5	Iranmanesh, M	0.029
6	Anglada C	0.026
7	Aldaco, R	0.026
8	Almeida, C	0.026
9	Appolloni, A	0.025
10	Abdallah, C	0.025

Fig. 13 Countries' collaboration network in the application of digital technologies in aquaculture SC research (2019–2023)

Countries' collaboration

There are 4 clusters containing 18 countries involved in the collaboration network in Fig. 13: Cluster 1, green color (Canada, Ghana, India, USA, New Zealand, Poland); Cluster 2, blue color (UK, Italy, Singapore, South Africa); Cluster 3 (Hungary, Austrailia, Malaysia, Tunisia, Iran, Lithuania); and Cluster 4 (China, Philippines). It is noteworthy to underline the high collaborations from Australia, Canada, and Hungary to several other countries. The presence of advanced research centers and institutes and high technological capabilities in these top collaborative countries, backed up by adequate funding, may account for the strong collaborations between these countries.

Furthermore, the collaborative countries in this research domain span different continents of the world that include Asia, Europe, North America, Oceania, and Africa, with the largest collaborations from Asia and the least from Africa. Some of the reasons for the low collaborative efforts from Africa may be because some of these researchers are somewhat limited to their home institutions and/or do not participate in research mobility, lack/inadequate access to advanced research facilities, and funding for conducting research in some of these countries and across the continent. This claim is further evidenced in Cerdeira et al. (2023).

This finding could be a call to action for governments, most especially in Africa, to provide more funding and opportunities for scientific studies that will aid the development of the aquaculture sector and education at large. Meanwhile, it is noteworthy that key players or institutions and sponsors have played a central role in collaborative efforts leading to collaborative networks that comprise authors from different countries and affiliations, thereby contributing immensely to the development and dissemination of knowledge through the design and implementation of technological models that can be applied across the several parts of the ASC, thereby showcasing the different potentials and challenges associated with their models while further suggesting opportunities that still need to be explored. These networks of authors have also provided qualitative and quantitative knowledge through comprehensive reviews of literature, aimed at enhancing comprehension of the application of digital technologies in ASC even from an interdisciplinary and multidisciplinary perspective and further identifying research gaps that must be addressed. These collaborative efforts have indeed also laid great emphasis and raised concerns on the issue of sustainability and climate change in aquaculture.

RQ3: What are the emerging knowledge themes in literature in the application of digital technologies in ASC?

The five major knowledge themes that emerged from the 46 documents eligible for inclusion in the qualitative synthesis of this study from 2019 to 2023, as stated in Fig. 1, are discussed under the following sub-sections to answer RQ3.

Application of digital technologies in ASC

The advent of digital technologies has led to significant advancements across various domains, including aquaculture (Ojo et al. 2022). Digital technologies extensively explored in aquaculture SC research encompass AI, blockchain technology (BT), IoT, robotics, drones, cloud computing, 3D printing, smart sensors, big data, digital twin (DT), computer vision, machine learning (ML), and deep learning (DL) in fisheries. The subsequent sub-sections discuss some of the areas of application of digital technologies across different facets of ASC.

Fish feeding management

Aquaculture heavily relies on accurate information regarding fish appetite to inform feeding and production strategies. However, traditional methods for assessing fish appetite are often inefficient and subjective. Hence, an automated method based on convolutional neural networks (CNN) and machine vision can assess fish feeding intensity effectively (Zhou et al. 2019a). The utilization of drones facilitates the collection of extensive data on fish feeding at aquaculture sites, serving as WIFI gateways for submerged cameras to establish direct communication with the cloud for tasks such as fish enumeration and estimating length of fish. This enhances the management of aquaculture farms and optimizes output (Ubina et al. 2021).

Fish detection

DL approaches have shown significant promise in the detection of underwater living fish due to the expansion of datasets and improved computational capabilities. DL techniques have even surpassed human specialists in identifying fish species (Yang et al. 2021; Villon et al. 2018; Cui et al. 2020). Additionally, computer vision is applied in aquaculture for fish detection and species identification (Yang et al. 2021; Li et al. 2020b).

Fish monitoring

Monitoring and analyzing fish behavioral changes in aquaculture are crucial for guiding fish feeding, evaluating fish health and welfare, and reducing water pollution (Zhou et al. 2019b; Liu et al. 2023). Precise information on water condition, dissolved oxygen content, and nutrients is essential in fish farming, not only in large-scale traditional applications but also in urban aquaculture. Live and automated monitoring can save time and reduce human error, improving fish farm productivity (Singh et al. 2023). Automated monitoring, including the use of ML to evaluate fish biomass and conduct behavioral analyses, aids in scientific aquaculture management by reducing losses due to diseases or overfeeding (Liu et al. 2023). Computer vision accurately quantifies fish behavior and estimates fish counts (Yang et al. 2021), while artificial intelligence (AI) maximizes crop output and machine vision remotely monitors fish without causing stress (Li et al. 2020b; Rejeb et al. 2022c). Cloud-based autonomous drones incorporating AI services and DL recognition models facilitate scalable and functional aquaculture surveillance (Ubina et al. 2021; Zhou et al. 2019b). DT models efficiently identify fishing net damage using sensor data, enabling more sustainable operations (Zhao et al. 2022; Su et al. 2023). Computer vision and AI are increasingly used in precision/smart fish farms (Liu et al. 2023), while DL advancements enhance prediction and control models for system parameters such as water quality (Yang et al. 2023b). These digital technologies have the potential to improve food security and align with SDG 12, which focuses on responsible production and consumption (Cooke et al. 2023).

Water quality management

Water quality is crucial in aquaculture, as poor management can reduce the economic benefits of aquaculture personnel (Guo et al. 2023). Metabolites like cyanotoxins and T&O compounds pose water quality challenges in aquaculture (Kibuye et al. 2021). AI-based deep transfer learning techniques automate water quality classification, simplifying deployment and saving expenses in the aquaculture industry (Guo et al. 2023). Sensors facilitate automated sea-condition monitoring, optimizing aquaculture processes (Wada et al. 2019). IoT allows effective monitoring of critical water quality metrics, enabling remote regulation of aquaculture processes (Bauer et al. 2021a, b; Teixeira et al. 2022). ML forecasts water quality metrics, while DT promotes sustainable management of the aquatic environment and aquaculture output (Zhao et al. 2021; Hassani et al. 2022).

Fishing vessels monitoring

Automated Visible Infrared Imaging Radiometer Suite (VIIRS) detects fishing vessels based on ML, aiding in the systematic detection of vessels (Syah and Abdillah 2021; Tsuda et al. 2023). VIIRS can identify illuminated fishing vessels at night, facilitating near-real-time detection of unlawful fishing and improving fishery resource management (Gorospe et al. 2016; Elvidge et al. 2018). Cross-correlating VIIRS with vessel monitoring and tracking systems like vessel monitoring systems (VMS) and automatic identification systems (AIS) enhances boat detection capabilities (Gorospe et al. 2016). Terrestrial-sourced AIS data streams, combined with recurrent neural networks (RNN), can detect fishing activities and aid in combating illegal, unreported, and unregulated (IUU) fishing, addressing environmental and climate concerns (Ferreira et al. 2022).

Waste management

Significant volumes of residues and by-products are produced throughout the seafood SC, extending from the ocean to the consumer's plate, seriously harming the environment and resulting in substantial financial loss (Hassoun et al. 2023; Sharma et al. 2021). Aquaculture, a well-established method of raising marine species, generates a substantial number of nutrient-rich wastes. To enhance the sustainability of conventional aquaculture, it is crucial to reuse nutrient-rich wastes and close the nutrient cycle (Lothmann and Sewilam 2023). Employing cutting-edge technologies like AI, big data, IoT, and smart sensors to minimize and valorize seafood waste and its by-products could be a promising avenue to improve the blue economy and sustainable food globally (Hassoun et al. 2023). Farmers can now utilize AI to access cutting-edge data analytics tools that enhance farming practices, boost productivity, and minimize wastage in biofuel and food processing while reducing negative ecological effects (Javaid et al. 2023).

Data management, trust building, and transparency in ASC

The aquaculture industry generates a large amount of data, but it is often not shared or systematized among operators compared to other industries. BT can augment these data for organizational objectives while increasing retailer and customer satisfaction through full traceability of farmed products. By connecting global parties, it can eliminate food fraud and waste, shorten transaction times, and strengthen relationships with institutional actors (Mileti et al. 2023; Altoukhov 2020; Ahmed and MacCarthy 2022). BT, a disruptive technology, can restructure the entire supply chain for sustainable practices (Munir et al. 2022). In addition, modernizing the seafood industry and promoting export prospects could be achieved by implementing an end-to-end supply chain system powered by BT and AI. The integration of BT with AI offers fish supply chains several benefits that enhance sustainability performance, leading to a reduction in data gaps (Tsolakis et al. 2023). Under certain conditions, BT can facilitate rapid trust-building between unknown supply chain partners, ensuring that orders, payments, accounts, and production are all tracked, thereby increasing trust among shareholders and customers (Alobid et al. 2022). Moreover, it can improve traceability and transparency in production by reducing illicit, unreported, and unregulated fishing, thus enhancing fair and ethical purchases, prudent handling, and resource conservation while promoting sustainable performance related to livelihoods, food security, and the environment (Tsolakis et al. 2021; Pakseresht et al. 2023). However, concerns remain regarding technological trust, governance, customer data access, border fraud, and willingness to pay (Rogerson and Parry 2020). Big data availability and analytics technology have revolutionized the aquaculture industry's ability to make data-driven decisions. More aquaculture producers are using data to aid in farm management and operational practices, investing in new technology to improve sustainability and profitability. With these impacts, data gathering, processing, and robust analysis may be automated and converted into a user-friendly and understandable format for fish farmers. They can capture data from remote and difficult-to-reach sites using low-cost sensors. Wireless network technology can now send an unlimited amount of data to the cloud for storage and analysis, enabling automatic and high-quality data collection (Lan et al. 2023).

Food quality

The food supply chain is more complex than other supply chains because it comprises perishable commodities that must be maintained at cool temperatures to guarantee quality. Food contamination has become a serious problem in recent years due to its perishable nature and long-distance transit (Vasanthraj Kaur et al. 2023). Furthermore, farmed aquatic produce, part of the commonly traded goods, has shown rapid expansion in recent years but continues to be associated with negative connotations compared to other agricultural sectors (Freitas et al. 2020). Market dynamics, consumer tastes, and concerns regarding food safety and sustainability all impact the sector's growth, necessitating the installation of quality assurance systems (Freitas et al. 2020). However, contemporary management systems serve to reduce environmental consequences and the distribution of unsafe or substandard products, lowering the risk of reputational damage, legal liabilities, and product recalls (Freitas et al. 2020). In terms of aquaculture quality, safety preconditions are related to product consumption security, environmental concerns, and sustainability. In recent times, the risk of the spread of infectious or hazardous agents and incidences of disease manifestations has grown, altering pathogen rates of replication and multiplication as well as extending transmission time-frames, spatial scope, and hosts' species (Freitas et al. 2020; Fèvre et al. 2006; Brugere et al. 2017). Ensuring the four pillars of food quality—freshness, safety, traceability, and authenticity—is therefore essential (Freitas et al. 2020). Reliable food product tracing can help reduce cases of food fraud, which costs an estimated $30 to $40 billion globally each year, with seafood being one of the most affected food categories (Treiblmaier and Garaus 2023). It is almost not possible to eliminate food hazards, but steps can be taken to enhance trust in food systems by applying novel technologies (Veeck et al. 2020). Traceability is a tool for guaranteeing food safety and public health, providing reliable information to consumers and improving process and product overall quality (Freitas et al. 2020; Iles 2007; Westerkamp et al. 2020). Tracking electronically and monitoring conditions via radio frequency identification (RFID) or wireless sensor networks helps to trace and track food products (Freitas et al. 2020; Musa et al. 2014; Badia-Melis et al. 2015). However, in intricate supply networks like the seafood industry, ensuring top-notch quality is challenging. The effectiveness of tracking systems increasingly depends on SC transparency (Freitas et al. 2020; Iles 2007; Westerkamp et al. 2020). Blockchain opens new avenues in seafood commerce and logistics, with huge potential to dramatically change value chain approaches, mitigate uncertainties and informational inaccuracies among stakeholders, and cater to consumer concerns regarding the provenance or sustainability of resources (Freitas et al. 2020; Bush et al. 2019). The applications of these digital technologies in the ASC further strengthen the findings of Zhang and Gui (2023); Rowan 2023; Ebrahimi et al. 2021).

Impact of COVID-19 on fishery SC and the role played by digital technologies

The COVID-19 pandemic has wrought severe disruptions in the food supply chain (FSC), impeding the essential flow of food products from farmers and producers to end consumers (Rejeb et al. 2022a). Moreover, the pandemic has compelled numerous food organizations to reassess their long-term plans. One-third of the global population faces direct impacts from food scarcity and disruptions in the food supply chain (Rejeb et al. 2022a).

Furthermore, the COVID-19 pandemic and its management measures substantially disrupted supply chains in the fishing industry, resulting in scarcity of important foods. Small-scale fisheries supply chains were particularly vulnerable to COVID-19 disruptions, experiencing disruptions across all nodes in the supply chain. Direct disruptions occurred due to workers contracting the virus, while indirect disruptions arose from limitations on consumers' capacity to buy seafood, resulting in reduced demand. Mobility and trade restrictions further decreased the need for production, resulting in several fatalities in the fishing community (Bassett et al. 2022). Some regional SC participants experienced disruptions because of halts in international markets and restaurant closures, underscoring teleconnected vulnerabilities (Bassett et al. 2022; Ivanov et al. 2014). The impacts propagated across supply chains, highlighting the extensive scope of ripple effects in intricately linked food distribution systems (Bassett et al. 2022; Ivanov et al. 2014). These findings are in line with Yusoff et al. (2021) and Monirul Alam et al. (2022).

Hence, the COVID-19 pandemic accelerated digitalization, impacting nearly every aspect of daily life (De' et al. 2020). Given the importance of moving beyond COVID-19, there is likely to be increased international interest in strategic funding initiatives that combine academia and industry to identify the next disruptive technology (Rowan and Galanakis 2020). As noted by Rowan (Rowan 2023), digital technologies can assist in addressing these concerns while also potentially disrupting fisheries and aquaculture.

Adoption of digital technologies to address food waste and promote the circular economy

Food waste is a worldwide concern with substantial economic, social, and environmental consequences, requiring a multifaceted approach to address the problem (Onyeaka et al. 2023). The fish value chain also generates waste. According to Onyeaka et al. (2023), a promising solution to this problem is the use of AI technologies and the circular economy (CE). Recently, the use of AI within the food industry has gained popularity as a means of reducing food waste and improving CE endeavors. AI has the capacity to supervise and optimize food production and supply chains, reallocate excess food, and aid in minimizing waste and promoting recycling initiatives. AI innovations optimize resource utilization while minimizing environmental negativity, resulting in a more sustainable and just food system.

The CE has gained traction among academics and practitioners, often linked to sustainability in the literature (Hoosain et al. 2023). It is viewed as an approach that values resources, emphasizing the reduction of environmental impacts through more effective and efficient resource use and recovery, resulting in less waste and emissions than linear take-make-dispose systems (Ellen MacArthur Foundation 2013; Santana and Ribeiro 2022; Chary et al. 2024). The CE provides a pathway for sustainability in closed-loop resource systems, but widespread implementation across industries is hindered by fragmented knowledge and diverse implementation methods (Singh et al. 2021). CE can be applied at different stages of the food system, including production, consumption, waste, and managing surplus. The current state of food waste and the CE is complex, with progress in some areas and persistent challenges in others. CE strategies aimed at tackling food waste face diverse obstacles such as cultural nuances, financial and operational challenges in businesses, regulatory hurdles, technological limitations, and SCM shortcomings (Jurgilevich et al. 2016). Nonetheless, AI-supported CE endeavors offer several potential benefits, including increased energy efficiency, longer product life-cycles, and improved processes of making decisions. Sustained investment and exploration in AI technologies are imperative to realizing the CE's full capability and reducing global food waste (Onyeaka et al. 2023). A successful transition to a circular economy requires the food sector to overcome today's complex food supply chain challenges, such as information asymmetry, poor stakeholder cooperation, and food safety concerns (Singh et al. 2021), where blockchain holds promise for improving data utility by enhancing trust among food value chain actors while reducing information asymmetry (Pakseresht et al. 2022).

Impact of climate change on fishes

The deep ocean is pivotal in regulating global climate by absorbing and sequestering heat and carbon dioxide, leading to warming, acidification, and de-oxygenation of deep-sea waters. This results in decreased food accessibility on the ocean floor (Morato et al. 2020; Mora et al. 2013; Gehlen et al. 2014; Chen et al. 2017; Sweetman et al. 2017; Perez et al. 2018; Sulpis et al. 2018). Climate change has also been observed to impact the distribution of commercial fish species. Rising water temperatures, intense water flow occurrences such as floods and droughts, and warming of marine environments are among the ways in which climate change can affect fisheries (Ruiz-Salmón et al. 2020). These changes, along with their forecasts, are poised to impact deep-sea efficiency, biodiversity, and distributions, endangering critical ecosystem services. Therefore, having knowledge of how climate change leads to changes in deep ocean species distributions is crucial for developing management tactics that accommodate such changes. These may include spatial measures aimed at preserving refuge areas or local fish populations, aiding conservation of vulnerable marine ecosystems, or securing sustenance, revenue, and livelihoods from fisheries (Morato et al. 2020; Cheung et al. 2017; Tittensor et al. 2010; Thresher et al. 2015; Gaines et al. 2018; Bates et al. 2019).

As a result, climate change could substantially reduce suitable habitat for deep-sea species with well-documented distributions by 2100 (Morato et al. 2020). Like the unprecedented disruption caused by COVID-19 across geographic boundaries, climate change, while progressing more slowly, will have a comparable global impact, directly affecting global food supply chain connections (Avelino and Dall'erba 2020). For instance, empirically, the evidence of how climate change impacts on fisheries and aquaculture in Nigeria is expanding (Ipinjolu et al. 2014). These events are seriously impacting communities' livelihoods and security of food in Nigeria. Elevated temperatures influence the aquatic environment and fish physiology, leading to changes in respiration rates, heightened feed intake, increased enzyme activities, and increasing consumption of oxygen and feed dissimilation (Ogunji and Wuertz 2023; Ipinjolu et al. 2014; Islam et al. 2022; Ern et al. 2023). These findings are consistent with Predragovic et al.'s (2023) and Maulu et al.'s (2021) assertions that climate change presents a significant threat to marine ecosystems and species, and the sector's sustainability is at risk because of climate change, which is not just a future concern but an immediate challenge.

Challenges and opportunities in integrating digital technologies in ASC

Despite the diversity of aquaculture, it encounters significant challenges (Rowan 2023). IoT-based technologies face constraints such as low communication rates, substantial network delays, and interruptions. Robotic systems encounter hurdles in establishing low-power long-range communication within conventional aquaculture farm environments surrounded by structures and tropical woodlands (Biazi and Marques 2023; Teixeira et al. 2022). Detecting fish via computer vision modeling encounters a multitude of obstacles, including varying light, minimal contrast, excessive noise, fish distortions, obstruction, and dynamic backgrounds (Yang et al. 2021). Traditional sensor measurement lacks stability, drifts, and has a short service life, poor anti-interference ability, and low accuracy, necessitating regular calibration and maintenance by users (Liu et al.

2023; Bushinsky and Emerson 2015; Larsen et al. 2016; Wei et al. 2019; Quay 2023). Our findings support Rastegari et al.'s (2023) study that the challenges are infrastructure-based and data-driven.

To address these challenges, developing intelligent sensors capable of transmitting and processing digital signals and field-adaptive compensation is critical (Liu et al. 2023; Bushinsky and Emerson 2015; Larsen et al. 2016; Wei et al. 2019; Quay 2023). New materials can improve dissolved oxygen sensors' performance without frequent maintenance, calibration, and cleaning, reducing staff workload (Liu et al. 2023). Fish biomass estimation using advanced sensors and communication technologies will become more accurate through close collaboration between engineers and fisheries experts (Li et al. 2020a). Robotic aquaculture control systems based on automated floating feeders can optimize fish feeding in pond farms (Gorbunova et al. 2020). Monitoring of open sea cages will progress towards a comprehensive, 3-dimensional, and smart approach, incorporating water quality assessment with monitoring of fish behavior (Kumar and Panwar 2020). Aquaculture's rapid expansion without proper planning and management raises concerns about its long-term viability. International policies encouraging technology transfer can improve aquaculture development (Jolly et al. 2023; FAO 2014). Government technical assistance varies by country, with examples such as tax breaks in China to boost fish aquaculture or special licenses in Norway for salmon farming companies developing technological alternatives (Jolly et al. 2023).

Digital technologies, such as IoT, hold promise for achieving economic, environmental, and societal sustainability goals. AI and machine learning can monitor microalgae in integrated multi-trophic aquaculture systems, aiding real-time decision-making (Wolfert and Isakhanyan 2022). These technologies can inform new fish and seafood processing methods, including automation, training, and standardization. Regulatory frameworks should be updated to address data security and privacy concerns arising from increased IoT device and digital platform use (El jaouhari et al. 2023).

Conclusion

This paper offers invaluable insights in understanding the application of digital technologies in ASC through a SLR based on the PRISMA approach to provide answers to the research questions posed in this study. Findings showed an increase in annual publications from 2019 to 2020, a slight dip in 2021, and a renewed rise from 2022 to 2023. The majority of publications came from institutions in Asia and Europe, with high levels of collaboration among researchers from these regions as well as North America and Oceania. In contrast, Africa had significantly fewer publications and weaker research collaborations.

Prominent keywords in this field include Sustainability, Climate Change, and Food Security, which reflect key priorities of the United Nations Agenda 2030 for Sustainable Development. Emerging themes highlighted the growing and diverse applications of digital technologies such as AI, blockchain, IoT, robotics, drones, cloud computing, 3D printing, smart sensors, big data, DT, computer vision, ML, and DL in areas like fish feeding management and monitoring, water quality and waste management, and detection and tracking fishing vessels, enhancing trust and transparency in ASC, and improving fisheries data management.

The insights from this comprehensive review can benefit the scientific community by providing valuable knowledge to support advancements in digital technologies.

Theoretically, it can contribute to new or refined frameworks for understanding digital transformations in ASC and also encourage merging insights through interdisciplinary research. Beyond the development of a future research agenda, our study's findings also provide implications for practice by highlighting the major benefits of adopting digital tools in ASC, which can help farmers in identifying the best practices for implementing digital solutions to improve real-time monitoring and logistics in aquaculture. Policymakers can help fisheries adapt to climate change while ensuring food security, economic viability, and marine biodiversity by integrating science, policy, and technology. Hence, a proactive, collaborative approach will be essential to mitigate risks and build resilience in this critical sector. This can be achieved through a combination of adaptive management strategies, international cooperation, technological scaling, and targeted support for at-risk fishing communities.

Future investigations should prioritize empirical studies that evaluate the impact of digital technologies in economic terms, i.e., cost–benefit insights that will help farmers assess the economic viability of adopting digital tools in different production scales across the ASC or social terms-that will address issues related to equitable access since digital divides may exclude marginalized groups if technologies are not affordable or adapted to local contexts.

Abbreviations *ASC*: Aquaculture supply chains; *BT*: Blockchain technology; *CA*: Correspondence analysis; *CE*: Circular economy; *DL*: Deep learning; *DT*: Digital twin; *FSC*: Food supply chain; *IUU*: Illegal, unreported, and unregulated fishing; *MCA*: Multiple correspondence analysis; *ML*: Machine learning; *SC*: Supply chain; *SCM*: Supply chain management

Author contribution Iyabo Toyin Adebayo: Conceptualization, formulation of research questions, methodology, data collection, data analysis, writing-original draft, visualization, writing-review & editing. Segun Ajibola: Conceptualization, methodology, discussions on AI applications, writing-original draft, critical review & editing. Ali Ahmad: Formulation of research questions, critical review. Pedro Cartujo: Discussions on digital technologies and critical review. Ibrahim Muritala: Writing, review & editing. Isa O. Elegbede: Review & editing. Pedro Cabral: Critical review & editing. Vanessa Martos: Project administration, supervision, validation, review, funding acquisition.

Funding This research was funded by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie-RISE, Project SUSTAINABLE (https://www.projectsustainable.eu) with grant number 101007702.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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