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REGULAR PAPER

FAIR data management practices to introduce circular economy in aquaculture: benefits, barriers and a preliminary roadmap

Rita Giuffrida[1] · Claudio de Majo[1] · Maria Giuffrida[1] · Ian D. Broadbent[2]

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Abstract

FAIR (Findable, Accessible, Interoperable and Reusable) data principles stand out as critical to ensure that data can be efficiently shared and used across diverse scientific, academic, and industrial domains, facilitating interoperability and informed decision making. However, industrial players are often reluctant to embrace FAIR data principles due to reasons such as the fear of losing competitive advantage and the lack of resources to convert their datasets. This study is one of the few attempts to shed light on the advantages FAIR data can offer, highlighting adoption drivers and barriers with a focus on the aquaculture industry. The research is developed relying on a mixed methodology consisting of semi-structured qualitative interviews and quantitative questionnaires addressed to a selected group of relevant stakeholders. As a result of the study, six policy recommendations of political, technological, social and environmental nature are offered to outline a path towards a more sustainable and efficient aquaculture industry, supported by measurable KPIs to assess their impact. The results collected by this study stress the importance of available FAIR datasets across platforms. Perhaps more importantly, they allow the classification of the benefits of key circular economy (CE) and FAIR data management practices for the aquaculture sector, as well as current main adoption barriers and enablers. Key barriers include data acquisition costs, lack of skills and knowledge of FAIR data benefits, concerns and confusion with open data and lack of investments in interoperable solutions. In contrast, key enablers include cost reduction to acquire data, best-practice regulations, awareness of FAIR benefits, education to innovation, collaboration incentives and complexity reduction through standardised solutions. Although the timely implementation of this study's final recommendation roadmap could favour impactful legislative changes to implement a more sustainable and efficient aquaculture sector, reliance on political will and targeted policymaking actions will in all likelihood delay their effective implementation.

Keywords FAIR · Data management · Aquaculture · Circular economy

1 Introduction

In today's data-driven society, effective data management practices have become essential for all organisations to exploit the full potential of their information resources. Among these practices, FAIR data principles, helping data be Findable, Accessible, Interoperable and Reusable [73], stand out as critical to ensure that data can be efficiently shared and used across diverse scientific, academic and industrial domains. As such, they facilitate interoperability and promote best practices. For instance, in the industrial sector, FAIR data can help make more informed decisions and identify areas that cause inefficiency [69]. Despite these benefits, industrial players are often reluctant to embrace FAIR principles due to reasons such as the fear of losing competitive advantage by making their data more accessible, and the lack of resources to invest in the infrastructure, training and maintenance activities that FAIR data require [42, 58].

In addition, the challenges associated with the implementation of FAIR data approaches constitute additional

✉ Rita Giuffrida
r.giuffrida@trust-itservices.com

Claudio de Majo
c.demajo@trust-itservices.com

Maria Giuffrida
m.giuffrida@trust-itservices.com

Ian D. Broadbent
ian@broadhorizonsconsulting.com

1 Trust-IT Services, Via Francesco Redi, 10, 56124 Pisa, Italy

2 Broad Horizons Consulting Ltd., 18 Abbotshall Drive, Aberdeen, Scotland 56124, UK

barriers to their adoption. While some studies investigate such challenges, these concerns should be weighed against the significant advantages FAIR data principles can offer, particularly in sectors that can benefit the most from applying a FAIR data approach, such as aquaculture [11]. This sector is one of the biggest ocean polluters producing around 27% of total plastic waste [14]. The aquaculture industry is particularly wasteful because it mainly follows a traditional linear economy model, where all production waste is discarded.

Circular economy (CE) assumes instead that industrial waste can be regenerated into raw materials for another industry [56]. Transitioning to CE would therefore be crucial for enhancing sustainability in aquaculture. To effectively make this transition, it is essential to understand and address inefficiencies within the current system. This is where FAIR data can play a transformative and facilitative role. In this context, the aim of this research is to investigate the potential contribution of FAIR data management principles to CE practices in the aquaculture industry.

This aim is achieved through four primary objectives: firstly, identifying and analysing feasible FAIR data management and CE practices; secondly, pinpointing enabling factors that influence the interplay between FAIR principles, CE and aquaculture; thirdly, identifying limiting factors that affect these relationships; and fourthly, crafting a roadmap that delineates how FAIR data management can promote the integration of CE within the aquaculture industry. This comprehensive approach seeks to optimise sustainability and efficiency in aquaculture through strategic data and resource management.

The research is developed starting with the definition and testing of initial prepositions linked to the research goals and research questions (RQs) stemming from the gaps within the current state of the art described in Sect. 2.

The main methodology, reported in Sect. 3, consists of semi-structured qualitative interviews to a selected group of relevant stakeholders acting at industrial level in the aquaculture sectors. Responses to the survey were analysed and contextualised within current literature. The findings are then described in Sect. 4. As a result, six policy recommendations have been formulated and gathered into a strategic roadmap facilitating the implementation of FAIR principles into a circular aquaculture industry. Tailored KPIs that can be used to assess the effectiveness and the impact of each recommendation are also provided for future reference to interested stakeholders. Finally, Sect. 5 concludes by outlining limitations and new potential research horizons stemming from this study.

2 Literature review

The adoption of FAIR data[1] is crucial to harmonise data and help researchers and industrial players access common and interoperable datasets, increasing data quality [30, 41]. FAIR data also help increase the reliability of data by eliminating duplicates [36]. Overall, these peculiar aspects of FAIR data help organisations acquire knowledge in a faster way, implement best practices, and improve the robustness of their models [47]. The application of FAIR principles also brings benefits from an economic point of view [24].[2]

While FAIR data management practices bring benefits in diverse contexts, they are mostly adopted in scientific research environments and rarely in the industrial context [62, 69]. Such a reluctance is mainly due to a lack of understanding of FAIR principles, often erroneously regarded as open data [37]. Sensitive datasets [58], lack of interoperable data infrastructures [69] and a general lack of investment to make datasets FAIR [42] are also hindering their adoption.

Among all the industries that show resistance to applying FAIR principles, aquaculture is one of the biggest industries in the ocean market as it is worth $281.5 billion and shows an annual growth rate of 15% in 2030 [26]. Given its large size, data are stored and collected in infrastructures like *Copernicus Marine Center*,[3] *EMODnet*,[4] *EurOBIS*[5] or in databases such as *ASFIS*[6] [12, 15, 16, 71]. These datasets are collected through vessel tracking and satellites that do not necessarily follow FAIR principles, increasing time and cost for data acquisition [16, 52]. In contrast, one of the most successful implementations of FAIR principles comes from the life sci-

[1] FAIR is used to describe datasets that meet the requirements of Findability, Accessibility, Interoperability and Reusability [73]. Datasets are Findable when they can be easily discovered by both humans and computers; they are Accessible when they can be accessed effortlessly and in open science environments. Data are Interoperable when they can be integrated with others using semantic rules and taxonomies and are Reusable when they can be replicated in different contexts and scenarios.

[2] A recent study by the European Commission has estimated that not applying FAIR data costs €10.2 billion to the European economy on an annual basis.

[3] The Copernicus Marine Center (https://marine.copernicus.eu/) is one of the biggest European data infrastructures that provides open access to marine data.

[4] The European Marine Observation and Data System—EMODnet (https://emodnet.ec.europa.eu/en) is a network of organisations built under the European maritime policy. It provides access to data in the area of bathymetry, biology, chemistry, geology, human activities, physics and seabed habitats.

[5] The European Ocean Biodiversity Information System—EurOBIS (https://www.eurobis.org/) provides access to marine species data collected in international seas.

[6] ASFIS (https://www.fao.org/fishery/en/collection/asfis/en) is a dataset, developed by FAO, that includes information on species, families and higher taxonomies of the aquaculture world.

ence and healthcare sectors, with the Pistoia Alliance being an example of FAIR data implementation promoting the sharing of pre-competitive leveraging legal frameworks to ensure data security and compliance [31, 72].

Aquaculture is one of the fastest-growing industries and plays a crucial role in the global food economy [10]. The growth of the aquaculture sector, however, has contributed to increased pollution in the ocean [65]. It is estimated, indeed, that 27% of plastic and solid waste in the ocean comes from fisheries and aquaculture practices [14].

In this context, access to FAIR datasets of information can facilitate the promotion of best practices favouring the transition from a linear to a circular economy and build sustainable management systems [1, 60]. CE is a new economic paradigm that has gained attention over the last years thanks to its potential applications to research and industrial sectors [53]. Based on principles such as waste and pollution reduction, recycling, natural regeneration and informed consumption, CE assumes that no waste should be generated because unused resources can become raw materials for reuse [19, 27, 54–56].

These environmental drivers generate a pressure to find circular solutions for the aquaculture industry such as wastewater treatments, the adoption of biofilters, bioaccumulation, multitrophic and land-based recirculating aquaculture systems to recycle nutrients [10, 70]. In order to exchange best practices in the circular aquaculture industry, it is crucial to develop FAIR data infrastructures to improve the performance of data management practices, which currently suffer from a lack of standards and data heterogeneity [45]. European initiatives like the Blue-Cloud[7] and Iliad[8] projects aim to overcome this barrier with the development of digital twins and open access systems based on FAIR principles, federating and integrating different datasets to favour the development of circular economy paradigms [5, 32, 61].

Overall, while FAIR management systems have helped the management of aquatic and environmental data and contributed to the improvement of observation data models [67], industrial applications are still in their infancy.

The qualitative review conducted in this paragraph has highlighted the following main points:

- Even though industries use large amounts of data on daily basis, they are reluctant to adopt FAIR data management systems;
- FAIR data help increase data reliability and help companies reduce the time needed to find information in different datasets;
- The level of adoption of FAIR principles and CE in aquaculture is still in its infancy stage.

[7] Blue-Cloud 2026 (https://blue-cloud.org/) is a EU-funded project.

[8] Iliad (https://ocean-twin.eu/) is a EU-funded project.

Based on this, the overarching research objectives presented in the Introduction are investigated through five research questions (RQs) which aim to highlight motives and CE-driven mechanisms to enable a wider industrial adoption of FAIR principles in aquaculture:

1. What are the CE practices that can be applied in the aquaculture sector?
2. What are the benefits of applying FAIR data management practices to the circular aquaculture industry?
3. What are the barriers that could prevent the application of FAIR data management systems in a circular aquaculture sector?
4. What are the enablers that support the implementation of FAIR data management practices in a circular aquaculture sector?
5. Which recommendations can be derived for the application of FAIR data management practices in a circular aquaculture industry?

As showcased in Table 1, each RQ aims to address the research objectives of this project work.

3 Methodology

This section presents the methodology applied to address the RQs stemming from the literature review.

The researchers adopted a mixed methods approach, starting with the general proposition that FAIR data management principles can help the adoption of circular economy practices in the aquaculture industry, and deriving a set of corresponding RQs that were informed by the literature review and secondary data. Primary data were gathered to explore the RQs via video interviews with stakeholders in the aquaculture industry (see Primary Data: Interviews below), and questionnaires issued to various categories of experts (see “Primary Data: Questionnaires” in Sect. 3.2). Two questionnaires were created, a qualitative one (open answer), collecting 10 questions and a quantitative one (multiple choice). The former conceived to provide a comprehensive explanation on the respondents’ utilisation of FAIR data management practices, understanding main principles, adoption practices, challenges and barriers (see Appendix B). In contrast, the latter tackled basic information on respondents’ role, company size, familiarity with FAIR principle and circular economy concepts (see Appendix C).

The research was reviewed and ethics approval granted by the Chair of the Faculty of Management and Law Research Ethics Panel at the University of Bradford on 12th September 2022. All participants providing primary data have been guaranteed anonymity.

Table 1 Link between RQs and objectives of the study

Research objectives	RQs
Identify and analyse possible FAIR data management and circular economy practices applicable in the aquaculture sector	RQ1: What are the circular economy practices that can be applied in the aquaculture sector? RQ2: What are the benefits of applying FAIR data management practices in the circular aquaculture industry?
Detect possible limiting factors impacting relationships among FAIR, circular economy and aquaculture	RQ3: What are the barriers that could prevent the application of FAIR data management systems in a circular aquaculture sector?
Detect possible enabling factors that can influence relationships among FAIR, circular economy and aquaculture	RQ4: What are the enablers that support the implementation of FAIR data management practices in a circular aquaculture sector?
Develop a roadmap to show how FAIR data management approaches can facilitate the adoption of CE in the aquaculture industry	RQ5: Which recommendations can be derived for the circular aquaculture industry in applying FAIR data management practices?

3.1 Primary data: interviews

While initial interviewees were selected leveraging on the authors' professional network, the snowball sampling technique was applied by asking each expert to suggest any other names of professionals from the field [57]. Despite aquaculture being an international industrial sector, interviewed experts were mainly based in Europe, due to the FAIR principles' large utilisation in Europe [23]. However, three experts based in America and Africa were also interviewed. In order to determine how many interviews were needed for this study, a minimum threshold of 10 interviews was established following common practice in literature, guaranteeing full concepts coverage and saturation [13, 29, 49].

The interviews were conducted over video calls through the Microsoft Teams platform and lasted 30 min on average. These helped identify the preliminary hypotheses, which were then tested through the questionnaires, and shared initial ideas on recommendations to apply FAIR data principles in the circular aquaculture industry. The interviews were consensually recorded and the conversations were transcribed through the MS Teams Transcription tool. During the online interviews, a semi-structured approach was followed so that the authors could also ask additional questions, following the flow of the interview and replies gathered [44].

Questions were differentiated per categories of expertise, although some general questions about circular aquaculture economy, FAIR data management were asked to all interviewees (see Appendix B. Such differentiation was motivated by each expert's specific backgrounds, leading to the tailoring of each question's focus on FAIR data management, circular economy or aquaculture industry, depending on specific expertise (Table 2).

The data collected through interviews were scrutinised using the Thematic Analysis that helped identify patterns or themes across all the interviews [7]. The analysis was conducted using the qualitative analysis tool NVIVO, which supported the automatic identification of keywords and patterns of codes (see Appendix E), leaving more time to derive original insights [18, 35].

3.2 Primary data: questionnaires

Questionnaires were shared online with the categories of experts, either members of the authors' professional network or specifically identified via business-oriented social media. In particular, the professional social network selected was LinkedIn, the largest one allowing to find new connections and groups by keywords. This platform allows authors to identify professional profiles and contacts linked to the aquaculture industry, which at the moment of starting the study counted approximately 18000 professionals worldwide and around 2000 companies [43]. Another adopted strategy consisted in finding members of professional groups, such as The Aquaculture Network, Fisheries and Aquaculture Professionals, Recirculating Aquaculture Systems (RAS), Seafood, Aquaculture and Fisheries Ethics (SAFE), Aquaculture without Frontiers (AwF), Aquaculture Products & Marketing Network (APMN), Voice of Aquaculture, Seafood, Fisheries & Institutions (VASFI), Aquaculture Nutritionists.

Additional participants were recruited through the European Aquaculture Technology and Innovation Platform (EATIP) and FAO. The members were found from the personal networks of the authors or via search on LinkedIn. The questionnaire required between 5 and 10 min to be responded and the questions asked were the same for all four professional categories of (*1*) Researchers of FAIR data management, circular economy, ocean governance and waste; (*2*) Data scientists and Managers of Data infrastructures that deal with the aquaculture industry; (*3*) SMEs and industrial players operating in the aquaculture industry; and (*4*) Marine and ocean governance members.

The questionnaires were administered through the free online tool, MS Forms, which is GDPR compliant [48]. The surveys were sent to an initial population of 1000 people with the aim to gain at least 100 responders, considering that the average online response rate is rather low and varies

Table 2 Area of expertise of the interviewees

Interv.	Area of expertise			Place of living
	FAIR[1]	CE[2]	Aquac.[3]	
#1	✓	✓	✓	Italy/The Netherlands (Europe)
#2	✓	✓	✓	Norway (Europe)
#3	✓			Italy (Europe)
#4		✓	✓	Italy (Europe)
#5	✓		✓	Germany (Europe)
#6	✓			Italy (Europe)
#7		✓	✓	Spain (Europe)
#8	✓			USA (America)
#9	✓	✓	✓	Norway (Europe)
#10			✓	Kenya (Africa)
#11	✓	✓		The Netherlands (Europe)
#12	✓	✓	✓	USA (America)
#13	✓	✓	✓	Mexico/Portugal (America/Europe)

[1]FAIR data management
[2]Circular Economy
[3]Aquaculture

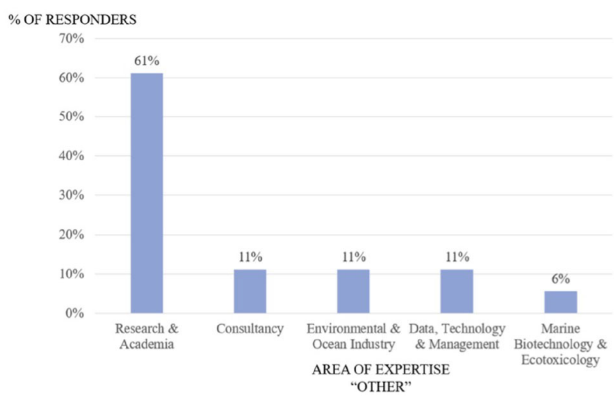

Fig. 1 Area of expertise of the responders in the other category (n = 102)

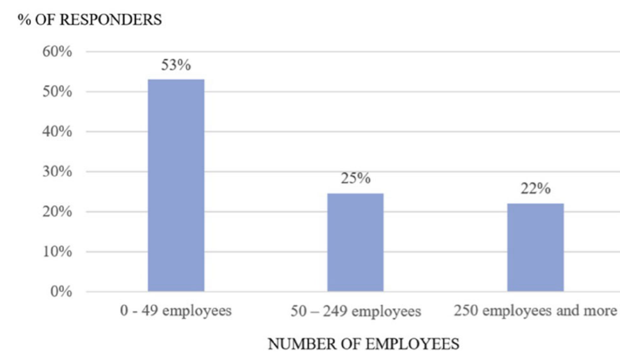

Fig. 2 Company size of people that took part in the questionnaire (n = 102)

between 13 and 29% [50]. As a result, the total people that took part in the questionnaire were 102, representing a good sample for the analysis. About 82% of respondents work in the aquaculture and fisheries sectors and the remaining 18% in other fields, including research and academia, data technology and management, environmental and ocean industry, marine biotechnology and ecotoxicology and marine consultancy. The details of respondents belonging to the "other" categories are reported in Fig. 1.

Overall, the sampled experts possess a high level of experience in the aquaculture sector. Most respondents have more than or 10 years of experience in the sector (51% and 20%, respectively), while the remaining 29% up to 5 years. More than half of them work for SMEs (53%). Such a landscape mirrors the nature of the aquaculture sector, which is highly fragmented and composed of several SMEs [26].

In terms of geographical location, respondents are spread all around the continents, with more than half coming from Europe (51%), followed by Africa (23%), Asia (11%), America (8%), Oceania (5%) and 2% living in different world locations throughout the year. The data collected through questionnaires were analysed via descriptive statistics, benchmarking and comparative data methods using Excel (Fig. 2).

3.3 Secondary data: reports and scientific repositories

To enrich the quality and quantity of data gathered through surveys and gain better understanding of FAIR data in the aquaculture sector [66], additional datasets were collected through secondary sources. The main sources for secondary data were peer-reviewed papers, non-peer-reviewed reports developed in the scope of research initiatives funded by the European Commission and scientific and industrial aquaculture repositories. This body of literature was selected per keywords through scientific search engines, such as Google Scholar, Scopus or Web of Science. Non-peer-reviewed reports were found on Zenodo, the search engine developed by the European Commission to store the main outputs and documents of EU-funded initiatives. Finally, aquaculture repositories were consulted browsing the most relevant databases of European and international organisations operating in the aquaculture sector, such as FAO.

3.4 Limitations and mitigation measures

While this methodology managed to address the RQs, it was run under the following constraints:

- **Sampling issues**: as previously remarked, interviewees were mainly from Europe given the widespread adoption of the FAIR concept [23]. This trend indicates a potential bias in the sample.
- **Interdisciplinary expertise constraints**: as the concept of FAIR data is rather new in the circular aquaculture sector, it was challenging to find experts in all three segments of CE, aquaculture and FAIR data. Therefore, the majority of people interviewed were experts in just one or two topics. Only two respondents had expertise in all three areas.
- **Lack of previous studies in the research area**: as previously highlighted, the academic literature presents only a few examples of applications of FAIR data management practices in the aquaculture industry. This lack of scientific publications leaves limited secondary resources to verify the research validity.
- **Budget constraints**: both interviewees and experts that took part in the questionnaire offered their time to help gather insights. However, it would likely have been possible to involve additional experts to take part in interviews if more funding was available to incentivise participation.

These limitations were overcome by analysing the available data with scientific approaches. Moreover, as also highlighted by the secondary data, the size of samples represents a valid amount of data for thematic and statistical analysis. Overall, the adopted methodology helped outlining a systematic approach to analyse the RQs identified in the literature review section. Each RQ addresses a specific objective which is handled by data collection and analysis techniques. These are summarised in Appendix D.

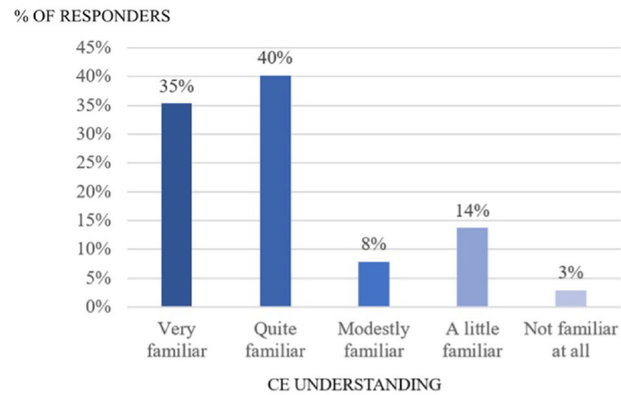

Fig. 3 CE understanding of responders ($n = 102$)

4 Results and discussion

In this section, the data are analysed in order to provide responses to all of the RQs derived from the research objectives in Table 1 of the methodology section.

RQ1: What are the circular economy practices that can be applied in the aquaculture sector?

RQ1 aims to achieve the Objective 1 "Identify and analyse possible FAIR data management and CE practices applicable in the aquaculture sector". Survey questions aimed to investigate the responders' understanding of the CE concept, the CE practices adopted by companies and how frequently these practices are applied. To understand this aspect, the responders had firstly to reply to two preliminary sub-questions that also help to set the scene regarding the level of understanding and adoption of CE:

- What is your understanding of the CE concept?
- Does your company adopt CE practices?

For the first question, responders could select a range of five options, built on a Likert-like scale ranging from very familiar to not familiar at all, about CE. As shown by Fig. 3, responses demonstrated a significant understanding of the CE concept, with 75% of the responders demonstrating familiarity with CE, while only the remaining 25% were a little familiar or not familiar at all.

For the second question, responders could select five choices as well, expressing different adoption levels of CE practices ranging from always to never (Fig. 4). By analysing the insights from this question, it is clear that the average level of implementation of CE practices mostly ranges between frequent (21%), usual (31%) or rare (21%), while only in 6% of instances it is constant. Conversely, 21% of companies adopt no CE practices.

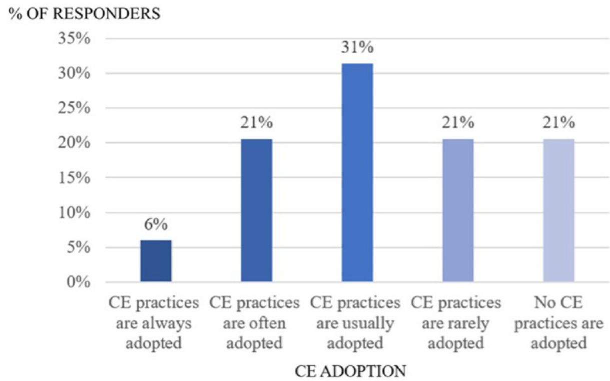

Fig. 4 CE application in aquaculture ($n = 102$)

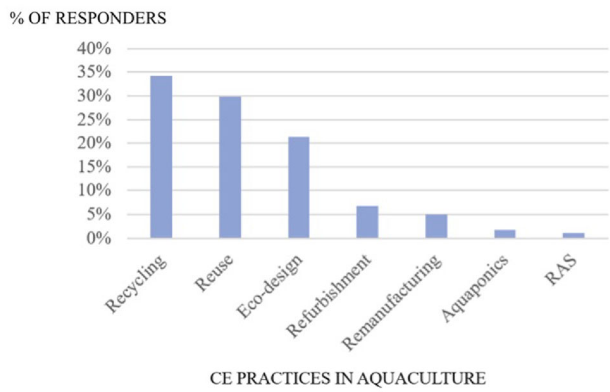

Fig. 5 CE practices applicable in aquaculture from responders ($n = 102$)

As it can clearly be inferred from the answers (Fig. 5), while CE is not predominantly endorsed in aquaculture, its application is possible. In particular the main practices adopted by respondents are:

- Recycling, Reuse, Refurbishment and Remanufacturing of gear and fish net materials;
- Eco-design to manufacture components and materials that can last longer and can more easily be reused and recycled;
- Aquaponics to combine the practices of fish farming and hydroponics, the method used to grow plants without soil, to facilitate the development of different species together and use the waste coming from fish as fertiliser for plants;
- RAS (Recirculating of Aquaculture Systems), an innovative technology to generate aquaculture products in an intensive way.

The interviews helped understand which CE practices can be applied in aquaculture with more detail. As already shown in the quantitative analysis, according to interviewees, the applicable practices are Reuse, Recycling and Reuse of materials, Aquaponics, RAS and Eco-design. However, already at this stage, the interviews also highlighted adoption issues within the aquaculture industry. While in aquaculture it is possible to introduce circular approaches, such has wastewater treatments, the adoption of biofilters, bioaccumulation, multitrophic and land-based recirculating aquaculture systems or eco-design materials [10, 38, 70], there is still resistance from the industry to implement them. This mirrors the statement from Interviewee 5 that "*While designing your aquaculture hardware, you have to make sure that it complies to standards to guarantee the site is circular and follows existing best practices and ways of working*".

The following RQs help to better understand how FAIR data management can help achieve benefits, as well as identifying barriers and possible enablers to their implementation.

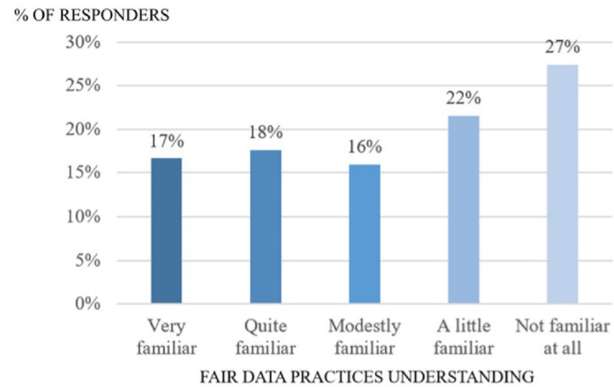

Fig. 6 FAIR Data understanding in the aquaculture and fisheries sectors ($n = 102$)

RQ2: What are the benefits of applying FAIR data management practices in the circular aquaculture industry?

RQ2 aims to support Objective 1 "Identify and analyse possible FAIR data management and circular economy practices applicable in the aquaculture sector." As in RQ1, responders were asked to indicate their level of knowledge by selecting responses from a range between very familiar to not familiar at all (Fig. 6). From the questionnaire it was found that only 17% of the involved people were very familiar with it and 27% had never heard of it.

Such a percentage is reflected in the overall lower adoption levels, with almost one-third of respondents not adopting FAIR data principles (28%) and 20% rarely adopting them. Conversely, only 9% of total respondents declare to always adopt them (Fig. 7).

As the majority of respondents do not seem to understand the benefits of applying FAIR best practices, they do not utilise tools or procedures to measure their impact. As a matter of fact, among the experts that took part in the survey,

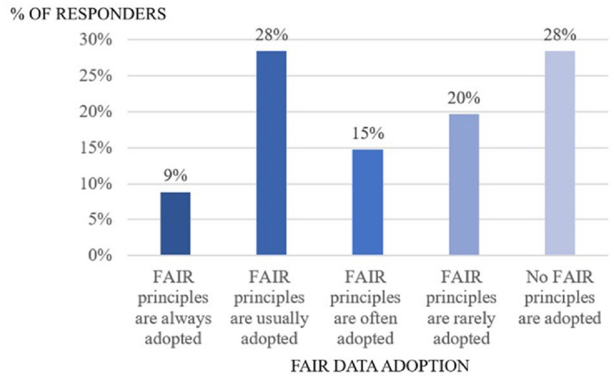

Fig. 7 FAIR data adoption in aquaculture ($n = 102$)

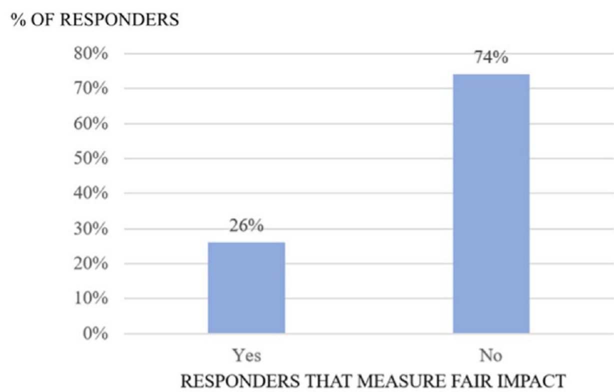

Fig. 8 Percentage of responders that measure FAIR data impact ($n = 102$)

only 26% of them measure the impact they generate, mainly relying on internally developed tools (Fig. 8).

While the FAIR data adoption is not high in the aquaculture industry, respondents also provide insights on how applying FAIR data principles in the aquaculture industry can help the implementation of CE practices and make it more sustainable, as well as to better recognise bottlenecks and find solutions [6]. The main benefits are summarised below.

1. **Data access**. FAIR data management facilitates the access and finding of data, giving aquaculture waste a second purpose and track CE performances. As one of the interviewees (Interviewee 12) highlights, "*collecting information on the type of waste products is useful to make it available to the broader world*". Moreover, "*sharing data helps the recirculation of waste*" (Interviewee 10) and "*provides precise information on production, schedule and location*" (Interviewee 8).
2. **Data monitoring**. Thanks to FAIR data, aquaculture industries can also monitor their systems more precisely. As remarked by Interviewee 12 in the context of farms "*as they move into indoor or recirculating aquaculture systems, I guess the whole idea behind that, is really reusing all of your waste products*". Moreover, Interviewee 5 reinforced the need of creating aquaculture monitoring systems based on FAIR principles to better track their waste consumptions.
3. **Data harmonisation**. Another benefit brought by the combination of FAIR, CE and aquaculture is the possibility to standardise and harmonise data and processes. As mentioned by Interviewee 1, in the context of standard processes, FAIR principles can help provide a more unified view of datasets at hand. In addition, FAIR data bring the opportunity to improve the system from an engineering point of view and lower the impact on the environment. As maintained by Interviewee 13, "*by making innovative research on circular economy in aquaculture available (or any other field for that matter), the application and expansion of the technology that can help achieve a sustainable industry, will be achieved faster helping in parallel achieve important EU goals such as Restore Our Ocean and Waters by 2030, and worldwide goals such as SDG14*".
4. **Data optimisation**. FAIR data also help organisations to optimise resources and make a profit out of it. As highlighted by Interviewees 7 and 11, datasets can be recycled and readopted according to CE principles, generating environmental benefits and even economic profits.

Overall, responses to RQ2 showcase how the application of FAIR principles in a circular aquaculture industry could bring several benefits and how sharing data and information is key to implement CE best practices in aquaculture [1]. The exchange of FAIR data helps companies accelerate their learning curves in developing management systems that promote environmental, economic and social sustainability [60]. However, to achieve a FAIR circular aquaculture industry, it is crucial to understand enablers and barriers, as showcased in RQ2, RQ3 and RQ4.

RQ3: What are the barriers that could prevent the application of FAIR data management systems in a circular aquaculture sector?

RQ3 aims to support Objective 2 "Detect possible limiting factors impacting relationships among FAIR, circular economy and aquaculture". The survey was explicitly focused on understanding the barriers that prevent players from applying FAIR data management. Multiple answer questions drew from main barriers expressed by the literature.

As shown by Fig. 9, survey responses confirmed the types of barriers highlighted from the quantitative analysis, but added additional ones. These can be divided into five main problems:

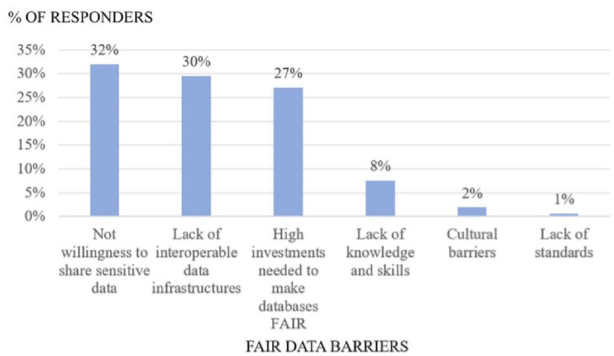

Fig. 9 Barriers to FAIR data management ($n = 102$)

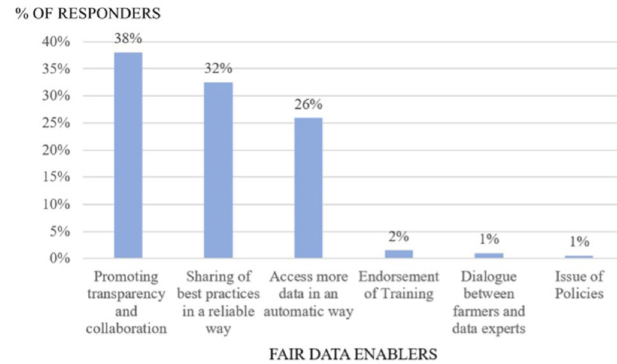

Fig. 10 FAIR data management enablers from the questionnaire ($n = 102$)

1. **Lack of skills and knowledge**. Interviewees consider this as the most crucial barrier to implement FAIR data practices in a circular aquaculture industry. In general, members of the aquaculture sector often lack skills to build interoperable infrastructures. Interviewee 3 provides a clear scenario of this barrier, stating that "*resistance might come from being scared about something that you don't know how it works. Change management can help implement this process step by step*". Moreover, as maintained by Interviewee 2, 7 and 13, lack of specific skills makes it difficult to create a widely applied FAIR data management in aquaculture.
2. **Fragmented structure of datasets**. Lack of investments in interoperable solutions hamper the sharing of FAIR best practices. The aquaculture industry needs interoperable data infrastructures [69] and additional technological investments might be needed to make them follow FAIR principles [42]. Companies often lack such resources, especially SMEs [46]. As highlighted by Interviewee 3, "*aquaculture players are scared because the FAIR principles seem to be too complicated and technical*".
3. **Confusion with open data**. Another crucial element that prevents FAIR data to be applied in a circular aquaculture industry is the belief that FAIR data means open data. As a result, companies are reluctant to share sensitive data due to cultural aspects, fearing that the latter needs to be openly shared with everyone, even sensitive datasets [8, 58]. Such concern was explicitly expressed by questionnaire respondents, who expressed fear of losing competitive advantage, as stated by Interviewee 11 and 13.
4. **Cultural aspects**. These barriers are also reinforced by cultural aspects. As highlighted by Interviewee 6, "*in general, the main barrier is a cultural one, because we are still tied to the vision that data is mine and I decide what to do with it. And I agree that people put a lot of effort in collecting data, but it's a pity not sharing them and making them FAIR because I don't see, in this way, the advantages coming from other researchers or industries' work*".

Thus, although sharing FAIR data also brings benefits from an economic and technological point of view, industries tend not to share data due to cultural aspects. As demonstrated in the discussion above, the barriers discussed by respondents also mirror those identified in the Literature Review.

RQ4: What are the enablers that support the implementation of FAIR data management practices in a circular aquaculture sector?

RQ4 aims to validate the Objective 3 "Detect possible enabling factors that can influence relationships among FAIR, circular economy and aquaculture". The majority of respondents (38%) believes transparent and reliable data sharing and collaboration promotion to be the most crucial enablers to promote FAIR practices. Training, issues of policies and establishment of dialogues between farmers and data experts are also important crucial enablers, but according to the survey respondents are less essential to facilitate the application of FAIR principles in a circular aquaculture context (Fig. 10).

The feedback provided through the interviews followed a similar trend to the one highlighted by the questionnaires, also finding correspondence in the literature. Respondents stressed the importance of available, shareable, reusable and interoperable datasets between platforms through standardisation and FAIR principles. These not only promote transparency and collaboration but produce several other benefits, via additional enabling mechanisms such as:

1. **Reduction of costs to acquire data**. As maintained by Interviewees 1 and 2 "*a FAIR management system makes the process of finding data cheaper and easier to spotlight critical issues. In this way, companies already know the causes of internal problems and can invest efforts to*

solve them". This is a crucial element to improve decision making and internal processes.

2. **Best practices enforced by regulations**. Formulate laws and regulations that oblige companies to make their internal datasets more efficient. As shared by Interviewee 9, effective guidelines and regulations about FAIR data implementations are extremely important in countries where the aquaculture industry is at the forefront. Laws and regulations that oblige companies to make their internal datasets more efficient should be formulated to enable this.
3. **Awareness of FAIR data benefits**. By creating the need of a functional network of data stewards promoting an informed consumption of materials and products [9] greater awareness can be achieved. As expressed by Interviewee 3, since for researchers or even professionals it is difficult to become experts in the FAIRification process, they need help in handling different datasets. For example, as outlined by Interviewee 4, to convince farmers about the benefit of getting in contact with data stewards it is essential to establish a dialogue between farmers and data management associations. This creates a virtual circle where improved dialogue between various actors leads to greater awareness of benefits, which in turn fosters even more dialogue and benefits.
4. **Innovation**. Educating all stakeholders who may be affected by the new economic paradigm [4], via such as the creation of CE platforms to exchange data products can also increase data accessibility. Interviewee 12 considered this a key enabler to let industries be grouped in a unique platform and reduce internal waste production.
5. **Personal incentives**. González-Domínguez et al. [28] suggest it is crucial to identify collaboration programmes between institutions to find mutually beneficial solutions. This is also remarked by Interviewee 11, who states that "*It is crucial to provide some form of compensation. This shouldn't necessarily be financial, it can also be related to recognition that there has been an exchange between two or more companies*".
6. **Reduction of Complexity**. Developing technologically-advanced solutions to analyse process bottlenecks and offer optimal solutions for waste reduction is an essential enabler [65]. Indeed, "*FAIR practices are often seen as too complex due to the methodologies and standardisation rules, making it useful to provide technical support through the adoption of management software providing technical support and upgrades*" as stated by Interviewee 5.

The set of identified enablers can play a role in (partially) overcoming the barriers to implementing FAIR data in a circular aquaculture industry. For instance, by reducing the costs to acquire data and enforcing best practices through regulations, stakeholders can be encouraged to adopt FAIR principles. Increased awareness of the benefits of FAIR data and innovation, along with educating all stakeholders about the new economic paradigm, can dispel misconceptions, confusion about open data and enhance understanding. Creating CE platforms for data exchange can increase data accessibility and reduce complexity, making it easier for users to engage with FAIR data. Providing personal incentives can motivate individuals to embrace these practices, overcoming potential cultural barriers.

RQ5: Which recommendations can be derived for the application of FAIR data management practices in a circular aquaculture industry?

RQ5 aims to achieve the Objective 4 to "Develop a roadmap to show how FAIR data management approaches can facilitate the adoption of CE in the aquaculture industry". All the inputs gathered to build the recommendations are derived from interviews, questions and main outcomes from other research questions. As summarised in Appendix A, the recommendations are gathered in relation to barriers to overcome, enablers and stakeholders which need to be involved to achieve the recommendations and classified per typology.

In the light of the datasets obtained, a strategic recommendations roadmap can be drafted, emerging from a cross-analysis of enablers, barriers and target stakeholder groups. As roadmaps are strategic representations of plans [25], a policy roadmap on FAIR data in the aquaculture sector should strive to contribute to improved efficiency and sustainability indexes. In this case, the proposed roadmap describes the actions to be taken into account to gain results by 2030, i.e., the final deadline of the United Nations Agenda to achieve the Sustainable Development Goals (SDGs) [68] and of the European Commission to achieve the Climate Target Plan [21]. More detailed target deadlines are provided per each recommendation.

Recommendation #1: Issue policies that promote the adoption of renewable energy to produce aquaculture products.

This recommendation highlights the need of producing aquaculture products using renewable energy, as stressed by the responses of Interviewees 5 and 7. By issuing policies, industrial players can feel the urgency of changing the energy supply systems they are currently using. Best practices on implementing renewable energy can be shared by FAIR data management systems that collect this type of information. Policies should be designed to help industries reduce the high investments needed to convert energy systems and increase their level of awareness towards these topics and innovation to build new infrastructures. Such a recommendation is mostly political and it requires the formulation of new policies and environmental issues, as the adoption of renewable energy reduces CO2 production [59].

In order to achieve this recommendation, it is crucial to engage with:

- **Policy makers** to issue policies that incentivise aquaculture players adopt renewable energy;
- **Researchers, scientists and environmental institutions** to gather information about trends and feasibility studies towards renewable energy applications in aquaculture;
- **SMEs and big enterprises** to showcase the benefits of adopting renewable energy in their daily business.

Recommendation #1 aims to be achieved by 2030 due to geographical, political, technical and financial factors [39]. First, countries follow different strategies to move from unsustainable energy sources to renewable ones. As an example, the European Commission has issued the Renewable Energy Directive in 2018 where 32% of the energy consumed should come from renewable sources [20] by 2030. Conversely, the US and Canada have based their energy consumption on hydropower with no clear strategy for a sustainable energy transition to renewables. Latin America, instead, adopts more than a quarter of primary energy from renewable energy. Asia and the Pacific have an electrification rate of 96.6%, although 85% of the energy for the region comes from fossil fuels. Finally, Africa does not provide clear evidence about local utilisation of renewable energy, despite its resources [33]. Moreover, clear assessments of the technical, financial, market and operational feasibility of building renewable energy infrastructures to support the aquaculture production are lacking.

Recommendation #2: Share best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through financial and non-financial incentives.

It is crucial to share data and information on best practices adopted in aquaculture for reuse, recycling, repairing and refurbishment practices. By sharing this information, all aquaculture players can improve decision-making, collaboration and innovation in their choices. To incentivise players to share information and data, it would be relevant to provide financial and non-financial compensations, as highlighted by Interviewee 11. This recommendation is related to the economic and environmental realms because it helps increase the reuse, remanufacture, recycle and refurbish of materials in the aquaculture industry. These practices require fewer virgin materials, which, on one side, reduces costs of acquiring new raw materials and, on the other side, lowers the environmental footprint [64].

The stakeholders involved to make this recommendation possible are:

- **Aquaculture workers, SMEs, large enterprises and data producers** to exchange information and best practices among each other;
- **Researchers and scientists** to showcase studies that highlight the advantages gained by sharing best practices;
- **Innovators** to find creative compensation methods that incentivise aquaculture players in cooperating together.

Recommendation #3: Share best practices to apply aquaponics and RAS through financial and non-financial incentives.

It is crucial to work with aquaculture players to convince them to share information and best practices on the implementation of aquaponics and RAS. Barriers and benefits are also shared with Recommendation #2, as well as stakeholder categories. This recommendation brings an environmental impact because it pushes aquaculture players to implement aquaponics and RAS, and this in turn lowers the environmental footprint [2].

Both Recommendations #2 and #3 should be achieved by 2028. Generally, the sharing of best practices is linked to the fear of losing competitive advantage as most aquaculture players are generally afraid to share data and information to lose their competitive advantage. Therefore, given the need to change people's behaviour towards their data management beliefs, it is indeed likely to take not less than 5 years to materialise their benefits. In this context, management change can stimulate awareness campaigns and innovative compensation mechanisms.

Recommendation #4: Create new jobs that support transfer of knowledge and best practices on how to build FAIR datasets.

Lack of skills makes it difficult for organisations and industries to understand the benefits brought by FAIR data. For this reason, it is essential to create new professional figures, training aquaculture players, as highlighted by the responses of Interviewees 3 and 4 to RQ3. This new profile can help overcome cultural barriers and lack of skills through training, improved dialogue between farmers and data experts, better decision-making and increased innovation. This recommendation brings social and economic impacts because it helps create new jobs thanks to the new profiles of data stewards, who share knowledge and best practices to make aquaculture systems more interoperable.

The players involved to achieve this recommendation include:

- Aquaculture workers, SMEs and large enterprises which represent the category of people that need to be trained;
- Researchers, scientists and innovators who can showcase best practices and create new knowledge and procedures to be shared;
- Data and service providers that own data and information.

Recommendation #5: Make interoperable systems cheaper thanks to economies of scale.

Building interoperable systems requires efforts and investments to harmonise different standards, semantic rules and technologies. While from a technological point of view, it is not easy to make systems fully interoperable, FAIR data management systems can lower these barriers and improve the quality of datasets by avoiding data duplication, increasing data and product traceability, improving processes and lowering costs of data acquisition. The aim of this recommendation is to invest in the building of interoperable systems, which will not only bring a technical benefit but also an economic benefit, to reduce costs by achieving economies of scale.

The stakeholders involved in the achievement of this recommendation are:

- **Aquaculture workers, data producers, SMEs and large enterprises** that can provide the datasets to be converted according to FAIR principles;
- **Researchers and scientists** to provide latest studies and research on how to make data interoperable;
- **Innovators** to find new creative and cheaper ways to make data interoperable.

Given their overall scope, recommendations #4 and #5 could realistically be achieved by 2030, considering that companies and governments should issue investments to create the new professional profile of data stewards, that help share best practices of applying FAIR principles in aquaculture. Investments could come from Governmental resources, like the Industrial Green Deal, which aims to transition the European industrial sector to a net-zero carbon emission one through technological advancements, job creation and the dissemination of best practices and new skills [22]. Additionally, data stewards can also share best practices on how to make systems interoperable and help farmers, SMEs and large enterprises reduce the costs needed to make their data FAIR.

Recommendation #6: Issue of policies that promote the adoption and creation (when missing) of standards for CE in aquaculture.

The development of CE standards supports the interoperable infrastructures, crucial to make data FAIR. While CE standards applicable in the manufacturing area already exist, lack of understanding of how to implement them in FAIR aquaculture systems persists. By issuing standards, aquaculture players can receive better guidelines and semantic rules on how to build their systems. Moreover, they can become more aware of how to build a FAIR data management system, improve internal processes and increase innovation levels.

The main players to be involved are:

- **Policy makers** to issue policies that clarify how to adopt standards in the FAIR circular aquaculture sector;
- **Research and academia** to gather details about the type of standards and information about CE standardisation rules that can be used in aquaculture;
- **SMEs and big enterprises** to showcase the benefits of adopting CE standards in building FAIR aquaculture systems.

Recommendation #6 could be achieved by 2026 considering the large number of already existing CE-related standards (mainly in the manufacturing sector). Moreover, although aquaculture-related standards do not take into account CE and FAIR principles together [3], they can be used as a starting point to develop new ones within the average time range of 3 years [34].

At this point, also Standards Development Organisations (SDOs) could be involved as additional stakeholder categories if there is, indeed, the need and opportunity to formalise industry-driven standards.

Implications and limitations

As showcased in the previous paragraphs, the provided recommendations have social, economic, political and environmental implications. **Social** recommendations include creating new working figures (data stewards) that can share best practices and knowledge with aquaculture players. From a **financial** standpoint, data stewards can generate revenues and reduce the risks associated with economic turndown [40]. Moreover, the adoption of CE practices, such as reuse, refurbishment, remanufacturing and recycling of materials helps industries reduce costs of acquiring new raw materials to produce products from scratch. In **policy** terms, the issuing of new laws and regulations helps to shape new CE standards and policies to adopt renewable energy [51]. Finally, from an **environmental** perspective, the adoption of aquaponics, RAS and CE practices can reduce the waste of aquaculture materials and help minimise the environmental footprint of the aquaculture industry [2].

The impact of these recommendations can be better quantified through Key Performance Indicators (KPIs), a quantifiable measure that helps organisations measure their success [17]. The eleven KPIs identified here help measure the impact potentially generated by each Recommendation. Given the implications of the research findings for society, policy, economics and the environment, KPIs have been designed and measured in relation to the ambitious targets of the SDGs designated by the United Nations [63]. Table 3 provides an overview of the KPIs and the impact they generate.

Table 3 KPIs to measure the recommendations' success. Source: United Nations (2015)

KPI	Related recommendation	Implication	Connected to which SDG
#1: Number of aquaculture sites that adopt renewable energy	#1: Issue of policies that promote the adoption of renewable energy to produce aquaculture products	Political environmental	SDG 7: Affordable and clean energy SDG 13: climate action
#2: % of reuse of aquaculture materials	#2: Sharing of best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through compensations (financial or non-financial)	Economic environmental	SDG 12: Responsible consumption and production SDG 14: life below water
#3: % of refurbishment of aquaculture materials	#2: Sharing of best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through compensations (financial or non-financial)	Economic environmental	SDG 12: responsible consumption and production SDG 14: life below water
#4: % of recycling of aquaculture materials	#2: Sharing of best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through compensations (financial or non-financial)	Economic environmental	SDG 12: responsible consumption and production SDG 14: life below water
#5: % of repairing of aquaculture materials	#2: Sharing of best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through compensations (financial or non-financial)	Economic environmental	SDG 12: responsible consumption and production SDG 14: life below water
#6: Number of aquaculture sites that apply aquaponics	#3: Sharing of best practices to apply aquaponics and RAS through compensations (financial or non-financial)	Environmental	SDG 14: life below water
#7: Number of aquaculture sites that apply RAS	#3: Sharing of best practices to apply aquaponics and RAS through compensations (financial or non-financial)	Environmental	SDG 14: life below water
#8: Number of new data stewards jobs created	#4: Creation of new jobs that can transfer knowledge and best practices on how to build FAIR datasets Social	Economic	SDG 8: decent work and economic growth
#9: Number of new standards created	#5: Issue of policies that promote the adoption and creation (when missing) of standards for CE in aquaculture	Political	SDG 9: industry, innovation and infrastructure
#10: % of data infrastructures that adopt standards	#5: Issue of policies that promote the adoption and creation (when missing) of standards for CE in aquaculture	Technical	SDG 9: industry, innovation and infrastructure
#11: Number of infrastructures that apply FAIR rules	#6: Make interoperable systems cheaper thanks to economies of scale	Economic technical	SDG 8: decent work and economic growth SDG 9: industry, innovation and infrastructure

5 Conclusions and future research

This research contributes theoretical and programmatic insights into how FAIR data management can shape the development of a circular aquaculture industry. In order to facilitate its implementation, a series of recommendations and a Roadmap to guide its implementation by 2030 have been proposed. The results collected by this study stress the potentially positive impact of adopting FAIR datasets to favour the implementation of circular economy practices in the aquaculture sector. Through a combination of quantitative and qualitative analysis, economy practices and FAIR data management practices for the aquaculture sector were detected by interviewing several stakeholders with direct stakes in the aquaculture sector. Regarding the application of CE practices in the aquaculture sector, the main applicable practices include reuse, recycling and reuse of materials, as well as aquaponics, RAS and eco-design; despite implementation, resistance remains at the industry level. In terms of FAIR data management practices, its potential key role in facilitating the adoption of CE practices and reducing current bottlenecks in the aquaculture sector was highlighted. In particular, the main benefits include facilitated data access, more precise monitoring mechanisms, data process harmonisation, optimisation and standardisation across the board, improved adoption indexes and the ability to optimise resource consumption to meet sustainability targets and facilitate economic growth. Just as importantly, this study's research has allowed to outline the current adoption barriers and key enablers. The former include data acquisition costs, lack of skills and knowledge of FAIR data benefits, concerns and confusion with open data and lack of investments in interoperable solutions. Conversely, the latter include cost reduction to acquire data, best-practice regulations, awareness of FAIR benefits, education to innovation, collaboration incentives, and complexity reduction through standardised solutions. Although the work provides a set of recommendations for policymaking, there are still some limitations that can be addressed by future research in this field. First, due to time and budget constraints, this research did not gather a wide sample of data to carry out complex statistical analysis of complex-solving problems. More time and resources would enrich the data sample and reach more solid results. Second, whilst data stewards are crucial to bring social and economic value to aquaculture players, both private and public actors need to allocate budget to train these new profile figures, stimulate knowledge and share best practices. Dedicated actions and studies documenting progress are therefore encouraged in this direction. Third, this study has privileged focussing on a specific industry, but there are other sectors where the approach here presented can provide valuable insights, help draw comparisons and demonstrate the relevance of FAIR methods in diverse environmental and industrial context. In particular, we plan to explore offshore wind environmental assessment, with a specific focus on cumulative impact assessment across multiple offshore wind projects. Finally, while each recommendation has relevant implications from social, political, environmental and economic viewpoints, these were not deeply analysed in this study, given the variety of other topics analysed to be able to reach these recommendations. In particular, legislative changes depend upon political will, and may take longer to implement than indicated in the Roadmap. Overall, the roadmap of derived recommendations outlines a first step in the path towards a more sustainable and efficient aquaculture through the adoption of FAIR data principles, supported by key enablers and measurable KPIs to assess their impact. The authors acknowledge that implementing these goals is not easy, but the effort and value of this paper lie also in the achieved aim to start formalising priorities and complementing the limited existing literature in the field. To build on this initial effort, however, each recommendation should be further explored and enriched in future studies.

Appendix A Policy recommendations derived from stakeholder survey

See Table 4.

Table 4 Policy recommendations derived from stakeholder survey

Recommendation	Type	Enablers (RQ3)	Barriers (RQ4)	Stakeholders
#1: Issue of policies that promote the adoption of renewable energy to produce aquaculture products	Political Environmental	Issue of laws and recommendations Increase of awareness Increase of innovation	High investments Lack of capacity	Policy makers Researchers, scientists SMEs Big enterprises Environmental institutions
#2: Sharing of best practices of reuse, recycling, repairing and refurbishment of aquaculture materials through compensations (financial or non-financial)	Economic Environmental	Sharing of best practices in a reliable way Data availability Data shareability Data reuse Improve decision making Increase of collaboration Increase of innovation CE platforms to exchange data Data accessibility	Fear of sharing sensitive data Fear of losing competitive advantage	Aquaculture workers Researchers, scientists Data producers Innovators SMEs Big enterprises Environmental institutions
#3: Sharing of best practices to apply aquaponics and RAS through compensations (financial or non-financial) -	Environmental	Sharing of best practices in a reliable way Data availability Data shareability Data reuse Improve decision making Increase of collaboration Increase of innovation CE platforms to exchange data Data accessibility	Fear of sharing sensitive data Fear of losing competitive advantage	Aquaculture workers Researchers, scientists Data producers Innovators SMEs Big enterprises Environmental institutions
#4: Creation of new jobs that can transfer knowledge and best practices on how to build FAIR datasets	Social Economic	Endorsement of training Dialogue between farmers and data experts Knowledge sharing Increase of awareness Improve decision making Increase innovation	Lack of skills Mix between FAIR and open data Cultural barriers Biased data	Aquaculture workers Researchers, scientists Data producers Service producers Innovators SMEs Big enterprises
#5: Issue of policies that promote the adoption and creation (when missing) of standards for CE in aquaculture	Political Technical	Issue of laws and recommendations Increase of awareness Increase of standardisation Labels creation Increase of innovation Processes improvement	No standardised methodologies to build FAIR systems No clear implementation guidelines Data available in different languages	Policy makers Researchers, scientists SMEs Big enterprises
#6: Make interoperable systems cheaper thanks to economies of scale	Economic Technical	Lower costs of acquiring data Data interoperability Data traceability Avoid data duplication Increase innovation Product traceability Processes improvement Technical support	High investments Different technologies used to build datasets No user-friendly infrastructures No interoperable datasets Lack of capacity	Aquaculture workers Researchers, scientists Data producers Innovators SMEs Big enterprises

Appendix B Questions to gather qualitative data

1. What's your understanding and your experience of FAIR data management practices? Have you seen it in practice?
2. What are the advantages of FAIR data management practices?
3. What are the disadvantages of applying FAIR data management?
4. Which stakeholders can benefit from adopting FAIR data management?
5. What is your understanding of the concept of circular economy?
6. Which role does FAIR data management play in facilitating the adoption of circular economy practices in the aquaculture industry?
7. What are the barriers that could prevent the application of FAIR data management systems in a circular aquaculture sector?
8. What are the enablers that support the implementation of FAIR data management practices in a circular aquaculture sector?
9. What are the circular economy practices that can be applied specifically in the aquaculture sector?
10. Is there someone else that you can introduce me to for conducting another interview?

Appendix C Questionnaire to gather quantitative data

1. In which sector do you work?
   a. Aquaculture
   b. Fisheries
   c. Other (please specify)
2. For how many years, have you worked in this sector?
   a. 0–5
   b. 6–10
   c. More than 10
3. What is the size of your company?
   a. 0–49 employees
   b. 50–249 employees
   c. 250 employees and more
4. Which target group does represent you?
   a. Researcher;
   b. Data scientists;
   c. Data infrastructures managers;
   d. SMEs and industrial players;
   e. Marine and ocean governance members;
   f. Other (please specify)
5. In which country do you work? (Open-ended question)

Circular Economy (CE) is a new economic paradigm where potentially no waste is generated as everything that represents waste for something can become raw materials for other sectors. After knowing this, please reply to the following questions:

6. I am familiar with the Circular Economy concept
   a. Not familiar at all
   b. A little familiar
   c. Modestly familiar
   d. Quite familiar
   e. Very familiar
7. My company adopts circular economy practices
   a. No CE practices are adopted
   b. CE practices are rarely adopted
   c. CE practices are usually adopted
   d. CE practices are often adopted
   e. CE practices are always adopted
8. What are the CE practices adopted by your company (please select all the ones that apply)?
   a. I don't apply CE practices
   b. Remanufacturing
   c. Refurbishment
   d. Recycling
   e. Reuse
   f. Eco-design
   g. Other (please specify)

FAIR data management is used to describe data that meet the requirements of Findability, Accessibility, Interoperability and Reusability. After knowing this, please reply to the following questions:

9. I am familiar with the concept of FAIR data management
   a. Not familiar at all
   b. A little familiar
   c. Modestly familiar
   d. Quite familiar
   e. Very familiar
10. My company adopts FAIR principles
    a. No FAIR principles are adopted
    b. FAIR principles are rarely adopted
    c. FAIR principles are usually adopted
    d. FAIR principles are often adopted
    e. FAIR principles are always adopted

11. FAIR data management brings the following benefits (please select all the ones that apply):
    a. No benefits
    b. Increase the data harmonisation level
    c. Increase the data interoperability level
    d. Increase the adoption of standards
    e. Facilitate the acquisition of knowledge in a faster way
    f. Facilitate the implementation of best practices
    g. Improve building of models
    h. Other (please specify)
12. Which tools and procedures do you adopt to apply FAIR practices?
    a. FAIR data guidelines developed by research projects
    b. Ontology-based software
    c. Open-source software
    d. Modelling systems
    e. Other (please specify)
13. My company measures the impact of FAIR Data Management
    a. No
    b. Yes, with FAIR Digital Objects
    c. Yes, with modelling schemes
    d. Yes, with dedicated software
    e. Yes, but with other tools (please specify)
14. Which types of barriers can prevent the adoption of FAIR practices in your company? (please select all the ones that apply)
    a. Not willingness to share sensitive data
    b. Lack of interoperable data infrastructures
    c. High investments needed to make databases FAIR
    d. Other (please specify)
15. Which types of enablers can prevent the adoption of FAIR practices in your company (please select all the ones that apply)?
    a. Sharing of best practices in a reliable way
    b. Access more data in an automatic way
    c. Promoting transparency and collaboration
    d. Other (please specify)
16. Are you available for a short interview? If so, share your email so that we can schedule an interview.

Appendix D Summary of the adopted methodology

See Table 5.

Appendix E Thematic analysis with NVIVO

See Figs. 11, 12, 13, 14, 15, 16, 17, and 18.

Table 5 Summary of the adopted methodology

Objectives	Data collection technique	Data analysis technique	RQs
Identify and analyse possible FAIR data management and circular economy practices applicable in the aquaculture sector	Interviews Questionnaire Secondary data (if available)	Thematic analysis Descriptive statistic, benchmarking, and comparative data Secondary analysis	RQ1: What are the circular economy practices that can be applied in the aquaculture sector? RQ2: What are the benefits of applying FAIR data management practices in the circular aquaculture industry?
Detect possible enabling factors that can influence relationships among FAIR, circular economy and aquaculture	Interviews Questionnaire Secondary data (if available)	Thematic analysis Descriptive statistic, benchmarking, and comparative data Secondary analysis	RQ3: What are the enablers that support the implementation of FAIR data management practices in a circular aquaculture sector?
Detect possible limiting factors impacting relationships among FAIR, circular economy and aquaculture	Interviews Questionnaire Secondary data (if available)	Thematic analysis Descriptive statistic, benchmarking, and comparative data Secondary analysis	RQ4: What are the barriers that could prevent the application of FAIR data management systems in a circular aquaculture sector?
Develop a roadmap to show how FAIR data management approaches can facilitate the adoption of CE in the aquaculture industry	Interviews Questionnaire Secondary data (if available)	Thematic analysis Descriptive statistic, benchmarking, and comparative data Secondary analysis	RQ5: Which recommendations can be derived for the circular aquaculture industry in applying FAIR data management practices?

Nodes

Name	Files	References
FAIR data advantages	12	37
FAIR data disadvantages	11	24
FAIR data stakeholders	12	24
CE for Aquaculture	9	23
FAIR, CE, Aquaculture Enablers	10	18
FAIR, CE, Aquaculture Barriers	11	23
FAIR, CE, Aquaculture Benefits	11	23

Fig. 11 Nodes classification

Nodes

Name	Files	References
FAIR data advantages	12	37
data traceability	2	2
product traceability	1	1
data availability	6	8
data reuse	3	4
data interoperability	4	4
data shareability	5	5
knowledge sharing	2	4
lower costs of aquiring data	4	5
improve decision making	2	2
increase of collaboration	2	2
increase of data standardisation	2	2
increase innovation	1	1
avoid data duplication	1	1

Fig. 12 Nodes and references—FAIR data advantages

Nodes

Name	Files	References
FAIR data advantages	12	37
FAIR data disadvantages	11	24
high investments	2	3
data available in different languages	1	1
different technologies	4	5
lack of skills	4	4
data privacy	3	3
no clear implementation guidelines	1	1
no standardised methodologies	5	5
biased data	2	2
no user-friendly infrastructures	1	1

Fig. 13 Nodes and references—FAIR data disadvantages

Nodes

Name	Files	References
FAIR data stakeholders	12	24
value chain stakeholders	3	3
decision makers, policy makers, govern	7	7
operative aquaculture workers	3	3
researchers, scientists	9	9
data producers	3	3
service producers	3	3
innovators	3	3
SMEs	7	8
big enterprises	6	7
environmental institutions	3	3
city planners	3	3
coastal management players	3	3

Fig. 14 Nodes and references—FAIR data stakeholders

Nodes

Name	Files	References
FAIR data advantages	12	37
FAIR data disadvantages	11	24
FAIR data stakeholders	12	24
CE for Aquaculture	9	23
aquaponics	3	5
reuse of materials	5	6
recycling of materials	5	5
repair of materials	2	2
eco-design	2	2
RAS	2	4
renewable energy	2	2
CE standards	1	1

Fig. 15 Nodes and references—CE for aquaculture

Nodes

Name	Files	References
FAIR data advantages	12	37
FAIR data disadvantages	11	24
FAIR data stakeholders	12	24
CE for Aquaculture	9	23
FAIR, CE, Aquaculture Enablers	10	18
laws and regulations	4	4
increase of awareness	4	4
labels creation	2	2
training	3	3
farmers associations	1	1
data accessibility to find cages locations	1	1
technical support	1	1
processes improvement	1	1
monetary compensation	1	1
CE platforms to exchange data and products	1	1

Fig. 16 Nodes and references—FAIR, CE, aquaculture enablers

Nodes

Name	Files	References
FAIR data advantages	12	37
FAIR data disadvantages	11	24
FAIR data stakeholders	12	24
CE for Aquaculture	9	23
FAIR, CE, Aquaculture Enablers	10	18
FAIR, CE, Aquaculture Barriers	11	23
Cost of aquiring data	3	3
not interoperable data	3	3
non-user-friendly systems	2	2
lack of capacity	3	3
lack of skills	4	4
no willingness to share data	2	2
cultural barriers	3	3
mix between FAIR and open data	2	2
fear of losing competitive advantage	2	2

Fig. 17 Nodes and references—FAIR, CE, aquaculture barriers

Nodes

Name	Files	References
FAIR, CE, Aquaculture Benefits	11	23
help to standardise processes	2	2
help to find data	4	4
Help to access data	4	4
help to harmonise data	2	2
help collect information	1	1
help make a profit	1	1
help optimise resources	1	1
help trace data	1	1
help trace products	2	2
help evaluate the circularity degree	1	2
help monitor aquaculture systems	2	2
keep track of CE performances	3	3
improve fish welfare	1	1
improve the engineering work of the system	2	2
lower impact on environment	2	2
help find a second use of waste	3	3

Fig. 18 Nodes and references—FAIR, CE, aquaculture benefits

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