sustainability

Review

Toward the Circular Economy in the Aquaculture Sector: Bibliometric, Network and Content Analyses

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Abstract: This paper offers an overview of circular economy strategies applied to the aquaculture sector. The growing challenges imposed on the sector by the strategies of the Green Deal impose new growth strategies in the name of sustainability. The scalability of these strategies is increasingly hampered by regulatory voids and by the absence of a universally accepted assessment method for measuring the impacts of current aquaculture systems. More than ever, a review of knowledge in the circular economy field is required to comprehend where the aquaculture sector is heading, and in order to make the required transition. The present review proposes a bibliometric analysis, a network analysis and a content analysis, which highlight a very new and expanding field of research. The studies were firstly analyzed from a micro (animal metabolism) to a macro perspective (policies, markets and society), emphasizing where research is still lacking. Furthermore, a second level of classification concerns the type of circularity approach proposed for the aquaculture system, which can be divided into open-loop or closed-loop strategies. Regarding the open-loop-related studies, the focus of the evaluation is devoted to the different bioeconomic values of the circularity strategies proposed for the biological flows entering and exiting the aquaculture system. The literature review offered insights into the identification of research threads that are developing around the aquaculture sector.

Keywords: aquaculture; circular economy; biomass value pyramid; multilevel perspective; review

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1. Introduction

Aquaculture has been recognized to be the agri-food sector with the fastest rate of development over the past few decades [1]. The implementation of sustainable intensification strategies is currently regarded as essential for the sector to achieve ecological and technological transformation while maintaining its market competitiveness. As noted by [2], the spread of circular strategies (CSs) across aquaculture and other agri-food industries, as well as other economic sectors, has the potential to provide promising opportunities for market expansion.

The new Green Deal was launched by the European Commission (EC) in 2019. This plan is a comprehensive strategy to achieve environmentally sustainable economic growth in Europe. In more detail, the EC has implemented the Circular Economy Action Plan (CEAP), a novel chance for the development of circular economy (CE) approaches in the aquaculture and other intensive goods sectors [3]. Moreover, the current programing (2021–2027) of the European Maritime, Fisheries and Aquaculture Fund (EMFAF) promotes the shift towards sustainable and low-carbon activities, clean and equitable energy and green and blue investments for the circular economy [4]. The CE rationale is to promote the eco-design of products to minimize waste and ensure the efficient and long-term preservation of existing resources [5]. Over time, the Green Deal's objective to modify existing legislation and the EMFAF's mission have become increasingly ambitious. Nevertheless, the scalability of the CS presents obstacles for the aforementioned goals. In their investigation, Regueiro et al. [6] provided numerous examples. Several regulatory voids exist regarding the viability of utilizing specific byproducts for human and animal consumption. This is especially true for the applications of food items grown in integrated systems such as integrated multi-trophic aquaculture (IMTA) or aquaponics. An additional example is the potential application of aquaculture-derived wastewater as a fertilizer [7]. In addition, many normative frameworks are derived from the agricultural experience, and now more than ever the policy network is required to devote more attention to the blue sector and its exceptionalism [8,9].

Beyond scalability of CSs, scholars started to highlight only in the last decade, probably due the advent of more structured European aquaculture policies and to the Green Deal's launch, the challenges associated with the adoption of circularity tactics, trying to propose more experimental applications and methodologies to facilitate the sector's transition to a more sustainable model [2,6,9]. Within this relatively newborn topic, two main aspects participate to create a research gap.

First, the aquaculture industry faces the difficult task of evaluating the overall impact of extant systems in order to identify the most effective areas for implementing circular practices. In relation to the socio-economic aspects, the study by Raffray et al. [10] is one of the few to attempt to measure the impact of fisheries and aquaculture sectors at the European level, seeking to understand the sector's potential for achieving the goals of the European Green Deal. In relation to the environmental impact specifically, Jacob et al. [11] conducted a review of circular economy assessments in aquaculture, emphasizing, for example, the presence of life cycle assessment (LCA) studies. Nevertheless, the diverse results and the limited potential of LCA to assess impacts for the entire industry validate the intricate nature of this challenge [12].

Second, most of the literature reports cases of the application of single practices on specific species, while only a few recent studies address the circular transition of the sector in a systemic manner. Recently, a study by Chary et al. [13] has highlighted the difficulty of translating the application of CE principles into aquaculture for the identification of best practices. Masi et al. [14] sought to identify dimensions within which to better define these actions: operations, product life cycles, farm culture and ecosystems. Their works emphasized that when introducing circular economy principles within an aquatic production system, it is essential to approach the transformation from multiple angles. According to De Rosa et al. [15], the CE implementation necessitates micro, meso, and macro analyses of the environmental and socio-economic context in which aquatic production operates. On the micro level, the metabolic efficiency of an animal is observed. The meso level refers to the animal farm and focuses on the exchange of energy and materials with the environment. Furthermore, the society, market and policies belong on the macro level, where it is essential to recognize the "circular" value of products.

In this complex scenario, there is a fragmentation of the studies attempting to deal with the aquaculture system's CE. The present study will examine the current literature regarding the adoption of CSs within the aquaculture sector to identify popular lines of research and those in which there is still a knowledge gap. The article will first discuss the methodological elements, followed by an explanation of the results obtained from bibliometric, network and content analyses. Ultimately, the conclusions will emphasize the contributions of the research and its limitations.

2. Methodology

2.1. Data Collection

The documents were extracted from the Scopus scientific database. The keywords were directly relevant to the investigated topic and were chosen by the authors through a combination of a literature review and brainstorming. The identified keywords for data extraction were "circular economy" and "aquaculture", which were connected through the Boolean operator "AND".

The search string is reported in Table 1. The extraction selected English-language studies. Book chapters and books were excluded, so scientific papers, reviews and conference proceedings were selected for the analyses. Furthermore, the extraction was restricted to particular subject domains (Table 1).

Table 1. Methodology for conducting research for data collection. Source: own elaboration.

Search query	TITLE-ABS-KEY (circular AND economy AND aquaculture) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "BIOC") OR LIMIT-TO (SUBJAREA, "EART") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ECON")) AND (EXCLUDE (DOCTYPE, "ch") OR EXCLUDE (DOCTYPE, "bk")) AND LIMIT-TO (LANGUAGE, "English")
Subject areas	"Environmental Science", "Agricultural and Biological Sciences, Engineering", "Social Sciences", "Biochemistry, Genetics and Molecular Biology", "Earth and Planetary Sciences", "Business, Management and Accounting", "Economics, Econometrics and Finance"
Publication type	Journal articles, reviews and conference papers
Database	Scopus
Period	1 January 2007–31 December 2022

Data extraction started on 31 March 2023 on the Scopus database, collecting 197 documents. Journal articles, reviews and conference papers were included in the query. After the 197 studies were identified, those to be reviewed were selected through a screening process. The latter included the exclusion of studies that were duplicate, incomplete in terms of the information provided, or not significantly related to the topic of adopting circular economy strategies in aquaculture. In the end, 153 were considered eligible to perform the analysis. Subsequently, citation details (including authors, affiliations, document titles, publication years), abstracts, and index keywords were extracted from a subset of 153 qualifying documents, following the PRIMA framework: Preferred Reporting Items for Systematic Reviews and Meta-Analyses [16] (Figure 1). In total, 153 studies were considered eligible to run the bibliometric analysis and network analysis, while 146 were eligible for the content analysis. In fact, a further screening removed 7 papers from the content analysis as they were strongly unrelated to the identified classifications. From the number of studies collected, it is evident that the topic is not cemented in the literature as it is relatively new, so the sample is limited.

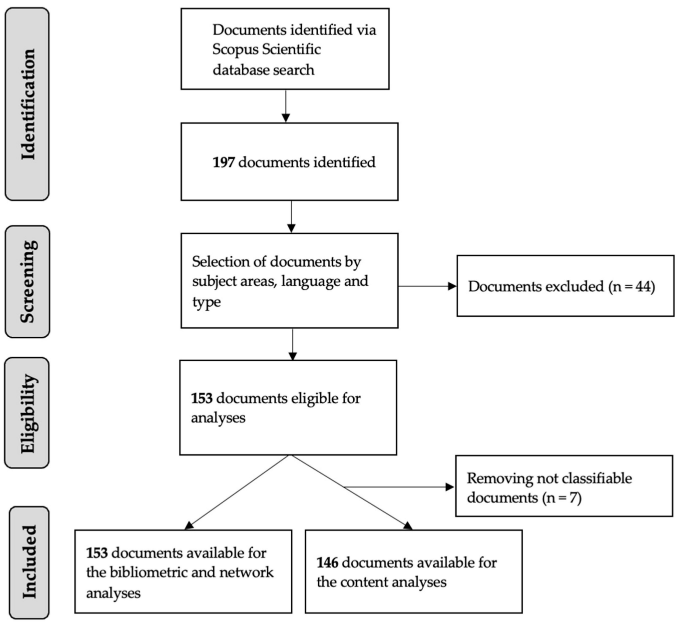

Figure 1. The research flow based on PRISMA. Source: own elaboration.

2.2. Systematic Review: Bibliometric, Network and Content Analyses

To carry out the complete analysis, data pertaining to the 153 qualifying documents were processed. The bibliometric research was carried out using the R software, and the more detailed the Bibliometrix package was used to convert the collected studies (format .csv) into bibliographic data. The study started elaborating the most important specifications such as the number of documents, sources, years, Keywords Plus (ID), Authors Keywords (DE), average citations per documents, number of authors, documents per author, author appearances, authors and co-authors per documents, international co-authorship, annual percentage growth rate, the authors and the journal with the highest level of activity on the topic, and the rank of countries most involved in the research field [17].

The network analysis was run using highly pertinent Keywords Plus (ID) in the Scopus index and the co-occurrence analysis was implemented, identifying the prevalent traits of the studied topic [18]. The network map was realized through the software VOS viewer (v. 1.6.14). A co-occurrence analysis of the index keywords was carried out via the full counting method, which assigns equal weight to each co-occurrence. A total of 1465 index keywords were identified and those with at least 5 occurrences were included. Furthermore, keywords not related to the topic were eliminated and 13 was set as minimum number of keywords per each cluster. The network visualization showed 83 keywords, with the circle diameters indicating the significance of the keywords based on their weight, the line thickness reflects the strength of the connections between the words, and the colors represent the various clusters that grouped the index keywords [19]. In line with van Eck and Waltman [20], the structure was developed by standardizing the intensity of the connections between the components using the association strength method.

The content analysis included 146 studies. In fact, 7 studies were excluded as they cannot be clearly linked to the criteria chosen for the classification. Two criteria have been chosen to classify the selected studies. The first one (Figure 2) divides studies on the circular economy into multi-level categories:

1. Micro level—circularity tactics directly affect animal metabolism;
2. Meso level—the proposed CSs concern energy and material exchanges between the aquaculture system and the environment;
3. Macro level—concerns the possibility of the market, society and policies to favor the diffusion of circular practices for the sector.

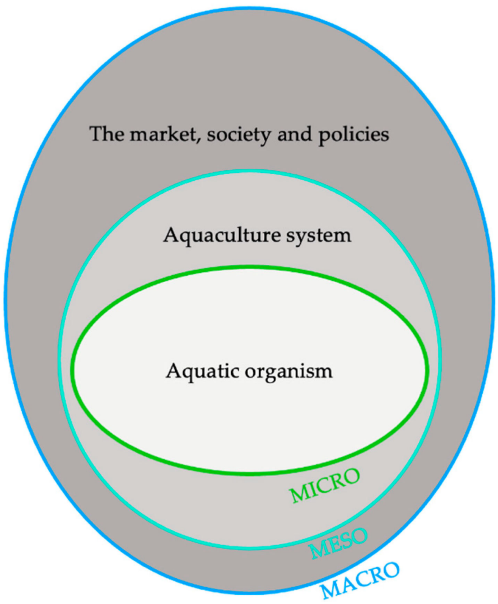

Figure 2. Scaling circular economy within the aquaculture sector. Source: own elaboration, adapted from the general framework of De Rosa et al. [15].

A second level of classification concerns the type of circularity approach proposed for the aquaculture system, which can be broken down into the following categories:

1. Studies that analyze "closed-loop" circularity strategies;
2. Studies that analyze "open-loop" circularity strategies.

The Ellen MacArthur Foundation's butterfly diagram [21] emphasizes that circularity strategies applicable to biological flows can be more or less closed-loop, starting from cascading ones (more closed-loop) to activating synergies with other economic sectors, e.g., for energy production, fertilizer, etc. (more open-loop). This classification reflects the possibility of creating loops more or less distant from the analyzed system, in this case the aquaculture system. Therefore, the study includes, in the "closed-loop" classification, circular strategies directly applicable to the aquaculture system; for example, the adoption of recirculating systems or on-farm integrated systems. Considered in the "open-loop" category, meanwhile, are the studies that primarily envision the circularity strategies that the aquaculture farm activates "far from the farm", for example, with other economic sectors, from agriculture to energy and cosmetics.

After the distinction between the two levels, the content analysis thoroughly focused on open-loop studies. Indeed, aquaculture systems are required to improve their capacity to regenerate themselves by improving the circularity and sustainability of input and output flows and by performing closed-loop strategies. Following this need, open-loop studies were analyzed and classified according to whether CSs were applied in the upstream (input flows) or downstream (output flows) phase with respect to the aquaculture system (core) (Figure 3).

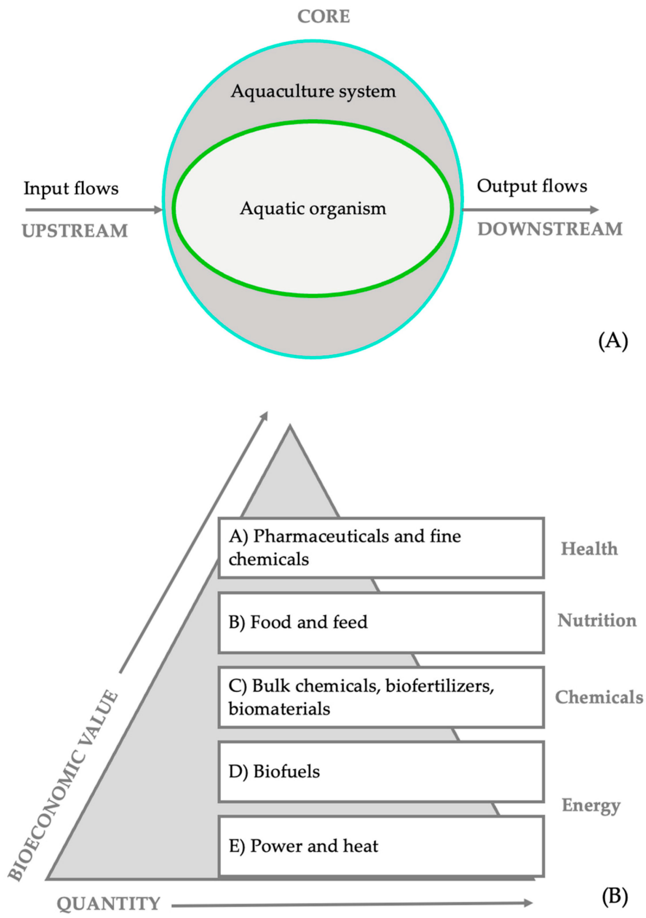

Figure 3. (**A**) Upstream and downstream phases of aquaculture system. Source: own elaboration. (**B**) The bioeconomic value of open-loop circular strategies. Source: own elaboration adapted from the general framework of Berbel and Posadillo [22] and Asveld and Van Est [23].

The proposed open-loop circularity strategies were analyzed for their bioeconomic value, following the Biomass Value Pyramid (BVP) (Figure 3). The BVP illustrates the whole range of goods with added value that may be obtained from agri-food biological waste materials. Burning the biomass and generating heat and power results in the lowest value, while the production of fine chemicals for pharmaceutical use represents the highest value [22,23].

3. Results

3.1. Bibliometric Analysis

The annual amount of scientific articles on the subject of the CE in aquaculture is depicted in Figure 4, which covers the period from 2015 to 2022. The trend in the graph shows that this is an emerging topic: the number of papers published has grown considerably, with an Annual Percentage Growth Rate of 85%. There has been exponential growth in recent years, from 39 papers in 2021 to 74 papers in 2022. Furthermore, in 2020 there was a substantial increase in the quantity of published papers, more than doubling in comparison to 2019. This event signified a pivotal moment and showcased an impressive expansion. At the European level, the reasons may be related to some political actions: in this period the implementation of CEAP was launched, and this may have influenced scholars in this sense.

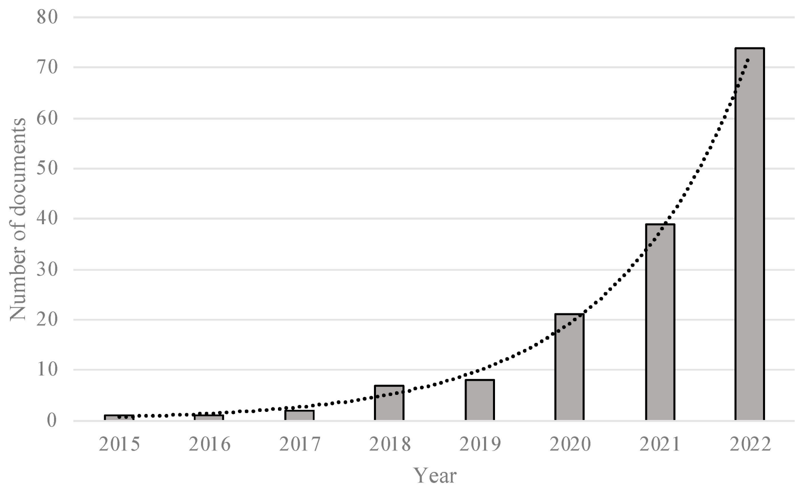

Figure 4. Publications on circular economy in aquaculture from 2015 to 2022. Source: own elaboration.

On average, each of the 153 papers in the sample, co-authored by 869 different people and published in 79 different journals, received 10.25 citations. Table 2 shows these key elements.

Table 2. Main elements of bibliometric analysis. Source: own elaboration.

Elements	
Documents	153
Sources (Journals)	79
Keywords Plus (ID)	1465
Authors' Keywords (DE)	574
Years	8
Average Citations per Document	10.25
Author	869
Documents per Author	0.176
Authors per Document	5.67
Author Appearances	1021
Co-Authors per Doc	6.67
International Co-Authorship	36.6%
Annual Percentual Growth Rate	84.94

Table 3 presents the most relevant journals in terms of papers and average citations in the examined sample. *Aquaculture* is the most productive journal, having the greatest number of published works during the period under review ($n = 11$), while the second is *Journal of Cleaner Production*. It emerges that the journals with the highest scientific impact on the topic of CE in aquaculture are *Aquaculture* and *Marine Drugs*. The latter, while ranking fifth in terms of published works, has an average number of citations per article of 103, placing it second after *Aquaculture* ($n = 150$).

Table 3. Top 10 journals by publication and citation number. Source: own elaboration.

Journals	Publisher	Number of Papers	Citations	Best Quartile	Impact Factor
Aquaculture	Elsevier	11	150	Q1	5.135
Journal of Cleaner Production	Elsevier	8	70	Q1	11.072
Sustainability (Switzerland)	MDPI	7	64	Q1	3.889
Foods	MDPI	6	38	Q1	5.561
Marine Drugs	MDPI	6	103	Q1	6.085
Science of the Total Environment	Elsevier	5	54	Q1	10.754
Frontiers in Marine Science	Frontiers	4	6	Q1	5.247
Aquaculture International	Springer	4	80	Q2	2.953
Reviews in Aquaculture	Wiley	4	90	Q1	10.618
Scientific Reports	Nature	4	78	Q1	4.997

Table 3 presents specific information regarding their relevance in terms of impact factor (IF) (year 2022) and their position in the Scopus indexing categories. It is important to mention that nine out of the top ten journals are located in the top 25th percentile (Q1) in the Scimago Journal Rank (SJR). The ranking system, as described by Sicilia et al. [24], assigns different values, in terms of weight, to the citations determined by the journal, thus increasing the significance of citations from more influential journals compared to those from less influential.

Table 4 presents the productivity metrics of the top five most prolific authors in the researched field; the H-index and the i-10 index are also included. According to Susarla et al. [25], these indices are well known and frequently applied to assess research, and give a more accurate picture of scholarly activity.

Table 4. Top 5 authors in terms of published papers. Source: own elaboration.

Author	Affiliation	Number of Papers	H-Index	i-10 Index
Olivotto I.	Polytechnic University of Marche—Italy	5	37	71
Zarantoniello M.	Polytechnic University of Marche—Italy	5	14	16
Aldaco R.	University of Cantabria—Spain	4	29	71
Giorgini E.	Polytechnic University of Marche—Italy	4	26	69
Johansen J.	Norwegian Institute of Bioeconomy Research—Norway	4	12	7

As shown in Table 4, three of the five most productive authors on the topic under review belong to Italian universities and, in particular, to the Polytechnic University of Marche. Norway and Spain have respectable numbers of published documents in the examined research area.

Table 5 shows the quantity of published papers where the authors are exclusively from one country (single-country publications) or multiple countries (multi-country publications). Italy exhibits the lowest presence of international collaborations, despite having the most extensive collection of publications in the field under investigation. Approximately

83% of the publications are solely authored by Italians. Conversely, approximately 50% of the papers published by scholars with affiliations at Spanish and Portuguese universities are the outcome of international collaborations. The United Kingdom achieves the most significant degree of impact per individual published paper, with an average citation rate of 17.89.

Table 5. Top 5 countries with the highest number of published papers and citations. Source: own elaboration.

Country	Number of Documents	Total Citations	Average Document Citation	Single-Country Publications (SCP)	Multi-Country Publications (MCP)	MCP Ratio
Italy	29	443	15.28	24	5	17%
Spain	18	176	9.78	8	10	55%
Portugal	15	152	10.13	8	7	47%
United Kingdom	9	161	17.89	5	4	44%
China	8	69	8.62	6	2	25%

3.2. Network Analysis

The purpose of conducting a keyword analysis, referred to as Keywords-Plus (ID) in the Scopus index, is to facilitate a search for documents pertaining to a specific topic. In total, 153 documents were analyzed, resulting in the identification of 1631 keywords. In accordance with Agnusdei et al. [17], an analysis was conducted to tally the occurrence of the index keywords in the collected papers to ascertain their frequency and establish a ranking.

The top ten Keywords-Plus (ID) are listed in Table 6. With 77 occurrences, the most common keyword is "aquaculture". There are numerous keywords pertaining to sustainability aspects in the top ten ranking ("circular economy", "sustainability", "sustainable development" and "economic aspect"), emphasizing the ecological dimension of the circular transition in the aquaculture sector. One reason for this could be that not everything that is sustainable can be defined as circular, yet everything that falls within circularity participates in the transition towards sustainable development [26]. A high frequency of words such as "biomass" and "waste management" emerges, underlining the tendency of the literature to consider CSs mainly in the end-of-life phase.

Table 6. Top 10 most frequently occurring index terms. Source: own elaboration.

Keywords-Plus (ID)	No. Occurrences/Frequency
Aquaculture	77
Circular economy	61
Fish	30
Animal	21
Sustainability	20
Biomass	15
Sustainable development	14
Animal food	12
Economic aspect	12
Waste management	12

Then, the analysis of the keywords' co-occurrence was performed and each of the clustered keywords was assigned to a single cluster. Figure 5 represents the network visualization which, by capturing linkages between keywords, identified three distinct clusters. These clusters represent three specific research areas in which CSs have been applied and which are interconnected: the upstream phase (red cluster), downstream phase (green cluster) and aquaculture system (blue cluster).

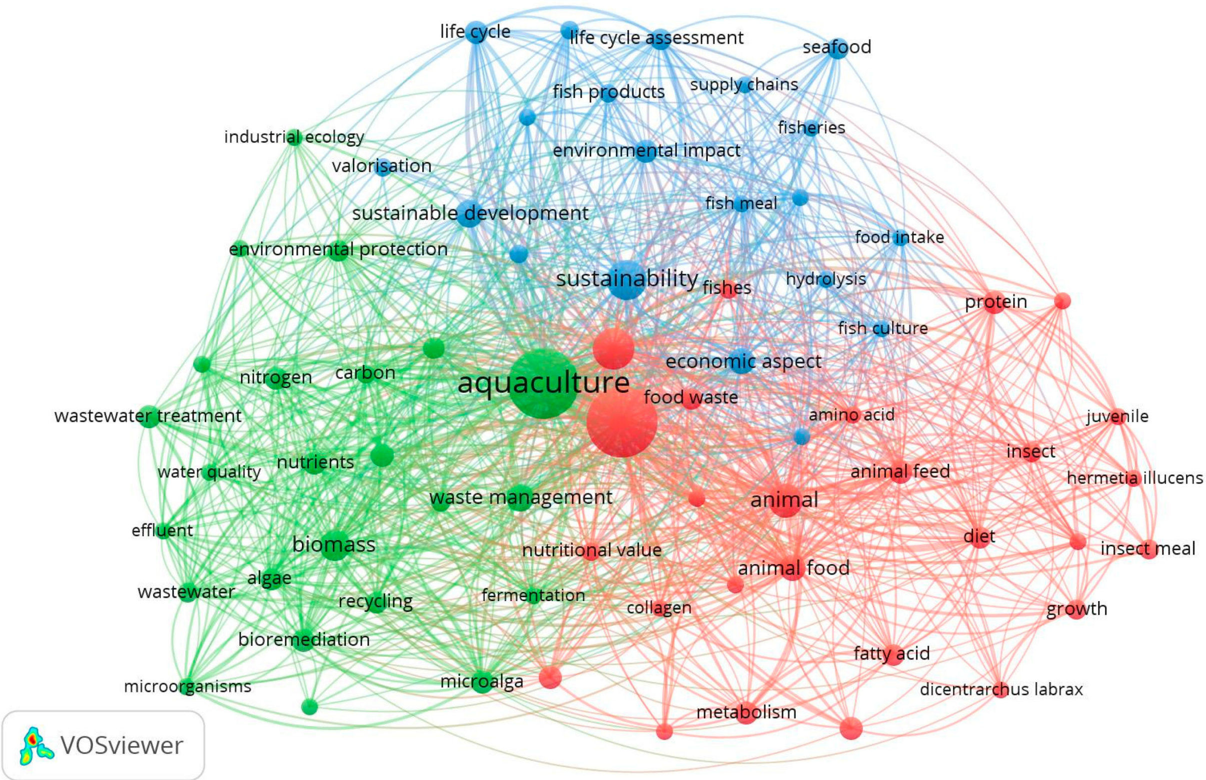

Figure 5. Network visualization depicting the analysis of keyword co-occurrence. Source: own elaboration, realized through the software VOS viewer (v. 1.6.14).

The "upstream phase" refers to a group of keywords, the red cluster, that pertain to the research area focused on the application of CSs to the input flows of the aquaculture system. This group of papers mainly focus their attention on analysis of animal feed [27,28] and connected aspects, like nutritional values [29,30]. In fact, there are keywords such as "animal feed", "nutritional value" and "growth".

Studies in the red cluster, therefore, have a design-oriented approach. Analyzing the upstream phase is crucial to acting in a circular perspective. This makes it possible to design an efficient system from the beginning, limiting inputs and improving the quality of equipment so as to prevent excessive production of both organic and inorganic waste [31].

The green cluster of keywords, named the "downstream phase", refers to the studies related to the output flows of aquaculture systems and, in particular, to wastewater treatment [32] and other aspects related to recycling [33] and bioremediation [34]. It could be explained as the phase in which the loop of the supply chain can be closed. Most of the keywords refer to waste management and, in general, to the end-of-life management of products.

The blue cluster of keywords named "aquaculture system" involves the study in which the environmental and economic impact of aquatic productions is analyzed through several methods such as life cycle assessment [6,35]. In this cluster there is a focus on sustainable development related to the aquaculture supply chain [36]. The keywords "life cycle" and "life cycle assessment" suggest that the aquatic products and their farming systems are often analyzed according to life cycle perspective.

Observing Figure 6, it is evident that the theme under investigation is very recent, and the keywords are the expression of the high fragmentation of the studies. The figure also shows that initially the first circular economy strategies in aquaculture were applied to the "downstream" phase, identifying them as a way of valorizing waste. As time progressed, studies arose to delve deeper into the environmental impact of aquaculture systems and, finally, more recent studies have focused on identifying strategies for the "upstream" part as well, mainly through proposing protein alternatives in fish diets.

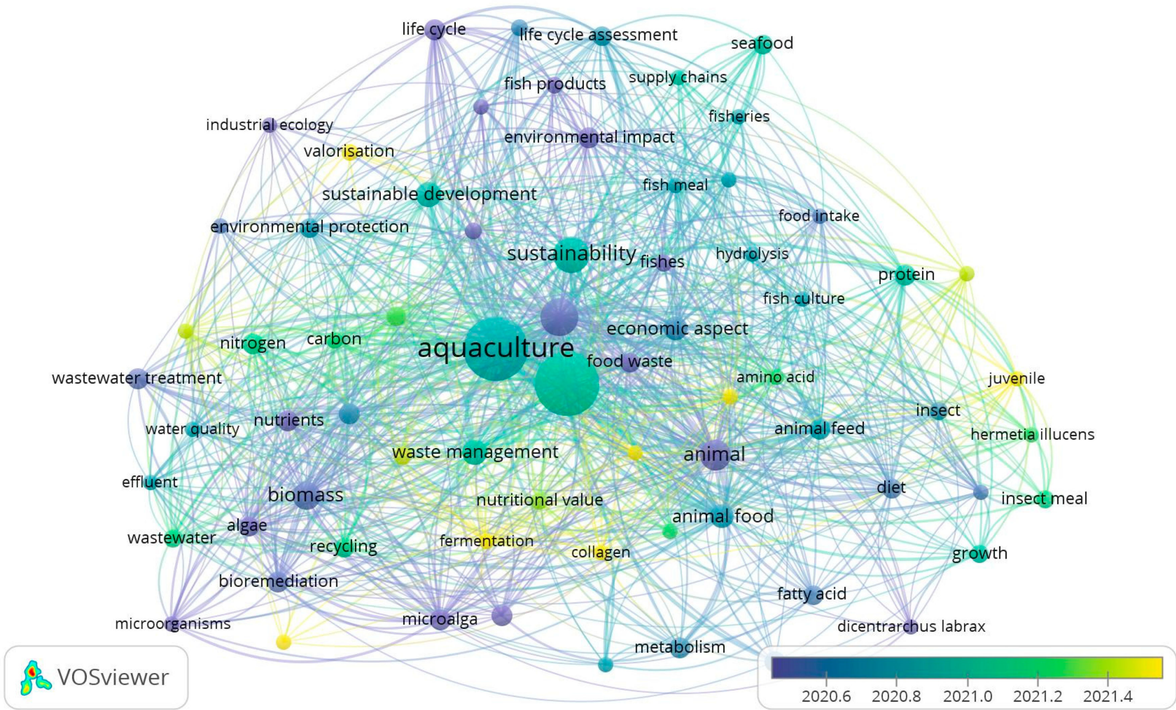

Figure 6. Overlay visualization of co-occurrence analysis. Source: own elaboration, realized through the software VOS viewer (v. 1.6.14).

3.3. Content Analysis

A first level of classification of the 146 documents assessed for the content analysis, as shown in Figure 7, is the level of application of different CSs.

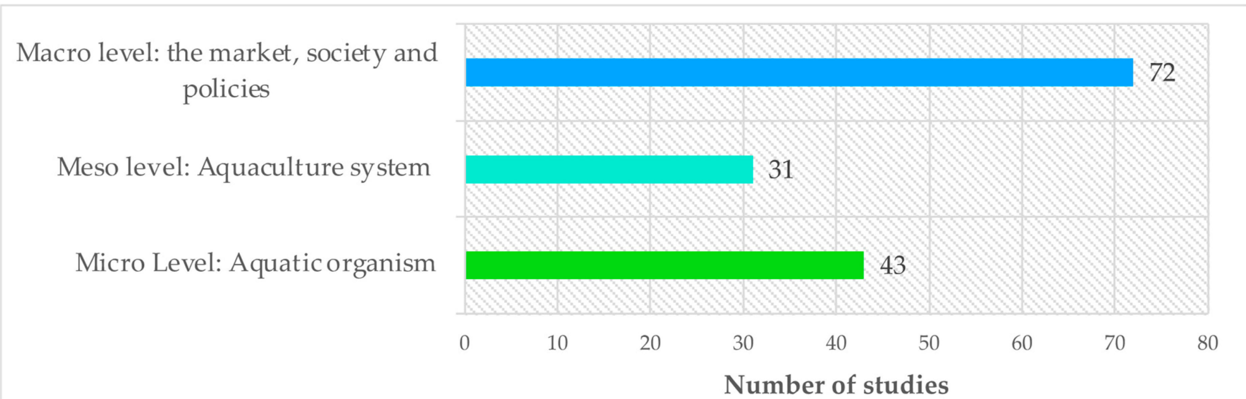

Figure 7. Studies classified in a multilevel perspective dealing with circular aquaculture systems. Source: own elaboration.

Some 30% of the studies delve into the micro level. The CSs for the micro level concern the flow of materials, or more generally the exchange of "energy" between the environment and aquatic organisms' metabolisms. Most of these studies suggest protein alternatives by testing the impact of various sustainable feed formulations on performance. A wide variety of other aspects, such as digestibility, hematological markers, carcass composition (including fatty acid profile) and textural features, were investigated [37]. Research on the usage of insect meal or feeds based on processed waste from the aquaculture, pig and poultry industries are among the most present. The utilization of microbial and algal biomass is also becoming increasingly relevant in the nutritional field [38,39].

In total, 21% of the analyzed studies can be categorized in the meso level, since they dealt with specific aquaculture systems which concern the husbandry of different aquatic organisms including fish, mollusks, crustaceans and plants. This dimension comprises research that has concentrated on the biological and technical material exchanges that take place between aquaculture systems and the environment. This research presented solutions to make aquaculture farms more sustainable. For instance, there is the potential for alternative uses of the discarded shells that are produced in mussel farming [40], as well as for the residual sludge of different aquaculture systems [36,41] and for proposed bioremediation strategies, such as the growth of microalgae [32].

The concept is about trying to improve the nutrient use of production systems [42]. Integrated systems such as aquaponic systems or IMTA, which also bring together several trophic levels, offer the advantage of a reduction in the use of external inputs and making the most of nutrients from farm waste [34]. These types of systems have been proposed as a way to achieve circularity [31]. In a similar vein, there is also the suggestion to manage technical flows in a circular manner. One example could be the potential recovery and recycling of polypropylene from mussel nets [43].

A total of 49% of the studies fall into the macro level, since they deal with aspects that go beyond the specific business logic. Research of this nature considers the political and societal landscape of the aquaculture industry's future but also aims to guide production systems to enhance the value of the circular goods and services produced towards new markets. Though they are few in number, studies that focus exclusively on society and politics address important issues [44]. In particular, they highlighted complexities seafood sectors will have to overcome to meet the objectives of the concepts of farm-to-fork and CEAP. The sector is not only expected to address sustainability and resilience [45], but also to try to quantify the environmental and socio-economic impacts of the existing aquaculture systems to pinpoint exactly where circular practices can be most beneficially implemented. More specifically, to quantify the social and economic effects of policy changes, such as the adoption of circular business models or, for example, the input–output models [10] that have been proposed. Furthermore, emerging practices should also be tested. Jacob et al. [11] examined a variety of methods for measuring the efficacy of circular economy techniques in the seafood sector, underlining: "the paucity of studies on the socio-economic dimension hampers the construction of revolutionary economic systems. . . and limits the ability of decision-makers to integrate circular economy practices into existing business models" (p. 1).

Only very few studies deal with the stakeholders' point of view. Ouko et al. [46] interviewed experts to better understand their perspective on alternative sustainable feed ingredients in aquaculture. Baldi et al. [47] and Piper et al. [48] talk about consumer attitudes towards more sustainably fed or reared aquaculture products. They are interested in consumer perceptions and how education on sustainable and environmentally friendly consumption can influence more circular purchasing choices [49,50].

Beyond the societal and political landscapes, most studies at the macro level focus also on the orientation of production systems to enhance circular products and services towards better market opportunities. For example, researchers discuss the main opportunities for aquaculture for wastewater treatment and by-product recovery, which can exploit the agrifood industry itself, as well as other economic sectors [8]. From the valorization of recovered nutrients for food or feed to the production of fertilizers for agriculture [29,51–53]. Other applications can be found in pharmaceuticals, cosmetics, construction, logistics, textiles and the energy sectors [54–57]. Hence, the importance of valorizing by-products in the light of the recent indications of the EC according to cascading mechanisms, in order to not only make production systems more sustainable but also to make the sectors increasingly independent for the input supply [58].

Opportunities also include systems and new technologies on the market to make aquaculture production more sustainable. From opportunities for production intensification through recirculating aquaculture systems (RAS) [59,60] to different technologies like membrane systems [61] or adsorption and detoxification (e.g., of antibiotics) of pharmaceutical compounds from wastewater [62,63].

A second level of classification concerns the type of circularity approach proposed for the aquaculture system, which can be divided into *open- or closed-loop* strategies (Figure 8).

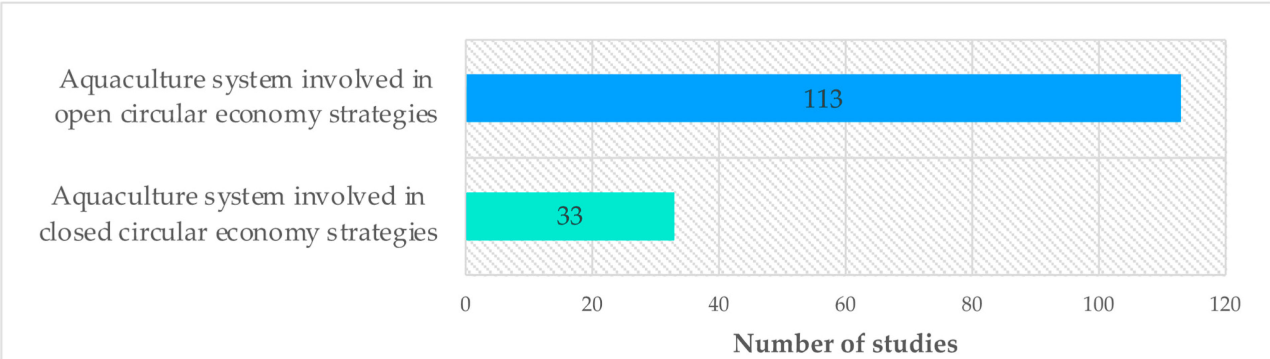

Figure 8. Open- and closed-loop circularity strategies for the aquaculture system. Source: own elaboration.

Closed-loop circularity approaches (23% of the studies) are well identified with the proposal of recirculating aquaculture, aquaponic and IMTA systems. The recirculation idea for an aquaculture system is by far the most prominent one to offer solutions for the CE. Carvalho Pereira et al. [64] combined shrimp farming with the production of algae from wastewater and sludge from farming. Other trials have been conducted in RAS with seabass and micro algae, by Villar-Navarro et al. [65]. Boffa et al. [66] and Cristiano et al. [67] proposed novel approaches (such as nanofiltration) to the treatment of sludge and to the valorization (through, for example, drying technologies) of fish mortalities in RAS.

Other researchers (e.g., [68]) have combined RAS with hydroponics. According to the findings of Fernández-Cabanás et al. [69] and da Costa et al. [70], combining the production of plants and fish in straightforward aquaponic systems would result in significant reductions in the number of inputs required for production. In addition, aquaponic systems have been incorporated into IMTA installations too [71,72]. IMTA provides a very promising route of circularity for aquaculture, which is also seen by many academics as a potential solution to raise the social acceptability of fish farming [31]. Cutajar et al. [73] proposed a study on a land-based IMTA, which combines fish and a natural marine polyculture of oysters and microalgae. Further trials include open-water applications, such as the study of d'Orbcastel et al. [31], discussing the cultivation of sea cucumbers in IMTA in a coastal farm.

On the other hand, 77% (n = 113) of the studies concern open-loop circularity strategies for the aquaculture system. This mainly includes CSs that can connect different industries with the aquaculture sector. Within this strand, 89% (n = 101) of the studies reported CSs applicable to the side streams of biological materials in an aquaculture farm. The BVP was used to classify the bio-economic value of the different strategies in the upstream and downstream phases of the aquaculture system, which represent its collateral phases.

As shown in Figure 9, most studies dealing with the upstream phase (n = 59) concern circular proposals with high bio-economic value.

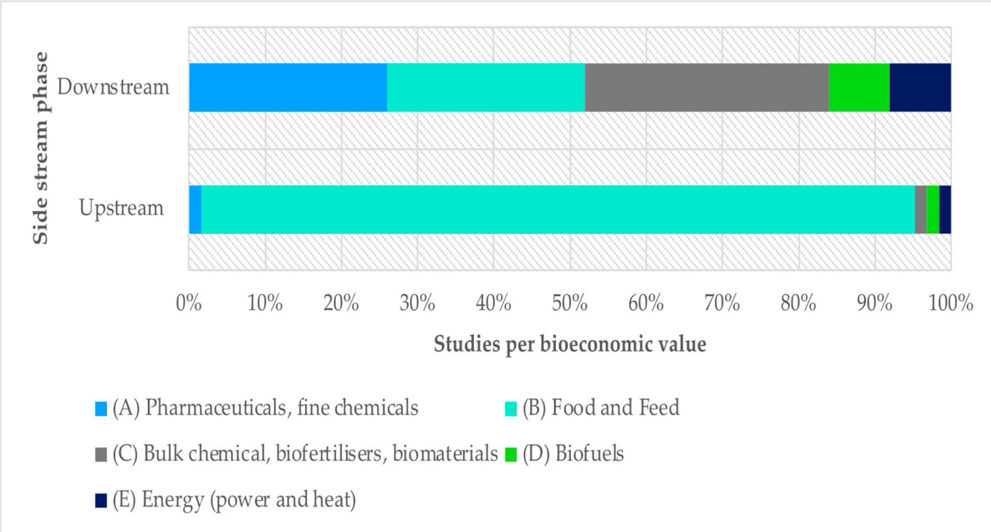

Figure 9. Open-loop circular strategies for the biological flows of aquaculture system and their bio-economic value. Source: own elaboration.

For the most part, this research is dedicated to the field of alternative proteins for aquatic feeds. By presenting an experimental trial on trout, Cappellozza et al. [74] and Terova et al. [75] recommended the utilization of insect meal. Trials have been also proposed for sea bass [76], tambaqui [37], zebrafish [77], sea urchins and other organisms [78]. Other studies advise using proteins from terrestrial animals and plants as a partial replacement. The majority of animal proteins come from poultry by-products, specifically for direct tests on turbot and carp [38,79]. Aquafeed incorporating shrimp remnants has also been proposed [80]. Soy by-products are one of the suggested plant proteins, and Voss et al. [81] reported an empirical test for tilapia. Yeast and waste grain from breweries have been used in sea bass and rainbow trout experiments as legitimate sources of protein [82,83]. Other suggestions call for the inclusion of high-quality proteins deriving from microalgae, such as spirulina. Some applications are in sea bass and catfish farming [35,84]. Also, a growing amount of research is being conducted on the potential of macroalgae for the bioactive compounds (BCs) they contain and that can be employed as feed [85]. Aquaculture may have the opportunity to become more sustainable through the search for alternative protein sources, such as dried microbial biomass [39]. Bacteria are emerging as new microbial protein sources, and Alloul et al. [86] investigated their application as a supply of protein for whiteleg shrimp.

Some research proposes using a more sustainable lipid source for aquaculture feeds: terrestrial animal fats from the agri-food industry [87]. Marques et al. [88] examined the effects of adding poultry fat to the diet of sea bass to assess metabolic changes. Some feed additives have also been proposed to modulate fat deposition with applications on trout and sea bass, such as glycerol recovered from the biodiesel industry [89] or unsaturated fatty acid extracts recovered, for example, from the waste of bluefin tuna [90].

The circular proposals for the valorization of biomass are more heterogeneous in the case of research dealing with the downstream phase (n = 42). The preparation of fish feed has, up until this point, been the primary focus of efforts to utilize waste. On the other hand, there is a considerable current demand for fine chemicals, which are defined as products that have a high bioeconomic value and have the potential to deliver important pharmaceutic and nutraceutical advantages [91,92]. BCs that have antioxidant, antimicrobial, anticancer, antihypertensive, antidiabetic and anticoagulant activities can be extracted from fish waste [93,94]. The most important items that can be extracted include collagen and gelatin, as well as oils, enzymes and bioactive peptides [95]. Eicosatetraenoic and docosahexaenoic acids are two of the most sought-after compounds made from omega-3 fatty acids, and they are derived from the muscle, head and viscera of fish [90]. Nitrogen compounds are another type of bioactive product that can be obtained through the process of waste recycling. These BCs can also be derived from fish bones. Bioactive peptides can be a source of nitrogen and amino acids, and they also have fascinating pharmacological effects. Another source of amino acids is collagen, which is derived from the skin of fish [73]. Among these applications, Malcorps et al. [29] conducted a study on five distinct species, these being Atlantic salmon, European sea bass, carp bream and turbot. The nutritional value of their heads, frames and trims was quite high, while by-products like as viscera and skins showed good promise for animal feed and non-food purposes (cosmetics, fashion and pharmaceuticals). Cutajar et al. [73] investigated the procedures of extracting fish oils and collagen from the waste biomass of Atlantic bluefin tuna.

The possibility of identifying a new use for aquaculture product processing waste is increasingly underlined. An example comes from the study by Honrado et al. [96], which demonstrates the possible incorporation of fish by-products as source of BC for food enrichment. Finally, Chen et al. [32] suggested growing microalgae in order to remediate the wastewater produced by shrimp farms. This type of algae is a potential source of lutein, which is a pigment that can be used as a dietary supplement. Other circular approaches of upstream flows regard the possibility to valorize waste to produce biomaterials, biofertilizers, biofuels and energy, which, according to the BVP [22], have a lower bio-economic value but can be produced in large quantities. The reuse of shell waste is a topic of great interest among researchers, as shown by the review by Zhan et al. [52], which describes various applications in agri-food (e.g., for wastewater reclamation or the production of food additives), but also for other uses. Among the applications, calcium carbonate extracted from mussel shell has been studied for the creation of biomaterials [40]. For example, it is used as an ingredient for fireproof materials [97] as a substitute for gypsum or for absorbent materials that can treat water pollution by retaining dyes and oil [98]. Extracts from fish scales have also been used to produce collagen modified polyester as a novel textile material [99].

Mardones et al. [36], Lopes et al. [100] and Santos et al. [53] are some of the studies that emphasized the strategy of recovering farm output streams as soil conditioners in agriculture and forestry. Other already popular strategies are related to biodiesel production [101]. For example, after extraction from digestate of the more solid material for biofertilizer production, aquaculture or agricultural effluents can be used to grow algae, which could become biomass for fuel production [33]. Algae can also grow directly from residual farm sludge [36,41]. Algal biomass has been also exploited for thermal energy production and there are already cases of integration between shellfish farming, algae and thermal biorefineries [102]. In this vein, Tumilar et al. [103] described the realization of eco-industrial parks that integrate aquaculture with electricity and biofuel production.

Within the strand "open loop circularity strategies", the remaining 11% of the research gathers rather heterogeneous studies. These also include studies related to the valorization of waste from aquaculture technical streams, such as studies on the management of microplastics [104] and gear and nets from farming activities [43].

4. Conclusions

A revision of the knowledge in the field of the circular economy is needed now more than ever to understand in which direction the aquaculture sector is heading to undertake this transition. Bibliometric results have shown that the topic of circularity in aquaculture is registering great interest. This not only shows a positive trend, but also that the literature is still very recent and much still needs to be explored.

The network analysis highlighted three macro research areas, those focused on making the aquaculture system more circular and those that seek to apply these new strategies to input or output flows. These areas of research all relate to the need to devise strategies to ensure the regeneration of natural systems, and thus to encourage closed-loop actions. However, what emerges is the absence of systemic and synergistic approaches that take into account the multidimensional value of the circular paradigm, still applied to individual phases or to individual aspects of the supply chain.

In the content analysis, the different classifications revealed several gaps. Regarding the first level of classification, a large number of studies focused on the macro level, while lower numbers are recorded for the micro and meso ones. In the macro perspective, though highly fragmented, the research considers: (1) the political and social environment in which the aquaculture companies will operate in the future and (2) actions to guide production processes toward circular goods and services for new market opportunities. Few studies focus on citizen/consumer expectations. On the micro level, most studies focus on the search for sustainable proteins and their effects on aquatic metabolism. The meso studies concern the exchange of material and energy flows between the aquaculture system and the environment. On the meso side, there is a lack of studies proposing business classifications on financial economic and sustainability criteria as well as impact assessments. In relation to environmental impact, fewer than 15 studies proposing LCAs were found. The need to explore more about life cycles has been confirmed by Crovella et al. [105], who showed the lack of studies on aquatic products. The actions directed towards decarbonizing their cycle can be beneficial both to the environment and the society [106] and the future role of blue carbon ecosystems is understudied in terms of adaptation and mitigation options [107]. Moreover, there are still very few studies that attempt to measure the current socio-economic impacts (e.g., [10]) of the actual production and consumption models in order to assess the effectiveness of sustainability and circularity choices with a change in practices. In this sense, it is also relevant to remark upon the lack of studies related to the contribution that technological innovation could provide to the sector in order to foster the transition towards circular models, although this has been recognized by scholars (e.g., [108,109]) as a driver to achieve sustainability. The adoption of innovation could offer numerous benefits for producers' decision-making processes [108] and to bring the consumer even closer, as proposed by Mileti et al. [109] who reported the possibility of tracking biomass from multitrophic systems with the blockchain system. In addition, no studies have been found addressing the development of circular business models or the contribution of machine learning to the development of the circular economy, as is the case (e.g., [110,111]) for other economic sectors.

The second level of classification concerns studies analyzing circularity tactics in recirculating or otherwise integrated systems (the "closed-loop" category) and those that primarily envision CSs linking the aquaculture system with other industries (the "open-loop" category). Many studies dealt with closed systems (e.g., IMTA, aquaponics), whose attention has also increased in the more recent literature (e.g., [112–114]).

Analysis of studies categorized as "open-loop" shows numerous studies emphasizing how process waste management can open up a new frontier for nutrient recycling for various economic sectors, offering both low- and high-value bio-economic goods and services. The algae sub-sector, according to the high heterogeneity of waste-to-value proposals, shows the greatest potential and versatility. Indeed, algae are to date one of the most widely supported solutions as "game-changers for the green revolution" [115]. Within the "upstream phase" category, most studies dealt with circular proposals with high bio-economic value; mostly about the research of alternative proteins for feed use. On the other hand, in the case of research conducted on the "downstream phase", the circular proposals for the valorization of biomass were more heterogeneous—from biomaterials, bioenergy and fertilizers to the production of fine chemicals. The review by Cooney et al. [116], confirmed the potential of synergies that the aquaculture sector could develop with other economic sectors.

The need for further research, as well as the presence of strong regulatory voids both for "open-loop" and "closed-loop" solutions block the scalability of CSs [6]. Generally, most of the proposed closed systems or waste-to-value proposals remain experimental in many cases. In order to fully capitalize on the circular potential of the sector, better regulatory clarity would help markets for fish by-products and waste to develop faster. Furthermore, it is imperative to establish supportive policies encouraging industry investments and promote aquaculture's inclusion in policy discussions more, as is conducting market analyses to determine citizen–consumer acceptance [2,116–118].

The limits of the research could be related to the low number of collected papers, as the field of research is very recent. Indeed, the bibliometric analysis showed papers on the topic started to be relevant around 2015, probably for the presence of a structured EMFAF and for the launch of the Green Deal Plan at the European level. Another limit is that the results of the analysis are highly dependent on the initial research query and in particular on the chosen keywords.

The literature review, albeit recent and focused on a very specific topic such as CSs, offered food for thought, particularly regarding the identification of research threads that are developing around the sector. In the current historical context, the discourse on the future of food, particularly with regard to protein, has evolved into a scientific and media debate. In this regard, the aquaculture sector has the potential and responsibility to provide viable solutions for overcoming the challenges posed at the European and global levels [119]. The implementation of sustainability models that incorporate CE principles is integral to the feasibility of these challenges. Practically, making the CE the core pillar of the company vision and governance could be a key point for operators to start the blue transition. In this sense, implementing dedicated business models could be a vehicle to increase the diffusion of circular practices and innovation in the sector [120].

Implications for future research, operators and policy makers relate to the need to consider the aquaculture systems as more integrated with society, markets and the environment. This new perspective can be fruitful in terms of finding solutions to the current regulatory uncertainty, poor availability of data and lack of precise methodologies capable of providing information on the sector's potential to provide positive externalities. The multilevel perspective proposed firstly by De Rosa et al. [15] and then in this paper, could be a starting point to increasingly rethink, in a systemic way, the aquaculture production model's potential to offer concrete answers to society, and not just the scientific community.

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