Extended Bibliometric Review of Technical Challenges in Mariculture Production and Research Hotspot Analysis

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Review

Extended Bibliometric Review of Technical Challenges in Mariculture Production and Research Hotspot Analysis

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Abstract: The growth in population and the higher need for aquatic products make the aquaculture industry the world's fastest-growing food industry. With its rapid development, production is facing various challenges to achieve sustainability and cost-effectiveness. Some obstacles in production are related to the design of mariculture cages, automatization, location of the farm, biofouling, feeding, waste management, and others. This paper deals with the extended bibliometric analysis of technical problems in mariculture based on keywords, citations, journals, and other factors by means of scientometric software, CiteSpace, and VOSviewer. Important keywords related to aquaculture and mariculture were obtained from the Web of Science platform and further analyzed by means of the mentioned scientometric software offering knowledge domain visualization and construction of knowledge maps. Apart from the identification of research topics of the highest importance, research hotspots are characterized as follows: technical, biological, digital, and environmental. The most cited articles are related to the environmental problems and solutions in marine aquaculture and the study of biofouling and how to control it. Other important documents with high citation rates are related to the cages, offshore mariculture, location conditions, and sustainability. This study recognizes trends by combining aquaculture production with floating structures for energy extraction of sea resources; thus, making aquaculture more interdisciplinary than before.

Keywords: aquaculture; mariculture; fish farming; scientometrics; CiteSpace; VOSviewer

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1. Introduction

Aquaculture includes the production of aquatic animals such as fish, molluscs, crustaceans, and aquatic plants and it has been one of the fastest-growing food industries for decades. Unlike capture production, which is mature in both fishing technology and fish processing, aquaculture is still a rising and developing area. Global aquaculture production reached 122.6 million tonnes in 2020—87.5 million tonnes of aquatic animals, and 35.1 million tonnes of algae [1]—and according to The World Bank [2] it hit a record of 126 million tonnes in 2021. In 2020, the highest levels of expansion in aquaculture were recorded in Chile, China, and Norway, while aquaculture production expanded in locations worldwide, except in Africa where the production decreased in the two main production countries, Egypt and Nigeria [1]. East Asia and the Pacific region had the highest aquaculture production with 94 million tonnes in 2018 [3].

Based on the salinity, there is freshwater and saltwater production, and based on the habitat, there is land-based or water-based aquaculture [4]. Mariculture production is the production of aquatic animals in salt water in a marine environment under the impact of waves, sea currents, wind, and other factors. Nowadays, global mariculture production accounts for approximately 40% of total aquaculture production; approximately 75% of mariculture production is related to crustaceans and molluscs production; while the remainder belongs to finfish production, including high-value marine and brackish water species (e.g., salmon, bream) in intensive farming systems in cages and net pens [5]. The increase in total mariculture production over the years is illustrated in Figure 1 which was generated according to data available in [1].

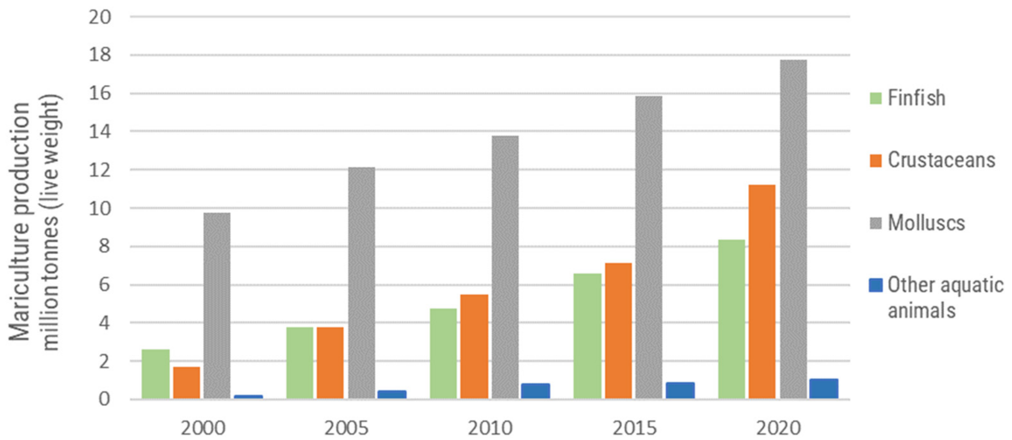

Figure 1. Mariculture production through the years according to [1].

Mariculture production begins with rearing from a land-based hatchery and, in some cases, in freshwater, as is the case with Atlantic salmon. When a fish reaches the appropriate weight and size, in the cages, it is then caught and transported to the harbor, and, later, to the factory for fish processing. This latter part of the production includes processing such as washing, chilling, skinning, filleting, cooking, smoking, salting, drying, preserving or canning, and dispatching [6].

1.1. Environmental and Technical Challenges in Mariculture Production

Mariculture has direct consequences on the environment, which are attributed to fish farm waste and potential effects on endemic species due to the introduction of non-native species or disease propagation, as well as indirect effects related to the production of fish feed [7]. Other types of marine pollution are eutrophication, acidification, toxins, plastics, and microplastics. Increased nutrient concentrations can cause eutrophication by increased phytoplankton production [8]. Fish convert part of the food into their biomass, and part is excreted as waste products of metabolism into the environment. The possible impact of fish farms on the seabed comes from the organic load caused by the intake of fish metabolites (feces, urine, and gill secretions) and to a less extent from uneaten food from the farm during the rearing cycle [9]. The fish-producing process generates solid and liquid waste such as ammonia, nitrites, phosphates, and other dissolved compounds in farming water [10], as well as CO_2, while their treatment represents challenges, as discussed in [11,12]. The presence of plastics and other sources of marine rubbish (bottles, cans, fishing gear, etc.) and their impact on the sea conditions and sea products were studied in [13–15]. Feng et al. [16] discovered microplastics in several fish species from mariculture production, where microplastics were attached to non-digestive tissues (skin and gills), and in the digestive tissues of the fish stomach, which can harm human health from eating fish.

To deal with the environmental problems, but also to improve the existing production, both producers and researchers are continuously looking for ways to ensure the long-term viability of production practices, their efficiency, and profitability. Gavrilović and Jug-Dujaković [17] investigated water quality, the increase in the number of diseases, and other factors which force producers and researchers to develop and apply new, more ecologically and economically acceptable technologies. Technical challenges in mariculture are illustrated in Figure 2. With the depletion of marine resources, efficient fishing output becomes increasingly important. Production input intensity, the scale of the operation, operator experience, education and training, adoption of new technology, and a variety of other management issues have an impact on production efficiency [18]. According to Rguez-Baron et al. [19], challenges to the development of sustainable mariculture production are:

- Production planning;
- Infrastructure and logistics;
- Energy;
- Regulatory adjustments;
- Safety.

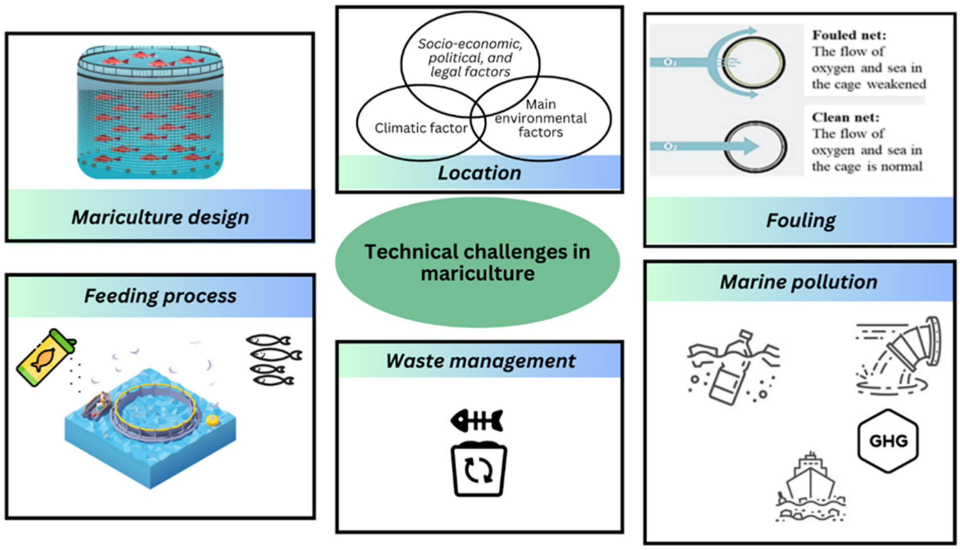

Figure 2. Technical challenges in mariculture.

The selection of the production location and the success of a project are heavily affected by non-technical factors such as the acceptability of the fish produced (consumer choice), marketing facilities, labor availability, as well as certain political or legal issues [20], while technical factors include design (cage and whole farm structure), waste management, feeding process, among others. Regarding accessibility, the geographic position is fundamental, while durability in higher waves allows for the potential of translocating maricultural objects farther offshore. Wind conditions, currents, water depth, and seawater parameters appropriate for individual species must be considered before establishing a fish farm. One of the most essential aspects of the design of a fish cage system, Figure 3, is predicting the wave forces operating on it, as well as structural integrity and economic sustainability. There are many criteria for defining the final type of cage production, and some were studied in [21–25]. Net cages of various types are used around the world to increase productivity. They can be of different shapes (square, rectangular, round, etc.), and net weights made of different materials (polyethylene, polyester, polyamide, polypropylene, etc.). Cage farming in the Adriatic Sea and the Mediterranean is still based on floating round cages, while submerged cage structures are increasingly being used in ocean farming.

The location of the fish farm greatly affects the quality of production. Peaceful locations with high water quality far from the tourist spots and ports are more suitable. Differences between offshore and coastal farming are presented in Table 1, according to [26].

Table 1. Differences between coastal and offshore farming.

	Coastal Farming	Offshore Farming
Distance	<500 m from shore	>2 km from the shore
Depth	<10 m	>50 m
Waves	1 m	Up to 5 m
Accessibility	100%	80%

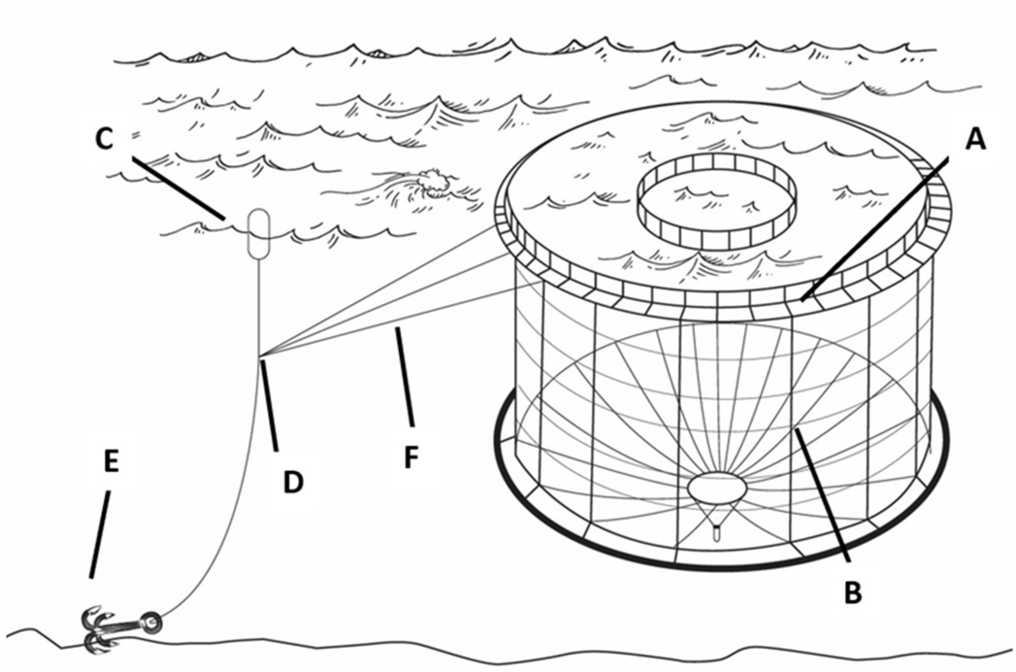

Figure 3. Schematic drawing of a cage and mooring system: A—HPDE pipe (high-density-polyethylene); B—net cage; C—mooring buoy; D—corner plates or ring; E—anchor; F—grid rope (poly steel rope).

Based on Figure 2, another important factor for viable mariculture production is fish feed, and most of the production costs are related to the feeding process. Rethinking mariculture production with an integrated mentality will be required to address the simultaneous issues of feed and energy demands, land and water requirements, and customer preferences [27]. Feeding can be operated manually or automatically, but it is more efficient to use automatic feeders. The feeding procedure accounts for around 50–75% of total expenses [6]. Some of the research that dealt with feeding technologies are conducted in [28–30].

A major problem that occurs in mariculture production is biofouling. Biofouling accumulation invading fish farms is thought to have largely negative consequences on the fish inside the cages, resulting in financial loss [31,32]. Lane and Willemsen [33] and Cronin et al. [34] studied the direct economic consequences of biofouling control. Biofouling growth is relatively fast because the waters surrounding mariculture operations are enhanced by organic and inorganic wastes (uneaten food, and fecal and excretory material) produced by high-density fish populations [35]. Ashraf et al. [36] studied the resistant biofouling cage nettings. Thus, the key focus in fish culture is on net fouling reduction, as this leads to damaged cage structure [37], and affects the fish's health, primarily due to limited flow-through of water, resulting in inadequate dissolved oxygen availability.

Mariculture development requires a number of natural resource inputs, such as high-quality water or space, food, or fingerling sources, as well as disease and predator control systems [38]. Proper planning and placement of the production program will increase the likelihood of return on investment for the individual mariculture project and contribute to the improvement of economic effects [39]. Garlock et al. [40] and Kumar and Engle [41] studied the production costs and innovative, intensive manufacturing technologies.

1.2. Development of Sustainable Aquaculture

Sustainability in aquaculture implies environmentally friendly, economically, and socially acceptable production. Hancock et al. [42] illustrated a three-pillar model (environmental, economic, and social) of sustainability. The environmental pillar refers to mariculture production considering pollution issues and the possible solution. The economic pillar considers all costs, and based on them, calculates the profitability over a longer period. The social pillar is focused on developing a socially acceptable production based on current trends and focuses on the human population in different terms (employment, profit, habitability, tourism development, etc.).

Worldwide, there are different regulations, funding, and projects with the goal to support and implement more sustainable methods in production. For example, the EU funded the development of the 'Monitoring Guidelines and Modelling Tools for Environmental Effects from Mediterranean Aquaculture' (MERAMED) program, which investigates environmental interactions near fish farms in the Mediterranean and develops models, methodologies, and standards for production optimization as well as environmental evaluation and monitoring [43,44]. The project, 'Monitoring and Regulation of Marine Aquaculture' (MARAQUA), focuses on a review of existing data and the development of agreed-upon rules for monitoring and controlling marine aquaculture and provides scientific recommendations [43]. Usage of the voluntary Eco-Management and Audit Program in the mariculture sector is expected to enhance productivity transparency while also improving resource management and environmentally sound practices [45].

Sociocultural and economic assessments are critical components in a thorough study of coastal resources and future mariculture development, and these assessments provide an economic framework within which adaptation strategies (solutions) can be investigated. A policy framework for coastal and marine management must address cross-sectoral concerns that jeopardize coastal resource management and national development planning [43]. The approach is to study and analyze existing institutional and legal frameworks for integrated coastal and marine management and mariculture development potential (including laws and enforcement) [43].

Research into the implementation of alternative power options into mariculture farms, with emphasis on renewable energy sources (RESs), indicates that both environmental and economic benefits are achievable with their higher share. Countries with many islands, isles, and rocks, are environments that are full of channels, coves, and bays, and represent good protection from strong winds, waves, or currents [46].

1.3. Research Gap, Aim, and Contribution of the Paper

The literature review presented above confirms that mariculture is a very important, wide, and propulsive field with extensive research content, ranging from broad theoretical analyses to case studies focusing on specific issues. However, some aspects such as sustainability and emerging digital technologies in this field appear in more recent references, implying their importance in the future. Therefore, an extensive bibliometric study in this area is needed to review the development process and to identify current research hotspots as well as future research directions. The contributions of this work can be summarized as follows:

- Detection of emerging topics in the field of mariculture published in the last decade;
- Summary of the conducted research and illustration of major knowledge groups in the field;
- Identification of the most cited journals and authors in the field;
- Identification of research hotspots;
- Summary of the current status and possible future development trends;
- Advantages and drawbacks of CiteSpace and VOSviewer and their differences for scientometric purposes, where the mariculture field is taken as a test case.

The novelty of this paper is to provide a broader insight into problems and challenges in aquaculture, with the use of scientometrics tools. Bibliometric analysis is a useful tool for searching the intellectual structure of a specific research field, handling large amounts of scientific data, and producing high-impact research. One of its strengths is the flexibility while it allows researchers to easily handle the data imported from various databases such as Scopus or Web of Science. Bibliometrics can be descriptive, such as counting the number of articles published by organizations or countries, as well as evaluative, such as using citation analysis to determine how those articles influenced other authors. While counting publications is useful for some comparisons, citation analysis allows us to look at the impact those articles have on others. The bibliometric analysis enables and empowers scholars to gain a comprehensive overview, identify knowledge gaps, generate novel research ideas, and position their contributions to the field. Well-conducted bibliometric studies can offer a solid starting point for advancement in a specific field in novel and meaningful ways.

In this paper, the CiteSpace and VOSviewer platforms are used as complementary tools for greater field coverage. Data selection is primarily based on research topic and keywords, and distinguished by authors, journals, and countries. CiteSpace is well-known and used around the world to review articles [47]. The program has clarity and interpretability of visualizations and visual analytic capabilities [48] and can be used to detect landmarks, hotspots, developing trends, and important points in a series of publications [49]. Users can navigate and explore various patterns and trends discovered in scientific papers, developing a wider grasp of the scientific literature than an unguided search through the literature. VOSviewer can display a map in a variety of ways, each highlighting a distinct facet of the map. The programs' viewing capabilities are notably beneficial for maps with at least a relatively significant number of elements (e.g., at least 100 items) [50]. The VOS mapping approach helps to lay out things on the maps and elements' location will reflect their similarity [51].

2. Methodology

2.1. Introduction to Analysis Tools

The interdisciplinary subjects of applied mathematics, information science, and computer science are all involved in scientific mapping. It is a new scientometrics and information metrology advancement. The scientometrics research community can help meet the demand of visualizing and analyzing the literature research in two ways: by developing quantitative techniques that use research process outputs to provide an assessment of the research process's efficiency and effectiveness, and by improving understanding of the characteristics of the research process itself [52].

CiteSpace is a Java-based computer tool for visualizing and evaluating the literature of a scientific area, or a knowledge domain [53], and it was used in this paper for analyzing the keywords in the field of mariculture.

VOSviewer is a bibliometric analysis software for constructing knowledge maps developed by Leiden University [50], and it can be used to perform co-word, co-citation, and literary coupling analyses [54].

Both programs, CiteSpace and VOSviewer, have their advantages and drawbacks which are summarized in Figure 4.

For example, one of the important factors for searching and analyzing the data is the time span, and it is possible to choose the appropriate time span in CiteSpace; this is not possible in VOSviewer. Comparatively, the VOSviewer offers slightly more efficient visual representations, in addition to heat maps. The most convenient function of the VOSviewer is the direct hyperlink to the web page of the published paper.

2.2. Data Collection

The collection of the required analysis data began with a search and filtering of articles, Table 2, in the Web of Science [55]. Firstly, a respected and comprehensive bibliographic database to provide broad access to high-quality journal articles as trustworthy sources of knowledge was chosen. Secondly, was the selection of the papers from a bibliographic database using appropriate keywords, with specific attention paid to the validity and representativeness of keywords. After searching for a certain topic, every publication related to the topic appeared. Then, data were filtered with the topic and appropriate keywords, which are illustrated in Figure 5.

Table 2. Search process in Web of Science.

Step	Action	No. of Articles
1	Keyword Search "aquaculture" OR "mariculture" OR "marine pollution" AND "environment*pollution" OR "waste management" OR "biofouling" OR "marine structures" AND "cage* net cage* wave* current" OR "location" AND "depth*water quality* RES"	176,383
2	Citation Topic Meso "Marine Biology", "Membrane Science", "Sustainability Science", "Bioengineering", "Energy and Fuels", "Management", Water Treatment", "Safety and Maintenance", "Water Resources", "Biosensors", "Knowledge Engineering and Representation", "Ocean Dynamics", "Design and Manufacturing", "Environmental Sciences", "Software Engineering", "Risk Assessment", "Oceanography, Meteorology and Atmospheric Sciences", "Remote Sensing", "Testing and Maintenance"	79,249
3	Web of Science Categories "Environmental Sciences", "Engineering Environmental", "Fisheries", "Water Resources", "Energy Fuels", "Environmental Studies", "Computer Science Artificial Intelligence", "Materials Science Composites", "Materials Science Characterization", "Ecology", "Oceanography", "Materials Science Multidisciplinary", "Materials Science Characterization Testing", "Engineering Multidisciplinary", "Energy Ocean", "Engineering Manufacturing", "Remote Sensing", "Engineering Marine"	52,391
4	Publication Titles "Aquaculture", "Desalination", "Journal of Cleaner Production", "Waste Management", "Aquaculture Research", "Desalination and Water Treatment", "Sustainability", "Water Research", "Resources Conservation and Recycling", "Waste Management Research", "ACS Applied Materials Interfaces", "Environmental Pollution", "Water Environment Research", "Fuel Processing Technology" "Journal of Environmental Sciences", "Marine and Freshwater Research", "Fishes", "Bulletin of Marine Science", "Aquaculture Economics Management", "Journal of Sea Research", "Estuaries and Coasts", "Water Science and Technology", "Science of the Total Environment", "Bioresource technology", "Aquacultural Engineering", "Journal of Environmental Management", "Aquaculture International", "Environmental Science and Pollution Research", "Chemical Engineering Journal", "Environmental Science Technology", "Marine Pollution Bulletin", "Applied Energy", "Renewable Energy", "Ecological Modelling", "Clean Technologies and Environmental Policy", "Journal of Environmental Engineering", "Energy Policy", "Environmental Earth Sciences", "Fisheries Management and Ecology", "International Journal of Environmental Technology and Management", "Reviews in Fisheries Science", "Journal of the World Aquaculture Society", "Reviews in Aquaculture", "Journal of Material Cycles and Waste Management", "Journal of Hazardous Materials", "Frontiers in Marine Science", "Water", "Marine Ecology Progress Series", "Marine Policy", "Environmental Science Water Research Technology", "Environmental Research", "Environment Development and Sustainability", "Environmental Engineering Science", "Reviews in Fisheries Science and Aquaculture", "Water Science and Technology Water Supply", "Applied Mechanics and Materials", "Frontiers of Environmental Science Engineering", "Mediterranean Marine Science", "Energies", "Journal of Water Process Engineering", "Renewable Sustainable Energy Reviews", "Journal of Experimental Marine Biology and Ecology", "Fuel", "Aquaculture Reports", "Energy Fuels", "Ocean Costal Management", "Fisheries Research", "Management of Environmental Quality", "Environmental Management", "Reviews in Fish Biology and Fisheries", "Sustainable Production and Consumption", "Materials", "Fisheries", "Aquaculture Environment Interactions", "Environmental Technology", "Journal of Environmental Chemical Engineering", "Aquaculture Nutrition", "Environmental Engineering and Management Journal", "Environmental Monitoring and Assessment", "International Journal of Life Cycle Assessment", "Remote Sensing", "Journal of Environmental Protection and Ecology", "Journal of Marine Science and Engineering", "Ocean Engineering", "Energy Conversion and Management", "Water Practice and Technology", "Fish and Fisheries", "Water Resources Research", "Ecological Engineering", "Fisheries Science", "Aquatic Living Resources", "Regional Studies of Marine Sciences", "Aquatic Conservation Marine and Freshwater Ecosystems", "Critical Reviews in Environmental Science and Technology", "Journal of Ecological Engineering", "Reviews in Fisheries", "ICES Journal of Marine Science", "Energy", "Marine Environmental Research", "International Journal of Environmental Science and Technology", "Marine Biology Research", "Oceans IEEE"	33,415
5	Language "English"	33,403

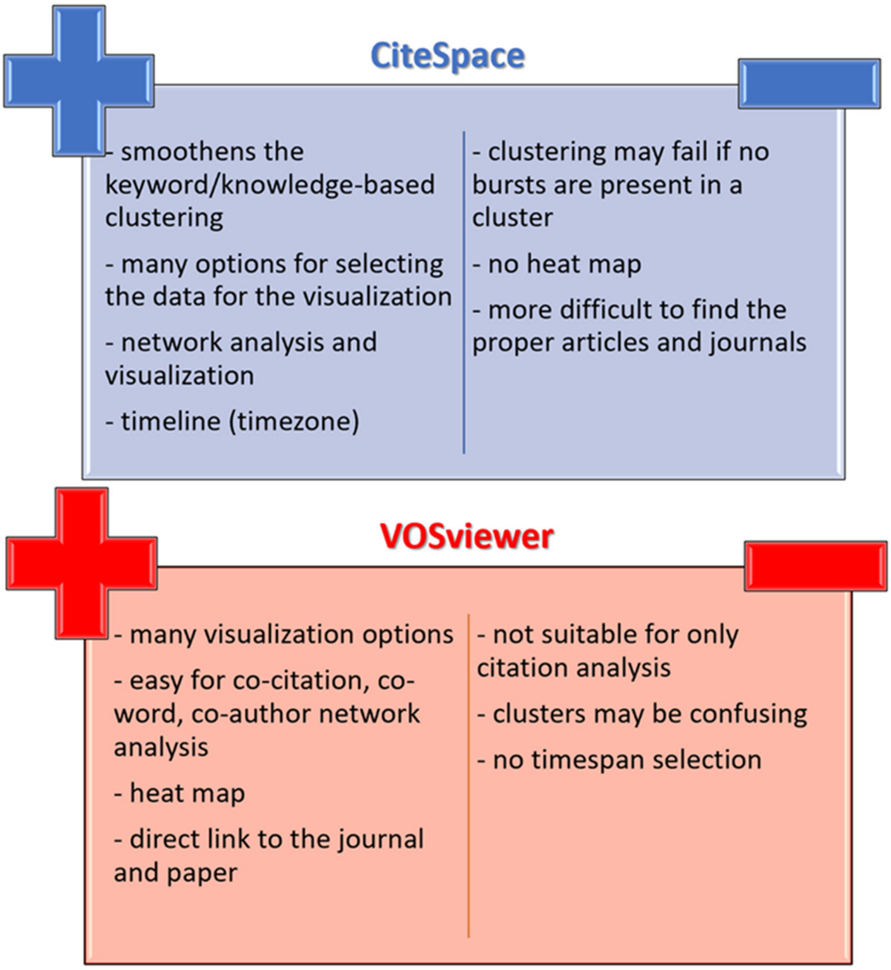

Figure 4. Advantages and drawbacks of programs CiteSpace and VOSviewer.

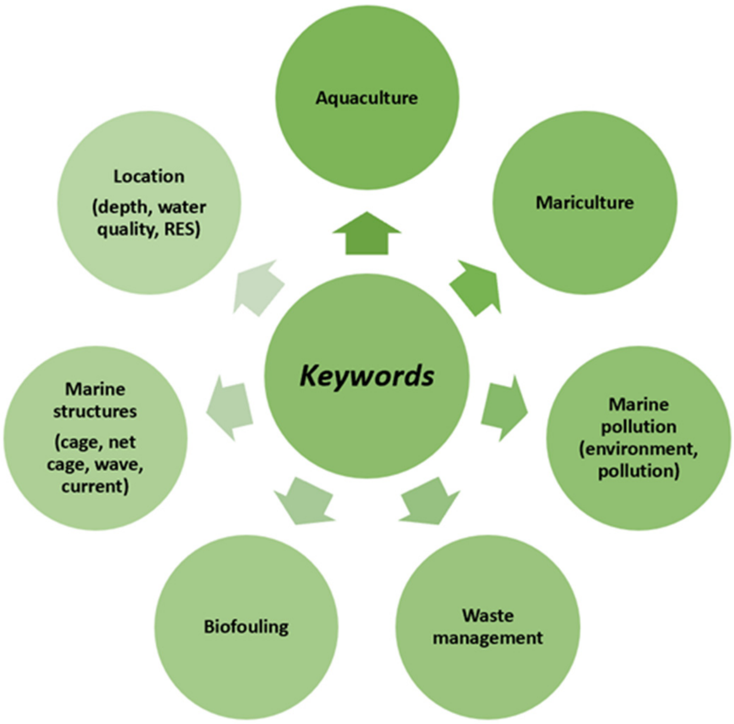

Figure 5. Keywords used as a searching tool in WoS.

These keywords were input data for searching the appropriate literature to analyze which problems and challenges occur the most in the field of mariculture; and among the technical problems, which keyword is the most cited and studied and which problems need more research. The flowchart of the application of CiteSpace and VOSviewer for the bibliometric survey is shown in Figure 6.

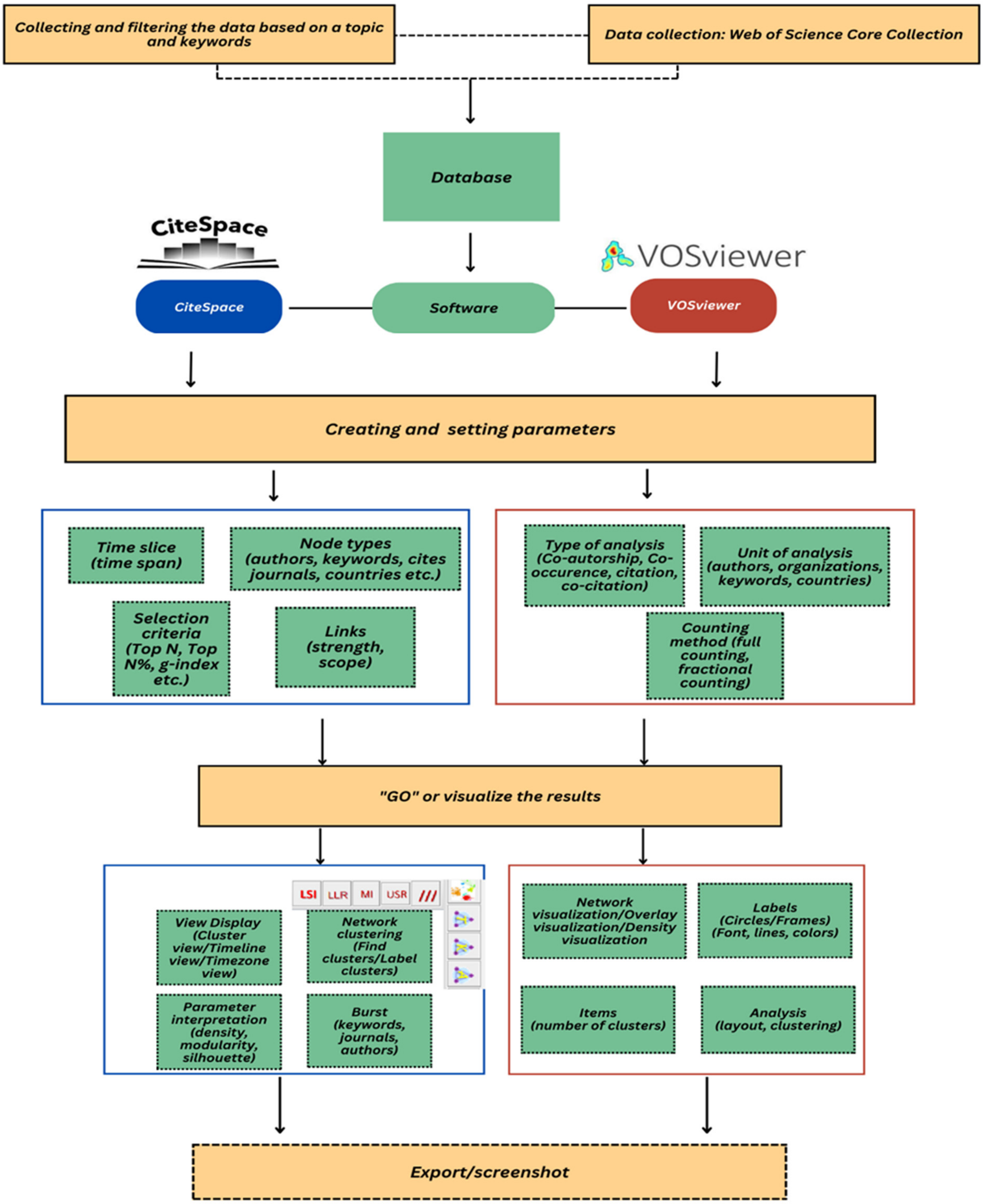

Figure 6. Flowchart of bibliometric analysis by CiteSpace and VOSviewer.

The first analysis was based on authors, title words, and keywords in the time range from 2013 to 2022, and the additional range from 2018–2022. Since keywords give a brief and exact high-level description of a text, keyword co-occurrence analysis is useful to show emerging trends and follow study topics across time. Keyword co-occurrence analysis based on CiteSpace involves two basic procedures: one procedure is to extract the keywords, then separate and categorize them to compute the frequency; the other procedure is to acquire a keyword co-occurrence matrix used for the analysis of keyword co-occurrence [48].

3. Results

3.1. Citation and Keyword Analysis

After analysis of technical problems and general research topics in mariculture, a visual representation of the results was made. Firstly, a citation report was performed, and as can be seen in Figure 7, publications related to mariculture in the period from 2017 to 2022 were analyzed together with citations. Publications reached a peak in 2021, and the number of citations in 2022 followed exponential growth. Figure 7 shows a growing interest in mariculture research, especially in 2020.

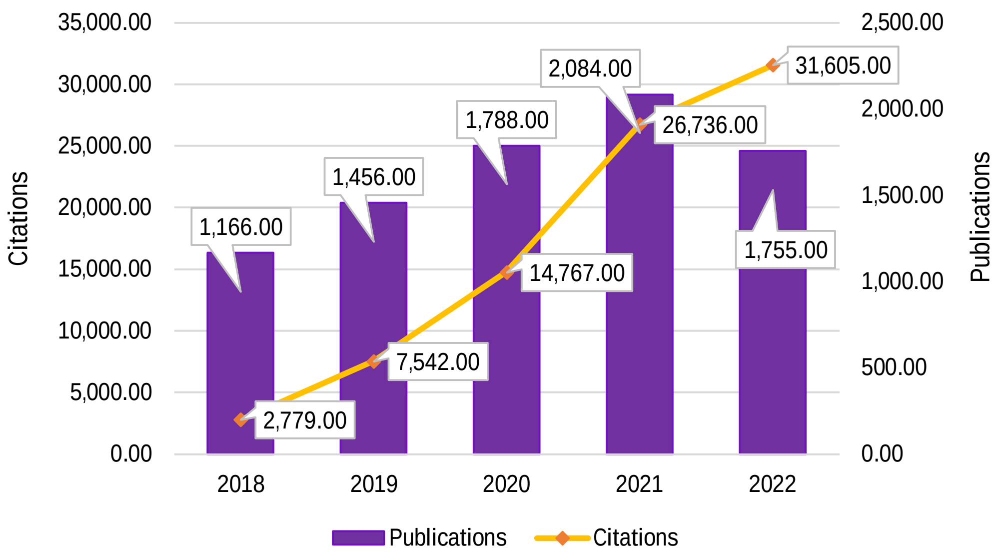

Figure 7. Number of publications and citations in the field of mariculture over time.

Figure 8 presents the results of keywords analysis from the references related to technical problems from 2013 to 2022. The colored parts are called clusters, while the numbers denote their relevance. Cluster #0, cage deformation, is the largest cluster and most often present in the published references, followed by cluster #1, farm waste, and cluster #2, environment. These clusters show trends in research on aquacultural problems in the observed period.

In Figure 9, keyword clusters for the period between 2018 and 2022 are shown. In the latest studies, fish cages represent the most common keyword in the studies, followed by solid waste as cluster #1, and Vietnamese aquaculture as cluster #2.

There are 43 clusters found in Figure 8 based on the research data from 2013 to 2022, and 22 clusters in Figure 9 based on the research data from 2018 to 2022.

Cluster #0 consists of studies related to the cages where Cheng et al. [56] proposed how to choose the type of fish cage as well as practical guidance for cage construction by using parametric research of five commonly used fish cages that take five circumferences of the floating collar, five depths of the net bag, five weights, and nine current velocities into account. Zhao et al. [57] analyzed choosing the fish cages using the artificial neural network. Liu, Wang, and Guedes Soares [58] used the finite element approach to investigate the mooring force in a fish cage array subjected to currents and waves. The benefits and drawbacks of various fish cage design to guide the viability of offshore fish farming were studied by Chu et al. [59]. Co-location with other synergistic businesses is explored as a possible future offshore fish farm model. Measurements of turbulence and flow field alterations inside a fish cage were conducted by Klebert and Su [60]. Their measurements revealed that, inside the cage, while the schooling fish lowered the flow, there was no evidence that they generated secondary radial and vertical flows.

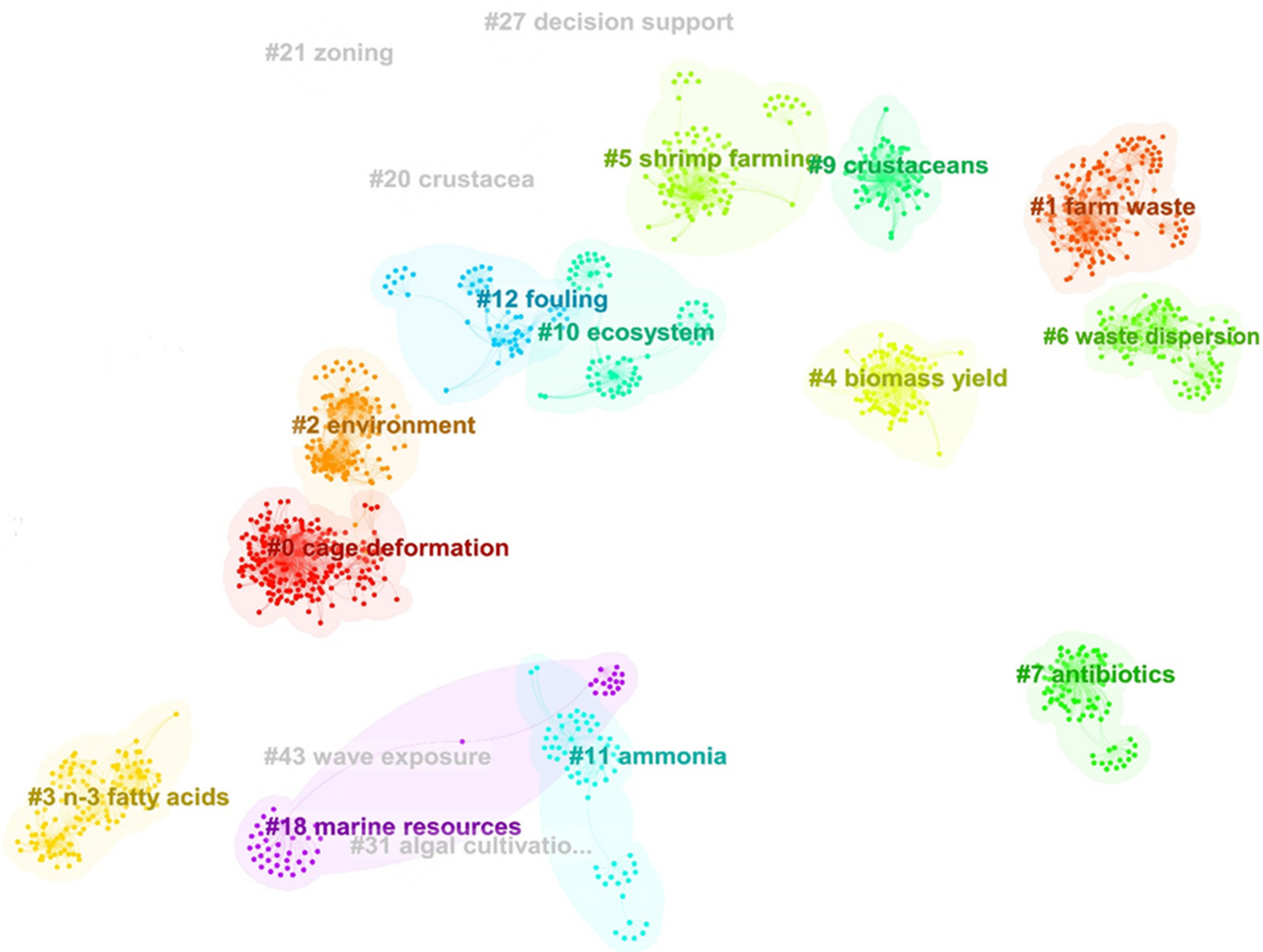

Figure 8. Clusters based on keywords 2013–2022.

Clusters #1 and #2 include waste and environmental problems in mariculture/aquaculture. Waste from open-cage mariculture, including uneaten feeds, feces, and dissolved nutrients, enters the marine environment immediately. Sustainable management outcomes are frequently based on waste distribution patterns, with biochemical tracing serving as a significant technique in understanding mariculture's footprint. White et al. [61] investigated the use of fatty acid (FA) analysis to trace marine aquaculture waste for this purpose, to discover specific biomarkers for environmental applications, and identify common problems. A review by Ramli et al. [62] studied the performance and practicality of incorporating an algal reactor into recirculating aquaculture systems (RAS). Considering the use of fish waste, Baltadakis et al. [63] investigated if juvenile European lobsters would eat waste from Atlantic salmon cages in a coastal integrated multi-trophic aquaculture (IMTA) configuration, and what effect it would have on growth. Schumann and Brinker [64] highlighted potential sources of solid waste in salmonid aquaculture, as well as the qualities of those solids and their consequences for system stability, and the quality of associated ecosystems.

The review of Lacoste et al. [65] summarized the major ecological interactions between off-bottom shellfish aquaculture and the environment, introduced research on the influence of benthic diversity on ecosystem functioning, and proposed a holistic approach to conducting aquaculture-environment studies. As part of this cluster, there are studies related to biofouling problems too. Giangrande et al. [31] proposed a monospecific system dominated by mussels and a multi-specific system with sabellids and mussels as the most abundant filter-feeders as candidates for bioremediation in integrated multitrophic aquaculture facilities. Montalto et al. [66] conducted research where biofouling assemblages associated with aquaculture facilities may help to reduce environmental effects while serving as input for re-use in other professions. Sievers et al. [67] combined heat and acid treatments for biofouling prevention which was revealed as successful. Park et al. [68] proposed benchmarks for numerical models in assessing the potential environmental impact of fish farm sites. In addition, Park et al. [68] and Welch et al. [69] performed research on the integrated approach and nutrient footprint including problems such as pollution, net materials, and biofouling.

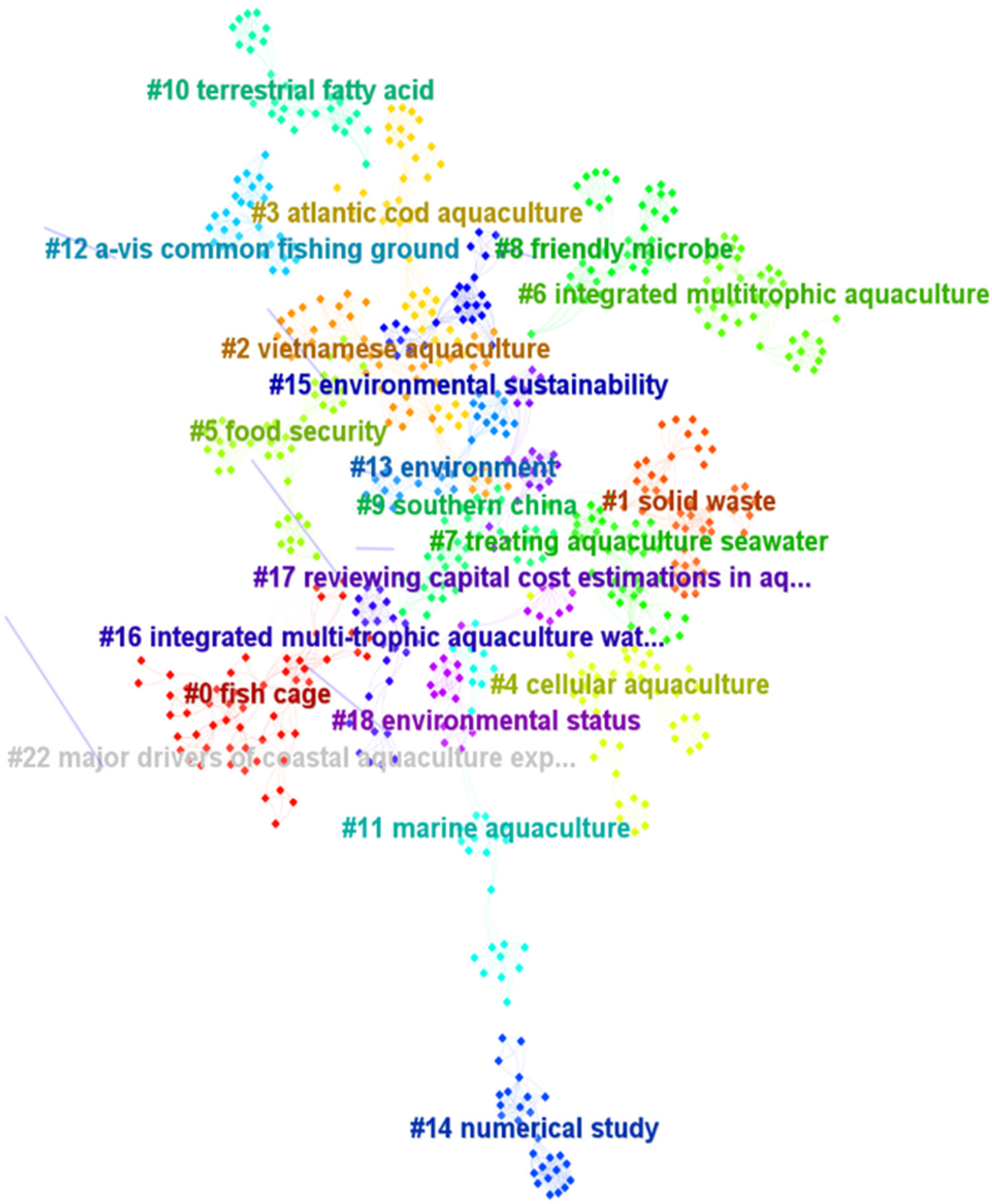

Figure 9. Keywords clusters from 2018–2022.

By analyzing the keywords in VOSviewer it is possible to see the interactions and amount of the most common keywords with co-occurrence analysis where the relatedness of items is determined based on the number of documents in which they occur together (Figure 10). The keyword "aquaculture" is the biggest cluster, followed by "environment" (grey cluster), "fish cage" (blue cluster), "mariculture", and others. Clusters differ in colors, but here it is not straightforward to see which authors used specific keywords.

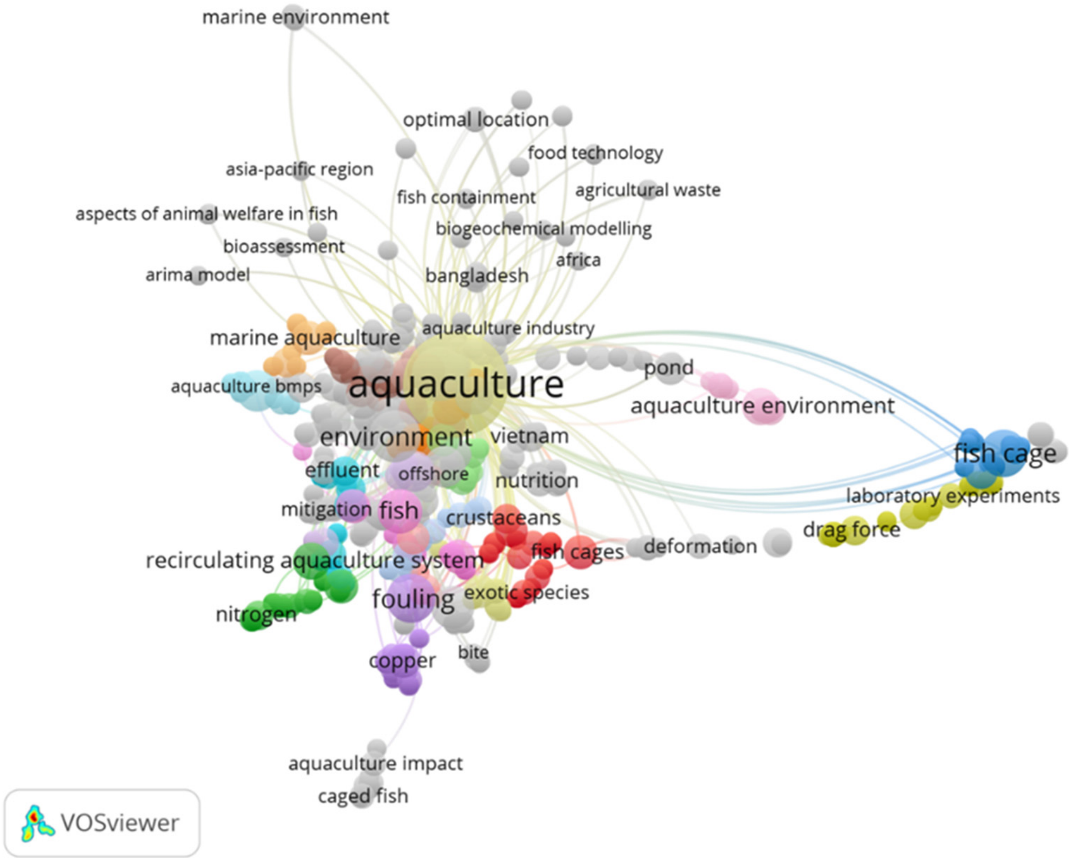

Figure 10. The most often used keywords in the documents related to the topics of aquaculture and mariculture.

3.2. Identified Hotspots

Hotspots are divided into four sections: technical, biological, digital, and environmental. Keywords are separated into these sections to show which parts of the production are studied the most and what they are related to. Figure 11 shows that, according to the keywords, the research focuses on the main categories—technical, biological, digital, and ecological. In terms of technology, many references deal with the construction of cages, forces, fouling, waste management, etc. The biological aspect is quite developed because for many years the main focus was on the organism itself (fish, shellfish, or others), which is why keywords are mostly related to diseases, viruses, or nutrition. Although specific focuses of publications can be found, all categories are interconnected and influence each other's outcomes. A good example is digitalization itself, where a database is established with the help of technological procedures (for example, numerical study), and then artificial intelligence or machine learning is introduced for faster and more efficient progress. The ecological component brings together all mentioned categories and tries to find the optimal contribution of methods and viewpoints to achieve a responsive, ecologically acceptable, and economically beneficial mariculture.

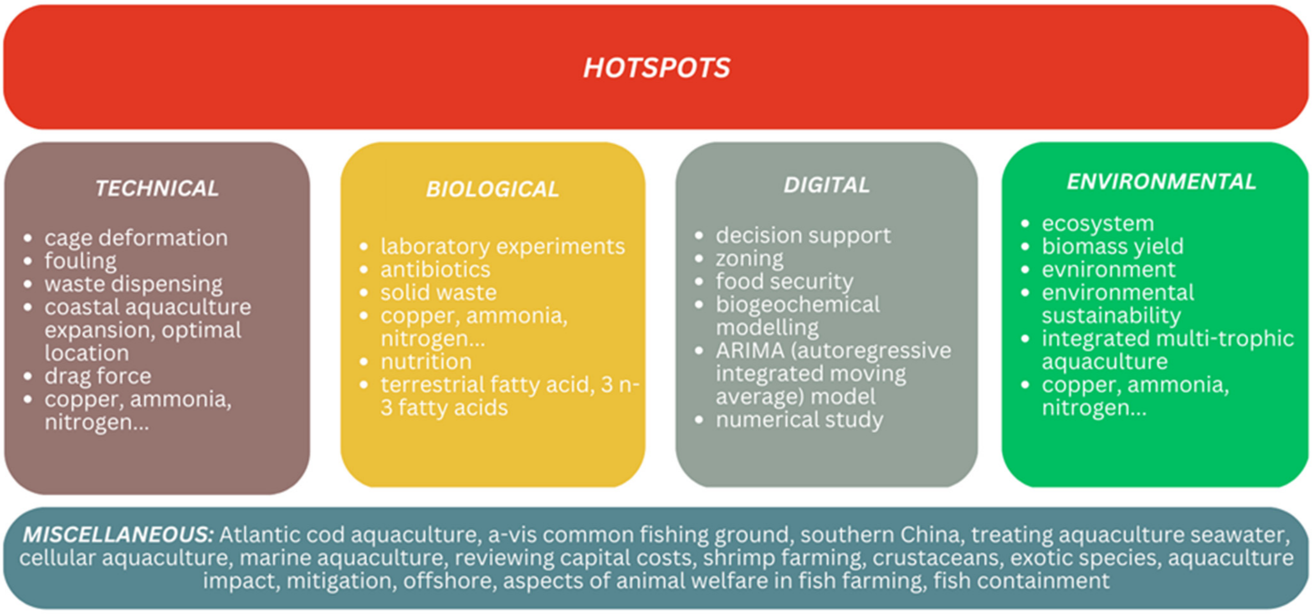

Figure 11. Research hotspots in mariculture based on the literature overview.

3.3. Authors' Analysis

In Figure 12, the most cited authors and their works are presented. Cluster #1 (red cluster) represents the most cited document of Troell et al. [70] which deals with ecological problems and solutions in mariculture production. In that cluster, there are studies into biofouling, marine aquaculture environment, and economic analysis by Montalto et al. [66], and the importance and role of GIS modelling to evaluate location for offshore farms [71]. In cluster #2, or the blue cluster, the most cited document is from [32], which is about biofouling. E-Jahan, Ahmed, and Belton [72], Tacon and Metian [73], and Alexander et al. [74] performed research into the food in mariculture where the focus is based on the stakeholder perceptions of conventional aquaculture which have been studied in terms of danger, influence on other users of mariculture and consumer aspects. In [59,75], cages for offshore mariculture and the concept of offshore fish farming are based on a united viewpoint, and the limitations of going offshore are highlighted. The review of Lulijwa et al. [76] focuses on the current state of antibiotic use, as well as the consequences on animal health and the environment. Most of these papers are related to sustainability [77,78]. Studies [79–81] are related to the analysis of mariculture, the development of mariculture, and the heat sensitivity of the species. Then, scientific guidance on the mariculture industry layout, modern ecological farming patterns, the development of mariculture technologies and pollution treatment facilities, as well as tools to assess risks in mariculture production and suggested solutions for future mitigation and adaptations, are urgently required to facilitate balanced sustainable development of mariculture [79,80,82]. According to [83], nutrients from mariculture will increase up to sixfold by 2050, exceeding the nutrient assimilative capacity in places of the world where mariculture growth is currently high. Ruff et al. [84] create a framework for greater insight into the role of government in mariculture development that is relevant across regions, giving useful context for identifying opportunities and challenges to mariculture expansion. Ruff et al. [84] stated that using sustainable culture systems is the key to improving and preserving the long-term health of mariculture zones and suggest moving farms offshore, and Liu and Su [85] presented the importance of the ecosystem on the example of China and how to prevent bigger marine pollution and negative impact on the environment.

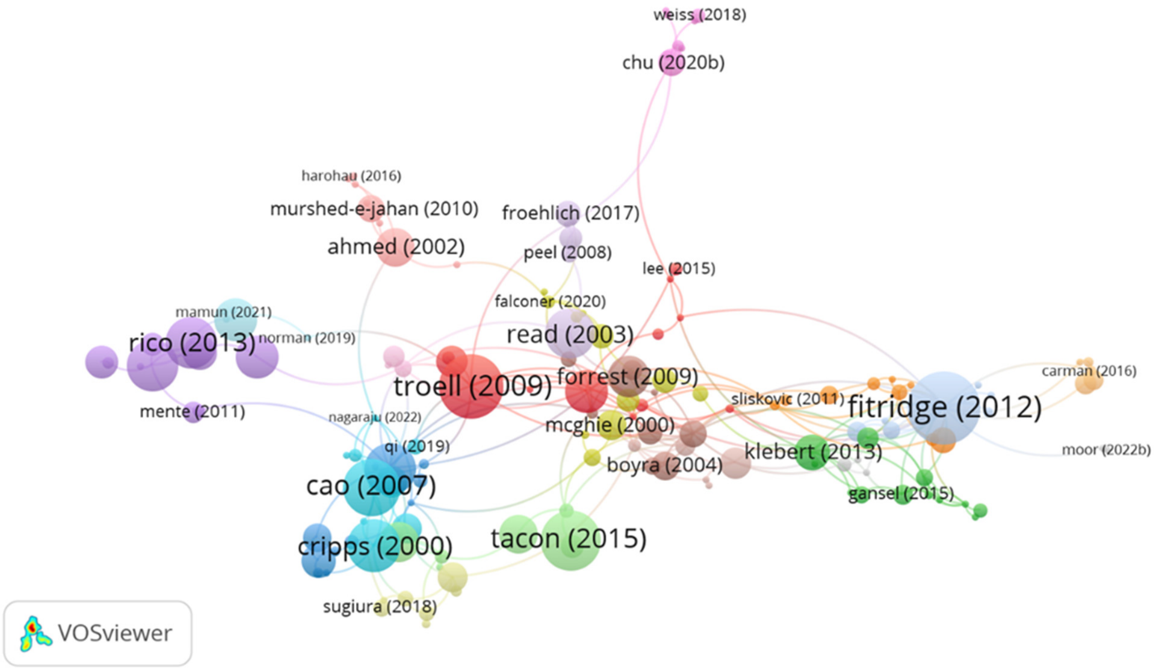

Figure 12. Authors of the most cited documents.

The same analysis was performed in CiteSpace as well, Figure 13, and based on the CiteSpace visualization the most cited paper is authored by Fitridge et al. [32] dealing with the impact and control of biofouling in mariculture. Related to the topic of biofouling, there are studies [37,86–90]. Food security and potential risks for mariculture were studied and most cited by Godfray et al. [91], Rosa [92], and Naylor et al. [93]. Cage, offshore mariculture, and how to make production more sustainable are discussed in [94–96].

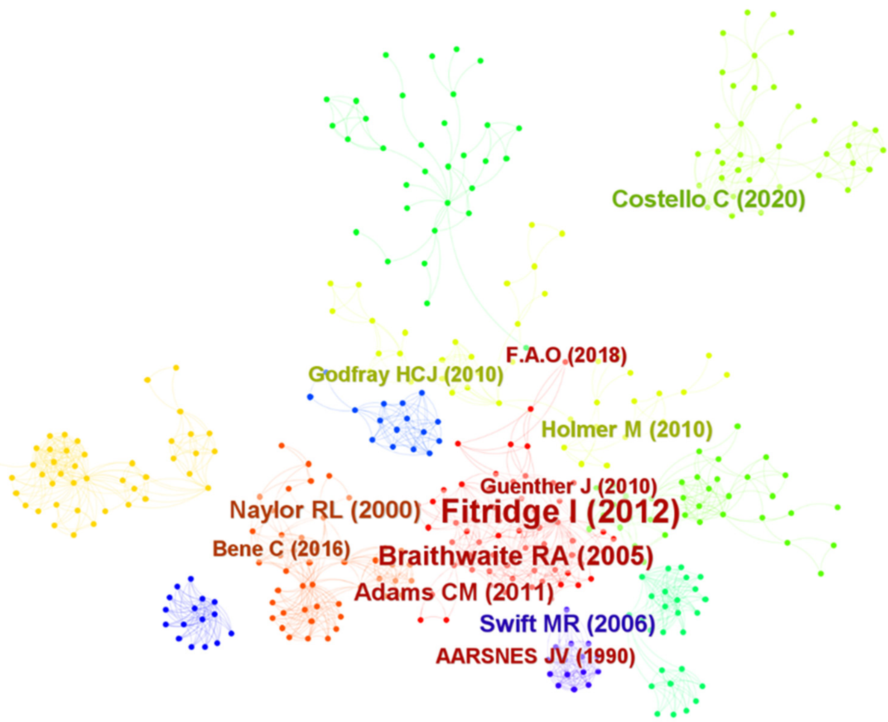

Figure 13. Authors of the most cited documents analyzed in CiteSpace.

3.4. Countries and Journals Analysis

In Figure 14, countries with the most research in the field of aquaculture or mariculture are presented. European countries, authors from Norway and Sweden, have published most of the studies, but afterward, there are authors from Scotland, Germany, Netherlands, Portugal, Spain, and others.

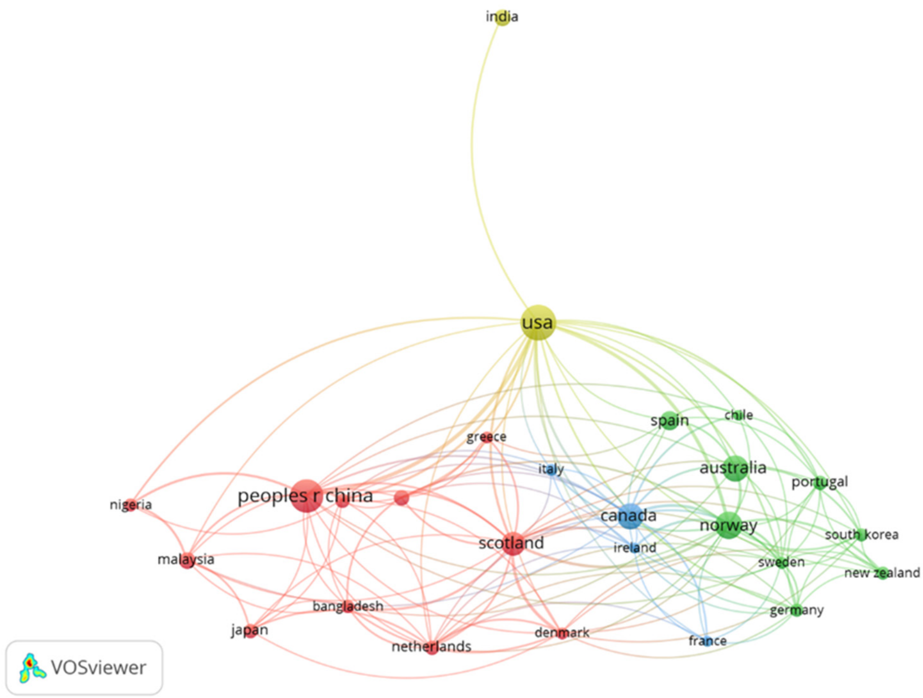

Figure 14. Countries with the most articles in the field of aquaculture and mariculture.

In Figure 15, the results of the same analysis, investigating which countries have the most cited documents and authors by means of CiteSpace, is shown with similar results.

Figure 15. Countries with the most articles in the field of aquaculture and mariculture analyzed in CiteSpace.

In Figure 16, a list of the top 13 cited authors with the strongest citation burst is shown. Authors whose studies had the biggest citation bursts from 2012–2023 are listed along with the journals.

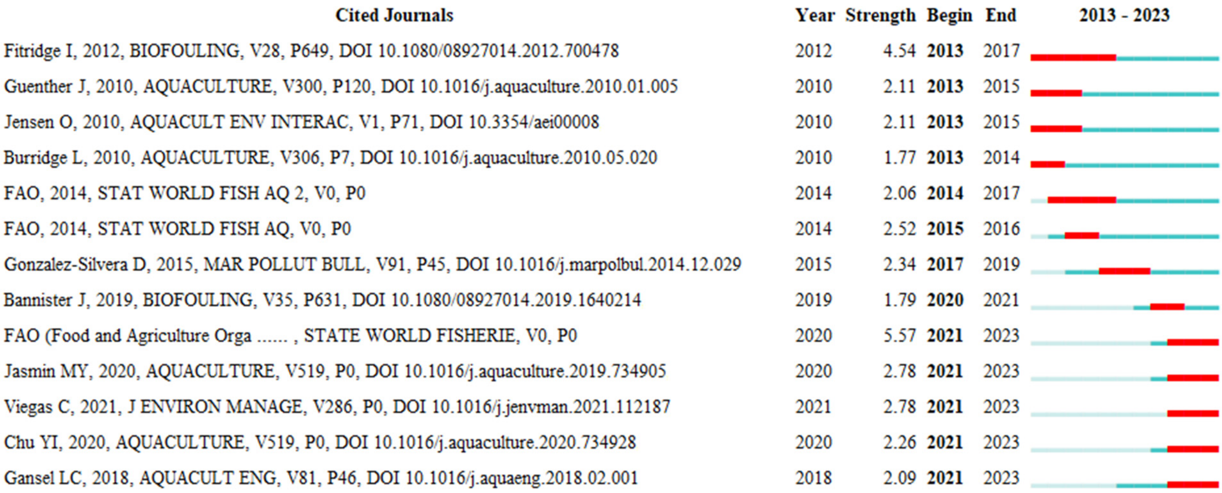

Figure 16. Top 13 cited authors 2013–2023, [5,32,59,97–105].

The highest citation burst was Fitridge et al. [32] with the study about the impact and control of biofouling in mariculture. Studies related to biofouling which had the highest citation burst were those by Bannister et al. [97], Gonzalez-Silvera [98], and Guenther et al. [99], while Jensen et al. [100] had a strong burst with the work about escaping native species from the cage based on the Norwegian sea-cage where they explained possible causes of escaping and solutions. Escape from the cage can have a big influence on the production outcome and environment. Burridge et al. [101] discussed the use of chemicals in salmon production and its impact on the production and environment. Jasmin et al. [102] analyzed the possibility of helpful bacteria in bioremediating aquaculture sludge is highlighted alongside the hazardous components in aquaculture waste. The Food and Agriculture Organization (FAO) publishes yearly reports about the State of the World Fisheries and Aquaculture [1,5,23,103] with all the data about mariculture production, species, division by the countries and its production outcome, challenges and problems in marine aquaculture, and other topic related to the fish industry; thus, it is expected that they will have a high citation burst, which means the significance of an individual article as a cited reference. As one of the technical problems, waste management was analyzed by Beveridge [29] and Viegas et al. [104], while a review of cage options for mariculture production, drag forces, and possibilities for offshore farming is reported by Chu et al. [59] and Gansel et al. [105].

Table 3 lists the most common journals related to fisheries and aquaculture. In the period from 2019 to 2022, the journal Fish and Fisheries had the most total citations.

Highlighted links between keywords, documents, authors, journals, and countries are presented in Table 4. Previously performed analyses showed that the most important articles, connected with keywords and most cited documents are published in Reviews in Aquaculture (five papers), Aquaculture (four papers), and Marine Policy where articles related to the development of aquaculture are mostly published, Aquaculture Environment Interactions with environmental waste related articles. Analyzing the countries, based on this paper, Norway and the USA have the most published papers, followed by China, Australia, and New Zealand. All these countries are known to have high aquaculture production; thus, these results are typical.

Table 3. The most common journals 2019–2022.

Source Title	Total Citations	Average Per Year	2019	2020	2021	2022
Fish and Fisheries	61	15.25	0	0	26	31
Reviews in Aquaculture	48	12	0	0	20	26
Aquaculture Nutrition	35	7	0	5	20	9
Fish Physiology and Biochemistry	33	11	0	0	8	24
Reviews in Fish Biology and Fisheries	31	6.2	1	8	8	13
Journal of the World Aquaculture Society	29	7.25	0	3	17	8
Aquaculture Nutrition	28	5.6	0	9	8	10
Aquaculture Research	25	5	0	6	10	8
Aquaculture Economics and Management	24	4.8	4	1	8	10
Reviews in Fisheries Science and Aquaculture	22	7.33	0	0	9	12
Knowledge and Management of Aquatic Ecosystems	18	4.5	0	0	12	6

Table 4. Summary of keywords, cited documents, authors, journals, and countries.

Keyword	Cited Document	Authors	Journal	Country
Ecology	Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems.	Troell et al. [70]	Aquaculture	Sweden, Norway, Canada, Chile, Israel, China
	Antibiotic use in aquaculture, policies and regulation, health, and environmental risks: a review of the top 15 major producers.	Lulijwa, Rupia, and Alfaro [76]	Reviews in Aquaculture	New Zealand, Uganda, Tanzania
	Vulnerability of China's nearshore ecosystems under intensive mariculture development	Liu and Su [85]	Environmental Science and Pollution Research	China
	Understanding and managing suspended solids in intensive salmonid aquaculture: a review	Schumann and Brinker [64]	Reviews in Aquaculture	Germany
	Biodiversity–Ecosystem Functioning (BEF) approach to further understanding aquaculture–environment interactions with application to bivalve culture and benthic ecosystems	Lacoste, McKindsey, and Archambault [65]	Reviews in Aquaculture	France, Canada
	Two cases study of fouling colonization patterns in the Mediterranean Sea in the perspective of integrated aquaculture systems	Giangrande et al. [31]	Aquaculture reports	Italy
	Characteristics of the flow field inside and around a square fish cage considering the circular swimming pattern of a farmed fish school: Laboratory experiments and field observations	Park et al. [68]	Ocean Engineering	Japan

Table 4. *Cont.*

Keyword	Cited Document	Authors	Journal	Country
Cage and location	Comparative study of five commonly used gravity type fish cages under pure current conditions	Cheng et al. [56]	Ocean Engineering	Norway
	A prediction on structural stress and deformation of fish cage in waves using machine-learning method	Zhao et al. [57]	Aquacultural Engineering	China
	Numerical study on the mooring force in an offshore fish cage array	Liu, Wang and Guedes Soares [58]	Journal of Marine Science and Engineering	Portugal
	Review of cage and containment tank designs for offshore fish farming	Chu et al. [59]	Aquaculture	Australia, Norway
	Turbulence and flow field alterations inside a fish sea cage and its wake	Klebert and Su [60]	Applied Ocean Research	Norway
	Offshore aquaculture: I know it when I see it	Froehlich et al. [75]	Frontiers in Marine Science	USA, UK
	Environmental issues of fish farming in offshore waters: perspectives, concerns, and research needs	Holmer [95]	Aquaculture Environment Interactions	Denmark
	Current forces on cage, net deflection	Aarsnes, Rudi, and Løland [96]	Engineering for offshore fish farming	Norway
	Open water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture	Chopin [71]	Reviews in Aquaculture	Canada
Waste	Terrestrial fatty acids as tracers of finfish aquaculture waste in the marine environment	White et al. [61]	Reviews in Aquaculture	Australia, Norway
	Integration of algae to improve nitrogenous waste management in recirculating aquaculture systems: A review	Ramli et al. [62]	Frontiers in Bioengineering and Biotechnology	The Netherlands, Malaysia, Japan
	European lobsters utilize Atlantic salmon wastes in coastal integrated multi-trophic aquaculture systems	Baltadakis et al. [63]	Aquaculture Environment Interactions	UK, Ireland
Biofouling	Functional role of biofouling linked to aquaculture facilities in Mediterranean enclosed locations	Montalto et al. [66]	Aquaculture Environment Interactions	Italy
	Methods to prevent and treat biofouling in shellfish aquaculture	Sievers et al. [67]	Aquaculture	Australia
	The nutrient footprint of a submerged-cage offshore aquaculture facility located in the tropical Caribbean	Welch et al. [69]	Journal of the World Aquaculture Society	USA
	The impact and control of biofouling in marine aquaculture: a review	Fitridge et al. [32]	Biofouling	Australia, Norway
	Potential environmental risks associated with biofouling management in salmon aquaculture	Floerl, Sunde, and Bloecher [86]	Aquaculture environment interactions	Norway, New Zealand
	Aquaculture environment interactions: past, present, and likely future trends	Edwards [87]	Aquaculture	Thailand
	Preventing ascidian fouling in aquaculture: screening selected allelochemicals for anti-metamorphic properties in ascidian larvae	Cahill et al. [88]	Biofouling	New Zealand

Table 4. *Cont.*

Keyword	Cited Document	Authors	Journal	Country
Biofouling	Biofouling in marine molluscan shellfish aquaculture: a survey assessing the business and economic implications of mitigation	Adams et al. [89]	Journal of the World Aquaculture Society	USA
	Drag force acting on biofouled net panels	Swift et al. [37]	Aquaculture engineering	USA
	Marine biofouling on fish farms and its remediation	Braithwaite and McEvoy [90]	Advances in Marine Biology	UK
Nutrition in aquaculture	The impacts of aquaculture development on food security: lessons from Bangladesh	E-Jahan, Ahmed, and Belton [72]	Aquaculture research	Bangladesh
	Feed matters: satisfying the feed demand of aquaculture	Tacon and Metian [73]	Reviews in Fisheries Science and Aquaculture	USA
	Improving sustainability of aquaculture in Europe: stakeholder dialogues on integrated multi-trophic aquaculture (IMTA)	Alexander et al. [74]	Environmental Science and Policy	UK, Norway, Italy, Israel
	Mariculture: significant and expanding cause of coastal nutrient enrichment	Bouwman et al. [83]	Environmental Research Letters	The Netherlands, USA, Chile, China
	Food security: the challenge of feeding 9 billion people	Godfray et al. [91]	Science	UK
	Integrated multitrophic aquaculture systems–Potential risks for food safety	Rosa et al. [92]	Trends in food science and technology	Portugal
	Effect of aquaculture on world fish supplies	Naylor et al. [93]	Nature	USA, Sweden, UK, Philippines
Development and sustainability	The rise of aquaculture by-products: Increasing food production, value, and sustainability through strategic utilization	Stevens et al. [77]	Marine Policy	UK, USA
	Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations	Bureau and Hua [78]	Aquaculture Research	Canada
	Governance and mariculture in the Caribbean	Ruff et al. [84]	Marine policy	USA
	Heat sensitivity of mariculture species in China	Ma et al. [79]	ICES Journal of Marine Science	China
	The evolution of mariculture structures and environmental effects in China	Han and Jiang [80]	Journal of Coastal Research	China
	Mariculture: a global analysis of production trends since 1950	Campbell and Pauly [81]	Marine Policy	Canada
	Mariculture development and livelihood diversification in the Philippines	Salayo et al. [82]	Marine Policy	Philippines

4. Discussion

Beyond CiteSpace and VOSviewer, there are other programs to visualize and analyze the literature research. Original data must be published, or their origin must be referenced, and methodologies, computations, and so on, must be detailed so that the "ordinary scientometrician" using the same procedure can receive the same figures, statistics, or indicators as Vinkler [106]. Scientific publications, along with their references, should provide enough information for comprehending the content and making the published results repeatable. Noor et al. [107] performed the analysis in R version 4.0.2 (R Core Team, 2019) for descriptive analysis to visualize the data and perform the basic statistical analyses in aquaculture for the Southeast region, and for scientometric analysis they used CiteSpace. The modularity Q index and mean silhouette metric were 0.9095 and 0.4068, respectively, and in this paper, it was 0.9003 and 0.9736, respectively, where high modularity indicates that the network spectrum clustering results were outstanding, with a total of 20 co-citation clusters arising from the investigation [107]. Noor et al. [107] stated that the socio-economic and environmental issues have the highest focus on research within the areas of aquaculture in Southeast Asia. Singh et al. [108] analyzed dynamics in Indian aquaculture using the scientometrics as well, and they showed that the number of journals in Indian aquaculture doubled in their period of research from 2007–2016. TS et al. [109] performed research on mapping the evolution in aquaculture using the WoS and VOSviewer. Their results showed that the number of papers in aquaculture studies is growing, and they showed that India had the strongest citation burst just like in this paper.

Apart from pure bibliometric analysis, these analyses still need to be combined with other relevant sources to have an insight into the development of aquaculture in practice as well as research trends in the development of floating structures. For example, many authors dealt with the implementation of renewable energy sources in the system. Liu et al. [110] proposed the aquaculture ship with self-wind power generation which aims to expand aquaculture to the open ocean, providing an economical and environmentally friendly option. The study of Michler-Cieluch et al. [111] reflects the potential for synergies and obstacles in integrating the operation and maintenance (O&M) activities of offshore wind farms and mariculture. The authors highlight the significance of clear communication, collaboration among stakeholders, and the development of effective regulatory frameworks to reduce the difficulties in integrating operation and maintenance tasks such as logistical complications or others. Wind farm buildings can operate as artificial reefs, fostering biodiversity and supporting marine ecosystems [111]. Mohamed et al. [112] suggest a conceptual design that includes a variety of renewable energy technologies. Offshore wind turbines, solar panels, wave energy converters, and energy storage systems are examples of technologies which are integrated to provide the necessary electricity for mariculture operations such as water circulation, aeration, lighting, and equipment, but confront problems such as high initial investment costs, maintenance requirements, and the variability of renewable energy sources [112]. Koričan et al. [4] proposed an alternative, electrified, mariculture system which includes a barge with renewable energy sources. Shaalan et al. [113] deal with the issues confronting the aquaculture business, such as limited access to the city, poor logistics, and insufficient infrastructure, and propose potential sustainable development options such as promoting small-scale aquaculture, integrating aquaculture with agriculture, and establishing appropriate regulatory frameworks. To ensure the successful establishment of offshore mariculture initiatives, Thomas et al. [114] emphasize the importance of sustainable practices, effective governance, and stakeholder participation, underlining the importance of additional study, policy development, and investment to enjoy these benefits while protecting the long-term viability and resilience of coastal ecosystems. Gentry et al. [115] suggest spatial planning concepts as a framework for guiding sustainable offshore aquaculture development including the choice of an ideal aquaculture location based on ecological characteristics, taking social and economic factors into account, the importance of including local communities, industry leaders, environmental organizations, and political agencies, guaranteeing compatibility with other marine uses. In [116] the Engel-Blackwell-Miniard model and the global Malmquist-Luenberger index were used to measure and analyze the technical efficiency and productivity of "mariculture area production efficiency" from both static and dynamic perspectives. Mariculture has a high potential for sustainable food production and economic growth, and the future of seafood production will most likely develop around mariculture production with an emphasis on the conservation of natural resources (water, biodiversity, climate, etc.) [117]. The integration of mariculture with other sectors such as renewable energy, coastal tourism, and ecosystem restoration offers intriguing opportunities. Co-location of offshore wind farms with mariculture enterprises, for example, can provide synergistic benefits such as shared infrastructure and decreased environmental impacts. Investments in research and development, innovation, and information sharing are crucial for mariculture's future prospects. Collaboration between scientists, industry stakeholders, policymakers, and local communities is critical for addressing difficulties, promoting sustainable practices, and ensuring the sector's long-term existence. According to [118], aquaculture is expected to produce 62% of fish for human consumption by 2030, and ensuring this supply is dependent on data-driven eco-intensification of the business. Mariculture can have a crucial role in providing seafood, economic development, and environmental conservation in the future through technological developments, species diversification, integration with other sectors, and supportive legislation. Future aquaculture policies and programs will necessitate a food systems approach that considers nutrition, fairness, justice, and environmental consequences and trade-offs across land and sea [119].

5. Conclusions

The mariculture industry faces some challenges, and this paper focuses on technical problems such as choosing the proper location, especially tending to offshore mariculture, optimal selection of farming cages, feeding process, biofouling problems, waste management or impacts on marine pollution. There are different programs for bibliometric analysis and in this paper, two programs were used: CiteSpace and VOSviewer.

The main contributions can be summarized as follows:

- Technical and environmental problems are more studied than other challenges. Focus should be not only on these problems, but on the location choice and its challenges, waste management, or feeding process in the mariculture production.
- Most publications in the field of mariculture were published in 2021, and the number of citations of publications are continuously growing.
- The most common identified hotspots are divided into four categories: technical, biological, digital, and environmental.
- Based on the citation analysis, the most cited articles are related to the environmental problems and solutions in the marine aquaculture and study of biofouling and how to control it. Other important documents with high citation rates are related to the cages, offshore mariculture, location conditions, and sustainability.
- Countries with highly developed aquaculture production are those with the most articles, such as the USA, China, Australia, Canada, Norway, and Scotland, as expected.
- The top three journals in the field of aquaculture are Fish and Fisheries, Reviews in Aquaculture, and Aquaculture Nutrition; they are all ranked with Q1 or first quartile.
- CiteSpace has more options for filtering and analyzing the data, and various combinations while analyzing cited journals, keywords, authors, abstract words, and others. VOSviewer is preferable for mapping the data and visualization (e.g., countries or keywords). Cluster differentiation is more accurately explained in CiteSpace, and it is more specific than in VOSviewer.

Based on this paper and the literature review, it can be concluded that mariculture will be even more important in the future. Thus, it is necessary to analyze, study, and perform experiments on the topics related to the mentioned problems in this study and how to deal with them in a more sustainable way. Future research could compare other databases, such as Scopus, PubMed, and EmBase, to WoS to look for contradictions in the data. The combination of precise literature research and more bibliographic software, in order to conduct more precise research, may lead to the goal of creating sustainable mariculture production. Since this scientometric analysis focuses on the total mariculture sector and activities, future research can expand on this topic by focusing on some of the most important species or groups in the marine aquaculture industry.

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Abbreviations

BEF	Biodiversity–Ecosystem Functioning
FA	Fatty Acid
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
HPDE	High-Density-Polyethylene
IMTA	Integrated Multi-Trophic Aquaculture
MARAQUA	Monitoring and Regulation of Marine Aquaculture
MERAMED	Monitoring Guidelines and Modelling Tools for Environmental Effects from Mediterranean Aquaculture
RES	Renewable Energy Sources
WoS	Web of Science

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