Heliyon 9 (2023) e17573

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

A bibliometric approach to understanding the recent development of self-sufficient fish feed production utilizing agri-food wastes and by-products towards sustainable aquaculture

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ARTICLE INFO

Keywords:
Bibliometric approach
Intellectual structure
Agri-food wastes and by-products
Fish feed
Sustainable aquaculture

ABSTRACT

The global agri-food industry generates a large volume of waste annually, which causes both environmental and economic problems. Recently, there has been a growing interest in the use of agri-food wastes and by-products to produce self-sufficient fish feed. This study aimed to analyze the intellectual structure of the recent research on the utilization of agri-food wastes and by-products as self-sufficient fish feed materials based on 922 Scopus-indexed core collection documents from 252 journals written by 4420 authors from 73 countries with an annual growth rate of 18.65% over the last four years (2019–2022). This bibliometric study implemented knowledge domain visualization (KDV) using VOSViewer and Biblioshiny in the Bibliometrix R-package to investigate the basic scientometric profile of the selected fields. The results showed that Dawood M.A.O., with PageRanks of 0.0732, 19 total publications, 695 global citations from 2019 to 2022, and closeness values of 0.25, was the most productive author within the field. Subsequently, China was determined to be the most productive country (93 valid documents) and have the strongest collaboration network. Major research hotspots in the field included aquaculture and sustainable aquaculture, fish feed with agri-food waste, rainbow trout species, the development of a circular economy, probiotic applications, and cell signaling cytokines and peptides. This bibliometric study provides comprehensive information on the intellectual domain and research landscape on self-sufficient fish feed and also shows how interest in this research topic and similar ones is growing.

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https://doi.org/10.1016/j.heliyon.2023.e17573
Received 19 February 2023; Received in revised form 20 June 2023; Accepted 21 June 2023
Available online 26 June 2023

1. Introduction

Over the past few years, various risks, including the coronavirus (COVID-19) pandemic, climate change, and geopolitical conflicts, have coincided to impact global agri-food systems, where more than a quarter of a billion people from 58 countries and territories experienced acute food insecurity, a lack of access to healthy diets, and malnutrition in 2021–2022 [1]. Even worse, based on the statistical data reported by the Food and Agriculture Organization (FAO) of the United Nations (UN), agri-food waste generation reached approximately 1.3 billion tons every year, or nearly one-third of all global agricultural products and foods produced for human consumption are wasted [2,3]. Agri-food waste refers to the disposal of unused agricultural products and foods appropriate for human consumption that have been rejected or discarded by choice or once the food has expired due to negligence [4].

In order to solve this problem, the UN has determined Target 12.3 in the Sustainable Development Goals (SDGs) agenda, which is that global agri-food waste at the retail and consumer levels must be halved per capita and food losses along the production and supply chains, as well as post-harvest, must be reduced by 2030 [5]. Based on agricultural commodities, agri-food waste and loss from farm to end consumer is estimated at 40–50% for fruit, vegetables, and tubers; 35% for fish; 30% for cereals; and 20% for oil seeds, meat, and dairy products [6]. In this case, fish, one of the most perishable raw agri-food materials compared to other matrices, commonly experiences the serious problems of food waste and loss, which in some lower-middle-income countries could be up to 40%, mainly due to limited access to cold chain storage facilities and processing technology [7]. Nevertheless, food waste from fish products has the potential to be utilized to produce highly nutritious feed ingredients and could substitute for fishmeal as a protein source in fish diet formulations [8,9].

Just as importantly, agro-industrial wastes, residues, and by-products, such as cassava leaf flour, gliricidia leaf flour, rice bran, molasse, corn stover (stems, leaves, husk, panicles, and cobs), soybean meal (SBM, a main by-product of the extraction of soybean oil), distiller's dried grains soluble (DDGS, a by-product of bioethanol fermentation), palm kernel meal (PKM, a main by-product of the palm kernel oil extraction process), dried bovine hemoglobin powder (DBH, a residue from cattle abattoir), fruit wastes (e.g. kiwi, pineapple, and papaya), and various dietary starches from rejected agricultural commodities (e.g. wheat, tapioca, rice, barley, sago, potato, pea, and waxy corn), could also be supplemented to produce high-quality fish feed [10–18]. The use of agro-industrial wastes, residues, and by-products as potential ingredients in fish diets should not be considered unworthy. Many researchers reported that these sources exert interesting molecular properties, bioactive compounds, hormones, and other exogenous chemical substances for supporting fish growth and increasing the quality of fish carcasses when used in fish feed [15].

As already reported by many previous authors, the majority of fish farmers use complete fish diets to support the growth and health status of farmed fish, which typically contain the following nutrients in varying percentage ranges: protein (18–50%), carbohydrate (15–20%), ash (±8.5%), phosphorus (±1.5%), lipids (10–25%), water (±10%), and trace amounts of additional vitamins and minerals [19]. Protein, as the most important, expensive, and irreplaceable nutrient in fish feed, requires accurate determination in the supplementation of the fish diet based on each species and life stage cultured [20,21]. For example, the feed protein content of shrimp, catfish, and tilapia accounts for nearly 30–35%, 28–32%, and 35–40%, respectively [19,22]. The nutritional content of fish feed varies depending on the species and life stage of the fish cultured [23]. When fish are reared in high-density indoor pound systems or confined in particular cages and are unable to forage freely on natural foods such as phytoplankton, zooplankton, annelids, worms, insects, and algae, a complete diet must be provided. In this context, the use of agri-food waste for the production of self-sufficient fish feed would be an appropriate sustainable strategy not only to hinder the operational cost of waste disposal but also a method to reduce the fixed cost of fish feeding in aquaculture, substitute the use of commercial fishmeal, and thus minimize the offered price to the consumer [15,20,24,25].

The term of self-sufficient fish feed itself was adopted from the official name of a national program in Indonesia, Gerakan Pakan Mandiri (GERPARI), or collective action to provide self-sufficient fish feed, initiated by the Directorate of Fish Feed of the Indonesian Ministry of Marine Affairs and Fisheries (MMAF) since 2013. This action aimed to independently manufacture fish feed using locally available materials from natural wastes and by-products in order to lower the dependency of small-scale farmers on imported ingredients and expensive commercial fish feed and reduce the production cost [26,27]. The natural wastes and by-products from the agri-food industries (e.g., cereal powders, cassava flour, groundnuts, and wheat bran), food and livestock (e.g., dairy products, eggs, slaughterhouses, fish processing plants, bakeries, and others), marine, and fishery have the potential to be processed further to make balanced nutritive raw materials and supplements for formulating self-sufficient fish feed [25,28]. In aquaculture, nutrition is a critical input because formulated fish feed accounts for the single largest cost and is responsible for roughly half of the variable production expenses [19].

In recent years, research on fish nutrition, particularly the use of fish and agri-food wastes and by-products, has widely advanced with the development of innovative and balanced commercial diets to promote the optimum growth and health of fish [21]. For example, the recent development of new species-specific fish feed formulations based on a nutrigenomics approach supports the aquaculture industry's expansion to meet rising demand for high-quality, healthier, affordable, and safer fish products. There have been previous reports that sought to understand fish waste management or the utilization of agri-food waste for sustainable alternatives in aquaculture using a bibliometric approach. For example, a detailed review using bibliometric and content analysis to identify the validity of the demand for fish waste management studies in the global and native research communities has been performed [16]. Another author has also reported the use of a bibliometric approach to create a map for providing an overview of the recent publications, showing the strength of the research across various countries, the potential collaboration numbers among research institutions, and demonstrating the main focus of the research topic of the utilization of agri-food waste for sustainable alternatives in aquaculture, which is growing in interest, especially in Europe [15].

Despite the fact that scientific articles report that the use of agri-food wastes and by-products is continuously increasing, there have been limited studies that present its intellectual landscape and knowledge domain overview in detail. The importance of collecting these studies is essential to identify, based on various retrieving metadata from highly reputed databases, what are the emerging topics, experimental innovations, and novelty of their research. In order to fill the gaps and provide a comprehensive visualization concerning the recent intellectual landscape and research hotspots of self-sufficient fish feed production using agri-food wastes and by-products and its relation to sustainable development and the blue economy, we performed knowledge domain visualization or scientography through the approach of bibliometric analysis. The metadata of the latest relevant publication was retrieved from 2019 to 2022 using the publicly available Scopus core database [29,30]. The findings depict the global research growth and trend of self-sufficient fish feed produced from agri-food wastes and by-products, which may inspire new scientific idea generation for future work in planning, illuminating, and developing innovative related studies. Thus, the aim of this study was to observe the growth, trends, patterns of author productivity, thematic evolution, and influential keywords of scientific literature in the aforementioned research field. It will provide researchers with a credible resource that could assist in understanding the current research focus in aquaculture fields and other primary scientometric information.

2. Materials and methods

In this study, by focusing exclusively on analyzing the intellectual structure of the recent publications on the use of agri-food wastes and by-products to produce self-sufficient fish feed, the knowledge domain under the represented area was enriched and examined. More specifically, according to the KDV methodology described elsewhere by Mostafa (2020) and Sancho (2020), this work led to the answers to the following research questions (RQ).

RQ-1. How has the research on self-sufficient fish feed produced from agri-food wastes and by-products evolved during the last four years?

RQ-2. What kind of potential collaborative partnership emerges among countries, authors, and institutions in the research field?

RQ-3. Which articles and authors are the most influential in the research field?

RQ-4. What are the main countries or regions where research on self-sufficient fish feed produced from agri-food wastes and by-products is taking place?

RQ-5. What are the main research topics and focuses emerging from the field?

RQ-6. What are the current emerging thematic trends and updates in research on self-sufficient fish feed produced from agri-food wastes and by-products?

To answer those six research questions, a KDV based on bibliometric analysis was performed [30]. Bibliometric analysis is an approach aimed at visualizing and summarizing the present state of the art of an emerging or existing research topic [31–33]. The data used for bibliometric analysis were retrieved from a single scientific search engine, Scopus, developed by Elsevier. Scopus is one of the largest database of abstracts, literature articles, and citations, including books, scholarly journals, and conference papers. Additionally, it has indexed more than 15,000 journals, around 265 million official websites, 18 million international patents, and other scientific documents [4]. The following keyword search string have been adopted in this study: (TITLE-ABS-KEY (“fish feed”) OR TITLE-ABS-KEY (“agri-food waste”) OR TITLE-ABS-KEY (“agri-food byproducts”) OR TITLE-ABS-KEY (“sustainable aquaculture")) AND (LIMIT-TO(PUBYEAR, 2022) OR LIMIT-TO(PUBYEAR, 2021) OR LIMIT-TO(PUBYEAR, 2020) OR LIMIT-TO(PUBYEAR, 2019)) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “re")) AND (LIMIT-TO(SUBJAREA, “AGRI")) AND (LIMIT-TO (LANGUAGE, “English")), which was inputted in order to exclude publications that does not meet the criteria. Comprehensively, a total of 922 valid sample documents, including research and the full-text data of articles and reviews in the online version and articles in press categories from 2019 to 2022, were retrieved from the Scopus database (accessed on December 1, 2022).

Technically, a set of title, abstract, and keywords of each selected publication were completely downloaded in comma-separated values (.csv) file format and subjected to the VOSViewer co-occurrence mapping (network, overlay, and density visualization) with the association strength method, which also shows the publication time from 2019 to 2022 as an important complementary factor. VOSviewer version 1.6.14 is a software tool for analyzing an extensive data volume of bibliometric networks, creating maps based on the data networks of the literatures, and exploring and visualizing graphical analysis (network visualization, overlay visualization, and density visualization) on these created maps [31,32,34,35]. A co-occurrence map was used to semantically represent the network containing among the verified selected keywords of the numerous papers. For the bibliometric analysis, all the terms in the search string demonstrated in the above-mentioned sections were considered substantial units of analysis. However, some slight adjustments were implemented accordingly. Herein we obtained 5 clusters with 430 items, 18,678 links, and 35,861 total link strengths, with the aquaculture item in cluster 1 as the strongest item, having 387 links with other relevant items, 234 occurrences, and 1741 total link strengths. Then, the data were further analyzed and interpreted with the Biblioshiny tool in the R package, which could be accessed freely at https://www.bibliometrix.org/home/. The bibliometrix software, written in the R language for scientific computation, provides a set of tools for quantitative research approaches in scientometrics and bibliometrics, including substantial existence, effective statistical algorithms, integrated data visualization tools, and access to high-quality numerical routine analyses [36].

3. Results and discussion

3.1. Scientific production, productive authors, and geographical analysis

To obtain an appropriate answer to the RQ-1, we followed Liang et al. (2022) by collecting and tracing the evolution of the research literature on self-sufficient fish feed produced from agri-food wastes and by-products that evolved during the last four years [31]. Fig. 1 depicts the annual scientific production of self-sufficient fish feed. The graph demonstrates an exponential annual growth rate of 18.65% among 252 identified journals, with the significant increase happening year by year from 2019 to 2022, where the scientific publication in 2019 was 176 documents and increased to 294 documents until December 2022. During the COVID-19 pandemic (2019–2020), the number of publications increased more slowly than those published after the pandemic ended. Another researcher reported that the COVID-19 pandemic has been identified as the major cause of the weakening of annual scientific production during 2019–2020, particularly publications related to the themes of fisheries and aquaculture [37]. The phenomenon was primarily due to the restrictions on the movement and research activities of scientists, and the cancellation of research funding caused scientific production to stagnate during the pandemic situation [38]. Different research projects perform admirably in specific contexts, such as the development of vaccines, medicines, and medical supplies and equipment, but perform poorly in others, with fisheries and aquaculture being no exception [39]. After the pandemic situation declined, research focused on fisheries, marine, blue economy, and fish feed topics obviously increased, as evidenced by an increase in scientific publications from 2021 to 2022 [40]. That increase is likely also supported by the demand to consume animal-based protein, vitamin D, vitamin E, and other functional nutrients from bioactive compounds derived from fishery products to maintain the quality of human health and the immune system so as to avoid pathogenic infection [38,41–43].

Furthermore, the overall development of the scientific literature on self-sufficient fish feed produced from agri-food wastes and by-products is also witnessed in the increasing number of authors (Table 1), productive journals (Table 2), countries involved (Fig. 2), citations per article (Fig. 3), and sources used (Fig. 4). The change in dominance among authors over time in the production of publications was analyzed using an author's dominance map and depicted in Fig. 4. It can be seen that Dawood M.A.O., from the Laboratory of Aquatic Animal Nutrition, Kagoshima University, Japan, and the Department of Aquaculture, Kafrelsheikh University, Egypt, is the most productive author within the field, with 19 total publications and 695 global citations from 2019 to 2022 (Fig. 5). Varying circle sizes with dark blue gradations demonstrate which authors are most influential and productive within the field, both in terms of total article number and citations. Moreover, Hoseinifar S·H., the second-most influential author, has a total of 399 citations from 9 relevant documents. Those influential authors with a larger number of citations indicate that their works are more adaptable and have a high impact value and intensity of knowledge flow from their publication [44]. From the bibliometric portfolio of various authors from many countries, it can be considered that agri-food wastes and by-products should be classified as potential natural resources rather than as unusable waste materials, and their conversion into fish feed, would be a viable alternative [9,45,46]. Many works from various researchers observed in this bibliometric study examined the viability of using agri-food wastes and by-products to formulate highly nutritious fish feed pellets for different freshwater fish species, including grass carp, tilapia, catfish, and grey mullet, in monoculture or polyculture practices. For example, Dawood M.A.O. utilized pineapple waste and by-products of papaya leaf,

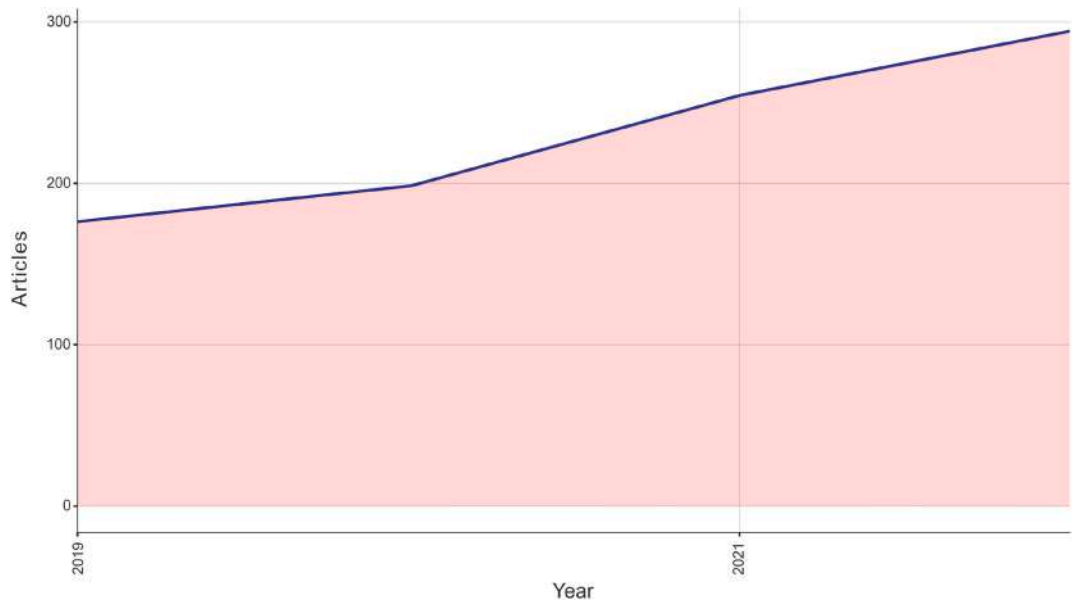

Fig. 1. Annual scientific production on the research literature on self-sufficient fish feed produced from agri-food waste and by-products during 2019–2022.

Table 1
The top 20 most productive authors.

Authors	Articles	Articles Fractionalized
DAWOOD MAO	19	4.57
HOSEINIFAR SH	9	1.47
VAN DOAN H	9	1.45
LIU Y	8	1.10
TESSER MB	8	1.22
LIU H	7	1.27
HUSSAIN SM	6	0.84
LI J	6	0.64
RAHMAN MM	6	0.68
WANG H	6	0.80
WANG J	6	0.75
YANG Q	6	0.75
COSTAS B	5	0.72
FROEHLICH HE	5	0.63
LI Y	5	0.62
LUNDH T	5	0.99
MONSERRAT JM	5	0.74
SEWILAM H	5	0.93
TAUFEK NM	5	0.93

Table 2
The top 20 most productive journals.

Sources	Articles
AQUACULTURE	115
AQUACULTURE RESEARCH	55
REVIEWS IN AQUACULTURE	53
AQUACULTURE INTERNATIONAL	34
AQUACULTURE REPORTS	31
AACL BIOFLUX	30
FISH AND SHELLFISH IMMUNOLOGY	26
ANIMALS	23
FRONTIERS IN MARINE SCIENCE	19
FISHES	12
FOODS	12
AQUACULTURE NUTRITION	11
WATER (SWITZERLAND)	11
EGYPTIAN JOURNAL OF AQUATIC BIOLOGY AND FISHERIES	10
FISH PHYSIOLOGY AND BIOCHEMISTRY	10
JOURNAL OF APPLIED PHYCOLOGY	9
JOURNAL OF INSECTS AS FOOD AND FEED	9
MARINE POLICY	9
AQUACULTURE AND FISHERIES	8
JOURNAL OF APPLIED AQUACULTURE	8

barberry fruit, olive oil, and other fruit processing residues as potential functional phytogenic fish feed additives to enhance the immune and antioxidative responses and tolerance of farmed fish to biotic and abiotic stressors [45–50]. Those agri-food wastes and by-products contain high concentrations of vitamins, minerals, flavonoids, polyphenols, peptides, and polysaccharides that provide help for reducing antimicrobial substances and increasing the biotic and abiotic stress tolerance in aquaculture [45,46,49].

In scientometrics studies using a bibliometric approach, the technical factors of concentration, evenness, stability, and consistency in the context of the author's productivity in the field are essential to increasing their scientific performance and dominance over time [29,30]. In order to empirically measure those scientific productivity factors and its frequency distribution, Lotka's law and Maximum Principle of Shannon's entropy statistical models are feasible and appropriate to be implemented. In particular, Lotka's law has been used previously in previous studies on marine, fisheries, and aquaculture, such as research progress on aquaculture [51], oyster [52], seafood quality [53], marine plastic pollution [54], Sri Lankan aquatic science [55], and coastal governance [56]. According to Lotka's law, the number of authors contributing n scientific contributions is roughly equal to those creating $1/n^2$ of those creating a single scientific contribution, and the number of authors Y(x) indicated in percentage, each with a total of x documents written, is inversely comparable to x, which is the scientific productivity of each author individualy [53,55]. In this research, a total of 922 valid documents written by 4420 authors and co-authors from 73 countries were collected, where every author was provided one credit to weigh their performance and productivity. It is observed that the majority (3860 authors; 87.3%) shared only one article; therefore, these existing data do not fit with Lotka's law (Fig. 6).

Lotka's law was also used to determine the authorship concentration of the field because it has been commonly used in identical scientometric studies [29,30,53]. The majority of authors observed in this study do not concentrate totally in this research field, which

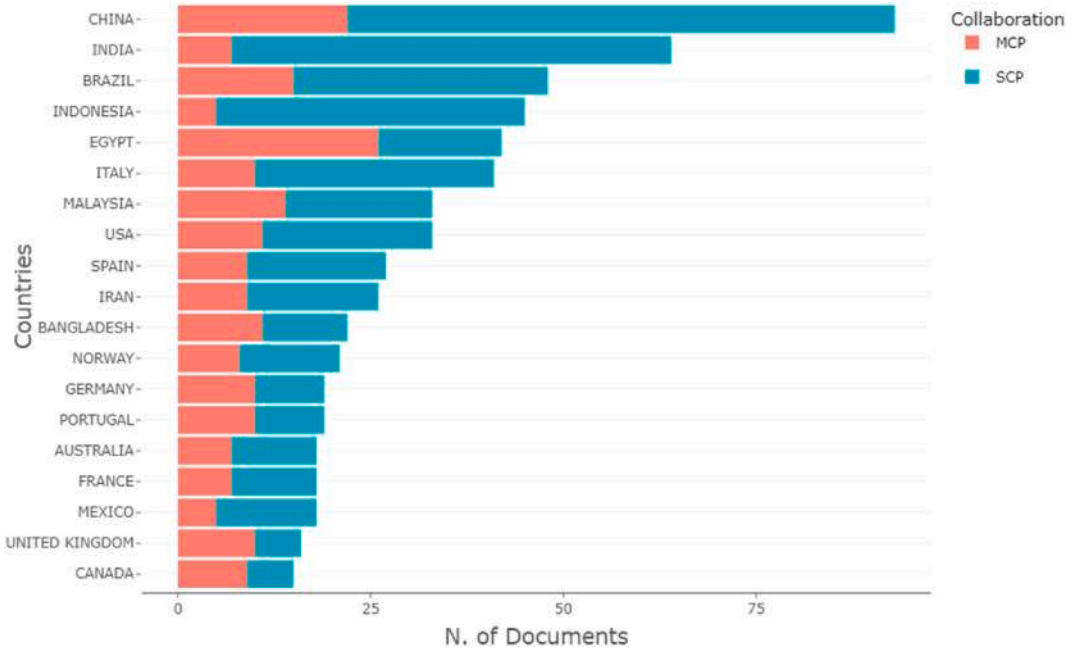

Fig. 2. Top 20 most productive countries in scientific production during 2019–2022. MCP = Multiple Country Publications; SCP = Single Country Publication.

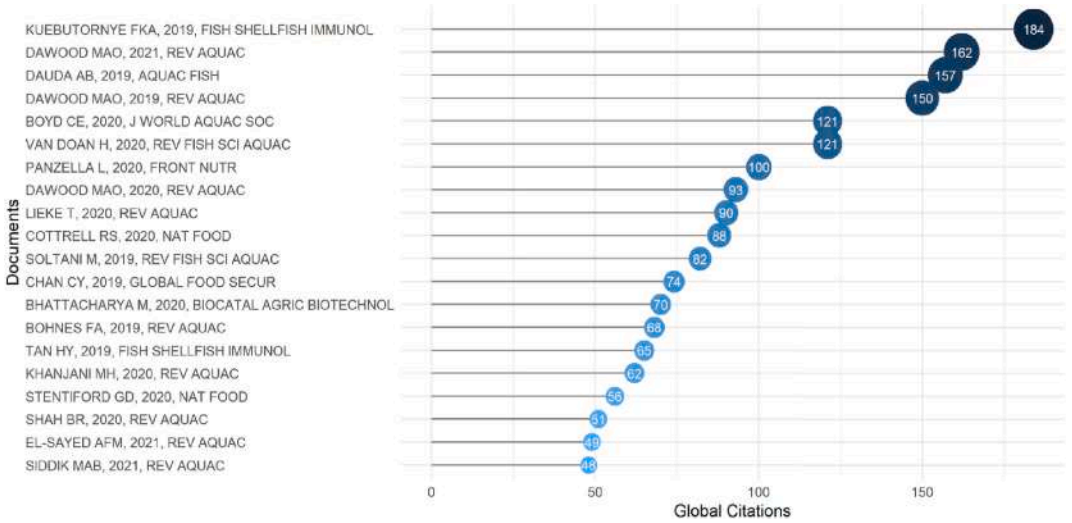

Fig. 3. Top 20 most cited documents during 2019–2022.

can be seen from the large tail of single-article authors, as depicted in Fig. 6. Generally, the top 3 influential authors have specific expertise in fish feed formulation, feed nutrition, and aquaculture; long experience performing research on the same topic; wide research collaboration worldwide with many researchers from different affiliations in the same field; and being supported by complete and up-to-date research facilities. As a result of their ability to focus exclusively on this area of research, they are capable of achieving higher levels of productivity, resulting in a substantial output of scholarly articles and patents [57–59]. Subsequently, based on a formal Kolmogorov-Smirnov goodness-of-fit test, the research on self-sufficient fish feed produced from agri-food wastes and by-products during 2019–2022 does not follow the Lotka distribution (p-value = 0.1243) with a goodness of fit of 0.5556 at a significance level of 0.05, where there is no significant difference between the observed and theoretical Lotka distributions.

Recently, geographic analysis has been widely implemented in numerous literatures of scientometric studies. In this research, geographic visualization and analysis are performed using the Biblioshiny tool in the Bibliometrix R package to create a world map of collaboration and country-level scientific production for the research on self-sufficient fish feed produced from agri-food wastes and

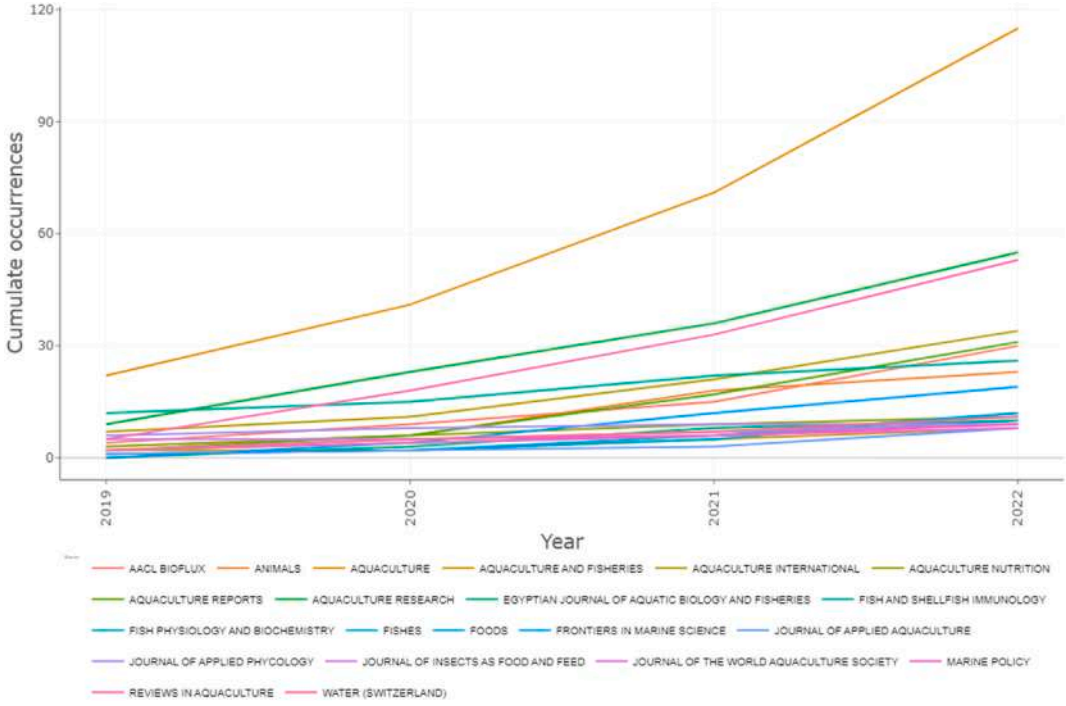

Fig. 4. Top 20 source trends dynamics during 2019–2022.

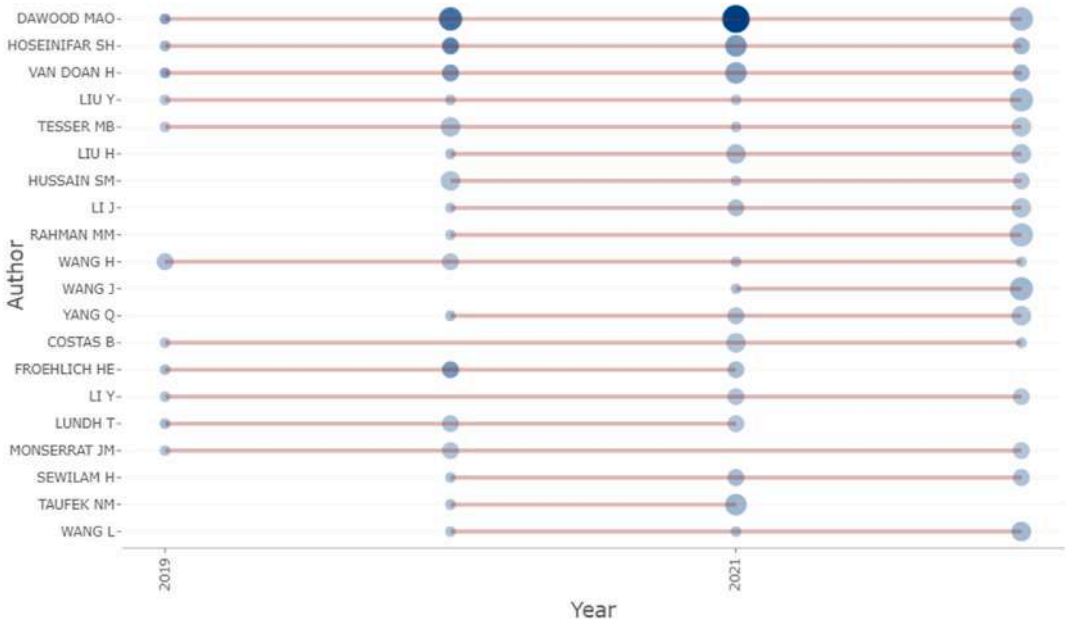

Fig. 5. Top 20 authors over time during 2019–2022.

by-products. It is also usually used to find where an occurrence happens and how it directly impacts the related fields [60]. Using a bibliographic world map, it is possible to provide a scientific landscape based on intellectual information and visualize the geographic location of authors, networks to their research collaborators, and the original version of their published articles [61,62]. As an example, geographic visualization was successfully used in research to map the global network of fisheries science collaborations [63]. The geographic map of the scientific landscape of the research on self-sufficient fish feed produced from agri-food wastes and by-products, is depicted in Fig. 7. The total number of citations is presented in proportional dark blue gradient colors visualized on the map, and the strength of publication collaborations is demonstrated in a red line with different width variations. It can be seen that

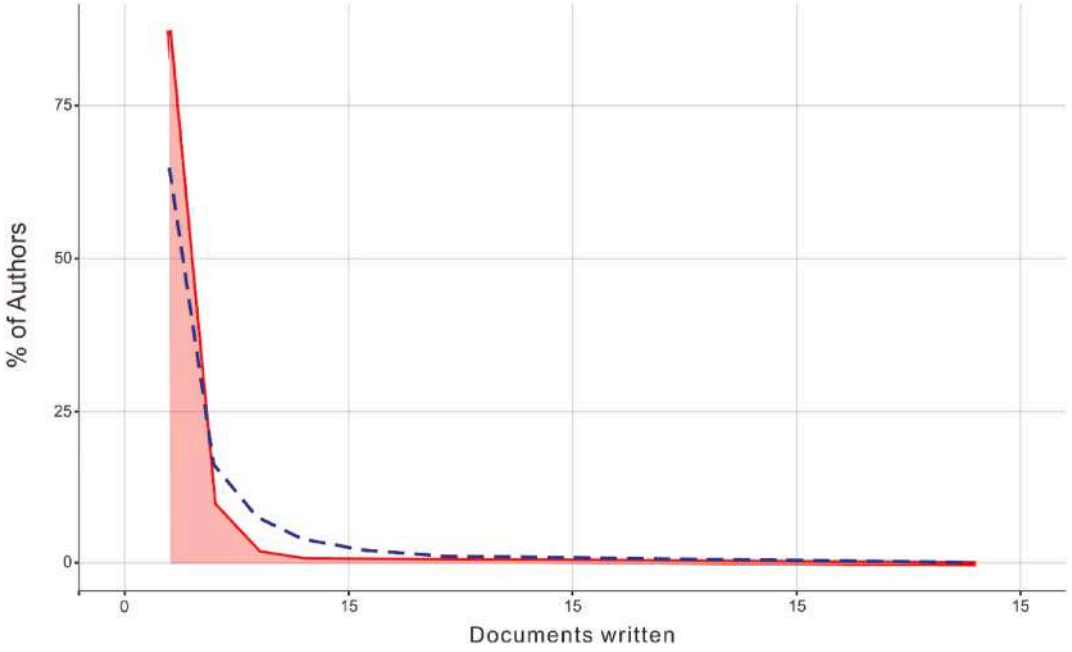

Fig. 6. The fit of research literature distribution and authors' productivity in comparison with Lotka's law.

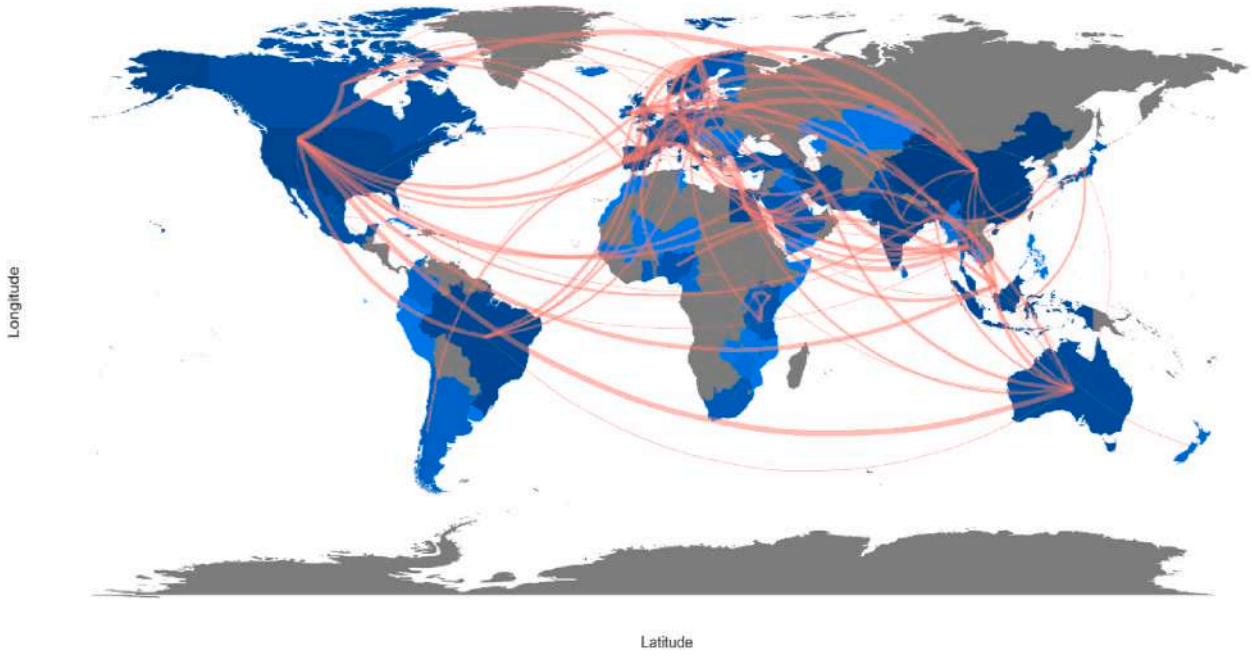

Fig. 7. Global collaboration map based on the location of authors, the number of scientific production, and networking link strength.

Spain and Portugal have the strongest publication cooperation (12 collaborations), followed by Egypt and Saudi Arabia (9 collaborations), Egypt and Germany, Malaysia and Bangladesh, and the USA and Canada, with 8 collaborations, respectively.

Among countries that produced scientific publications in the field of self-sufficient fish feed produced from agri-food wastes and by-products, China is the most productive country with 93 valid documents, followed by India, Brazil, Indonesia, and Egypt with 64, 48, 45, and 42 valid documents, respectively. Herein we found 5 countries from 5 different continents with high citation numbers; those are China, Egypt, Italy, the USA, and Australia, with total citations of 781, 733, 424, 399, and 321 citations, respectively. These findings also aided the researchers in answering RQ-4. Indeed, China, which ranks as the world's biggest fishing country either as the producer or consumer of fish and fish by-products, accounting for nearly one-fifth of the total marine catch worldwide (more than 85%

is caught domestically), has a strong interest in improving their research in all aspects of the aquaculture industries [64,65]. It is important to note that Indonesia, as the biggest maritime country in the Southeast Asia region, has made big strides in expanding its marine and aquaculture businesses, education, innovation, research, and development. Indonesian government helps different groups work together to improve the quality of their science and technology. This is why they are seen as the most productive country in the field in the Southeast Asia region, with a large number of publications [66–68].

Citations in scientific publications are used for different purposes of research assessment, particularly in measuring research performance, scientific quality, impact, or influence [69,70]. The performance of research and academic institutions worldwide to produce scientific publications regularly, the impact of published documents, collaboration between institutions, and the evaluation of influential articles in a field could be evaluated using citation metrics [71,72]. It is also important to highlight that we looked at the total number of article citations and not just the number of articles that were published, which is mainly because citations could be an appropriate indicator of how active and productive a research field is.

3.2. Research collaboration network analysis

3.2.1. Collaboration networks

To answer RQ-2, Fig. 8 shows a network map of the people who worked together or shared co-authorship on the research on self-sufficient fish feed made from agri-food wastes and by-products. The co-authorship network based on country location of authors analyzed by the Walktrap clustering algorithm comprises 3 clusters, with the USA having the strongest betweenness (28.694) among relevant countries with a closeness and page rank of 0.029 and 0.068, respectively (Fig. 8 (a)). Various informative findings can be potentially interpreted from the observed graph, such as that it can be seen that Dawood, M.A.O. in cluster 7, Yang, J. in cluster 1, and van Doan H. in cluster 7, with PageRanks of 0.0732, 0.0666, and 0.0605, respectively, were regarded as the top 3 most influential authors in this scientific field. Those authors have the biggest node size in the co-authorship collaboration network, which means that they have strong contributions, high citation numbers, and extensive interconnection with other authors in the field. In the evolution of academic research, the role of influential authors is powerful to shape and define the interaction network, the change of scientific perspective, and the flow of intellectual information worldwide [57,58]. The influential authors with high citation numbers indicate that they have a significant impact on the academic research field, calculated based on the amount at which their relevant peers cite their scholarly article [73]. Nowadays, authors as professional researchers, particularly in aquaculture sciences, perform their scientific work in a complex dimension that includes contacting various research sponsors, collaborators, publishers, institutions, industries, and other colleagues, as well as registering and commercializing their patents, copyrights, inventions, and innovations [74–77].

Online publication of journal articles has made it possible to easily track citations and interactive features, such as the number of article downloads, which has resulted in the creation of a new set of indices that can be used to assess and value the relative value of contributions made by various researchers, journals, and articles [78–80]. Indicators of researcher performance and dominance in a field concentrate on one or a combination of four essential aspects that include the value of the topics, the quantity of researcher outputs, the number of connections, and the scientific impact of the publications or authors on society [81]. Research collaboration is required to maintain sustainability, reduce costs, and address complex scientific issues in research works that otherwise cannot be solved or addressed by individual researchers [82,83]. From Fig. 8 (a) and (b), it can be seen that there were some strong connections between some nodes and other nodes, indicating that the countries or authors in the environment of global co-authorship collaboration deal with and discuss common research topics, interests, works, and agendas. In bibliometric studies, the similarity connection refers to the network of underlying disciplinary or thematic research and is known as homophily [29,30,84].

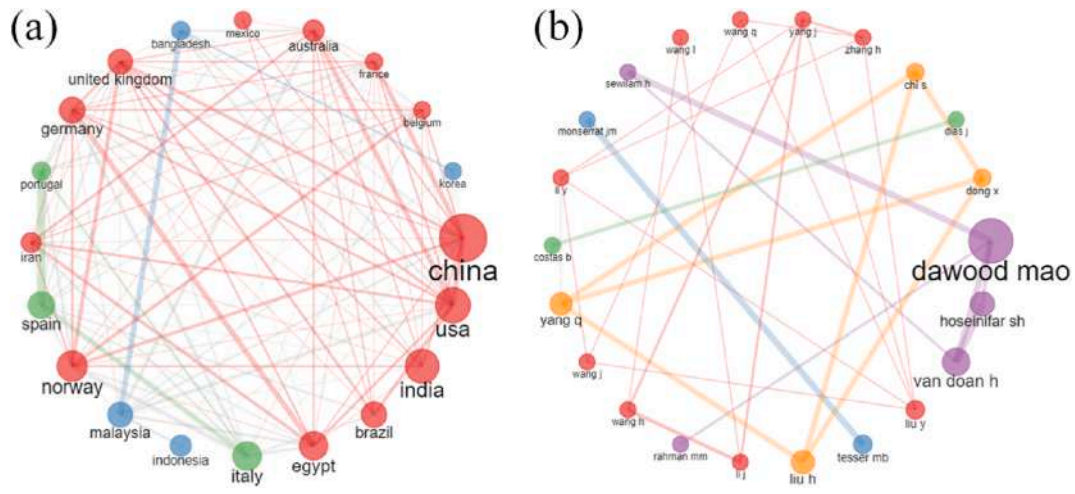

Fig. 8. Global co-authorship collaboration map based on the location of authors, the number of scientific production, and networking link strength.

According to the analysis of the global co-authorship collaboration network based on authors' contributions to answer RQ-3, the strongest closeness was found in cluster 4, where Dawod M.A.O. was observed with the highest closeness, followed by van Doan H., Hoseinifar S·H., Sewilam H., and Rahman M.M., with the closeness values of 0.25, 0.20, 0.17, 0.17, and 0.14, respectively, demonstrating a possible homophily factor. While responding to RQ-4, China was determined to be the most powerful country in the world within the field with the strongest collaboration network, primarily with France (7 connections), the United States (7 connections), and Norway (5 connections). Besides, China also built collaboration networks with 5 connections to Norway and the UK and 3 connections to Australia, Belgium, Hong Kong, India, and Malaysia, as can be seen in Fig. 8 (a). Future researchers could create new ideas by producing new research articles that link unconnected clusters. Those new articles have potential as scholarly bridges, as they could provide links between the disconnected clusters shown in Fig. 8 (b). Authors connecting those separate clusters could receive citations from other authors in both clusters, and they could play an essential role in bridging nodes in the network. As such, the authors could be assigned as the intermediary collaborators that connect multiple clusters in the global collaboration network.

Food waste is a serious global sustainability problem with negative effects on environmental, economic, and social aspects that needs effective collaborations and interventions from various stakeholders to ensure the best possible use of the available food resources and to support global food security [2,3,9,16]. Collaborative research on the barriers and opportunities for reducing and preventing agri-food waste is essential to facilitating the massive exchange of new ideas and best practices by bringing the development and implementation of innovation and technology that can be a more appropriate solution to alleviating the problem of food waste and loss [5,6,15]. According to a previous bibliometric report highlighting the pressures that hinder the adoption of sustainable practices in the context of the valorization of agri-food waste into beneficial products, those barriers include government issues, less

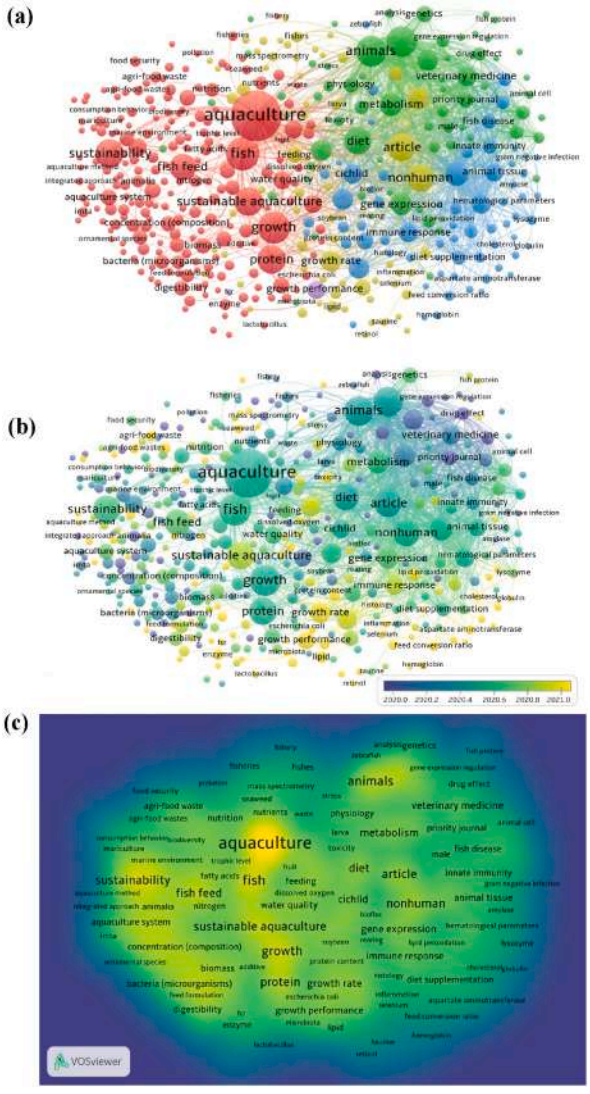

Fig. 9. Co-occurrence network visualization map of the terms found in the abstract. (a) Network visualization; (b) overlay visualization; and (c) density visualization.

public participation, unorganized local participation, training and skill development, a lack of infrastructure, standard quality, processing technology, and cost [16]. In this study, analysis results showed that there have been strong research collaborations among countries to find out the ideal way to process agri-food wastes and by-products to produce high-quality fish feed and propose recommendations to reduce organic waste worldwide to support sustainable development. This collaboration should be maintained in the long term with more innovative agendas.

3.2.2. Co-occurrence network and keywords analysis

The co-occurrence network analysis of the terms in the publication of self-sufficient fish feed produced from agri-food wastes and by-products, which was obtained from the Scopus database, is widely used in bibliometric studies to determine the potential relationship between two bibliographic items that present in the same research field. The co-occurrence network matrix is commonly used to analyze text that incorporates a specific graphic visualization of potential relationships between authors, affiliations, countries, concepts, or other relevant entities available in the metadata [85]. The items of the matrix consist of row and column headings, and the intersection of those indicates the existing co-occurrence network [86]. In this study, a specific filtering procedure of the co-occurrence network matrix has been used to eliminate items with a low frequency due to their low occurrence and representativeness, making the results more interpretable. Co-occurrence network analysis concentrates on evaluating and interpreting counts of co-occurring terms within a domain of a unit collection [86,87].

Herein, the co-occurrence network was analyzed using the LinLog/modularity normalization tool in the VOSViewer, with random starts at 1, the minimum number of term occurrences set to 5, the iterations maximum set to 1,000, the initial step size of 1.00, the step size reduction of 0.75, the step size convergence of 0.001, and the random seed of 0. It was found that 408 items met the standard of the specified threshold, 5 main clusters, 17,596 links, and 38,677 total link strength, with the item of aquaculture in cluster 1 having the largest links (365), total link strength (1,818), and occurrences (234) (Fig. 9 (a), (b), and (c)). An agglomerative bottom-up hierarchical clustering approach was used in the computation of LinLog/modularity normalization to construct the clusters and a co-occurrence matrix based on selected terms extracted from the titles of the publications with an occurrence of $\geq$2 adjusted from the initial input setting in the clustering stage [32,88,89]. The most relevant items had previously been modified to limit the appropriate items contextualized to the research field.

According to Fig. 9 (a), (b), and (c), in cluster 1, there were dominant items with strong occurrence and total link strength, which include fish, sustainability, growth, protein, fish feed, and sustainable aquaculture, while in cluster 2, we could see that article, nonhuman, growth rate, and fish meal were the dominant items. Besides, the most dominant items that influence other items within the investigated research field in clusters 3, 4, and 4 were controlled study (56 occurrences), animal (90 occurrences), and growth performance (34 occurrences), respectively. Besides having many links to the other related items, those identified items also have the potential to shape the orientation and perspective of some research topics and lead to the emergence of further novelties in various research topics. Furthermore, these dominant items could be selected as potential indicators for new topics, priorities, and trends in the research of self-sufficient fish feed produced from agri-food wastes and by-products since wide nodes close to the center of the co-occurrence network or research hotspot indicate the important research trends [30,32].

To determine the emerging contents of the scientific publications to answer RQ-5, keyword analysis extracted from the abstract could be performed generally to form a word cloud or tag cloud for characterizing the main conceptual level of abstraction, screening the thematic trends in a specific research field, and identifying the recent research progress in a particular topic [90]. Fig. 10 depicts a word cloud of the keywords in the scholarly publication of self-sufficient fish feed produced from agri-food wastes and by-products

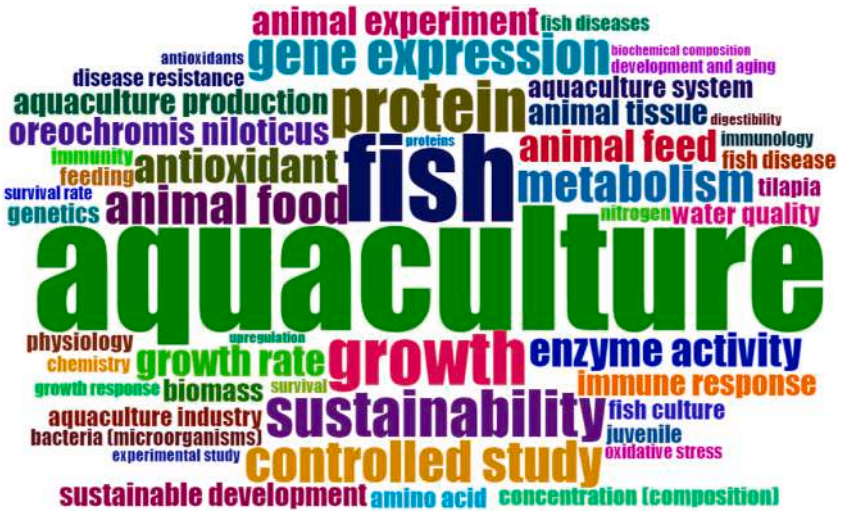

Fig. 10. Word cloud of the common keywords used by the authors in Scopus-indexed publications (size represents the frequency of use of keywords).

available in the abstract. The words constituting the visual graph of the word cloud show the occurrence frequency of a specific word written in an article, where the larger the word in the graph, the higher the frequency in observed documents, and vice versa. It can be seen that the most repetitive keywords with high frequency were aquaculture (166 times), fish (117 times), growth (73 times), protein (69 times), sustainability (63 times), controlled study (56 times), gene expression (56 times), animal food (53 times), metabolism (51 times), antioxidant (46 times), enzyme activity (45 times), animal feed (43 times), growth rate (42 times), and animal experiment (39 times) (Table S1, Fig. 10).

The keyword evolution trends and occurrences could highlight recent updates in global research topic development and reveal patterns of scientific production [91]. A future research or literature gap is required to define specific convergences and divergences, diverse directions, and construct a universal paradigm of the future of a research field. For these purposes, co-occurrence and word cloud analysis could be performed accordingly [92]. Fig. 11 indicates article keywords that have experienced fluctuating changes in frequency during 2019–2022, specifying potential keywords and the body of knowledge in the research of self-sufficient fish feed produced from agri-food wastes and by-products, which can be identified from the growth of topics that emerge in a particular period, show their progress in importance, and then disappear [93]. According to the answer to RQ-5, some topics, such as aquaculture and sustainable aquaculture, fish feed with agri-food waste, rainbow trout species, the development of a circular economy, probiotic application, and cell signaling cytokines and peptides, are likely considered major research hotspots in self-sufficient fish feed research (Fig. 11).

3.3. Intellectual landscape

3.3.1. Thematic evolution

In this thematic evolution analysis to answer RQ-6, a two-plot Sankey diagram was used to visualize a multifaceted flow, trend, and connection among article keywords to other keywords, from inward flows presented in 2019–2021 to outward flows in 2022. Fig. 12 shows a Sankey diagram of the keyword article in the publication of self-sufficient fish feed produced from agri-food wastes and by-products in which the keywords were extracted from the collection with the maximum degree of precision. It can be seen that the width of the boxes for aquaculture, growth, polyphenols, food security, and growth rate were the five main keywords with the highest occurrence that were used intensively by several authors in their publications during the period of 2019–2021, indicating that those keywords covered several themes within the research field of self-sufficient fish feed produced from agri-food wastes and by-products. The inclusion indices and stability of aquaculture (with the domain of words such as aquaculture, fish feed, sustainability, tilapia, fish, aquaponics, fish farming, fish meal, and toxicity) to integrated multi-tropical aquaculture (IMTA) and feed were the same (1.00 and 0.02), while the occurrence of aquaculture in IMTA (10) was higher than aquaculture in feed (3).

The inclusion index of the growth in gene expression (0.50; 6 occurrences) and growth rate for *Cyprinus carpio* (1.00; 3 occurrences) from 2019 to 2020 to 2022 was the highest compared to other connections, while food security and polyphenols were the same and did not change (1.00; 7 occurrences) (Table S2, Fig. 12). This is also indicated by the divergence of the keywords' channels and growth used by the authors to share their research findings in various online publications, where the word aquaculture included *Aeromonas hydrophila*, agri-food waste, aquaculture, feed conversion ratio (FCR), bioactive compounds, circular economy, feed, IMTA, *Oreochromis niloticus*, and sustainable aquaculture. Experimental studies on FCR, bioactive compounds, feed, immune response, gene expression, and IMTA are essential in aquaculture production [45–50]. For instance, the self-sufficient fish feed produced from agri-food wastes and by-products, particularly using fruit wastes from pineapple skin, pineapple crown, jackfruit skin, jackfruit pulp, grated coconut, and mixed fruit wastes (jackfruit pulp + grated coconut), to promote fish growth performance and stimulate immune system's response against fish diseases, has been successfully examined [46].

From the above study, it has been reported that the FCR in observed Malaysian mahseer fish (*Tor tambroides*) fed with fruit-waste diets was significantly lower ($p < 0.05$) compared to the biological control. When the fish were challenged by *Aeromonas hydrophila* disease, the survival rates of mahseer and tilapia fed with fruit-waste diets were still significantly higher ($p < 0.05$) compared to the biological control. Thus, the valorization of agri-food wastes and by-products, such as the fruit waste aforementioned, into self-sufficient fish feed is critical to avoid environmental pollution and contribute new potential sources of raw materials for both fish and other animal feeds [46,94,95]. Fruit wastes and by-products, including rinds, skins, seeds, and pulps, are auspicious sources that contain abundant bioactive compounds, including antioxidants, antimicrobials, essential vitamins, phytochemicals (phenolics, flavonoids, and carotenoids), possessing valuable nutritional properties, and various functional substances [45–50,95].

3.3.2. Conceptual structure

In Fig. 13 (a) and (b), a factorial analysis as a statistical approach was applied to specify joint keywords in response to concealed (unnoticed) keywords and answer RQ-5 and RQ-6 as well. In this factorial analysis, several parameters for performing multiple correspondence analysis (MCA) were applied, including automatic clustering, a maximum number of terms set at 50, and the scope of analysis being the keywords plus the publication data records [29,30]. The variability among the corresponding keywords with a lower number of unconsidered keywords was identified and reduced in order to minimize independent latent keywords in the publication data records [29]. Due to its ability to identify a smaller number of underlying variables in an extensive number of observed variables, the factorial analysis was applied to specify the latent keywords or factors that cause a commonality in the publication data records [36]. Through factorial analysis, two main clusters of 45 observed keywords in dimension 1 (88.33%) and dimension 2 (4.78%) were clearly elucidated (Fig. 13 (a) and (b)). The specific frequent keywords commonly used on the publication in this field depicted in the cluster in blue (28 keywords), indicated research direction and orientation on the growth studies of self-sufficient fish feed produced from agri-food wastes and by-products. The boundary keyword points included amino acid, growth rate, enzyme activity, *Oncorhyncus*

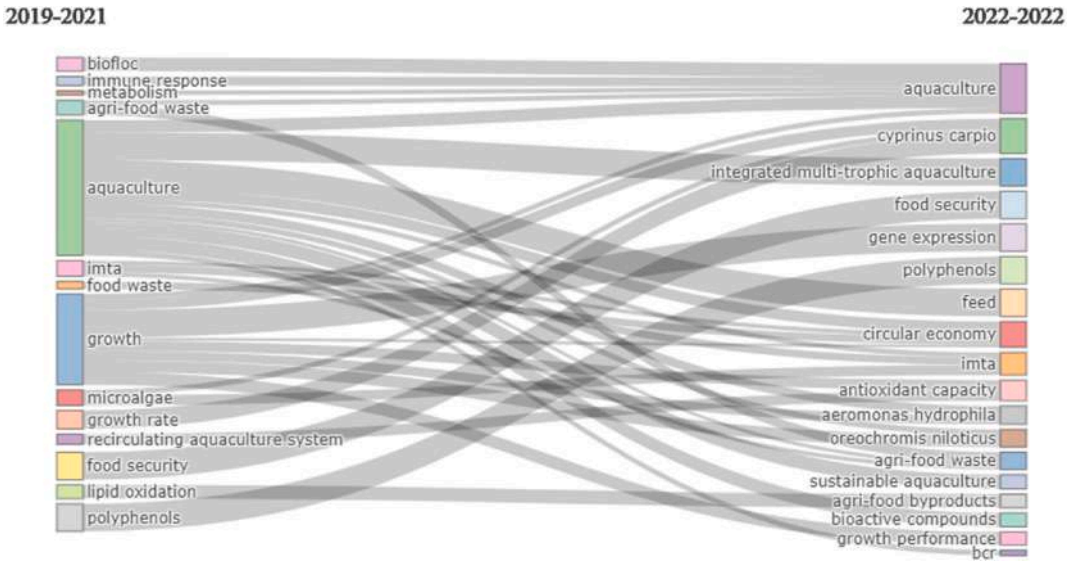

Fig. 11. Potential keywords and the fluctuation of body of knowledge in the research.

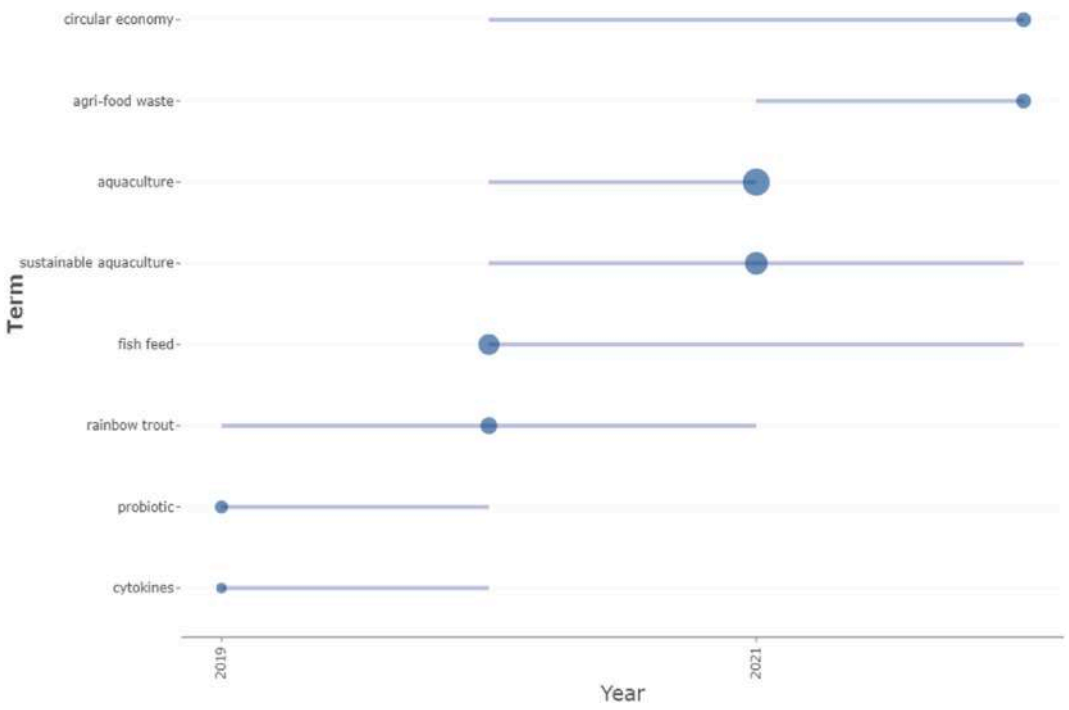

Fig. 12. Thematic evolution of the observed research field during the period of 2019–2022.

mykiss, gene expression, cichlid, growth, antioxidant, sustainable development, aquaculture production, fish culture, aquaculture system, and concentration/composition. While other clusters in red included common keywords (17 keywords), boundary keyword points included animal experiment, animal tissue, fish disease, priority journal, veterinary medicine, animal feed, genetics, diet, and immune response (Table S3, Fig. 13 (a) and (b)).

4. Conclusions

This study aims to record the various research developments in producing self-sufficient fish feed using multiple locally available agri-food wastes and by-products. Generally, the technical processes start from the waste collection, separation, conversion of agri-

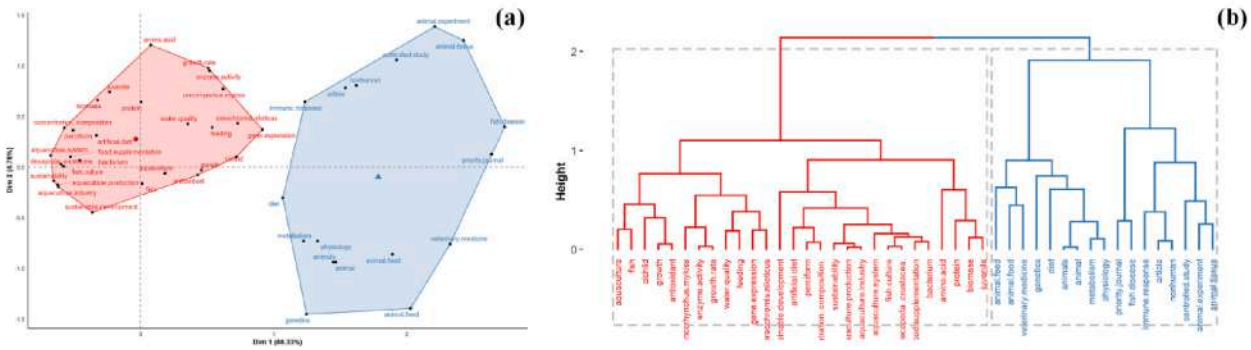

Fig. 13. Factorial approach using MCA elucidates conceptual structure map (a) and topic dendrogram (b).

food wastes and by-products into another added value products, such as fishmeal, fish oil, fish protein hydrolysate SBM, DDGS, PKM, DBH, and multiple dietary starches. This research first uses the potential application of bibliometric approach by using VOSViewer and Biblioshiny in the Bibliometrix R-package to address the current status of observed field, research contexts, knowledge domain such as the most influential scholars, core journals, major trends, and research hotspots in the global level. Secondly, the investigative research further explores interest growth and insightful developments for expanding knowledge in producing self-sufficient fish feed by utilizing agri-food wastes and by-products and its relation to supporting the global agenda towards sustainable aquaculture and the blue economy. Besides, it allows us to understand that novelty, timeliness, and consistency in publication are the most essential factors in the development of this research field.

The number of publications on the observed field has become more popular and grown significantly in the last four years, following the increase in interest among various related entities in fish feed production, including the fishery and marine industries, government, and academia, as well as the development of innovative technologies for producing high-quality fish feed. The generalized conclusions drawn from this study are as follows.

a) During the COVID-19 pandemic (2019–2020), the research on the observed field was significantly stagnant, but after the pandemic (2021–2022), the research progress significantly increased, indicating that the research topics on fishery and agri-food waste were continuously interesting and growing (RQ-1).
b) Dawood, M. A. O., Yang, J., and van Doan H. were determined to be the top 3 most influential authors in this scientific field, having the strongest contributions, high citation numbers, and extensive interconnections with other authors in the field. Their international collaborations and the environment of global co-authorship were mainly focused on developing common research topics, interests, works, agendas, and access to research funding (RQ-2 and RQ-3).
c) China, Egypt, Italy, and the USA significantly contributed to the development of self-sufficient fish feed and sustainable fishery studies with an enormous amount of high impact factor research publications, collaborations, and extensive credit (in citations) from the international scholarly community (RQ-4).
d) The most repetitive keywords with high frequency have been compiled from the articles' abstracts, including aquaculture, fish, growth, protein, sustainability, controlled study, gene expression, animal food, metabolism, antioxidant, enzyme activity, animal feed, growth rate, and animal experiment (RQ-5).
e) Research in utilizing agri-food wastes and by-products to produce self-sufficient fish feed has significantly increased in the last four years, with a significant emerging interest in research performed on IMTA, the circular economy, bioactive compounds, and growth performance (RQ-6).

Future bibliometric research could be performed by investigating major upstream and downstream activities in the value and supply chains in the production of self-sufficient fish feed, cost analysis of the valorization of agri-food wastes and by-products to produce self-sufficient fish feed, and systematic literature on the effect of diet supplementation of self-sufficient fish feed on fish growth performance. The bibliometric approach used in this study is strongly recommended to be applied to other topics as well. It may aid in the retrieval of complete metadata, bibliometric portfolios, and visualization of the intellectual landscape from a collection of abstracts, publications, and citations. The fact that we only utilized articles from the Scopus database was a significant constraint and a potential source of inadequate literature inclusion. Future research might incorporate various kinds of publications (e.g., books, conference papers, and so on) as well as other scientific databases, such as the Web of Science and Dimensions, that support and subsequently broaden the evaluation results by unpacking new ideas, understandings, research viewpoints, and trends. The findings of this study should be supplemented by a bibliometric or systematic literature review that contrasts the pandemic's effects on the research on the various food industries and other economic sectors (such as the marine, fishery, and agricultural supply chains). In future research, bibliographic coupling-based literature clustering could be applied, as the current method is static and retrospective. Bibliographic coupling may produce distinct clustering outcomes compared to co-citation analysis, which is a forward-looking and dynamic methodology.

Funding

This study was financially supported by the National Research and Innovation Agency of Indonesia under Grant No. B-4252/III·12/HK.November 00, 2022.

Author contribution statement

Adhita Sri Prabakusuma, Budi Wardono, Mochammad Fahlevi, Armen Zulham, Mas Tri Djoko Sunarno, Mat Syukur: Conceived and designed the analysis; Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Mohammed Aljuaid, Sebastian Saniuk: Analyzed and interpreted the data; Contributed analysis tools or data; Wrote the paper.

Tenny Apriliani, Radityo Pramoda: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data associated with this study has been deposited at Figshare: https://doi.org/10.6084/m9.figshare.21879066.v1.

Additional information

Supplementary content related to this article has been published online at [URL].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We would like to extend our heartfelt appreciation to King Saud University, Riyadh, Saudi Arabia for funding this work through the Researcher Supporting Project (Grant No. RSP2023R481). The authors also thank Mr. Dadan Permana, Dr. Jonny Walker Situmorang, Mr. Sarman Paul Lumbantobing, and Ir. Moral Abadi Girsang from the Research Center for Cooperative, Corporation, and People's Economy for providing a valuable review and making comments and suggestions for improving the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17573.

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