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Bibliometric Analysis of the Effects of Aquaculture on Mangrove Forests

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ABSTRACT

Mangroves are coastal ecosystems that stand out for their biodiversity, carbon sequestration, and natural flood defences. These ecosystems face significant threats from human activities, particularly aquaculture. This research uses bibliometric techniques such as the evolution of scientific production, bibliographic coupling by country, and co-occurrence of keywords to identify trends, collaboration networks, and emerging research areas using the Scopus database, chosen for its broad coverage of high-quality academic journals and peer review. This analysis describes the evolution and trends in mangrove studies, covering environmental, social, and legal issues. The methodological process was divided into three stages: design and data collection strategy, filtering and validation of the literature, and quantitative analysis to identify trends and thematic evolutions. A total of 993 documents from 39 countries have been reviewed, with the main contributions coming from China, the United States, and Indonesia. The study identified four priority areas for the development of research and future trends on the following topics: a) evaluation of heavy metal pollution, b) blue carbon and its impact on climate change mitigation, c) conservation and protection strategies, d) the use of remote sensors and machine learning for monitoring mangrove loss. These approaches are crucial for conserving mangroves, improving understanding and response capacity to climate change, and contributing to Sustainable Development Goals, considering the socioeconomic value of these ecosystems.

1. INTRODUCTION

Mangroves are ecosystems found in tropical and subtropical coastal areas, generally developing in interface (terrestrial-marine) and intertidal (flood-prone) regions [1]. Mangroves are tolerant to salinity and flooding due to their roots growing in muddy areas and managing to transfer oxygen from the atmosphere [2]. Globally, in 2020, its extension was estimated at 14.8 million hectares, where South and Southeast Asia (36%) housed the highest concentration of mangroves, followed by North and Central America (17.4%), West and Central Africa (15.58%), South America (14.4%), and Oceania (8%) [3]. Approximately 47% of the world's mangroves are distributed across five nations: Indonesia, Brazil, Nigeria, Mexico, and Australia [4]. These ecosystems provide ecosystem benefits, both direct and indirect, to nearby human, animal, and plant communities, contributing to biodiversity and ecological balance in coastal systems [5-8]. In addition, they are an essential part of the economy of surrounding communities, being a source of forest resources, fish and shellfish species, and ecological tourism, which provide employment and economic opportunities [9].

Mangroves are natural protective barriers of coastal areas against natural phenomena, such as storms and floods [10]. They contribute to mitigating the effects of climate change through the capture of CO_2 from the atmosphere. One part is converted into oxygen through photosynthesis, and the other is transported and stored in muddy areas (soil or sediment) for long periods, eventually returning to the ocean and being converted into oxygen [11, 12].

Despite being a coastal ecosystem of great importance, they face multiple threats compromising their survival. Among the main risks are deforestation, which decreases and alters the biodiversity of the ecosystem [13], industrial pollution that results in the presence of heavy metals in the sediments, increasing toxicity, affecting the health of forests [14], change in water salinity as a result of climate change, affecting plants and animals that are not adapted to more saline conditions [15], overexploitation of fishing resources [16], invasive species, which alter the physical and chemical properties of the soil and change its environmental conditions [17] and aquaculture that can destroy habitats, reduce biodiversity, degrade soil and water quality, alter hydrology and emit carbon [18]. Over the past five decades, these activities have contributed to the deforestation of approximately one-third of the world's mangrove forests [19].

Of these activities, aquaculture stands out for its rapid growth, with an annual increase of 5.8% between 2001 and 2016 [20]. This sector was responsible for 26.7% of the global loss of mangrove area between 2000 and 2020 [4].

The environmental problems derived from aquaculture expansion generate environmental concerns regarding the sustainability of the ecosystem [21, 22]. These concerns range from chemical alterations in the soil that affect fertility due to eutrophication caused by nutrient overloading [23] to the dependence on energy resources due to increased mechanization and aeration and filtration systems that increase the carbon footprint [24].

Numerous case studies exist on the environmental impacts of aquaculture in mangrove areas. For example, research in the Jiulong River Estuary Mangrove Nature Reserve (China) assessed greenhouse gas fluxes (N_2O, CH_4 and CO_2) in mangrove sediments and aquaculture ponds, influenced by sewage dredging [25].

Likewise, in Dongzhai, China, researchers examined contamination due to the accumulation of antibiotics in mangrove waters and sediments, which arise from using fish and shellfish cultures to prevent and treat diseases, causing alterations in the ecosystem's biodiversity [26]. Similarly, a study in the Hanjiang River estuary found that high concentrations of macronutrients (nitrogen and phosphorus) and organic load (organic carbon) were generated from aquaculture effluent, causing an alteration in the chemical composition of the soil and the mangrove health [27].

The need for adequate public policies becomes evident in defining specific areas for aquaculture, focusing on reviewing practices against the risks of sea level rise and climate change [28] and promoting energy efficiency as part of the sustainability measures [29]. These policies are crucial not only for the environmental impacts but also for the social repercussions, as observed in the mangroves of Sundarbans (India), where the expansion of the shrimp industry has caused economic inequalities and overexploitation of forest resources [30]. In contrast, in the case of Bangladesh, policies balance aquaculture practices with the sustainability of mangroves [31].

In the scientific literature, studies have been conducted to analyze the impacts of aquaculture activities on mangroves, as the research of Tengku Hashim et al. [32], which documented the negative aspects of aquaculture related to eutrophication, microplastic pollution, ecosystem degradation and introduction of Non-Native Species. Several bibliometric studies have identified aquaculture as a primary factor threatening mangroves [33]. In addition, the emerging approaches related to climate change and its mitigation, the use of remote sensors to study the distribution and state of mangroves, their role in carbon storage (blue carbon) and their importance in risk protection are pointed out in flooding, especially in areas susceptible to sea level rise [33, 34].

Despite scientific advancements providing a general overview of research on mangroves and their relationship with global factors such as climate change, a comprehensive bibliometric assessment is needed to analyze the impacts of aquaculture on mangroves quantitatively.

Based on these considerations, this study aims to answer the following research questions: What are the current trends in research on the effects of aquaculture on mangrove forests from 1975 to 2023? How does aquaculture affect mangroves, and what strategies have been implemented to mitigate these adverse effects? What tools and approaches are used to study the impacts of aquaculture on mangroves, and how do they help manage them?

This study performed a bibliometric analysis of the effects of aquaculture activities on mangrove ecosystems using the Scopus database. This research covered nearly five decades of publications, identifying the evolution and trends in the field. This analysis's findings can guide future studies and practices, provide inputs for developing effective conservation policies and strategies, and promote sustainable development in aquaculture activities.

2. MATERIAL AND METHODS

The methodology combines quantitative techniques, emphasising the statistical analysis of titles, abstracts, and keywords on the relationship between mangroves and aquaculture, with the application of the VOSviewer and Bibliometrix software. This allows us to extract methodologies, priority scientific groups, work topics or subtopics through frequencies, periods and clusters of scientific development. Bibliometric tools allow analysing the evolution of scientific knowledge on a research topic in a given period [35, 36]. Figure 1 shows the methodological diagram of the study.

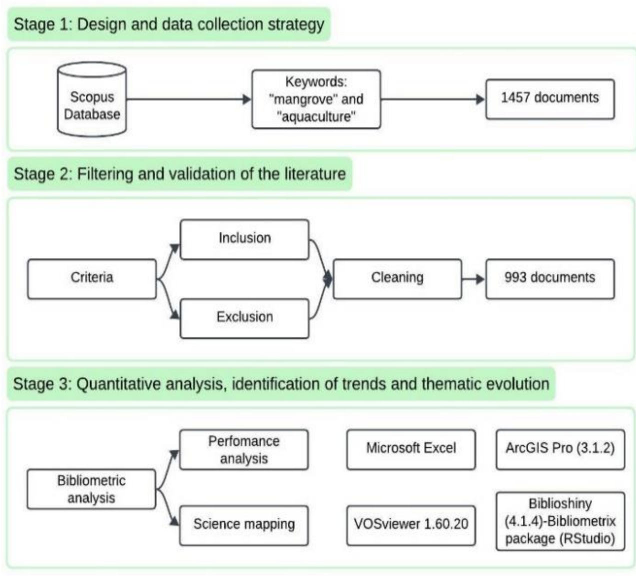

Figure 1. Study methodological scheme

2.1 Stage 1: Design and data collection strategy

The database and the search strategy to be explored were defined in the first stage. Databases such as Scopus, Dimensions, and Web of Science are essential for organizing and accessing academic publications in bibliometric analyses [37]. Scopus offers a balanced approach, with approximately 96.42% of its journals also covered by Dimensions and 99.11% indexed in Web of Science [38]. Scopus database was selected due to: i) the wide range of academic disciplines (240), ii) global coverage of journals, conferences and books with high impact in the scientific community with more than 94 million records, 7000 publishers [39, 40], iii) frequent use by researchers, institutions and students to the analysis and monitoring of relevance in different research fields [41, 42], iv) the quality of the documents through metrics [43, 44], and v) export of the database in different formats (e.g., CSV, RIS) [45].

The search criteria on the Scopus platform were selected based on two key terms: "mangrove" and "aquaculture", which help to understand the interaction between these two fields of study [46, 47]. The word "mangrove" refers to forests or shrubs adapted to saline and flood conditions [48], while "aquaculture" includes activities focused on the breeding of aquatic organisms in artificial conditions [49]. This search strategy aims to cover studies and trends that include environmental [50], social [51], public policies [52] and sustainability [53, 54] aspects.

Data was searched and downloaded on March 15, 2024, using search variables among titles, abstracts, and keywords [55]. The search equation was (TITLE-ABS-KEY (mangrove*)) AND (TITLE-ABS-KEY (aquaculture)), obtaining 1457 results.

2.2 Stage 2: Filtering and validation of the literature

Inclusion and exclusion criteria were applied, where the type of document was limited to articles only due to the rigorous peer review process before acceptance and publication, which ensures the quality and reliability of the research [56], reducing the number to 1069 articles of interest. Likewise, publications from the year 2024 were excluded, obtaining 1049 documents. Finally, only articles in English were selected for their relevance, dissemination and acceptance among researchers from different countries, resulting in 995 scientific articles [57].

Subsequently, the database with the bibliographic information was extracted in .CSV format (comma-separated data), where it was categorized mainly by year, title, authors, area of study, journal, and number of citations, among other relevant parameters for the analysis [58].

2.3 Stage 3: Quantitative analysis, identification of trends and thematic evolution

In this phase, data analysis was performed using two bibliometric techniques: i) scientific production analysis to understand and interpret the current state of research in the field of study and its links concerning countries, authors and related institutions [59]; and ii) scientific mapping, which allows identifying the interrelationships between several variables using a co-occurrence analysis in keywords, author citations, and publication entities, to be represented visually through co-occurrence networks [60]. Bibliometric citation analysis techniques [61], including the study of scientific production, were employed to identify trends and periods of increased research activity. A country's co-authorship analysis revealed international collaboration patterns and potential growth areas [62]. Bibliographic coupling by country highlighted how different cultures and political systems contribute to knowledge generation [63]. Author Keyword co-occurrence mapping identifies research trends, thematic groups, and emerging topics, providing a comprehensive understanding of the field's development and evolution [64, 65].

For this bibliometric study, four programs were used: i) Microsoft Excel (Office 365) for preprocessing and data cleaning, eliminating records without author, duplicates and incomplete fields [66] (obtaining 993 scientific documents), as well as for the creation of tables and graphs of scientific production concerning the topic of interest [67]; ii) VOSviewer (version 1.60.20) for the construction and visualization of interrelationships in bibliometric maps [68, 69]; iii) ArcGIS Pro (version 3.1.2) for the elaboration of thematic maps representing the spatial distribution of the contribution by countries and regions [70, 71]; iv) Biblioshiny (version 4.1.4) using the R language Bibliometrix package to explore and create the thematic map and thematic evolution graphic [72, 73]. The mapping was performed with the author's keywords and the application of the Louvain clustering algorithm [74] because it considers the density of connections between elements and the connectivity between them.

3. RESULTS

3.1 Performance analysis

3.1.1 Evolution of scientific production about aquaculture and mangrove

Scientific production was evaluated from 1975 to 2023, covering 993 published articles with 33,222 citations. Figure 2 represents the evolution of the scientific contribution to the topic of study over time.

Publications on the effects of aquaculture on mangrove forests have shown a growing trend over the years, from 1975 to 2023. It can divide this growth into three main periods:

Period 1975-2011: In this initial period, 265 publications were identified, representing approximately 26.7% of the work related to the field of study, and this time marked the stage of exploration, foundation and learning about the impact and interactions between aquaculture practices and mangrove conservation. The most cited article is "Mangroves among the most carbon-rich forests in the tropics" by Donato et al. [75], published in Nature Geoscience, with 1867 citations, where he examines the decline of tropical mangroves due to coastal development and aquaculture, focusing on how this loss affects carbon emissions, the importance of mangroves in global carbon storage and cycling. In this period, the main topics were addressing topics such as the economic value of mangrove ecosystems [76], socioeconomic impact [77], extinction risks [78], and coverage analysis with remote sensors [79-81] and pollution impacts on mangroves by heavy metals [82], effluents [83], and aquaculture [84, 85].

Period 2012-2019: During this period of eight years, the production of scientific literature was 342 publications, which is 34.4% of the total. In this period, the most cited article was "Rates and drivers of mangrove deforestation in Southeast

Asia, 2000-2012" by Richards D.R., published in Proceedings of the National Academy of Sciences of the United States of America, with 720 citations [86], which highlights the factors behind mangrove deforestation in Southeast Asia, which served to understand the pressures faced by these ecosystems. In turn, during these years, studies addressed topics such as climate change [87], cover mapping [88-90], and the distribution and status of mangroves worldwide [11, 91], conservation [92-94], mangrove forest degradation [95, 96], carbon stores [97-100], and sustainability [101-104]. Therefore, the study on the sustainability and environmental impacts of aquaculture on mangrove ecosystems gained greater attention.

Period 2020-2023: The last four years have seen the most significant number of publications, with 386 articles, equivalent to 38.9% of the total. This increase denotes continued interest and commitment to understanding and mitigating the impacts of aquaculture on mangroves. The article "Global declines in human-driven mangrove loss" by Goldberg et al. [105], from Global Change Biology, with 385 citations, indicates a positive trend towards reducing mangrove loss caused by human activities, suggesting a shift towards more sustainable practices.

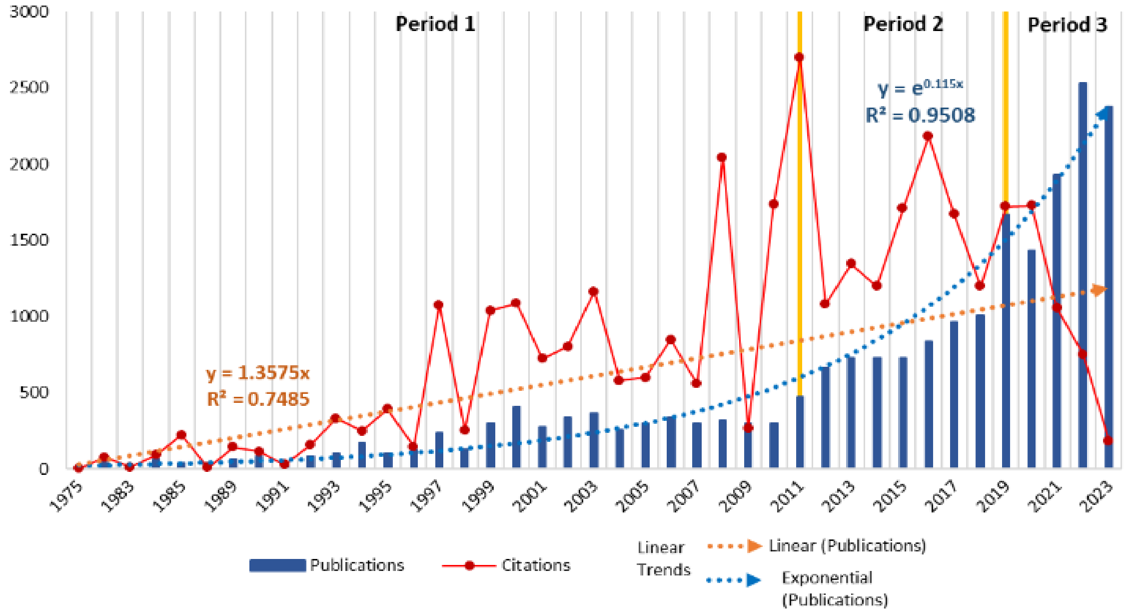

Figure 2. Publication and citation trends in the study of aquaculture and mangroves

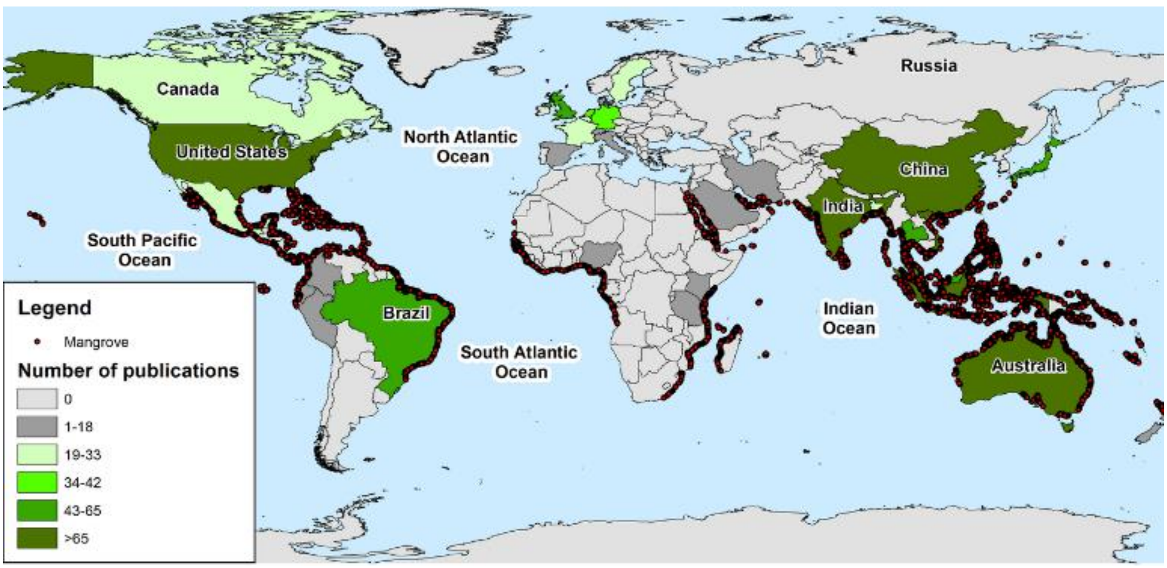

Figure 3. Geographic distribution of mangrove and scientific production

3.1.2 Scientific contribution by countries

Figure 3 represents the map with the regions and their scientific production, highlighting countries such as China, Indonesia, and India (Asia), the United States (North America), and Australia (Oceania). The map also shows the distribution of mangroves worldwide [106], with large areas of mangroves in some areas, such as Indonesia and Australia, coinciding with intense research activity in this field.

Research on mangroves and aquaculture receives contributions from 39 countries in Asia, America, Europe, and Oceania (Table 1). Firstly, Asia leads in the number of publications, with China and Indonesia, with 135 and 119 articles, respectively, exceeding 9000 citations.

The United States contributes 135 documents and 11,055 citations in America, while Brazil and Canada have 56 and 25 documents, respectively. In Europe, the United Kingdom leads production with 65 papers and 4,556 citations, and Germany has 42 documents and 1,831 citations. In Oceania, Australia leads with 91 papers and 7,319 citations. Finally, the African region presents a smaller number of publications.

3.1.3 Co-authorship analysis by countries

Countries like the United States, United Kingdom, Indonesia, and Australia (Figure 4) have many publications, citations, and solid collaborative links, establishing a predominant co-authorship network with geographical regions such as Asia or Europe.

The United States and the United Kingdom lead the top countries with a significant degree of international co-authorship with European and Asian countries, showing diversity in their associations. On the other hand, China maintains collaborations with its Asian and Western neighbors, reflecting both a regional and globally collaborative approach. Australia, like the United States, links effectively with Pacific and Asian countries and maintains significant relationships with Western nations, demonstrating its central role in ocean and environmental research.

Table 1. Countries and regions with more contributions

No.	Country	Region	Number of Publications	Citation Count
1	China	Asia	135	3567
2	United States	América	135	11055
3	Indonesia	Asia	119	5689
4	India	Asia	116	3146
5	Australia	Oceanía	91	7319
6	Vietnam	Asia	90	3030
7	United Kingdom	Europa	65	4556
8	Thailand	Asia	64	1543
9	Japan	Asia	60	2996
10	Malaysia	Asia	59	2373

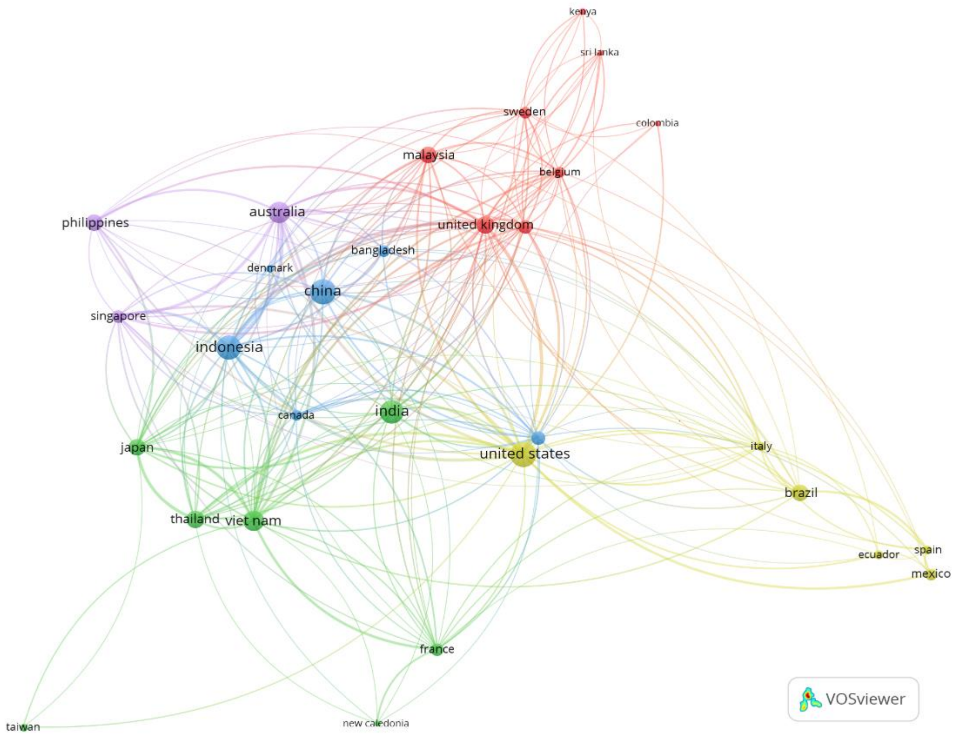

Figure 4. Collaboration network between countries

3.1.4 Co-occurrence by author's keywords

In a bibliometric study, co-occurrence analysis for author keywords allows the identification of research areas that are consolidated and emerging. In this way, the evolution and existing synergies are revealed [107-109]. Based on the analysis performed with the VOSviewer tool, 993 articles and 2553 keywords were extracted. In addition, the threshold of the words was seven occurrences. As a result, a map of co-occurrence networks highlighted 62 keywords, and in Figure 5, a group of circles of different sizes represents the frequency of the term, and the closeness of these circles indicates their correlation.

Cluster 1, "Climate change and ecological restoration" (265 occurrences), studies and trends focus on the interaction between human activities and the mangrove ecosystem. The terms that stand out in this cluster are blue carbon (45 occurrences) which denotes the importance of the ecosystem service that mangroves provide for carbon sequestration [110-112] and their contribution to climate change mitigation [113-115]. Similarly, the terms restoration (35 times) and deforestation (28 times) indicate interest in evaluating and tracking degraded mangrove areas with an emphasis on monitoring and follow-up of these ecosystems [116-118].

Cluster 2, "Aquaculture and marine conservation" (428 occurrences), the term with the highest occurrence is "Aquaculture" (229 times). Research appears on mangrove conservation [119], sustainable practices in the production of aquatic organisms [120], and policies and regulations regarding productive activities (fisheries) in coastal sectors [121].

Cluster 3, "Remote Sensing and Land Cover Change" (222 occurrences), remote sensing is the term with the highest occurrence (58 times). Land Use and Land Cover Change (LULCC) topics stand out for the evaluation and monitoring of mangrove ecosystems [120, 121], as well as a predominance in the use of Landsat satellites for monitoring estuaries and coastal areas [122], anthropogenic activity [123, 124], and studies on sea level changes in coastal regions [125].

Cluster 4, "Contamination and health of aquatic ecosystems," studies focus on heavy metal contamination (19 occurrences) in mangrove waters and sediments due to aquaculture activity [126-129], the eutrophication process (18 occurrences) due to nutrients such as nitrates and phosphates, and the proliferation of bacteria resistant to antibiotics as a result of human activity in aquaculture [130, 131].

Cluster 5, "Mangrove Conservation and Water Quality", the term "mangrove" predominates (326 occurrences). The presence of studies in the countries of Vietnam and Thailand is recurrent due to their contributions to the conservation and protection of mangroves, promoting the restoration and growth of biological diversity by improving plant structure and mitigation of carbon emissions into the environment [132], also the contribution of genetic research for the sustainable management of mangrove resources [133], financial incentives and public policies that address the challenges of governance with government entities [134], and studies of pollution and its influence on the quality of water bodies [135].

Cluster 6, "Estuarine Ecosystems and Geospatial Analysis", the term with the most occurrences is "estuary" (25 occurrences). This cluster represents the line of studies focused on estuaries and coasts as ecological transition zones and also analyzes issues related to the impact of effluents with nutrients on mangroves from shrimp farming activities [136, 137]. In this line, there are also works related to Geographic Information Systems (GIS) and the predominance of the NDVI spectral index as a tool for monitoring and analyzing plant health [138, 139] as well as the effects of urban development on native mangrove species [140].

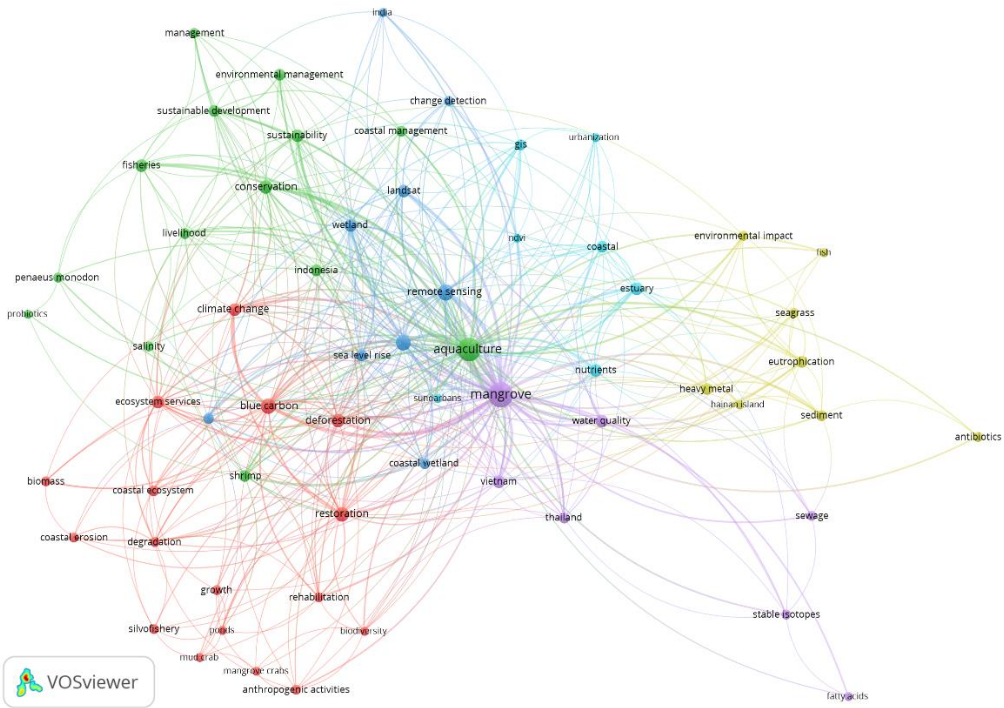

Figure 5. Keyword network

3.1.5 Analysis of bibliometric trends in aquaculture and mangrove research

Figure 6 shows the thematic map based on centrality and density. The thematic map classifies the mangrove and aquaculture literature into four categories or quadrants:

i) Quadrant I-motor themes: the first group comprises the themes of "Heavy Metal", "Sediment", and "Seagrass", along with the "Hainan Island" region, analyzing areas to assess pollution and ecological health in marine ecosystems [141]. In parallel, Landsat and Change Detection facilitate land-based change monitoring and carbon management, especially in Madagascar, an essential biodiversity and conservation region [142].

ii) Quadrant II-niches themes: The analysis reveals specialized themes such as "Acanthus ilicifolius", "Antibacterial activity", "Polyunsaturated Fatty Acids", and "Biomass", highlighted for their relevance to mangrove conservation and biomedicine. The "Environment" theme reinforces the need for sustainable practices that integrate ecological health with aquaculture, advocating an integrative approach that brings together research and practical application for natural resource management and conservation [143, 144].

iii) Quadrant III-emerging or declining themes: represented by terms such as "sustainable development", "environmental management", "resilience" and "valuation". These themes are gaining prominence, reflecting a shift towards sustainability in aquaculture practice and recognising the need to manage mangrove resources more effectively [145]. Resilience and valuation indicate an emerging interest in assessing the ability of mangrove ecosystems to withstand and recover from environmental and economic disturbances [146].

iv) Quadrant IV-basic themes: The themes of "Blue Carbon", "Restoration", and "Conservation" appear in the first group focused on understanding and mitigating the effects of "Deforestation" on mangroves, crucial for climate and conservation strategies [112, 136]. In parallel, 'Mangrove', 'Aquaculture', and 'Estuary', especially in regions such as Vietnam, highlight the interactions between aquaculture and coastal ecosystems where the conversion of the mangrove ecosystem by the implementation of shrimp aquaculture activities has led to the clearing of 37100 ha of mangrove forest between the years of 1964 and 1997, underlining the concern and need for sustainable and conservation practices [137]. In addition, tools such as 'Remote Sensing' and LULC surveys are fundamental for monitoring, facilitating management and conservation [138-140].

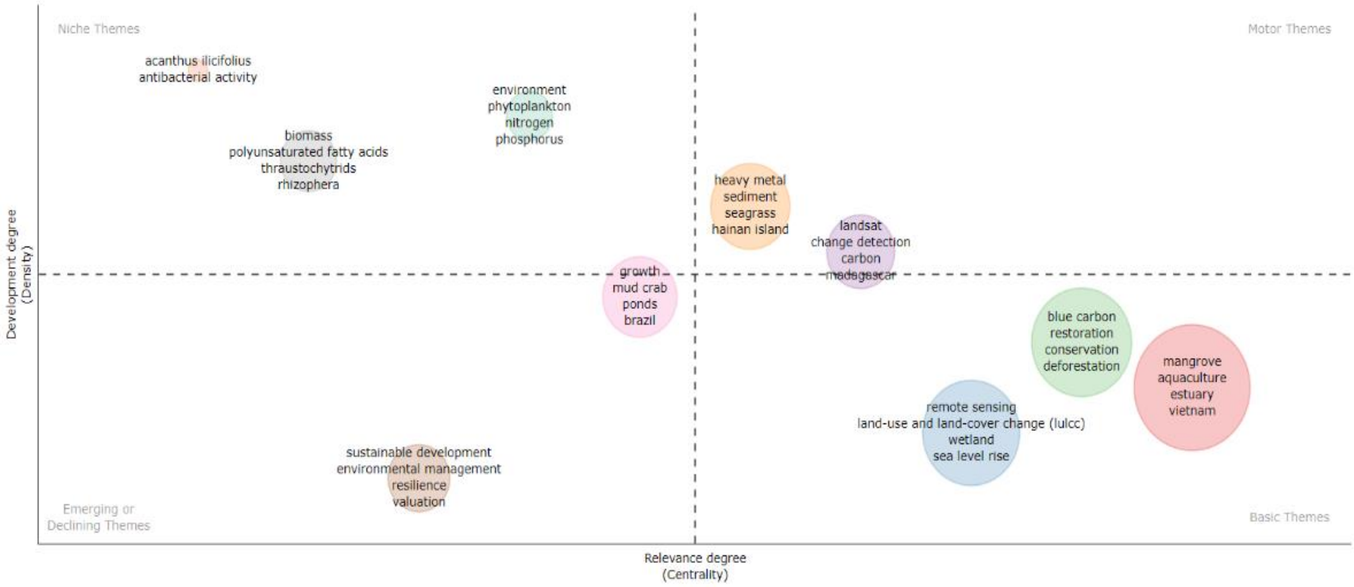

Figure 6. Map of intensity and centrality of topics in mangrove and aquaculture studies

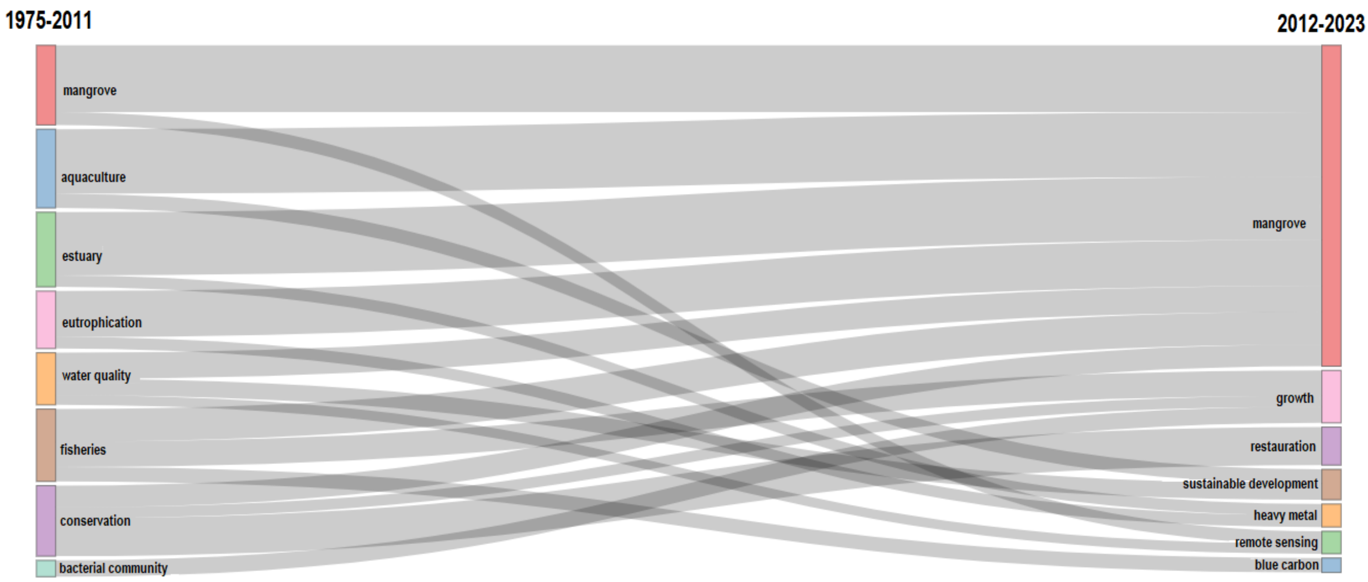

Figure 7. Evolution of research on the effects of aquaculture in mangrove forests (1975-2023)

The Sankey diagram in Figure 7 represents transfers or relationships of how research topics have evolved [147, 148]. Topics such as "eutrophication", "water quality", and "fisheries" appeared from 1975-2011 and focused on the use of ecological engineering techniques to mitigate the environmental impacts of intensive mariculture such as the successful use of algae (Gracilaria) as biofilters [149], concerns arise about the worldwide depletion of wild fish stocks, the growth of the aquaculture industry and the effects of eutrophication on marine life [150] causing jellyfish blooms [151], phytoplankton (hypoxia) [152], macroalgae and coral diseases (fertilization problems) [153].

After eutrophication have looked towards conservation and the role of blue carbon in response to climate urgency and sustainability [18, 154-156]. Advances in remote sensing have revolutionized spatio-temporal monitoring [157], while interdisciplinarity enhances integrated management. The term "fisheries" persists, adapting to reflect sustainable practices and the economic importance of healthy ecosystems, emphasizing a balanced approach between conservation and human use, taking into account strategies and techniques such as funding Blue Economy projects [158], species management for the prevention of predation of younger organisms [159], the rescue of more sustainable practices through ancestral knowledge of tribes or local communities, especially for diadromous and amphidromous fish species, as well as for coral reef and mangrove species [160], and the integration of ecosystem services in coastal management plans, as in the case of Java, Indonesia, through the differentiated management of mangroves [161].

For the topics on the right side of the most recent period (2012-2023), the emergence of "restoration", "sustainable development", "heavy metal", "remote sensing", and "blue carbon" was identified, reflecting an evolution in research towards aspects of sustainability, environmental impact and advanced monitoring techniques. Intensive aquaculture activities can leave "legacy" pollutants such as the bioaccumulation of "heavy metals". The ability of mangroves to act as phytoremediation agents by absorbing heavy metals and accumulating them in their tissues is highlighted [31], especially in Xylocarpus and Bruguiera species [162]. There is a research trend to holistically analyse the risk of heavy metals contamination by analysing various economic industry activities such as agriculture, mining, construction and aquaculture [163, 164]. Additionally, in remote sensing, the use of nonlinear mathematical analysis for the evaluation of mangrove regression and prediction of the effects of aquaculture in various scenarios stands out [165].

4. DISCUSSION

The analysis of scientific production in 1975-2023 highlights a significant growth in research on the effects of aquaculture on mangrove forests, reflecting a growing concern and recognition of the importance of mangrove habitats, not only as natural barriers against extreme weather events but also as crucial carbon sinks in the fight against climate change. Donato et al. [75], supported this, emphasizing the high capacity of mangroves to store carbon.

The evolution of research reflects a change in focus and understanding of the impact of aquaculture on mangroves. In the initial phase, the focus is on understanding the economic value and socioeconomic effects of mangrove ecosystems, as well as identifying the risks of extinction and contamination by anthropogenic activities as mentioned by Polidoro et al. [78], who highlighted the increasing threat and vulnerability of mangroves to extinction due to various anthropogenic pressures including aquaculture.

After 2012-2019, the focus shifted to climate change impacts, mangrove conservation and sustainable aquaculture practices, reflecting a transition towards finding a balance between economic development and environmental conservation. During this period, the literature expanded to include the mapping of coverage, distribution and status of mangroves worldwide, as well as the sustainability of aquaculture practices. In addition, the Sustainable Development Goals (SDGs) of the United Nations [166, 167], appear in this period, highlighting SDG 14 (Underwater life) and SDG 15 (Life of terrestrial ecosystems) concerning marine ecosystems. Likewise, the field of study is strengthened thanks to SDG 13 (Climate action) for studies on climate change and the contribution of mangroves as carbon stores [53].

In the last four years, 2020-2023 shows a renewed focus on strategies to reduce mangrove loss and promote more sustainable aquaculture practices, as indicated by Goldberg et al. [105]. This study points to a trend toward decreasing human-driven mangrove loss, suggesting progress toward sustainability in the interaction between aquaculture and mangroves.

The analysis of the scientific contribution by country reveals that Asia and America lead research in this field, given the high concentration of mangroves and aquaculture activities in these regions, where also the existing collaboration of the United Nations Environment Program (UNEP) and Global Environment Facility (GEF), helps develop projects in 21 countries in these regions, resulting in the protection and recovery of more than 500,000 hectares of mangroves and the creation of 254,000 hectares of protected areas, and initiatives in countries such as Brazil that adopts legislation aligned with UNEP with emphasis on sustainable practices and biodiversity conservation [168].

Particularly relevant regions include Southeast Asia, North and South America, and specific areas such as Singapore and Belize. In Southeast Asia, countries such as Indonesia, the Philippines and Thailand have implemented mangrove restoration techniques, including direct planting and hydrological rehabilitation, thus recovering mangrove cover, stability and biodiversity [169]. In Belize and Singapore, experiments are carried out focused on adaptive management techniques involving urban and rural areas to integrate ecological functions in the recovery and rehabilitation of mangroves [170]. In Bali, specifically in the Perancak estuary, it was evaluated as the production of leaf litter and macrozoobenthic biodiversity, contributing to the restoration of mangroves that were part of former aquaculture pond areas [171].

Another interesting practice is those implemented in the Philippines and Myanmar, where an approach based on surrounding communities and the help of biological and socioeconomic studies is articulated to develop a commitment to long-term conservation practices [172]. In Brazil, they study the genetic diversity of mangrove species using Inter-Simple Sequence Repeat (ISSR) markers, comparing natural populations and restored areas [173]. In Florida (United States), techniques for the survival of mangroves on the coastline are being explored through breakwaters (buffer) that reduce speed and height, preserving young mangroves [174]. These studies and approaches apply various strategies to address mangrove sustainability, including collaboration between different science sectors to guide conservation policies and practices.

Keyword co-occurrence analysis reveals emerging and established focus areas, from climate change and ecological restoration to remote sensing and pollution impacts. The findings of this study highlight the need to adopt a multidisciplinary approach to mangrove conservation, integrating both ecological complexity and economic activities such as aquaculture. These results align with our objective of investigating how aquaculture practices can affect mangrove conservation and exploring sustainable solutions. A growing database on the negative effects of aquaculture on these ecosystems highlights the urgency of implementing more sustainable aquaculture practices. McSherry et al. [175] suggest that Integrating Mangroves within shrimp Aquaculture (IMA) systems may be a viable strategy. However, this integration can lead to fragmentation and compromise the ecological functionality of mangroves compared to intact ones, offering a 'false promise' of sustainability by not fully recreating the natural conditions necessary for biodiversity and ecosystem services. On the other hand, the case study in the Mekong River Delta in

Vietnam recognises these challenges. However, it emphasises practical solutions such as training in sustainability standards and promoting international certifications to encourage more responsible and profitable aquaculture practices [176], suggesting improvements in waste management and the reduction of chemical inputs, which may help alleviate the pressure on mangrove ecosystems.

Despite the potential benefits of sustainable aquaculture practices, several significant challenges still need to be addressed. Implementing new technologies and practices can be costly and time-consuming, and resistance to change can be a barrier [177]. Adding to the fact that many of the strategic objectives are based on reforested or afforested mangrove areas, it is essential to ensure that these areas survive and thrive in the long term for conservation efforts to be effective [175]. Additionally, the lack of knowledge of carbon credit mechanisms limits the ability of communities to take advantage of the potential benefits that could offer economic incentives for mangrove conservation [178]. The success of mangrove-aquaculture links management is that practices align production with international standards to promote environmental sustainability through public-private partnerships, providing the necessary support.

The present bibliometric analysis faces the following limitations: i) using a database (Scopus), omitting other similar platforms such as Web of Science and Dimensions, ii) the data collection period spans from 1975 to 2023, excluding any advance in relevant research that is part of the first quarter of 2024, iii) the consideration of documents indexed only in English.

5. CONCLUSION

The study analyzes 48 years of publications related to the effects of aquaculture on mangroves in the Scopus database. Two contrasting perspectives exist in the evolution of scientific production: the negative impacts of aquaculture on mangroves and the actions and strategies that are carried out to conserve the ecosystem.

Studies identify a variety of negative impacts derived from aquaculture: a) anthropogenic pollution that includes the release and accumulation of heavy metals in sediments and soils, effluents, and toxic chemicals such as pesticides from the aquaculture industry and other activities surrounding areas; b) the deforestation of mangrove forests promoted by the expansion and demand for spaces for aquaculture, and urban areas, whose leading promoter is the economic growth and development of the population seeking to migrate to coastal areas with resources for their subsistence; c) hydrological alterations and changes in land use and cover structure are impacts with long-lasting repercussions such as changes in water flows and sedimentation, alterations in biodiversity, and impact on the ecological; and d) eutrophication that negatively affects aquatic life and the health of mangroves causing excessive growth of algae and reduction of oxygen in the water as a result of the excessive use of nutrients used in the breeding of aquatic species. These impacts threaten the biodiversity of mangroves and affect their ability to provide essential ecosystem services such as carbon storage, protection against extreme weather events, and resource depletion for surrounding communities.

There are trends towards the recognition of implementing management practices that integrate both the economic needs of aquaculture and the conservation of mangrove ecosystems. Sustainability strategies include mangrove restoration techniques like direct planting, hydrological rehabilitation, community-based practices that encourage local participation and buffer zones for mangrove conservation. Southeast Asia, America, and specific locations such as Singapore and Belize are implementing these practices and evaluating the integration of ecological functions in urban and rural areas. Additionally, research combining biological and socioeconomic approaches is emphasized in Brazil and Myanmar to develop long-term conservation commitments. International collaboration and support from global programs such as the UNEP and the GEF are also highlighted, facilitating the protection and recovery of mangrove areas.

The thematic analysis identified driving themes, such as the effects of contamination by “heavy metals,” the study of organic contaminants, and the development of criteria for evaluating ecological risks. Another notable application is those related to “blue carbon” in preserving ecosystems that facilitate carbon sequestration. The use of “remote sensing” is of great relevance, focused on the monitoring and predicting future regression scenarios of mangroves in the face of anthropogenic activities.

The last four years of scientific production have underscored the need to integrate planning and development into environmental policy, ecological restoration, and sustainable practices to ensure evidence-based interventions and long-term sustainability. Author Keyword co-occurrence analysis has identified emerging areas, such as climate change, ecological restoration, remote sensing, and pollution impacts, emphasizing the complexity of mangrove aquaculture and the necessity for multidisciplinary approaches.

Future research should focus on optimizing aquaculture practices to mitigate their effects on mangroves. These include exploring sustainable methods such as Integrated Mangrove and Shrimp Aquaculture (IMA), developing restoration techniques for mangroves affected by water and sediment pollution due to the accumulation of heavy metals and chemicals from aquaculture activities, and employing advanced tools such as remote sensing and machine learning to assess and monitor mangrove health and project future scenarios. These practices will enhance the resilience of coastal ecosystems, maintain biodiversity, and ensure the economic sustainability of aquaculture communities. Integrating these studies will contribute to more effective environmental management policies and promote aquaculture development and coexistence with mangrove conservation.

The challenges include ecological effectiveness, technological and economic barriers, and regulatory and market difficulties. This diversity of challenges underscores the need for multidimensional sustainability approaches encompassing technical improvement, management, and regulatory adjustments.

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