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RESEARCH

Bioactive compounds in aquaculture

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Abstract

Bioactive compounds represent a rapidly advancing frontier in aquaculture nutrition, promising solutions to reduce antibiotic dependence, enhance aquatic species resilience, and improve feed sustainability. Yet, the global research landscape driving these innovations remains fragmented. This comprehensive science mapping analysis employs bibliometric and scientometric tools, including CiteSpace and R packages, to analyse the trajectory and impact of research concerning bioactive compounds in aquaculture. Here, we present a comprehensive scientometric synthesis of 17,932 publications and 818,643 cited references from the Web of Science Core Collection (1975–2023), spanning 160 countries and analysed through co-citation, burst detection and cluster network mapping. Our analysis reveals a pronounced surge in publications from 2019 to 2023, reflecting rising demand for functional feeds under climate and disease stressors. Research is strongly concentrated in China (~26% of outputs), the USA and Spain, while contributions from Africa and Latin America remain limited, showing persistent regional disparities. The field is shaped by 31 distinct knowledge clusters, with core themes focused on oxidative stress, gut microbiota and alternative proteins, especially insect meals and algal sources. *Oreochromis niloticus* emerges repeatedly across clusters, and this shows its role as a nutritional model in feed trials and microbiome studies. Co-citation metrics identify seminal works (e.g. Dawood et al., El-Saadony et al., Naylor et al.) that have guided functional additive research, though over-reliance on these few sources risks narrowing future inquiry. Papers with high sigma values (e.g. Turchini, Torstensen, Ng) signify conceptual turning points in lipid replacement strategies. Despite advances, long-term performance data, species-specific microbiota insights and environmental fate assessments of bioactive feeds remain scarce. We recommend a reorientation toward ecosystem-informed nutrition, integrating fish health, water quality and socio-economic viability across diverse geographies and production systems. This review offers a data-driven roadmap for funding bodies, researchers and policy stakeholders to strategically align innovation in bioactive compounds with the global imperatives of sustainable and equitable aquaculture.

Keywords Feed additives · Global research disparities · Gut health and oxidative stress · Life below water · Scientometric trends

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Introduction

Aquaculture is projected to supply nearly two-thirds of the global seafood demand by 2030, largely due to overfishing and the decline of wild fish stocks (Anderson et al. 2019). In 2020 alone, aquaculture accounted for 50% of global aquatic animal production, reaching 88 million tonnes (FAO 2020). The economic footprint of the sector is equally significant, with the market valued at $249.75 billion in 2023 and expected to reach $264.17 billion by 2024, reflecting a compound annual growth rate (CAGR) of 5.8% (Research and Markets 2025). This growth is driven not only by the rising demand for seafood but also by the increasing use of aquaculture products in pharmaceuticals, nutraceuticals and ornamental markets, all of which contribute to food security and socio-economic development (Leal et al. 2018). Despite its rapid expansion, aquaculture faces critical sustainability challenges. Intensive production systems often lead to nutrient-rich effluent discharge, contributing to eutrophication and harmful algal blooms (Goto et al. 2023). Concurrently, climate change imposes physiological stress on cultured species and alters aquatic ecosystems, threatening productivity (Maulu et al. 2021). To address these challenges, the sector must adopt innovative and environmentally sustainable practices (Austin et al. 2022). One such promising innovation lies in the integration of bioactive compounds—proteins, peptides, polysaccharides, lipids, and secondary metabolites—into aquaculture feeds and water systems. Derived from sustainable sources like algae, seaweeds, plants, halophytes, and microbial biomass, these compounds can enhance growth performance, immunity and stress resilience in aquatic species, while also reducing environmental burdens (Hermsen 2020).

Marine phenolics such as phlorotannins (Abhari and Mousavi Khaneghah 2020) and phytogenics like terpenes and phenolics (Firmino et al. 2021) have demonstrated immunomodulatory and antioxidant effects. Thymol and thymoquinone, for instance, improve feed efficiency and disease resistance in Nile tilapia (Ibrahim et al. 2022), while enhancing antioxidant enzyme expression. Seaweed-derived polysaccharides also offer immunostimulatory benefits while requiring no arable land or freshwater, enhancing sustainability (Radwan et al. 2022). However, challenges remain regarding compound stability, species-specific efficacy and cost-effectiveness. For instance, encapsulation techniques are needed to enhance compound delivery in aquatic environments (Caipang 2020), and extraction costs can limit scalability (Firmino et al. 2021; Abhari & Khaneghah 2020). Additionally, valorising aquaculture by-products rich in proteins and bioactives represents a circular economy opportunity (López-Pedrouso et al. 2020). Yet, adoption is constrained by processing complexity, regulatory barriers and economic feasibility (Sarker 2023; Stevens et al. 2018; Suleiman & Rosentrater 2018).

To date, although reviews have addressed the nutritional and functional benefits of bioactives (e.g. Mutalipassi et al. 2021; Durazzo et al. 2022; Kussmann et al. 2023), no comprehensive scientometric review has synthesised the global research landscape on bioactive compounds specifically within aquaculture systems. A scientometric review enables the systematic mapping of research evolution, key actors, emerging themes and strategic gaps using bibliometric and network analyses.

Research questions

This study aims to fill this gap by conducting the first scientometric analysis of global literature on bioactive compounds in aquaculture, using CiteSpace and R-based bibliometric tools to assess the state of knowledge, trends and global contributions in this rapidly evolving field. The analysis spans from 1975 to 2023 and offers a strategic overview of how the field has evolved and where it is headed.

Specifically, this study addresses the following research questions:

1. What are the global publication trends and geographic distribution patterns in bioactive compound research in aquaculture over the past decade?
2. What are the key thematic clusters and emerging research fronts identified through co-citation and keyword analysis?
3. Which references and keywords have had the greatest citation impact and burst activity, and what do they reveal about influential paradigms and potential biases in the field?
4. Where are the critical knowledge gaps and underexplored areas in bioactive compound research for aquaculture, and how can these inform future research priorities?

As such, the study aims to support more informed decision-making among researchers, funders, policymakers and industry stakeholders, ultimately accelerating the adoption of bioactive compounds in sustainable aquaculture.

Materials and methods

In this study, a Systematic Bibliometric Review (SBR) was employed to rapidly classify and analyse thousands of peer-reviewed articles relevant to bioactive compounds in aquaculture. This approach, grounded in established systematic review principles (Booth 2016; Chen and Song 2019; Brunton et al. 2020), follows a structured search guided by a well-defined research question and clearly articulated inclusion and exclusion criteria. The Web of Science Core Collection was selected as the primary data source due to its comprehensive coverage of high-impact journals across the natural and applied sciences. Specifically, the dataset included the Science Citation Index Expanded (SCI-EXPANDED, 1975–present), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (AHCI), and other indices such as the Emerging Sources Citation Index (ESCI) and Conference Proceedings Citation Index. These sub-databases were chosen to ensure rigorous inclusion of peer-reviewed literature while excluding grey literature, policy reports or non-scholarly sources.

Using Web of Science exclusively allowed for a high level of consistency in metadata formatting, citation structures and indexing standards, which are essential for reliable performance of scientometric tools such as CiteSpace. Although we acknowledge that including additional databases (e.g. Scopus, PubMed) could have expanded coverage, our approach prioritised data uniformity and citation integrity, which are critical for co-citation, cluster and burst analysis. Future comparative studies could integrate multi-database sources to triangulate findings across platforms. A full overview of the search strategy and methodological workflow is presented in Fig. 1. The final search strategy included the following keyword terms:

Bioactive compound: (“bioactive* compound*” OR “secondary metabolite*” OR “phytochemical*” OR “terpene*” OR “monoterpene*” OR “sesquiterpene*” OR “triterpene*” OR “diterpene*” OR “alkaloid*” OR “indole alkaloid*” OR “quinolizidine alkaloid*” OR “isoquinoline alkaloid*” OR “phenolic compound*” OR “phenol*” OR

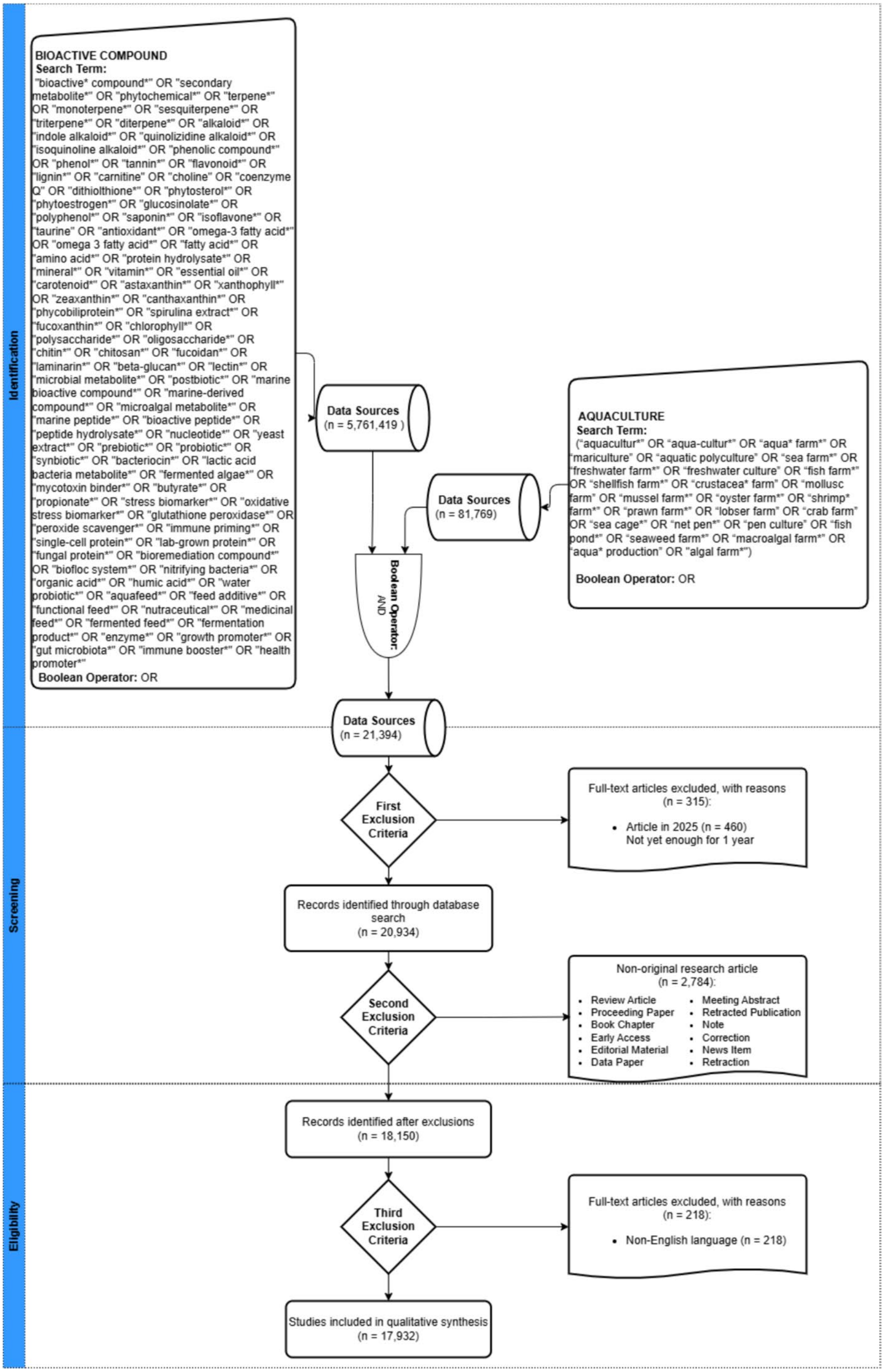

Fig. 1 Methodological framework for the current study

"tannin*" OR "flavonoid*" OR "lignin*" OR "carnitine" OR "choline" OR "coenzyme Q" OR "dithiolthione*" OR "phytosterol*" OR "phytoestrogen*" OR "glucosinolate*" OR "polyphenol*" OR "saponin*" OR "isoflavone*" OR "taurine" OR "antioxidant*" OR "omega-3 fatty acid*" OR "omega 3 fatty acid*" OR "fatty acid*" OR "amino acid*" OR "protein hydrolysate*" OR "mineral*" OR "vitamin*" OR "essential oil*" OR "carotenoid*" OR "astaxanthin*" OR "xanthophyll*" OR "zeaxanthin*" OR "canthaxanthin*" OR "phycobiliprotein*" OR "spirulina extract*" OR "fucoxanthin*" OR "chlorophyll*" OR "polysaccharide*" OR "oligosaccharide*" OR "chitin*" OR "chitosan*" OR "fucoidan*" OR "laminarin*" OR "beta-glucan*" OR "lectin*" OR "microbial metabolite*" OR "postbiotic*" OR "marine bioactive compound*" OR "marine-derived compound*" OR "microalgal metabolite*" OR "marine peptide*" OR "bioactive peptide*" OR "peptide hydrolysate*" OR "nucleotide*" OR "yeast extract*" OR "prebiotic*" OR "probiotic*" OR "synbiotic*" OR "bacteriocin*" OR "lactic acid bacteria metabolite*" OR "fermented algae*" OR "mycotoxin binder*" OR "butyrate*" OR "propionate*" OR "stress biomarker*" OR "oxidative stress biomarker*" OR "glutathione peroxidase*" OR "peroxide scavenger*" OR "immune priming*" OR "single-cell protein*" OR "lab-grown protein*" OR "fungal protein*" OR "bioremediation compound*" OR "biofloc system*" OR "nitrifying bacteria*" OR "organic acid*" OR "humic acid*" OR "water probiotic*" OR "aquafeed*" OR "feed additive*" OR "functional feed*" OR "nutraceutical*" OR "medicinal feed*" OR "fermented feed*" OR "fermentation product*" OR "enzyme*" OR "growth promoter*" OR "gut microbiota*" OR "immune booster*" OR "health promoter*") AND Aquaculture: ("aquacultur*" OR "aqua-cultur*" OR "aqua* farm*" OR "mariculture" OR "aquatic polyculture" OR "sea farm*" OR "freshwater farm*" OR "freshwater culture" OR "fish farm*" OR "shellfish farm*" OR "crustacea* farm" OR "mollusc farm" OR "mussel farm*" OR "oyster farm*" OR "shrimp* farm*" OR "prawn farm*" OR "lobser farm" OR "crab farm" OR "sea cage*" OR "net pen*" OR "pen culture" OR "fish pond*" OR "seaweed farm*" OR "macroalgal farm*" OR "aqua* production" OR"algal farm*").

To analyse and visualise the structure and evolution of research on bioactive compounds in aquaculture, we used a combination of CiteSpace (version 6.3) and R-based bibliometric packages (bibliometrix and ggplot2). CiteSpace was selected for its robust clustering algorithms and ability to reveal temporal dynamics, citation bursts and pivotal publications. The R environment was used to complement CiteSpace outputs with descriptive statistics and data visualisations.

Key scientometric metrics were defined and applied in the analysis. Silhouette values, ranging from −1 to 1, quantify the consistency and homogeneity of clusters, with values above 0.7 indicating strong internal coherence and well-separated thematic structures. Centrality scores, particularly betweenness centrality, measure a node's importance within the network based on its position as a bridge between clusters—higher values indicate more influential publications or institutions in connecting disparate research areas. Citation burst scores identify references or keywords that have received sudden, intense attention over a specific period, signalling emerging hotspots or paradigm shifts. These metrics enabled a rigorous mapping of research frontiers and knowledge gaps in the field.

Results and discussion

Global trends in research volume and distribution

The analysis reveals a dramatic growth in research on bioactive compounds in aquaculture over the past decade. From 1975 until around 2010, publication output was modest, but a sharp uptick occurred thereafter, peaking around 2019 (Fig. 2A). This surge corresponds with rising interest in sustainable aquaculture solutions and alternatives to antibiotics in fish farming (Bondad-Reantaso et al. 2023). It aligns with global trends: aquaculture has expanded rapidly to meet food demand, prompting intensified research into improving fish health and production efficiency. For instance, Rosamond Naylor (2021) and colleagues' 20-year review noted that aquaculture's growth has been accompanied by heightened attention to sustainability challenges. Our findings corroborate this, showing that recent years (2019–2023) saw the highest volume of publications, likely driven by the need for innovative, eco-friendly practices in aquaculture. The FAO's "Blue Transformation" initiative aims for a 35–40% increase in aquaculture production by 2030 to meet rising seafood demand and combat global hunger; thus, sustainable intensification has become crucial, explaining the booming scholarly interest in bioactive feed additives and fish health management (FAO 2022).

Regional distribution

The distribution of publications spans 160 countries (Fig. 2B), yet output is highly concentrated among a few leading nations. China leads overwhelmingly with 4735 records, accounting for approximately 26.4% of all publications, which aligns with its global dominance in aquaculture production. The USA follows with 1468 publications (8.2%) and holds the highest centrality score (0.34), positioning it as the most influential bridging nation in the citation network (Fig. 3). Spain ranks third in publication count (1090; 6.1%), followed by India (1026; 5.7%), Brazil (1017; 5.7%), and Norway (760; 4.2%). While China dominates in quantity, it ranks fourth in centrality (0.11), suggesting its work is more internally networked than internationally connective. France (n= 545; centrality =0.20), Canada (n= 474; centrality =0.11), and Belgium (n= 237; centrality =0.11) also rank high in influence despite smaller publication volumes, showing their importance as international collaborators and citation hubs (Fig. 2D). In contrast, countries such as Egypt (n= 660; 3.7%), South Korea (n= 441; 2.5%), Malaysia (n= 424; 2.4%), and Chile (n= 334; 1.9%) contribute substantially to the field but show much lower centrality scores ($\leq$ 0.01), indicating limited integration into broader global networks.

Several countries with relatively small publication counts have disproportionately high centrality, pointing to key opportunities for knowledge exchange. For instance, Denmark (centrality =0.09), Scotland (0.08), and Germany (0.07) serve as important bridges in the citation network despite lower research volume, reflecting strategic roles in connecting disparate research groups. However, large swathes of Africa, South America, and Southeast Asia remain underrepresented. Brazil (n= 1,017; 5.7%) and Chile (n= 334; 1.9%) are notable Latin American contributors, while Egypt is the leading African nation. South Africa (n= 93; 0.5%), Nigeria (n= 53), and Kenya (n= 20) remain on the periphery. The Caribbean and Pacific Island nations are scarcely present, with only isolated entries like Jamaica (n= 1), Solomon Islands (n= 1), and Fiji (n= 1). The visual network (Fig. 3) confirms the

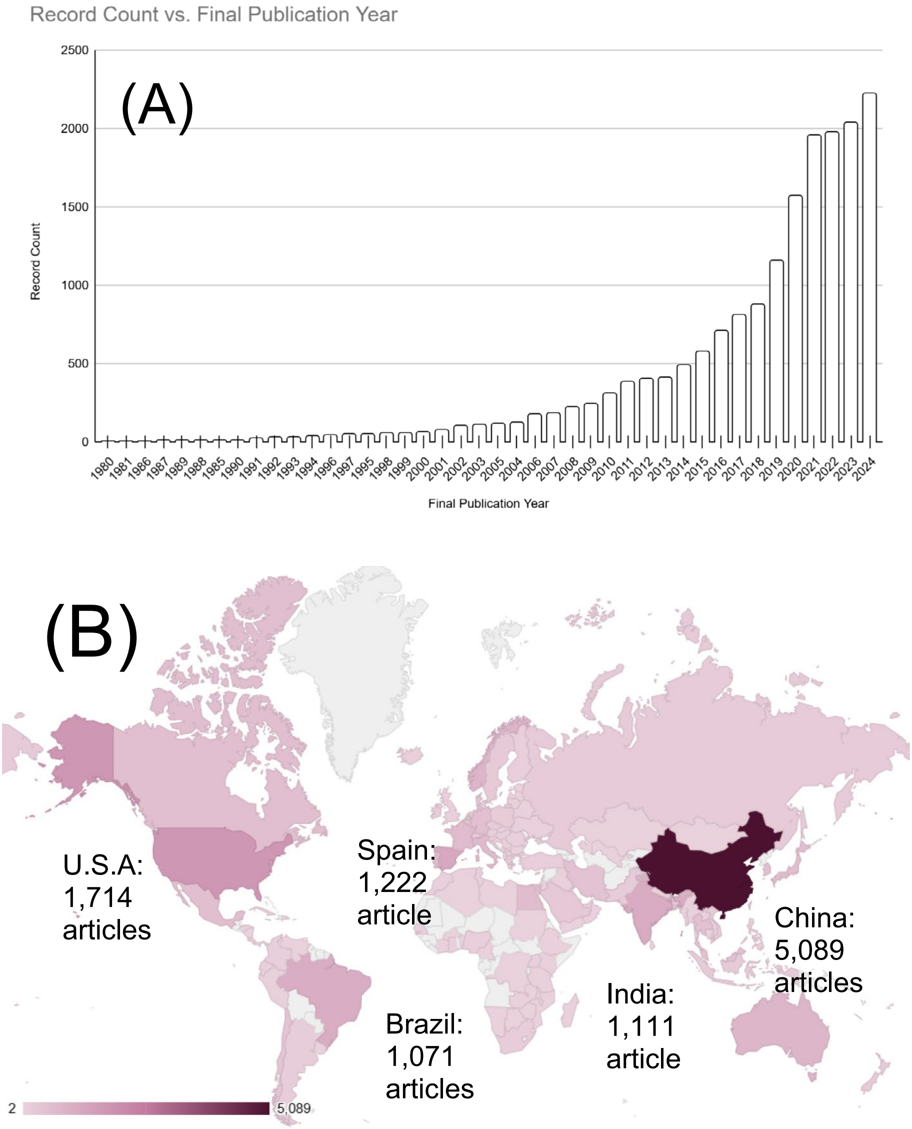

Fig. 2 **A** Publication evolution from 1975 until 2023, and **B** there is a total of 160 countries involved in the bioactive compound in aquaculture

dominance of North American and European nodes and the relative invisibility of regions with significant aquaculture activity but limited research connectivity.

This imbalance mirrors both global aquaculture production and funding disparities, but also suggests a deep knowledge gap. Local challenges—such as species-specific nutrient needs, endemic disease pressures and environmental conditions in tropical systems—are not adequately represented in the literature. This limits the global applicability of current

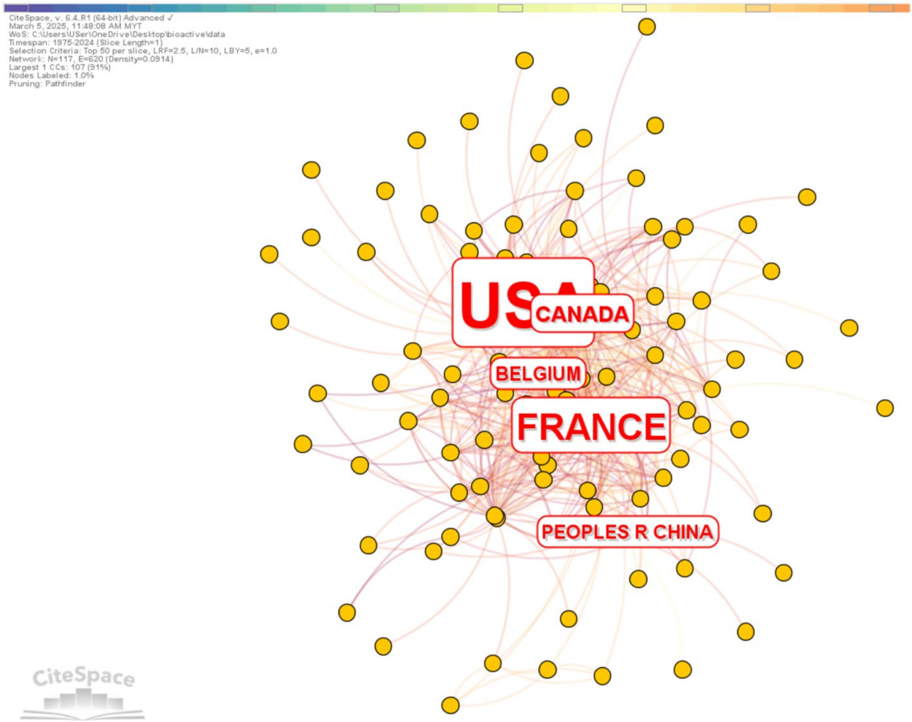

Fig. 3 Higher influential collaboration countries generated through centrality score at Cite Space software

findings and risks reinforcing a one-size-fits-all approach to bioactive compound application (Coppola et al. 2021; Moreira et al. 2021). To ensure aquaculture innovation is globally relevant and inclusive, international agencies must support capacity-building initiatives and equitable partnerships (Mair et al. 2023; Sonobe & Saito 2023). Strengthening research infrastructure in low-output nations, enabling South–South collaborations, and integrating diverse ecological and socio-economic contexts will help correct the geographical skew in the bioactives literature. As stressed by the FAO (2022), inclusive aquaculture research is a prerequisite for sustainable and resilient food systems.

Contributing organisations

There were 9509 institutions contributing to global research on bioactive compounds in aquaculture, from a total of 17,932 identified affiliations. This indicates a broad but fragmented institutional landscape. The collaboration network visualised in Fig. 4 shows that a limited number of institutions act as dominant knowledge hubs. The Ministry of Agriculture and Rural Affairs, China, had the highest publication output ($n = 900$; 5.02%), followed by the Chinese Academy of Fishery Sciences (CAFS) (n=782; 4.36%) and the Chinese Academy of Sciences (CAS) (n=666; 3.71%). Other major contributors include the Egyptian Knowledge Bank (EKB) (n=593; 3.31%), Ocean University of China (n=435; 2.43%), and Shanghai Ocean University (n=424; 2.36%). From Europe, the University

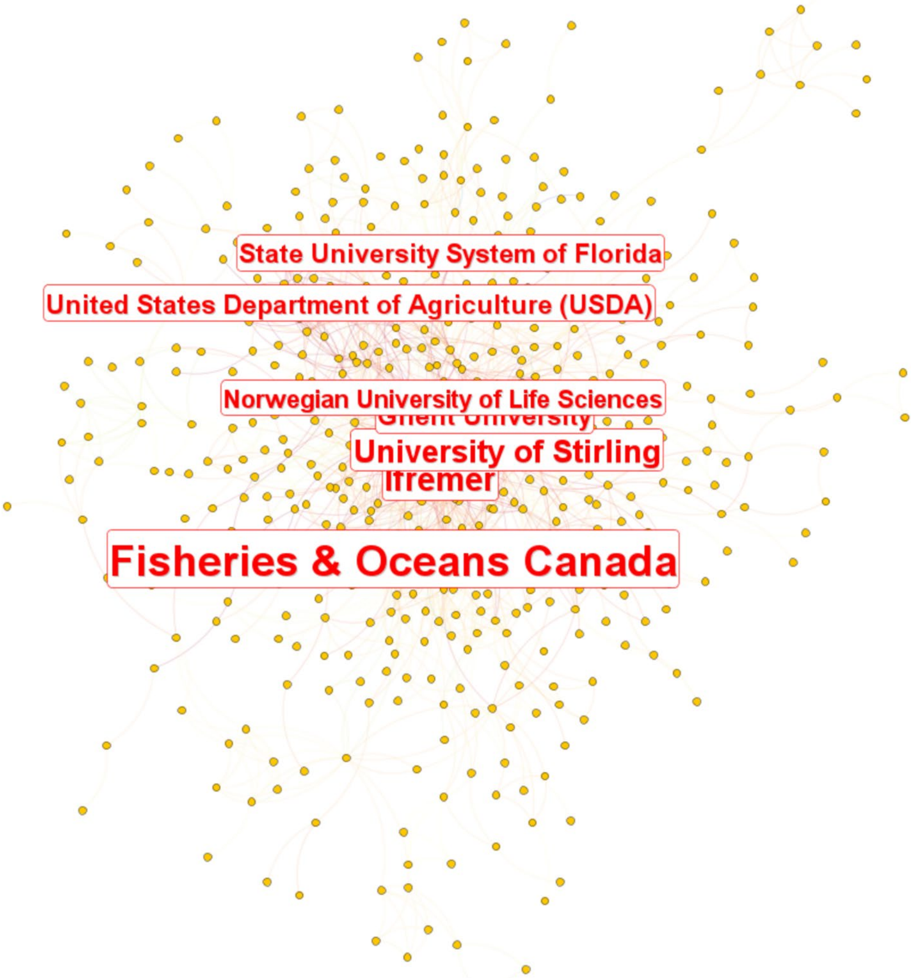

Fig. 4 Network map of institutional collaboration in the field of bioactive compound in aquaculture, where each node symbolises an institution and yellow lines between them represent citation-based cooperation

of Stirling (UK) ranked 16 th globally (*n*=213; 1.19%), leading in areas such as sustainable aquafeeds and the nutritional modulation of fish health. This institution, alongside Ghent University, Wageningen University and Research, and IFREMER, plays a key role in regional research leadership. In Latin America, Universidade do Porto (*n*= 248) and CIBNOR—Centro de Investigaciones Biológicas del Noroeste (*n*=181) also demonstrated significant output.(Fig. 4).

However, output volume does not necessarily correlate with international influence. CiteSpace centrality analysis reveals that institutions such as Fisheries and Oceans Canada, IFREMER, and University of Stirling have some of the highest betweenness centrality scores (0.12, 0.09 and 0.09, respectively), positioning them as critical bridges in the global research network. These institutions not only produce impactful science but also enable information flow between otherwise disconnected research communities. In contrast, many high-output institutions—particularly within Asia—showed zero centrality, suggesting limited global integration. For example, while Laoshan Laboratory (n = 393), Guangdong Ocean University (n = 202) and Shanghai Ocean University are prolific, they operate largely within national or regional silos. This trend is also reflected in newer institutions and those from the Global South. For instance, Kafrelsheikh University (n = 158), National Institute of Oceanography and Fisheries, Egypt (NIOF) (n = 135), and Universiti Malaysia Terengganu (n = 122) are contributing to the literature but remain under-connected internationally.

The temporal analysis (based on first publication year in CiteSpace) also indicates how newer institutions (e.g. Laoshan Laboratory, post-2020) are rising in output but have yet to establish global linkages. In contrast, older institutions with lower output (e.g. Universidade Federal de Santa Catarina (UFSC), first appearing in 1994, n = 161) often have more extensive historical collaborations. The international collaboration map (Figs. 3 and 4) supports this view. Countries such as the United States, France, UK and Canada are central nodes, facilitating research across continents. Meanwhile, institutions in Africa, Latin America and Southeast Asia appear peripherally or not at all, highlighting disparities in network inclusion.

This imbalance reflects a missed opportunity. The international collaboration map (Figs. 3 and 4) confirms this imbalance: countries like the USA, United Kingdom and France show high network centrality—indicating their role as bridging nodes—whereas many African, Latin American and even some Southeast Asian nations have few or no active nodes, pointing to poor integration into global citation and collaboration networks. Promoting collaboration with these underrepresented regions is not merely about inclusion—it is a strategic imperative. Many of these countries possess rich biodiversity, unique aquaculture species and underutilised bioresources that could advance global knowledge on novel bioactive compounds (Purwaningsih et al. 2021). Furthermore, integrating diverse farming systems (e.g. brackish water aquaculture in South Asia or integrated pond systems in sub-Saharan Africa) can yield new insights into context-specific functionality of bioactive feed additives. To achieve a more equitable and effective research landscape, it is essential that international research councils, funding bodies and development agencies establish targeted programmes and consortia to connect these regions with established centres of excellence in China, Europe and North America (Ocampo-Ariza et al. 2023; Pettorelli et al. 2021). This includes twinning schemes, joint Ph.D. programmes and multi-institutional project calls that require North–South or South–South partnerships. Strengthening global networks and investing in research infrastructure across underrepresented regions can ensure that the field of bioactive compounds in aquaculture is both scientifically robust and globally applicable, as it would then reflect the diversity of species, environments and practices that define aquaculture in the twenty-first century.

Top funding agencies

There were 14,903 distinct funding agencies supporting research on bioactive compounds in aquaculture—an intriguing figure that surpasses the number of contributing institutions (n = 9,509). This discrepancy is indicative of multi-source and co-funding dynamics, where single-research outputs are often backed by multiple agencies across regional, national and international levels (El-Ouahi 2023).

The top funding agency by a considerable margin was the National Natural Science Foundation of China (NSFC), with 2298 supported records (12.82% of the dataset), reaffirming China's central role in aquaculture research funding and scientific output. This dominance is followed by the European Union (EU), responsible for funding 650 publications (3.63%), reflecting the impact of Horizon 2020, Marie Curie Actions and other major EU instruments. Brazil's CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) (n= 583; 3.25%) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) (n= 451; 2.52%) represent strong national-level investment from Latin America in aquaculture R&D. Chinese national programmes further consolidate this leadership, with the National Key Research and Development Program of China (n= 523; 2.92%) and its related variants (e.g. "Key R&D" and "Basic Research" programmes) appearing across the top 20 funders. These programmes often target sector-specific innovation—particularly agriculture, food security and marine biotechnology—and are also reflected in regional allocations such as the Natural Science Foundations of Guangdong, Shandong and Zhejiang Provinces. Funding bodies such as FCT (Fundação para a Ciência e a Tecnologia) from Portugal (n= 350; 1.95%) and the Spanish Government (n= 347; 1.93%) show sustained European investment in marine bioresources and sustainable aquafeeds. The Research Council of Norway (n= 251; 1.40%) also ranks high, aligning with national strategic priorities around marine sustainability and biotechnology commercialisation.

Notably, funding from Japan is split across multiple agencies, including MEXT (Ministry of Education, Culture, Sports, Science and Technology) (n= 187; 1.04%) and JSPS (Japan Society for the Promotion of Science) (n= 173; 0.97%), targeting high-technology research and feed innovation in species like kuruma shrimp and Japanese flounder. North America is represented by the US Department of Agriculture (USDA) (n= 183; 1.02%), NSF (n= 103) and NIH (n= 51), though their relative proportions remain modest compared to Asian and European contributions. Canada's NSERC (n= 147; 0.82%) also appears, pointing to focused efforts on immunology and cold-water species.

Emerging funders from the Global South are steadily increasing in presence. Agencies such as ICAR (India) (n= 96), NRF (South Africa), KACST (Saudi Arabia) and TÜBİTAK (Turkey) are present, though currently with lower record counts. These reflect early-stage strategic investment in national aquaculture agendas and biotechnology platforms. Additionally, entities like King Saud University, Universidad Nacional Autónoma de México (UNAM) and Malaysia's Ministry of Higher Education also feature prominently in co-funded works. Despite this geographical breadth, the field remains highly concentrated in top-tier economies, both in funding provision and output. There remains significant untapped potential for funding harmonisation, co-development schemes and South–South cooperation, particularly in regions rich in biodiversity but underrepresented in the research landscape (e.g. East and West Africa, the Pacific Islands). To address this, multilateral and philanthropic funders—such as CGIAR, USAID and the European Commission Joint Research Centre—could play a pivotal role in bridging regional research divides by integrating bioactive aquaculture into wider sustainable development and food systems agendas. Equally, funding alignment under initiatives like the Blue Transformation framework (FAO 2022) and regional aquaculture development plans could stimulate coordinated research across continents. Strategic policy-level action is now required to build durable funding pipelines, incentivise transdisciplinary collaborations and integrate bioactive research with climate resilience, food security and biodiversity restoration policies. Doing so would ensure that innovation in bioactive aquaculture feeds reflects not only scientific priorities but also societal and planetary needs.

Keywords in Bioactive Compounds in Aquaculture Research

A total of 1802 distinct keywords were identified in the scientometric analysis of bioactive compound research in aquaculture, offering a detailed view of thematic priorities over time. Not surprisingly, the keyword “aquaculture” appeared most frequently ($n =$ 2,248; centrality 0.10), as expected, anchoring nearly all studies in this domain. Beyond this, the most co-occurring terms were “expression” ($n =$ 1095; 0.05), “metabolism” ($n =$ 545; 0.09), “fatty acids” ($n =$ 557; 0.08) and “growth performance” ($n =$ 1021; 0.03), all of which show the dominant nutritional and physiological lenses through which bioactive compounds are evaluated (Dawood et al. 2022; Elumalai et al. 2020). Notably, “resistance” ($n =$ 731; 0.05), “protein” ($n =$ 741; 0.05) and “bacteria” ($n =$ 527; 0.05) also feature prominently, pointing to the central role of immune modulation and antimicrobial properties in feed trials (Firmino et al. 2021; Ke et al. 2021). Keywords like “lactic acid” ($n =$ 432; 0.07), “chlorophyll” ($n =$ 56; 0.06) and “biochemical composition” ($n =$ 102; 0.04) reflect increased interest in microalgae, plant extracts and bioactive pigments as functional additives. The species most represented in the keyword dataset include “rainbow trout” ($n =$ 203; 0.07), “Atlantic salmon” ($n =$ 158; 0.06) and “*Oreochromis niloticus*” (tilapia; $n =$ 127; 0.05), aligning with the industry’s global production focus and the common use of these species in digestibility and growth assays (Andrade et al. 2024; Santigosa et al. 2020). “White shrimp” and “*Penaeus monodon*” appear less prominently despite their economic significance (Maity et al. 2020), revealing a lingering taxonomic bias in the literature favouring finfish over crustaceans.

Keyword centrality adds further nuance: “metabolism” (0.09), “water quality” (0.07), “phytoplankton” (0.07) and “fatty acid” (0.07) had the highest centrality after “aquaculture,” suggesting these are not only frequent terms, but also pivotal in connecting thematic clusters in the literature. By contrast, high-frequency terms like “growth performance” and “oxidative stress” ($n =$ 557; centrality 0.03) have low centrality, implying they are well-studied but largely confined to narrow subfields. Some key functional endpoints such as “immune response”, “antioxidant capacity” and “gut microbiota” are underrepresented in both frequency and centrality—despite being common in experimental designs. This suggests a lag in consistent keyword usage, which may hinder literature synthesis and systematic reviews. Moreover, there is a relative scarcity of system-level keywords (e.g. “pond”, “recirculation”, “integration”), pointing to a gap in linking bioactives to broader ecosystem outcomes. Collectively, the keyword data reflect a field deeply entrenched in proximate biochemical responses but still growing into more holistic, systems-oriented evaluations. The high centrality of environmental and metabolic terms suggests increasing interest in functional links between feed formulations and whole-body or environmental outcomes. Yet, standardisation of terms—especially around gut health and immune modulation—is still lacking, potentially limiting cross-study comparisons and meta-analyses.

Going forward, research should not only broaden species coverage (particularly for crustaceans and tropical species), but also refine and unify terminologies related to gut health, microbiome, resilience and bioefficacy. Harmonising keyword use will help clarify impact pathways and facilitate clearer evidence synthesis in this fast-growing field.

Figure 5 presents a Word Cloud Analysis capturing the most frequently occurring keywords in the field of bioactive compounds in aquaculture. As expected, “fish”, “acid”, “fatty” and “growth” dominate the visual field, reflecting a strong emphasis on nutrition and performance metrics in aquafeed research. The prominence of terms

Fig. 5 Keywords distribution through the Word Cloud Analysis within the field of bioactive compound and aquaculture

like "protein", "composition", "sediments", "larvae" and "Penaeus" indicates the wide taxonomic and ecological range of the studies, encompassing early life stages, benthic systems and key crustacean species. Notably, "marine", "sediments", "bacteria" and "community" appear alongside nutritional terms, suggesting increasing integration of environmental and microbial perspectives. The presence of "feeding", "dietary", "lipid", "vitamin", "algal", "water quality", "oxidative stress" and "immune" reinforces the focus on functional feeds and health parameters. Moreover, keywords like "culture", "pond", "system", "DNA", "enzyme" and "microbial" point to a growing body of research linking dietary bioactives to broader system-level and cellular processes. Altogether, the diversity of terms reflects a maturing field that is moving beyond isolated feed trials to address molecular mechanisms, environmental context and species-specific performance—all essential for developing climate-smart, health-promoting aquafeeds.

Keywords burstness

Keywords burstness analysis usually refers to the sudden attraction of the terms used within the field. The keyword burst analysis (Table 1) gives a clear picture of how the field has shifted over time. Some terms have seen sudden spikes in use, pointing to periods of intense focus or emerging research themes. The term with the strongest burst is lactic acid bacteria (2009–2018), which makes sense given the surge of interest in probiotics and gut health during that period. Likewise, body composition (2019–2024) and exposure (2002–2024) reflect a more recent emphasis on physiological responses to diet and environmental stressors—especially relevant as more work moves toward integrative nutrition and toxicology. Rainbow trout (2009–2018) and *Oncorhynchus mykiss* have both featured prominently, showing their role as a key model species in feed and bioactive trials.

Table 1 Top 25 of keywords burstness in the knowledge about bioactive compounds and aquaculture, generated from the metadata through Web of Science Core Collection database from 1975 until 2023

Keywords	Year	Strength	Begin	End	1976 - 2024
lactic acid bacteria	2007	**46.11**	2009	2018	
body-composition	1997	**44.6**	2019	2024	
exposure	1992	**41.12**	2022	2024	
rainbow-trout	1991	**40.13**	2009	2018	
antioxidant	1994	**38.27**	2021	2024	
trout oncorhynchus mykiss	1998	**35.91**	2012	2018	
larvae	1990	**35.02**	2001	2017	
strains	1992	**34.89**	1992	2015	
bass dicentrarchus labrax	2008	**33.76**	2008	2017	
phytoplankton	1991	**30.25**	1991	2014	
gene	1997	**29.36**	2004	2017	
penaeus monodon	1995	**28.07**	2004	2013	
amino acids	1991	**27.29**	2012	2016	
cloning	1997	**26.35**	2008	2015	
fatty acid	1994	**25.9**	1994	2016	
sea	1996	**24.65**	1996	2016	
white shrimp	2018	**24.09**	2018	2019	
infection	1995	**23.16**	2020	2022	
parameters	2017	**23.09**	2021	2024	
toxicity	1991	**22.02**	2022	2024	
pacific oyster	1995	**21.7**	2003	2014	
shrimp	1995	**20.75**	2009	2016	
gut microbiota	2017	**20.56**	2021	2024	
food	1991	**20.45**	2016	2018	
purification	1995	**20.08**	1995	2014	

Similarly, *Dicentrarchus labrax* (2008–2017) and *Penaeus monodon* (2010–2018) show up in the burst list, reflecting their importance in both fish and shrimp nutrition studies.

What stands out is the persistent presence of antioxidants (2011–2024), which aligns with the longstanding interest in oxidative stress and immune modulation—two of the key mechanisms through which bioactive compounds are thought to exert their effects (Hu et al. 2025). Meanwhile, gut microbiota is one of the most recent terms to show up (2018–2024), capturing the field's current shift towards host–microbe interactions and microbiome-informed feed strategies (Deng et al. 2023). Terms like phytoplankton, cloning and gene suggest earlier interests in genetic and ecological foundations, whereas fatty acid and amino acids (1990 s–2010 s) track with the nutritional profiling focus of the last two decades. The burst data mirrors how the field has evolved—from core nutritional and species-specific studies toward more mechanistic and systems-level thinking.

Co-cited References Analysis

The co-citation analysis provides a detailed view of the intellectual foundation underpinning research on bioactive compounds in aquaculture. Table 2 summarises the top 15 co-cited references, with their publication types, sources, taxa focus and thematic relevance. This network of references reflects not only the research hotspots but also the interdisciplinary nature of the field. At the top of the list is the FAO's 2022 "State of World Fisheries and Aquaculture" (SOFIA) report, which continues to anchor much of the global discourse on aquaculture development. Although not a primary scientific study on bioactives, its inclusion signals the policy relevance of dietary innovation, especially the mention of seaweeds as low-calorie aquatic foods rich in bioactive compounds, dietary fibre and micronutrients. It serves as a contextual scaffold for nutrition-based research trends in aquaculture.

A key thematic cluster emerges around functional feed additives, dominated by review articles. Notably, Dawood et al. (2018) and Dawood (2021), both published in *Reviews in Aquaculture* (Q1), synthesise current knowledge on feed additives, with emphasis on their role in gut health, immune modulation and stress resilience—central concerns in sustainable aquaculture. Similarly, El-Saadony et al. (2021) and Kuebutornye et al. (2019)—published in *Fish & Shellfish Immunology*—provide extensive overviews of probiotics and beneficial microbes, highlighting their potential as alternatives to antibiotics. The prominence of gut microbiota research is further reinforced by the inclusion of Egerton et al. (2018), Hoseinifar et al. (2018) and Wang et al. (2018; 2019). These reviews collectively trace the rise of microbiome-focused nutrition, particularly the use of probiotics, prebiotics and synbiotics to modulate host health. However, while these studies are highly cited, most remain descriptive or meta-analytical, with limited mechanistic experimentation in aquaculture species.

Another influential strand is feed ingredient sustainability. Hua et al. (2019) (published in *One Earth*, Q1) and Naylor et al. (2021) (*Nature*, Q1) critically evaluate the ecological costs of traditional aquafeed ingredients and promote alternatives such as insect meal, macroalgae and microbial biomass. Although not exclusively focused on bioactive functionality, these studies show the dual imperative of nutrition and environmental impact—especially where novel ingredients introduce biofunctional properties. Interestingly, Bolyen et al. (2019), a correspondence in *Nature Biotechnology*, appears in the list due to its relevance to microbiome data analysis workflows (QIIME 2). While not an aquaculture paper, its co-citation indicates the increasing use of molecular tools and sequencing data pipelines in gut health studies. Similarly, Kumar et al. (2016), introducing MEGA 7 for

Table 2 Top 14 co-cited references in the field of bioactive compound and aquaculture, generated from the CiteSpace software and their summary of findings

References (type of publication)	Year	Sources (quartile if WOS indexed—2022)	Type of animals	Summary
FAO (Report)	2022	Flagship report of The State of World Fisheries and Aquaculture (SOFIA)	Finfish/shellfish/seaweed/etc	Seaweed rich in bioactive compound, dietary fibre and micronutrients and often view as healthy and low-calorie aquatic food
Naylor et al. (Review)	2021	Nature (Q1)	Finfish/shellfish/algae/mollusc	Analysis of the use of wild fish in aquafeeds with farmed salmon remain a good source of omega-3 fatty acids
Dawood et al. (Review)	2018	Reviews in Aquaculture (Q1)	Finfish/shellfish	Comprehensively used and updates on functional feed additives and useful applications for improving feeds in aquaculture
El-Saadony (Review)	2021	Fish & Shellfish Immunology (Q1)	Fish (finfish and shellfishes)	Beneficial bacteria of probiotics in aquaculture diets such as microbes
Bolyen et al. (Correspondence)	2019	Nature Biotechnology (Q1)	Not related	Microbiome data–related potential and application in various sectors such as agriculture
Hua et al. (Review)	2019	One Earth (Q1)	Finfish/shellfish	Alternative protein sources in aquafeeds diets such as fishery by-products, insect meal, microbial biomass, macroalgae and food waste
Kuebutornye et al. (Review)	2019	Fish & Shellfish Immunology (Q1)	Fish	The use of probiotics in aquaculture species, especially for alternative in feed utilization
Fazio (Review)	2019	Aquaculture (Q1)	Finfish	Not related to the bioactive compound, mostly on the haematological parameters and analysis from the fish species
Egerton et al. (Review)	2018	Frontiers in Microbiology (Q2)	Marine fish	Gut microbiome in aquaculture of marine species
Dawood (Review)	2021	Reviews in Aquaculture (Q1)	Finfish	Strong correlation between nutrition or balanced aquafeeds and intestinal health for sustainable aquaculture production
Kumar et al. (Original Research Article)	2016	Molecular Biology and Evolution (Q1)	Not related	The introduction of MEGA 7, a software related to the genetic analysis

Table 2 (continued)

References (type of publication)	Year	Sources (quartile if WOS indexed—2022)	Type of animals	Summary
Hoseinifar et al. (Review)	2018	Frontiers in Microbiology (Q2)	Not available	Probiotics and prebiotics as alternative to the antibiotics in dietary administration of feed additives
Wang et al. (Review)	2019	Fish & Shellfish Immunology (Q1)	Not available	Recent status of aquatic probiotics in China aquaculture
Wang et al. (Review)	2018	Reviews in Aquaculture (Q1)	Fish	Systematic review of research on fish gut microbiota in the development of probiotics and prebiotics

genetic analysis, signals the methodological overlap between nutrition, genomics and host–microbe interactions. Some co-cited references, such as Fazio (2019) in *Aquaculture*, do not deal directly with bioactive compounds but rather with haematological parameters in fish. Their frequent citation may reflect their utility in assessing physiological responses to dietary interventions. This shows how health biomarkers—while not always specific to bioactives—remain essential endpoints in nutritional trials (Oliveira et al. 2024).

A critical observation from this analysis is that the vast majority of top co-cited articles are review-based. This heavy reliance on secondary literature suggests a field still in consolidation, with ample room for hypothesis-driven experimentation. There are many fragmented research groups that could benefit from more interdisciplinarity and knowledge sharing. Moreover, nearly all sources are in Q1 journals, signalling a high-quality evidence base but also a concentration in global North publishing systems. So, the co-citation network highlights the central role of gut health, probiotics, sustainable ingredients and immunonutrition as conceptual anchors in the field. However, it also reveals significant reliance on tools and frameworks from adjacent disciplines (e.g. genomics, environmental science). The dominance of reviews and methodological papers over primary mechanistic studies suggests a need for more empirical validation of bioactive compounds in aquaculture—especially under commercial conditions and across diverse species. Bridging this gap will be vital to translate conceptual promise into scalable nutritional solutions.

Major Clusters

There are several key clusters within the scientometric network on bioactive compounds in aquaculture, each reflecting thematic shifts and critical areas of innovation in fish and shellfish nutrition, environmental management, and health resilience. While most clusters contain a single node, they represent dense citation linkages and evolving conceptual directions.

Cluster no. 0 (“Persian Sturgeon”) is the most prominent, marked by a high silhouette score (0.973) and numerous high-burst publications. This cluster is centred on microbial modulation, immunonutrition and alternative proteins, particularly the use of insect meals and gut microbial shifts in fish such as *Oreochromis niloticus* and *Dicentrarchus labrax*. It includes landmark studies such as Antonopoulou et al. (2019) on *Tenebrio molitor* in diets and Gallo et al. (2020) on the fish gut microbiome. The FAO’s State of World Fisheries and Aquaculture 2022 report anchors this cluster, showing its foundational relevance to global aquafeed and food security dialogues. Several papers within this group exhibit intense citation bursts (e.g. Naylor et al. 2021; Dawood et al. 2018), indicating their catalytic role in shaping contemporary feed strategies aligned with blue transformation narratives.

Cluster no. 1 (“Partial Substitution”) focuses on lipid replacement strategies in aquafeeds, particularly the partial substitution of fish oil with plant-based oils. It is highly central (centrality: 0.05) and contains key metabolic and lipidomic studies, notably Torstensen et al. (2005) and Christie (2003), both of which demonstrate strong network connectivity. These works show the biochemical, ecological and economic implications of dietary lipid sources—an ongoing concern in both salmonid and marine finfish sectors given sustainability constraints on wild-caught forage fish.

Cluster no. 2 (“Persian Sturgeon”), while labelled identically to cluster no. 0, reveals a distinct thematic focus on immunoprophylaxis and probiotic innovation. Studies such as Sung et al. (2009) on *Artemia* protection via heat shock proteins and Tapia-Paniagua et al. (2012) on *Shewanella putrefaciens* in *Solea* and *Sparus* culture illustrate a pivot toward microbial feed additives as alternatives to chemotherapeutics. This aligns with a broader regulatory and industry movement away from antibiotics and towards functional, health-promoting feeds in larval and juvenile production systems.

Cluster no. 3 (“Mangrove Creek”) and cluster no. 4 (“Water Column”) are environmentally focused clusters that explore biogeochemical responses to aquaculture, particularly sediment nutrient cycling and eutrophication from cage and pond systems. These include seminal works by Burford and Longmore (2001), Alongi et al. (2000) and Pitta et al. (2005), addressing nitrogen budgets and organic matter fluxes. Their inclusion highlights a recurring theme: the environmental externalities of intensive aquaculture and the necessity of integrating ecological feedbacks into feed design and farming systems modelling.

Cluster no. 5 (“Seawater Fatty Acid”) and cluster no. 6 (“Live Microalgae”) trace the evolution of lipid biochemistry in aquaculture, particularly the origin and fate of essential fatty acids in both natural and synthetic diets. Studies by Parrish et al. (1992), Nichols et al. (1996) and Robert and Trintignac (1997) reflect early work on photobioreactors, algal DHA enrichment and the taxonomic differentiation of feed microalgae. These clusters reflect the metabolic foundation upon which much of today’s functional feed development rests—especially with increasing interest in algae-based lipids as sustainable LC-PUFA sources.

Cluster no. 7 (“Organic-Matter Mineralization”) delves into benthic impacts from aquafeed inputs and their microbial mineralisation pathways. Holmer and Kristensen (1994) and Morrisey et al. (2000) investigate the cascading impacts of uneaten feed and faeces on sulphate-reducing bacteria, sediment oxygen demand and site recovery. These works frame environmental carrying capacity in practical terms and are pivotal for policy-driven reforms in marine spatial planning and IMTA systems.

Among the more specialised clusters, Cluster no. 13 (“Dietary P”) stands out for its focus on phosphorus metabolism and nutrient regulation. The pivotal study by Coloso et al. (2003) examining phosphate transporter expression in trout has laid the groundwork for precision phosphorus management in aquafeeds—a growing concern given the environmental repercussions of phosphate discharge. This work intersects environmental physiology, nutrient bioavailability and effluent management, making it foundational for the development of low-pollution or “eco-efficient” feeds.

Cluster no. 15 (“Plasma Level”) focuses on endocrine responses and the physiological correlates of dietary inputs, including sex steroid levels and astaxanthin delivery. The inclusion of studies on sex differentiation in *Dicentrarchus labrax* and larval clownfish culture (Avella et al. 2007) bridges reproductive endocrinology with larval nutrition and pigment delivery, areas of critical importance for ornamental and broodstock feed formulation. This cluster is a reminder that the physiological outcomes of feed components extend beyond growth and FCR, into complex hormonal and reproductive domains.

Cluster no. 17 (“Unsaturated Fatty Acid”) and Cluster no. 18 (“Feed Value”) both speak to long-standing preoccupations in aquaculture nutrition with lipid quality and alternative protein valuation. The inclusion of Rothuis et al. (1999) in the former highlights the synergy between integrated farming (rice–fish culture) and lipid nutrition—an intersection that is increasingly relevant for food systems integration and nutrient recycling. Cluster no. 18’s inclusion of Glencross and Vielma’s works on lupin inclusion and phosphorus utilisation reflects the strong tradition of legume evaluation and mineral–protein interactions, still active areas of inquiry in developing novel plant feedstuffs.

Cluster no. 29 (“Crustacean”), spearheaded by Tacon (1996), is notable for its early critique of translational gaps between controlled nutrition trials and on-farm reality. This epistemological reflection—rare in feed literature—shows a tension still present today: the disconnect between experimental rigor and practical applicability in shrimp and prawn systems. As crustacean nutrition moves towards holobiont-targeted strategies and environmental synchronisation, revisiting these foundational criticisms can guide more integrative and farmer-responsive feed development.

Cluster no. 32 (“Example”) and cluster no. 20 (“Marine Sponge”) delve into the cultivation of marine invertebrates for bioactive compound production. These clusters, though peripheral to mainstream aquafeed design, are crucial for the emerging field of *functional aquaculture*—where the species itself becomes a biotechnological resource. The sponge-focused studies, particularly on *Mycale* spp. and *Callyspongia*, highlight efforts to cultivate high-value secondary metabolites in open and semi-controlled systems, which could inform bioactive extraction protocols and even IMTA co-culture strategies.

Cluster no. 39 (“Nutrient”) and cluster no. 40 (“Pecten”) relate more directly to wastewater nutrient cycling and bivalve aquaculture systems. Liu et al. (2014) and Hernández et al. (2005) explore microbial remediation and macroalgae biofiltration—approaches that directly support biofloc systems and effluent polishing. These works provide early empirical support for circular and regenerative aquaculture concepts that are gaining traction in both RAS and coastal farming contexts.

Cluster no. 60 (“*Leucaena leucocephala*”) is a particularly intriguing historical node. Vogt et al. (1986) explored the use of *Leucaena* leaves in *Penaeus monodon* diets, which is notable for being one of the earliest applications of histology to assess plant ingredient impact in crustaceans. Although *Leucaena* is not widely used today due to mimosine toxicity, this work presaged the histopathological techniques we now consider standard in feed evaluation.

Cluster no. 104 (“Quality Parameter”) and cluster no. 180 (“Wild White Seabream”) highlight the intersection between feed quality, environmental exposure and final product safety. Studies by Hemre et al. (2004) and Friesen et al. (2008) suggest that seasonality, pollutants and dietary manipulations can alter the compositional quality of farmed fish, raising important implications for traceability, consumer perception and human health risk assessments.

Lastly, Cluster no. 193 (“Dietary Lysine Requirement”) revisits an enduring topic: amino acid balancing in alternative protein feeds. With lysine as one of the most limiting amino acids in plant-based diets, this cluster links closely to the metabolic work of Zhang et al. (2008) and reminds us that despite modern innovations, precise essential amino acid profiling remains central to performance optimisation—especially in marine carnivores.

Across all clusters, Nile tilapia (*O. niloticus*) repeatedly appears in the MI labelling (Mutual Information)—even when not thematically central. This reflects its dominance as a model species across functional feed, water quality and microbiome studies, showing the species’ methodological versatility and relevance for both global South aquaculture and high-throughput nutritional research. From a temporal perspective, most clusters are anchored in research from the early 2000 s to mid-2010 s, with more recent citation bursts spotlighting the integration of genomics, microbiota profiling and climate-resilient feed systems. The exceptional burst strength of the FAO 2022 report (289.70) and Naylor’s omega-3 commentary (88.29) suggest that feed innovation is increasingly evaluated not only for its nutritional performance but also for its contribution to planetary boundaries and blue economy resilience.

In sum, the network of 31 clusters presents a layered view of aquaculture nutrition science, where advances in lipidomics, microbial ecology, sustainable feed ingredients and environmental monitoring converge. The field is transitioning from siloed optimization of growth and feed conversion towards holistic, systems-level thinking—where feed is both a nutritional tool and an ecological driver.

Document burstness

Table 3 reveals literature burstness, in this case, the top 25 most influential publications that have generated intense academic attention in recent years, as measured by citation bursts within the Web of Science Core Collection. These articles reflect critical inflection points in the bioactive compound and aquaculture research landscape, bridging global policy directives, cutting-edge microbiome science and functional nutrition. Unsurprisingly, the FAO's 2022 *State of World Fisheries and Aquaculture* (Blue Transformation) dominates with an unprecedented burst strength of 289.7, highlighting the centrality of

Table 3 Top 24 articles with the strongest citation burst on the studies about bioactive compound and aquaculture research based on the Web of Science Core Collection

References	Year	Strength	Begin	End	1975 - 2024
FAO, 2022, THE STATE OF WORLD ...... DS BLUE TRANSFORMATION, V0, P0, DOI	2022	**289.7**	2022	2024	
Naylor RL, 2021, NATURE, V591, P551, DOI 10.1038/s41586-021-03308-6, DOI	2021	**88.29**	2021	2024	
El-Saadony MT, 2021, FISH SHELLFISH IMMUN, V117, P36, DOI 10.1016/j.fsi.2021.07.007, DOI	2021	**71.46**	2022	2024	
Dawood MAO, 2018, REV AQUACULT, V10, P950, DOI 10.1111/raq.12209, DOI	2018	**69.8**	2020	2024	
Bolyen E, 2019, NAT BIOTECHNOL, V37, P852, DOI 10.1038/s41587-019-0209-9, DOI	2019	**62.57**	2021	2024	
Hua K, 2019, ONE EARTH, V1, P316, DOI 10.1016/j.oneear.2019.10.018, DOI	2019	**61.25**	2021	2024	
Kuebutornye FKA, 2019, FISH SHELLFISH IMMUN, V87, P820, DOI 10.1016/j.fsi.2019.02.010, DOI	2019	**54.91**	2020	2024	
Egerton S, 2018, FRONT MICROBIOL, V9, P0, DOI 10.3389/fmicb.2018.00873, DOI	2018	**54.56**	2019	2024	
Fazio F, 2019, AQUACULTURE, V500, P237, DOI 10.1016/j.aquaculture.2018.10.030, DOI	2019	**53.31**	2020	2024	
Kumar S, 2016, MOL BIOL EVOL, V33, P1870, DOI 10.1093/molbev/msw054, 10.1093/molbev/msv279, DOI	2016	**53.3**	2016	2021	

Table 3 (continued)

Dawood MAO, 2021, REV AQUACULT, V13, P642, DOI 10.1111/raq.12492, DOI	2021	**51.99**	2021	2024
Hoseinifar SH, 2018, FRONT MICROBIOL, V9, P0, DOI 10.3389/fmicb.2018.02429, DOI	2018	**49.63**	2020	2024
Hoseinifar SH, 2020, REV FISH SCI AQUAC, V29, P198, DOI 10.1080/23308249.2020.1795616, DOI	2020	**43.2**	2022	2024
Kumar S, 2018, MOL BIOL EVOL, V35, P1547, DOI 10.1093/molbev/msy096, DOI	2018	**40.68**	2020	2024
Wang AR, 2019, FISH SHELLFISH IMMUN, V86, P734, DOI 10.1016/j.fsi.2018.12.026, DOI	2019	**40.56**	2021	2024
Turchini GM, 2009, REV AQUACULT, V1, P10, DOI 10.1111/j.1753-5131.2008.01001.x, DOI	2009	**40.43**	2010	2014
Dawood MAO, 2016, AQUACULTURE, V454, P243, DOI 10.1016/j.aquaculture.2015.12.033, DOI	2016	**39.66**	2017	2021
Wang AR, 2018, REV AQUACULT, V10, P626, DOI 10.1111/raq.12191, DOI	2018	**39.63**	2019	2024
Butt RL, 2019, FRONT ENDOCRINOL, V10, P0, DOI 10.3389/fendo.2019.00009, DOI	2019	**39.24**	2021	2024
Tamura K, 2013, MOL BIOL EVOL, V30, P2725, DOI 10.1093/molbev/mst197, 10.1093/molbev/msr121, DOI	2013	**38.68**	2014	2018
Akhter N, 2015, FISH SHELLFISH IMMUN, V45, P733, DOI 10.1016/j.fsi.2015.05.038, DOI	2015	**38.07**	2016	2020
FAO, 2018, THE STATE OF WORLD FISHERIES AND AQUACULTURE-MEETING THE SUSTAINABLE DEVELOPMENT GOALS, V0, P0	2018	**37.49**	2019	2022
Yukgehnaish K, 2020, REV AQUACULT, V12, P1903, DOI 10.1111/raq.12416, DOI	2020	**34.86**	2021	2024
Boyd CE, 2020, J WORLD AQUACULT SOC, V51, P578, DOI 10.1111/jwas.12714, DOI	2020	**33.83**	2022	2024

sustainability and food systems discourse in aquaculture research. This report sets the tone for integrating climate resilience, circular economy principles and innovation into future feed strategies, especially in policy-aligned research. Following closely, Naylor et al. (2021, *Nature*) captured wide scholarly attention (burst strength: 88.29) for its incisive analysis of the environmental costs and scalability of aquaculture. The paper's emphasis on limiting reliance on wild fishmeal sources aligns tightly with ongoing research into functional bioactives, insect meals and halophyte-based feeds. Within the scientific sphere of immunostimulants and alternative feed additives, several highly cited reviews by Dawood, El-Saadony, Hoseinifar and Kuebutornye illustrate the surge of interest in nutritionally mediated immunity. For instance, El-Saadony et al. (2021) and Dawood (2018), *Rev Aquacult*) have informed formulation strategies incorporating phytogenics, probiotics and immuno-nutrients. These articles signal a pivot from purely growth-centric feed formulations toward disease resilience and gut health. Importantly, Egerton et al. (2018) and Bolyen et al. (2019) represent a shift towards microbiome-informed aquaculture. The former provides a microbial framework for fish gut health, while the latter introduces *QIIME 2*, a critical tool for analysing microbial communities. Their strong citation bursts reflect a broader trend: microbiota modulation is becoming a mainstream lens for assessing bioactive compound efficacy. Other notable contributions, such as Hua et al. (2019) on feed sustainability metrics and Fazio (2019) on physiological biomarkers in fish, show the growing sophistication in linking bioactive compound delivery with physiological performance, environmental indicators and systemic health. These citation bursts trace a clear narrative arc: from foundational reviews and environmental critiques to mechanistic and systems-based studies, the field is maturing towards integrated, health- and sustainability-focused feed design.

General discussion

This scientometric synthesis reveals a dynamic and maturing research landscape for bioactive compounds in aquaculture, increasingly shaped by the sector's dual imperative for sustainability and productivity. Drawing from 17,932 publications and over 818,000 cited references, the field has accelerated sharply post-2010, with a distinct surge between 2019 and 2023. This growth aligns with regulatory shifts (e.g. antibiotic bans), escalating disease burdens in intensive systems and rising feed costs—all of which are driving the search for functional additives and sustainable ingredients (Bondad-Reantaso et al. 2023; FAO 2022).

At the thematic core of this expansion are gut health, oxidative stress and alternative proteins. Gut microbiota has emerged as a hotspot since 2018, with clusters centred on probiotics, lactic acid bacteria and dietary modulation strategies—showing a pivot toward host–microbe–diet interaction frameworks (El-Saadony et al. 2021; Caipang 2020; Wang et al. 2019; Egerton et al. 2018; Hoseinifar et al. 2018). Simultaneously, keywords like "oxidative stress" (with over 700 mentions) and "immune response" reflect escalating concerns about fish welfare under high-density farming and climate stressors (Moss et al. 2023). Equally, the prominence of clusters related to probiotics, phytogenics, and immunostimulants reveals a strategic move toward reducing antibiotic use and improving fish robustness through natural dietary means (Caipang 2020; Wang et al. 2019). Research on alternative feed ingredients, most notably insect meal, microalgae and plant-derived compounds, remains foundational. High-impact studies (e.g., Nogales-Mérida 2019) continue to shape discourse around protein and lipid replacement. Yet, the resurgence of older themes like fish oil replacement and dietary fatty acids (e.g., Cluster no. 0) highlights enduring nutritional challenges that are still being refined (e.g. how to balance fatty acid nutrition as feed resources change) and the field's long memory. Papers with high sigma values (e.g. Turchini, Torstensen, Ng) stand out as conceptual turning points, blending citation bursts with structural influence and signalling that lipid metabolism remains a central research axis. There is evidence of cyclic interest—certain topics may re-emerge as new technology makes solutions feasible (for example, early interest in algae as feeds reappearing now with improved cultivation techniques).

Critically, the analysis also identifies undercurrents and structural imbalances that require redress. First, geographic skew remains stark: China (26% of publications), the USA (8%) and Spain (6%) dominate output, while Africa and much of Latin America are underrepresented. This limits discovery of region-specific bioactive resources—such as endemic and medicinal plants or waste streams—that could offer sustainable feed solutions. Second, and crucially, the field would benefit from broader hypothesis exploration beyond the few dominant paradigms. To avoid stagnation, researchers and funding agencies should also encourage exploratory studies on novel bioactive sources. Our burst analysis of cited references suggested a heavy reliance on a handful of key sources including review articles and a small pool of influential references, and this suggests conceptual bottlenecking. For instance, Dawood et al. (2018) and FAO reports anchor multiple clusters, yet original mechanistic studies—particularly at molecular or microbiome level—are comparatively sparse. While numerous studies document positive effects on growth or immunity, fewer delve deeply into the molecular or microbiological mechanisms. For example, we know probiotics can improve outcomes, but more research is needed on host-microbiome-pathogen interactions to fine-tune probiotic use (Deng et al. 2023; Wang et al. 2019). Likewise, many plant compounds are known to be antioxidant or antimicrobial, but their specific modes of action in fish (and any long-term effects or optimal dosages) remain under-studied. Third, there is limited species diversity. Nile tilapia dominates across clusters, reflecting its role in nutrient trials, tolerance studies and live feed experiments (Ibrahim et al. 2022; Radwan et al. 2022). Most probiotic and microbiome studies remain limited to a small number of species—often tilapia, carp or salmonids—leaving important commercial groups such as crustaceans and molluscs comparatively underexplored. Species-specific responses to bioactive compounds remain poorly characterised in shellfish, crustaceans and emerging aquaculture candidates. Likewise, larval nutrition—captured in clusters such as no. 193 (live feed, lysine, early weaning)—is gaining traction but still lacks large-scale application or standardised protocols (Wang and Jeffs 2013).

The diversity of clusters we found is heartening—it shows many ideas being tested—but efforts should be made to connect these ideas and fill any blind spots. One such blind spot might be the long-term environmental and economic implications of using certain bioactive compounds at scale. Few studies have addressed the cost-effectiveness of these interventions or their impact on product quality and consumer acceptance. As the field matures, integrating economic analysis and considering regulatory aspects (for instance, approval of feed additives) will be important for real-world implementation. Moreover, practical deployment issues remain a blind spot. While functional additives show promise, there is scant evidence on their long-term effects across full production cycles, or their influence on post-harvest product quality, feed conversion ratios under variable farm conditions and consumer acceptability. Bioactive delivery methods also present challenges: compounds like essential oils face leaching and oxidation risks; others suffer from poor palatability or instability. Economic feasibility is another underexplored area—particularly for small-scale producers. What emerges from this scientometric landscape is a research field poised for transformation, but not yet fully integrated. Many promising themes—microbiome manipulation, phytochemical synergy, stress mitigation—are evolving in disciplinary silos. Closing this gap requires integrative frameworks that connect nutrition, genomics, microbiology, environmental science and behavioural ecology. To translate this research into practice, the following gaps must be addressed:

- Topical gaps: Mechanistic understanding of bioactive function is still limited.
- Geographic gaps: Africa and parts of Latin America remain underrepresented.
- Structural gaps: Fragmented collaboration networks impede interdisciplinary integration.

To bridge these gaps, research funding should be directed toward:

- Underexplored species and systems (e.g. shellfish, integrated systems).
- Long-term trials linking microbiota modulation, fish performance and health.
- Region-specific innovations leveraging indigenous resources.

The knowledge gained from these trends should guide not only academic inquiry but also policy and industry practice. The heavy focus on functional additives' benefits (growth promotion, immune enhancement, etc.) documented in the literature provides evidence for regulators to consider these additives in fish health management plans. For instance, as probiotics prove their efficacy, governments might update aquaculture guidelines to incorporate probiotics as a recommended best practice for disease prevention. Some countries have already begun doing this as part of antibiotic reduction strategies (Fachri et al. 2024). The sustained interest in replacing fish oil and other marine resources in feeds also resonates with policy: it shows the need for continued support for alternative ingredient development (insects, algae, microbial meals), some of which may require policy approval or investment in production infrastructure. The trends in keyword bursts like "oxidative stress" and "immune response" highlight the importance of fish welfare in intensive production, supporting the case for stricter environmental monitoring and the integration of stress-reduction supplements in feeds. The data-driven understanding of where the field has been and is headed allows stakeholders to make informed decisions that synergize scientific progress with aquaculture development goals.

Conclusion

This scientometric analysis offers a critical lens into how the research landscape of bioactive compounds in aquaculture nutrition has developed, and where it must now go. The prominence of review articles in the most co-cited references—particularly those focusing on probiotics, immunostimulants and gut microbiota—reflects the field's strong conceptual momentum. However, the relative scarcity of original experimental studies in the top-cited literature reveals a central limitation: the evidence base guiding bioactive compound use in aquafeeds remains heavily theoretical, with limited species-specific, context-specific or mechanistically grounded data. This presents both a challenge and an opportunity. The dominance of themes such as gut health, oxidative stress mitigation and microbiome modulation indicates a strong industry and academic alignment around improving host resilience through dietary interventions. However, most existing studies stop short of integrating nutritional biochemistry, microbiome science and performance outcomes into a cohesive framework. For bioactive compounds to become true nutritional tools—rather than promising but piecemeal additives—future research must build multi-scale evidence linking compound chemistry to host physiology, gut microbial ecology and growth or health metrics under real-world farming conditions. Moreover, the concentration of research output in select geographies, coupled with the underrepresentation of low- and middle-income aquaculture regions, suggests a skew in the bioactive pipeline. Indigenous plants, marine microflora/fauna or regionally cultivated herbs may harbour untapped functional potential—but are systematically underexplored due to capacity limitations. This imbalance not only limits innovation but also narrows the nutritional relevance of current research to high-income or salmon-centric systems. Expanding the geographic and species breadth of studies—particularly on underutilised species (e.g. molluscs, crustaceans, herbivorous fish)—should therefore be a priority. Ultimately, this review shows that the field is not short of innovation, but rather in need of cohesion and contextualisation. To consolidate what has been written in this section, our data suggests moving towards an ecosystem-informed nutrition approach, one that links bioactive use to health, performance, welfare, environment and socio-economics. This is now essential to translate research into practice and ensure that bioactive compounds become a practical and accessible cornerstone of sustainable aquaculture. Therefore, to bring these innovations to real-world/practical settings, three strategies are essential:

1. Research insights must be presented in formats that suit different end-users:

   Policymakers need clear, evidence-backed recommendations for regulation and national planning.
   Aquafeed companies and farmers need validated protocols and case studies demonstrating cost-benefit or productivity gains.
   Funding agencies and NGOs need strategic maps showing where the knowledge gaps are and which regions or species are underserved.

2. It is not enough to know that probiotics or antioxidants work, we must integrate them into farm-level trials, develop actionable frameworks and guidelines for optimal dosage and combinations, and test economic viability. Large-scale demonstration projects, particularly in underrepresented regions, can serve as knowledge transfer vehicles.
3. To avoid knowledge loss or duplication, research outputs must feed into:

   Public databases (e.g. on feed additives, gut microbiome profiles, bioactive efficacy).
   Policy briefs and regulatory frameworks.
   Curricula and training materials that embed cutting-edge science into education, especially in the Global South.

Table 4 includes specific end-users and knowledge translation pathways for each key scientometric insight, suggesting ways we can preserve knowledge, scale its impact and ensure bioactive compound research in aquaculture contributes meaningfully to food security, environmental health and economic growth.

Table 4 Scientometric insights and future directions for bioactive compounds in aquaculture

Research focus	Scientometric insight	Key data/figures	Identified research gaps	Strategic actions and policy recommendations	End users/knowledge translation pathway
Temporal publication trends	Publication surge post-2010, peak in 2019	Figure 2A: Publication trajectory	Unclear if peak tied to policy, disease outbreaks or funding trends	Analyse links to policy (e.g. antibiotic bans), align funding with trends	Funding bodies (strategic calls); science policy think tanks (trend reports)
Geographic distribution	Dominated by China, USA, Spain; Africa and Latin America under-represented	Figure 2B: Global output map	Limited inclusion of regional species, bioresources and indigenous knowledge	Establish South-South partnerships, invest in local feed research centres	International NGOs, development agencies, regional aquaculture ministries
Institutional collaboration	Low network density, key hubs in China and UK	Figure 3–4: Collab. networks	Knowledge remains siloed, weak inter-institutional flow	Incentivise twinning programmes, fund cross-country consortia	Universities, funding agencies, capacity building initiatives
Oxidative stress and immunity	Frequent keywords, focus on resilience	Figure 5: Word cloud, burst terms	Mostly short-term trials, lacking multigenerational data	Fund full grow-out studies, develop immune health guidelines	Farmers, aquafeed developers, veterinary regulators
Gut health and microbiota	Burst post-2018; probiotics dominate	Keyword burst analysis	Weak mechanistic studies, most focus on few species	Launch integrative nutrition–omics trials; approve probiotic uses in feed regulation	Feed companies, aquaculture vets, regulators
Alternative ingredients (insects, algae)	Insect meal and microalgae are trending; strong cluster activity	Clusters no. 2, keyword: "insect meal"	Industrial-scale validation, palatability issues, economic modelling gaps	On-farm pilot studies, tax incentives for insect/algae production	Aquafeed firms, investment bodies, extension officers
Influential frameworks	FAO (2020, 2022), Naylor et al. (2021), Dawood et al. (2018) are structural anchors	Highest burst, central nodes	Risk of narrow inquiry and reliance on dominant paradigms	Fund hypothesis-disruptive research; re-examine old but relevant frameworks	Curriculum designers, early-career researchers, grant reviewers
Emergent species and nutrient foci	Nile tilapia dominates clusters; cluster no. 193 on larvae, lysine, live feeds	Cluster no. 0, no. 193, no. 51	Precision larval nutrition underexplored; species bias	Design species-diverse larval feed trials; explore underrepresented taxa (e.g. catfish, crustaceans)	Larval feed companies, shrimp farms, research hatcheries

Table 4 (continued)

Research focus	Scientometric insight	Key data/figures	Identified research gaps	Strategic actions and policy recommendations	End users/knowledge translation pathway
Centrality and sigma analysis	Turchini, Torstensen, Ng papers have high sigma—lipid metabolism pivotal	Burst and sigma data	Fatty acid balancing remains unsolved across oils	Revisit long-chain PUFA metabolism studies under new diet regimes	Lipid researchers, ingredient suppliers, policy boards on feed approvals
Environmental and ecosystem impact	Lacking studies linking gut outputs to water quality	Keyword + burst mapping	Missing integration between fish health and farm ecology	Promote ecosystem-based nutrition studies	Integrated aquaculture researchers, environmental regulators, water quality labs
Product quality and post-harvest effects	Rarely studied in context of bioactive diets	Manual review of focus terms	Impact of diets on fillet taste, shelf life, consumer traits unknown	Cross-cutting trials linking bioactive diet to fillet quality	Food scientists, processors, marketing boards
Social and economic dimensions	Socioeconomic feasibility underexplored	Cluster absence on this topic	Lack of data on adoption by smallholders	Conduct livelihood impact studies of feed innovations	NGOs, extension services, sustainable aquaculture hubs

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Declarations

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