TREND EVALUATION ON WASTE PRODUCTS AS POTENTIAL ALTERNATIVES FOR FISH FEED: A BIBLIOMETRIC ANALYSIS

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Abstract:

Due to the need for sustainable and cost-effective aquaculture feed solutions, waste products are being studied as fish feed alternatives. Moreover, considering the environmental concerns and the depletion of fishmeal resources, agricultural residues, industrial by-products, and organic waste are being investigated as feed ingredients. Scopus and VOSviewer data will be employed to assess this emerging field's research trends, key contributors, and collaborative networks, as well as to map keyword and co-authorship networks in 1,236 publications from 2014 to 2024. A significant increase in publications

occurred after 2017, with the highest research output between 2021 and 2023. China, Indonesia, and the United States (US) lead in publications and citations, indicating a global focus on sustainable aquaculture. The analysis also highlights keywords like "animal feed," "waste management," "biomass," and "sustainability," indicating a strong focus on waste product valorisation for feed quality. The findings reveal international collaboration and a multidisciplinary approach integrating environmental science, agricultural technology, and nutritional evaluation. Due to resource efficiency and environmental sustainability, waste-derived feed alternatives are becoming more popular. This study sheds light on current research, suggests future directions, and emphasises the need for innovation in waste-based feed solutions for aquaculture.

Keywords:

Waste, Fish, Feed, BiblioMetric Analysis

Introduction

The rising global demand for fish has exerted considerable pressure on conventional fishmeal sources, leading to overfishing and environmental degradation. In addressing these challenges, researchers and aquaculture professionals are investigating alternative feed components sourced from waste materials, such as agricultural by-products, food waste, and insect biomass. These alternatives seek to diminish dependence on fishmeals and foster sustainable aquaculture practices by reducing waste and encouraging a circular economy. Thus, research has demonstrated the feasibility of utilising agricultural by-products, including soybean meal and pumpkin seed cake, as effective alternatives to fishmeal without negatively impacting fish growth performance (Sezgin & Aydın, 2021; Wu et al., 2021). Accordingly, the integration of microalgae and insect-based feeds has demonstrated the potential to improve the nutritional quality of fish diets while mitigating environmental issues linked to traditional fish feed production (Goyal et al., 2021; Zlaugotne, 2023).

The use of waste products as alternatives for fish feed corresponds with the increasing focus on sustainability in the aquaculture industry. Research demonstrates that approximately 30% of agricultural waste can be repurposed for feed production, resulting in a zero-waste scenario (Cahya et al., 2022). Furthermore, life cycle assessments of diverse alternative protein sources, such as black soldier fly larvae and microalgae, indicate their potential to rival traditional fishmeals regarding environmental impact (Goglio et al., 2022; Zlaugotne, 2023). Hence, by utilising these novel feed ingredients, the aquaculture sector can diminish its environmental impact while simultaneously improving the economic sustainability of fish farming enterprises. Notably, the trend of using waste products as alternatives for fish feed is essential for satisfying the rising global demand for fish while fostering sustainable practices that safeguard marine ecosystems and ensure food security (Montoya-Camacho et al., 2018; Ogunji et al., 2021).

Literature Review

Incorporating waste products in fish feed formulations has surfaced as a viable approach to tackling sustainability issues in aquaculture. Recent trends indicate a notable transition towards the use of agricultural residues, industrial by-products, and microbial proteins as alternative protein sources. Correspondingly, Abdel-Tawwab et al. (2024) emphasised the incorporation of chitosan nanoparticles derived from Bacillus subtilis in fish diets. It illustrates their effectiveness in alleviating heavy metal toxicity and improving the growth performance of Nile

tilapia. Meanwhile, Pesante et al. (2024) assessed microbial proteins sourced from agricultural residues, demonstrating the potential of these alternative protein sources to mitigate the environmental impact of conventional fishmeal in accordance with the growing demand for sustainable aquafeed components. A significant trend is the valorisation of aquaculture waste into valuable feed components, emphasising nutrient recycling and waste minimisation. Liu et al. (2024) investigated the biotransformation of aquaculture wastewater utilising microalgae such as *Chlorella sorokiniana*, which effectively purified the wastewater while generating a nutrient-dense protein source for fish feed. This corresponds with the research conducted by Waldemer et al. (2024), who examined the effects of high-protein fish feed on methane emissions in aquaculture ponds, highlighting the significance of waste management practices. These studies collectively emphasise a transition to circular economy strategies in aquaculture, focusing on repurposing waste as a resource to diminish the environmental impact and enhance resource efficiency.

The quality and safety of feed components derived from waste are essential factors in formulating alternative fish feeds. Rodriguez-Romeu et al. (2024) investigated the consumption of plastic fibres by sardines, which presents considerable health hazards and underscores the escalating problem of microplastic pollution in aquatic ecosystems. At the same time, Devi et al. (2024) conducted a comprehensive evaluation of microplastic prevalence in commercial fish feeds across various continents, uncovering extensive contamination with polymers such as polyethene terephthalate and polystyrene. These findings underscore the necessity for rigorous quality controls and inventive solutions to mitigate contamination risks linked to waste-derived feed ingredients. Furthermore, recent studies have concentrated on improving the digestibility and nutritional quality of feed components derived from waste, in addition to waste valorisation. Mohammady et al. (2024) examined the fermentation of sugar beetroot bagasse with probiotic strains to enhance its nutritional profile, successfully substituting soybean meal in the diets of Nile tilapia. This method increased protein content and decreased fibre levels, leading to enhanced growth and health outcomes for the fish. Similarly, Dadkhodazadeh et al. (2024) employed solid-state fermentation to augment the protein content and antioxidant characteristics of fish waste, illustrating its viability as a high-value feed additive.

Notwithstanding these advancements, challenges persist in optimising inclusion levels and ensuring consistent quality of waste-derived feed components. Wang et al. (2024) investigated the substitution of fishmeal with poultry by-product meal, supplemented with dried porcine soluble, emphasising the intricacies of balancing nutrient composition while preserving growth performance. The results suggest that although waste products present feasible alternatives, further optimisation of feed formulations is necessary to guarantee economic viability and optimal fish health. The existing research highlights considerable knowledge deficiencies, especially regarding the long-term impacts of utilising waste-derived ingredients in fish feed. Accordingly, Abdel-Hady et al. (2024) examined consumer apprehensions about incorporating animal waste in fish feed, influencing market acceptance and presenting possible health hazards. There is a distinct necessity for further research concentrating on thorough risk evaluations, nutritional analysis, and the formulation of protocols for the safe utilisation of waste-derived feed ingredients. The trend of employing waste products as alternatives for fish feed is promising; however, further investigation is necessary to harness its potential fully. Therefore, future research must tackle contamination issues, enhance fermentation processes, and assess the long-term health effects on fish. Furthermore, additional research is required to

connect laboratory-scale experiments with commercial-scale applications, guaranteeing the effective integration of these sustainable practices into the aquaculture sector.

Research Question

a. What are the research trends in the application of waste in fish feed studies according to the year of publication?
b. Who published the most related articles?
c. What are the types of documents by subject of research?
d. Who are the top 10 authors based on citation by research?
e. What are the popular keywords related to the study?
f. What are co-authorship countries' collaboration?

Methodology

Bibliometrics combines, manages, and analyses bibliographic data derived from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). In addition to general descriptive statistics, such as the classification of the primary author, the year of publication, and the journals in which the work was published (Y. C. J. Wu & Wu, 2017), Complex techniques, including document co-citation analysis, are also included. A comprehensive bibliography and dependable results derive from an iterative process that involves the identification of appropriate keywords, a literature search, and a thorough analysis in a successful literature review (Fahimnia et al., 2015). In light of this, the study endeavoured to concentrate on top-tier publications, as they provide valuable insights into the theoretical perspectives influencing the evolution of the research domain. The Scopus database was utilised for data collection in order to guarantee data reliability (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Additionally, to ensure the inclusion of publications of superior quality, only articles published in academic journals that were rigorously peer-reviewed were considered, with the deliberate exclusion of books and lecture notes (Gu et al., 2019). Scopus, renowned for its comprehensive coverage, was instrumental in acquiring publications from 2014 to December 2024 for subsequent analysis.

Data Search Strategy

The advanced search string in Scopus is a potent instrument that enables researchers to generate intricate and precise search queries in order to extract specific information from the extensive Scopus database. This attribute is particularly advantageous for conducting comprehensive subject investigations, systematic literature reviews, and bibliometric analyses. The advanced search interface enhances the search process, which allows for using Boolean operators, field codes, wildcards, proximity operators, and nested queries. The search string and the selection criterion for the search are presented in Tables 1 and 2.

Table 1: The Search String

Scopus	TITLE-ABS-KEY (halal AND food) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final"))

Table 2: The Selection Criterion is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2014 – 2024	< 2014
Literature type	Journal (Article) and Proceeding	Book, Review

Data Analysis

VOSviewer is a user-friendly bibliometric tool developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands (van Eck & Waltman, 2010, 2017). This tool is extensively employed for visualising and analysing scholarly literature, excelling in creating intuitive network visualisations, clustering related items, and generating density maps. Furthermore, the adaptability of this approach facilitates the analysis of co-authorship, co-citation, and keyword co-occurrence networks, equipping researchers with an in-depth insight into research environments. The engaging interface and ongoing enhancements guarantee effective and adaptable investigation of extensive datasets. The capacity of VOSviewer to calculate metrics and tailor visual representations and its adaptability with diverse bibliometric data sources renders it an essential tool for researchers aiming to gain understanding in intricate fields of study.

One of the remarkable aspects of VOSviewer is its ability to convert complex bibliometric datasets into visually comprehensible maps and charts. The software demonstrates exceptional capabilities in network visualisation, particularly in clustering related items, analysing patterns of keyword co-occurrence, and producing density maps. Moreover, investigators gain from its intuitive interface, allowing beginners and seasoned professionals to navigate research environments effectively. The ongoing advancement of VOSviewer guarantees its position as a leader in bibliometric analysis, providing essential insights through the calculation of metrics and the ability to create tailored visual representations. In addition, the ability to adjust to various forms of bibliometric data, including co-authorship and citation networks, establishes VOSviewer as a flexible and essential resource for researchers aiming to gain profound insights and a comprehensive understanding within their fields of study.

Data containing publication year, title, author name, journal, citation, and keywords in PlainText format were obtained from the Scopus database, covering the timeframe from 2014 to December 2024. The analysis of these datasets was conducted utilising VOSviewer software version 1.6.19. Thus, by employing VOS clustering and mapping techniques, this software enabled the analysis and creation of maps. Presenting a different perspective from the Multidimensional Scaling (MDS) method, VOSviewer emphasises the arrangement of items in low-dimensional spaces, guaranteeing that the closeness between any two items truly represents their connections and likeness (van Eck & Waltman, 2010). In this regard, VOSviewer resembles the MDS methodology (Appio et al., 2014). VOS employs a more appropriate method for normalising co-occurrence frequencies, such as the Association Strength (AS_{ij}), which is calculated in contrast to MDS, which primarily engages in the computation of similarity metrics like cosine and Jaccard indices (Van Eck & Waltman, 2007):

$$AS_{ij} = \frac{C_{ij}}{w_i w_j}$$

It is described as "proportional to the ratio of the actual co-occurrences of i and j to the anticipated co-occurrences of i and j, under the assumption that the co-occurrences of i and j are statistically independent"(Van Eck & Waltman, 2007).

Result And Finding

What Are The Research Trends In The Application Of Waste In Fish Feed Studies According To The Year Of Publication?
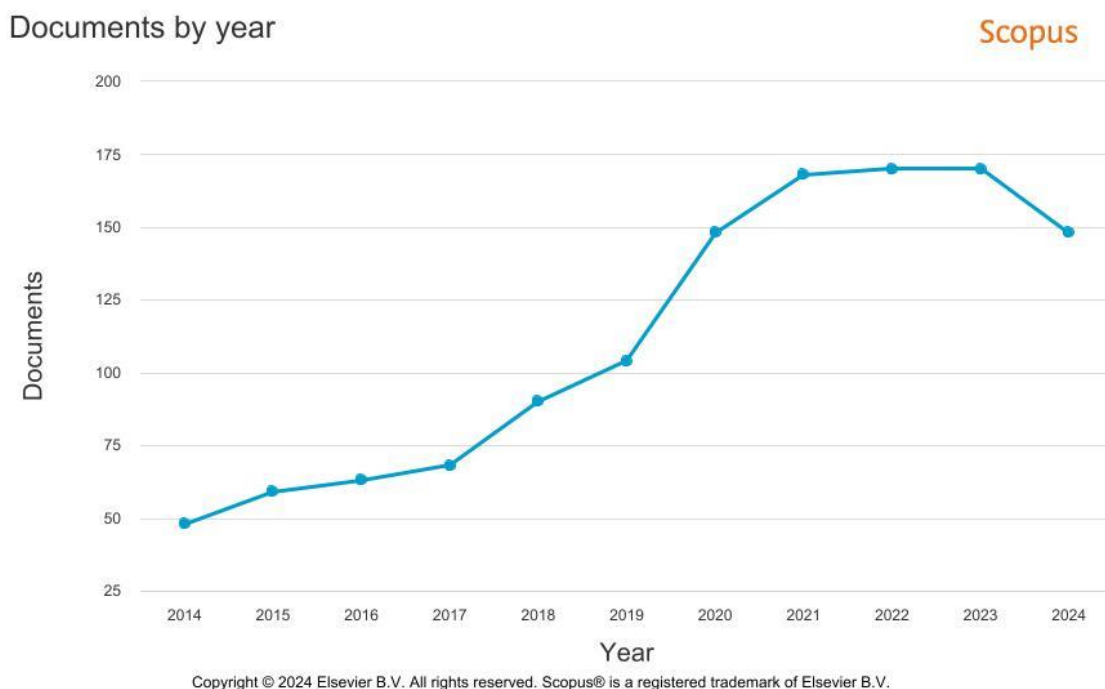
Figure 1: Plotting Document Publication By Years.

The figure illustrates a gradual increase in research interest over the decade in the trend of publications on waste products as potential alternatives for fish feed from 2014 to 2024. A gradual increase was observed from 2017 onwards, following a modest count of approximately 50 documents per year between 2014 and 2016. This upward trend is likely indicative of the increasing emphasis on sustainable aquaculture practices and the identification of waste valorisation as a promising avenue for mitigating the environmental effects and expenses associated with conventional fish feed. Notably, the significant increase in publications around 2019 suggests a surge in interest, which coincides with a rise in global awareness of the limitations of traditional fishmeal resources and the necessity of alternative feed solutions to support the expanding aquaculture industry.

The number of documents stabilises at approximately 175 annually, with the peak in publications occurring from 2021 to 2023. Several studies have been conducted to validate the potential of various waste products, such as agricultural residues, industrial by-products, and microbial proteins, as viable feed alternatives. This plateau suggests a phase of consolidation in research. Nevertheless, the slight decrease in 2024 suggests a potential change in the research focus or the volume of publications. This could result from reevaluating priorities within the

field or new challenges, emphasising the necessity of more comprehensive studies that address the long-term effects, economic feasibility, and practical implementation of waste-derived feed in commercial aquaculture. While the general trend indicates a robust scientific interest, it also suggests potential areas for future research, particularly in safety concerns and optimising waste product utilisation.

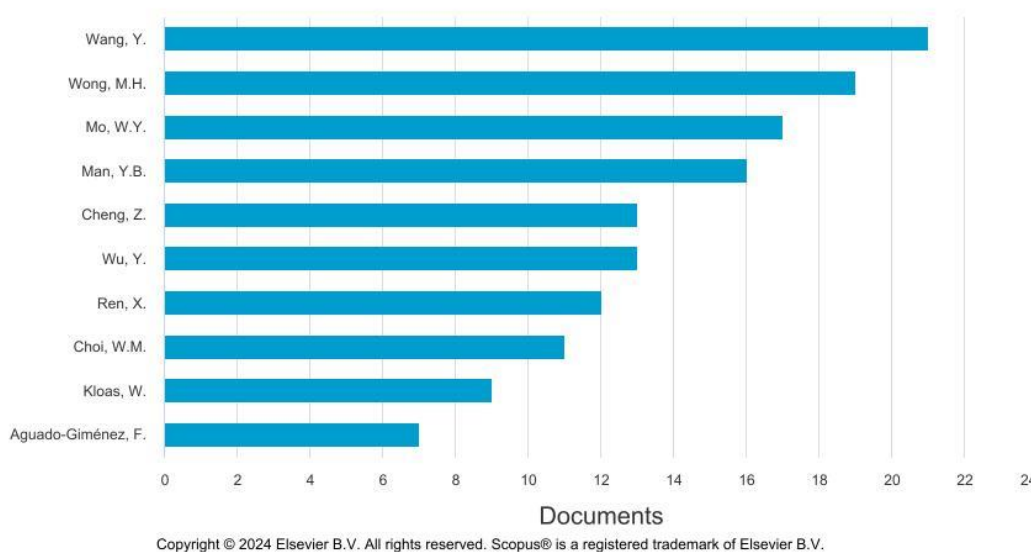### *Who Published The Most Related Articles?*

Figure 2: Plotting the authors's name and publication's number

The examination of the most prolific authors in the field of waste products as potential alternatives for fish feed reveals a concentrated group of researchers who have made substantial contributions to the literature. The figure illustrates that Wang, Y., is the primary author, with a total of 20 publications. The high number of publications indicates a consistent and robust emphasis on this subject, which is likely to involve extensive research into the exploration of various waste products. This includes agricultural residues and industrial by-products as alternatives to conventional fishmeal. Meanwhile, Wong, M.H., who has 18 publications, is closely followed, suggesting he is actively involved in related studies. This engagement may be focused on environmental sustainability and innovative feed ingredients in aquaculture.

Mo, W.Y., Man, Y.B., and Cheng, Z. are the subsequent authors, each of whom has a substantial number of publications, ranging from 14 to 17. These authors adopt a collaborative or interdisciplinary approach, frequently investigating various aspects of waste product utilisation in fish feed. This includes economic feasibility, environmental impact, and nutritional assessment. A more specialised or emerging research interest in this area is suggested by authors such as Ren, X., Choi, W.M., and Kloas, W., who have contributed between 8 and 12 documents. Their contributions are likely to concentrate on niche topics within the broader field, such as the utilisation of unique processing techniques or specific waste sources. Moreover, the increasing international interest in this research theme is further evidenced by the presence of authors such as Aguado-Giménez, F., which underscores the

necessity of ongoing research into alternative protein sources to satisfy the requirements of sustainable aquaculture. This distribution of publications among key authors denotes a research community that is both well-established and diversely focused, indicating that there are ongoing opportunities for novel investigations and strong leadership in the field.

Table 3: Details on Numbers of Documents Published by Authors and their Percentage

AUTHOR NAME	NUMBER OF DOCUMENT	PERCENTAGES (%)
Wang, Y.	21	1.699
Wong, M.H.	19	1.537
Mo, W.Y.	17	1.375
Man, Y.B.	16	1.294
Cheng, Z.	13	1.052
Wu, Y.	13	1.052
Ren, X.	12	0.971
Choi, W.M.	11	0.890
Kloas, W.	9	0.728
Aguado-Giménez, F.	7	0.566

The authors who have made the most significant contributions to the research area that concentrates on waste products as potential alternatives for fish feed are identified in the table. Accordingly, Wang, Y. is the author with the most publications (21), which accounts for 1.699% of the total. This implies a substantial and consistent research focus in this field, which is likely to involve a comprehensive examination of alternative feed ingredients derived from various waste sources. At the same time, Wong, M. H. has made substantial contributions with 19 publications (1.537%) following Wang, Y. It appears that both authors are prominent figures in this field, potentially addressing sustainability challenges and offering innovative feed solutions for aquaculture.

Mo, W.Y. and Man, Y.B. are two other notable contributors, each contributing 17 (1.375%) and 16 (1.294%) publications, respectively. Their relatively high publication counts indicate a robust research interest, which may involve interdisciplinary approaches and collaborations. In addition, Cheng, Z. and Wu, Y. each have 13 publications (1.052%), which suggests a consistent level of interest in the subject matter. The active involvement of various researchers in this emerging field is further exemplified by the presence of Ren, X. (12 publications, 0.971%) and Choi, W.M. (11 publications, 0.890%). Despite the fact that Kloas, W., and Aguado-Giménez, F. have made fewer contributions (9 and 7 publications, respectively), their work still reflects the expanding international scope of the research. This indicates widespread interest in the development of sustainable fish feed solutions. In general, this distribution of contributions underscores a research community that is both robust and diverse, with the potential for ongoing innovation and growth.

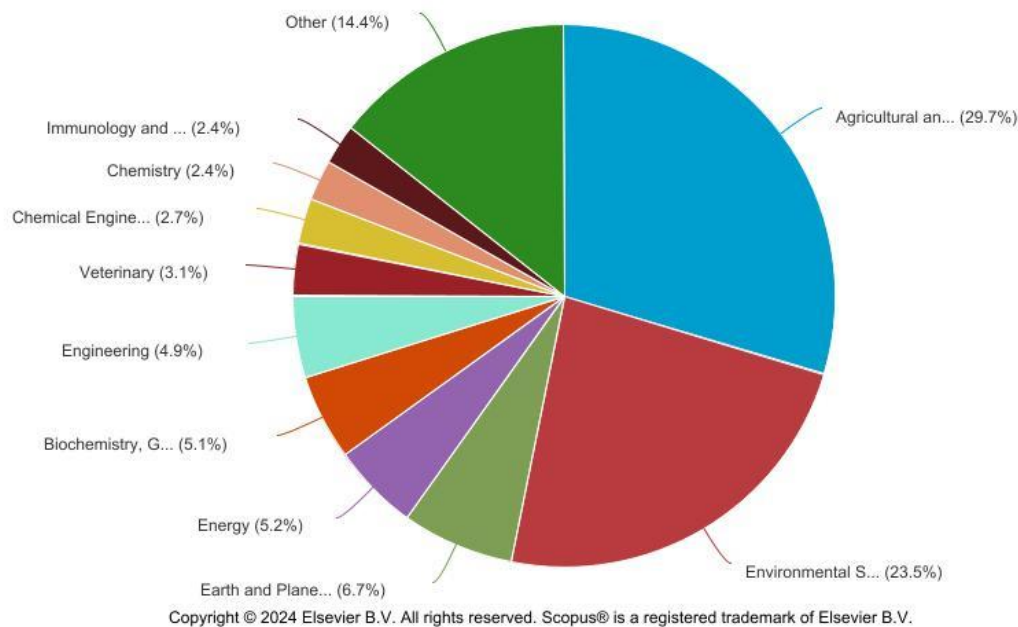*What Are The Types Of Documents By Subject Of Research?*

Figure 3: Plotting the Percentages by Subject Area

The pie chart above illustrates the distribution of publications across various subject areas pertinent to investigating waste products as potential substitutes for fish feed. The "Agricultural and Biological Sciences" category comprises the largest percentage of documents (29.7%). This emphasises the critical role of agriculture in the development of alternative feed ingredients that are derived from plant-based or agricultural waste. Notably, this dominance indicates a significant emphasis on exploring agricultural by-products, including crop residues and food processing waste, as sustainable alternatives to conventional fishmeal. Meanwhile, the second largest category is "Environmental Science" (23.5%), which underscores the growing concern regarding environmental impacts, such as waste management, resource recycling, and the reduction of the ecological footprint of aquaculture practices.

"Earth and Planetary Sciences" (6.7%), "Energy" (5.2%), and "Biochemistry, Genetics, and Molecular Biology" (5.1%) are additional significant subject areas that collectively suggest a multidisciplinary approach in this field. The participation of "Engineering" (4.9%) indicates ongoing endeavours to develop innovative processing technologies for waste utilisation. In comparison, "Veterinary Science" (3.1%) suggests that research is focused on animal health and feed safety. The smaller contributions from "Chemical Engineering," "Chemistry," and "Immunology and Microbiology" (each approximately 2.4%–2.7%) suggest that targeted studies on the microbial processing of waste products and the chemical characterisation of waste are needed. In the "Other" category (14.4%), the broad interest and potential applications of waste-based fish feed across different scientific disciplines are reflected, as it represents diverse contributions from fields that are not explicitly listed. This distribution underscores the

interdisciplinary nature of this research, which is designed to balance sustainability, resource efficiency, and feed quality in aquaculture.

Who Are The Top 10 Authors Based On Citation By Research?

Table 4: List of Top 10 Most Cited Authorship

Authors	Title	Year	Journal Title	Cited by
Lalander C.; Diener S.; Zurbrügg C.; Vinnerås B. (Lalander et al., 2019)	Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (Hermetia illucens)	2019	Journal of Cleaner Production	412
Nguyen T.T.X.; Tomberlin J.K.; Vanlaerhoven S. (Nguyen et al., 2015)	Ability of Black Soldier Fly (Diptera: Stratiomyidae) Larvae to Recycle Food Waste	2015	Environmental Entomology	394
Ewald N.; Vidakovic A.; Langeland M.; Kiessling A.; Sampels S.; Lalander C. (Ewald et al., 2020)	Fatty acid composition of black soldier fly larvae (Hermetia illucens) – Possibilities and limitations for modification through diet	2020	Waste Management	303
Han Q.F.; Zhao S.; Zhang X.R.; Wang X.L.; Song C.; Wang S.G. (Han et al., 2020)	Distribution, combined pollution and risk assessment of antibiotics in typical marine aquaculture farms surrounding the Yellow Sea, North China	2020	Environment International	275
Liu X.; Chen X.; Wang H.; Yang Q.; Ur Rehman K.; Li W.; Cai M.; Li Q.; Mazza L.; Zhang J.; Yu Z.; Zheng L. (X. Liu et al., 2017)	Dynamic changes of nutrient composition throughout the entire life cycle of black soldier fly	2017	PLoS ONE	269
Poyatos-Racionero E.; Ros-Lis J.V.; Vivancos J.-L.; Martínez-Máñez R. (Poyatos-Racionero et al., 2018)	Recent advances on intelligent packaging as tools to reduce food waste	2018	Journal of Cleaner Production	230
Martínez-Alvarez O.; Chamorro S.; Brenes A. (Martínez-Alvarez et al., 2015)	Protein hydrolysates from animal processing by-products as a source of bioactive molecules with interest in animal feeding: A review	2015	Food Research International	224
Belghit I.; Liland N.S.; Waagbø R.; Biancarosa I.; Pelusio N.; Li Y.; Krogdahl Å.; Lock E.-J. (Belghit et al., 2018)	Potential of insect-based diets for Atlantic salmon (Salmo salar)	2018	Aquaculture	206
Mertenat A.; Diener S.; Zurbrügg C. (Mertenat et al., 2019)	Black Soldier Fly biowaste treatment – Assessment of global warming potential	2019	Waste Management	203
Boyd C.E.; McNevin A.A.; Davis R.P. (Boyd et al., 2022)	The contribution of fisheries and aquaculture to the global protein supply	2022	Food Security	192

The table provides insights into the most cited articles related to waste products as potential alternatives for fish feed, highlighting influential works in this field. The most cited publication is by Lalander et al. (2019) with 412 citations, which examined the effects of feedstock on larval development and process efficiency using Black Soldier Fly (*Hermetia illucens*), published in the *Journal of Cleaner Production*. The high citation count indicates the significant impact of this research, likely due to its focus on sustainable waste treatment and the application of insect-based feeds in aquaculture. Nguyen et al. (2015) follow closely with

394 citations, highlighting the ability of Black Soldier Fly larvae to recycle food waste, reflecting strong interest in the bioconversion capabilities of insects and their potential to reduce food waste while providing a nutrient-rich feed source.

The data also demonstrate a consistent interest in insect-based feed alternatives, as observed in the works of Ewald et al. (2020) and Mertenat et al. (2019), which focused on the fatty acid composition of insect larvae and the global warming potential of biowaste treatment, respectively. Notably, studies such as Belghit et al. (2018) and Mo et al. (2018) explored the potential of insect-based diets and food processing waste, highlighting the shift towards sustainable protein sources for aquaculture. Additionally, Hu et al. (2021) contributed to advancing aquaculture technology with real-time detection methods for uneaten feed, illustrating the integration of innovative technologies in waste management practices. Overall, the high citation counts across these studies reflect the growing emphasis on sustainable aquaculture practices and the pivotal role of waste-derived feed alternatives in reducing environmental impacts and supporting the industry's sustainability goals.

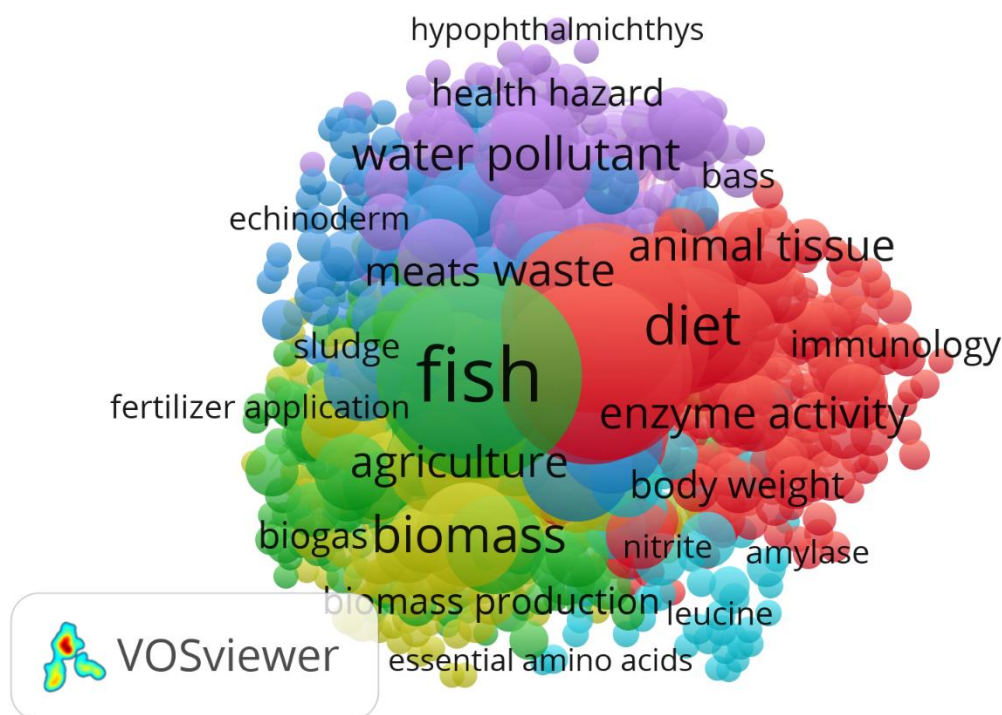*What Are The Popular Keywords Related To The Study?*

Figure 3: Network Visualisation Map of Keywords' Co-Occurrence

The data extracted from VOSviewer software provides a detailed overview of the most frequently occurring keywords and their co-occurrence in studies related to the trend evaluation of waste products as potential alternatives for fish feed. The analysis highlights a diverse range of topics, highlighting the frequency and the total link strength, indicating the interconnectedness and relevance of specific themes in the research field. In particular, key terms such as "animal feed" (123 occurrences) and "waste management" (47 occurrences) exhibit strong link strengths, indicating their central role in the body of research. The total link

strength of "animal feed" stands out, suggesting significant connectivity across multiple studies, suggesting a primary focus on exploring waste as a sustainable feed option in aquaculture. Additionally, "aquaculture" and "sustainability" also appear frequently (238 and 48 times, respectively), further emphasising the industry's shift towards sustainable practices and the importance of waste valorisation.

Another notable keyword is "biomass," which has 86 occurrences and a high total link strength. This reflects the increasing interest in utilising agricultural residues and organic waste as biomass sources for alternative feed. The frequent appearance of terms such as "protein," "fermentation," and "digestibility" highlights the emphasis on the nutritional evaluation and processing methods of waste materials to enhance their suitability as fish feed. The interconnected nature of keywords like "recycling," "bioremediation," and "circular economy" further underscores the multidisciplinary approach taken by researchers, aiming to develop environmentally friendly and economically viable solutions for waste utilisation in aquaculture feed production.
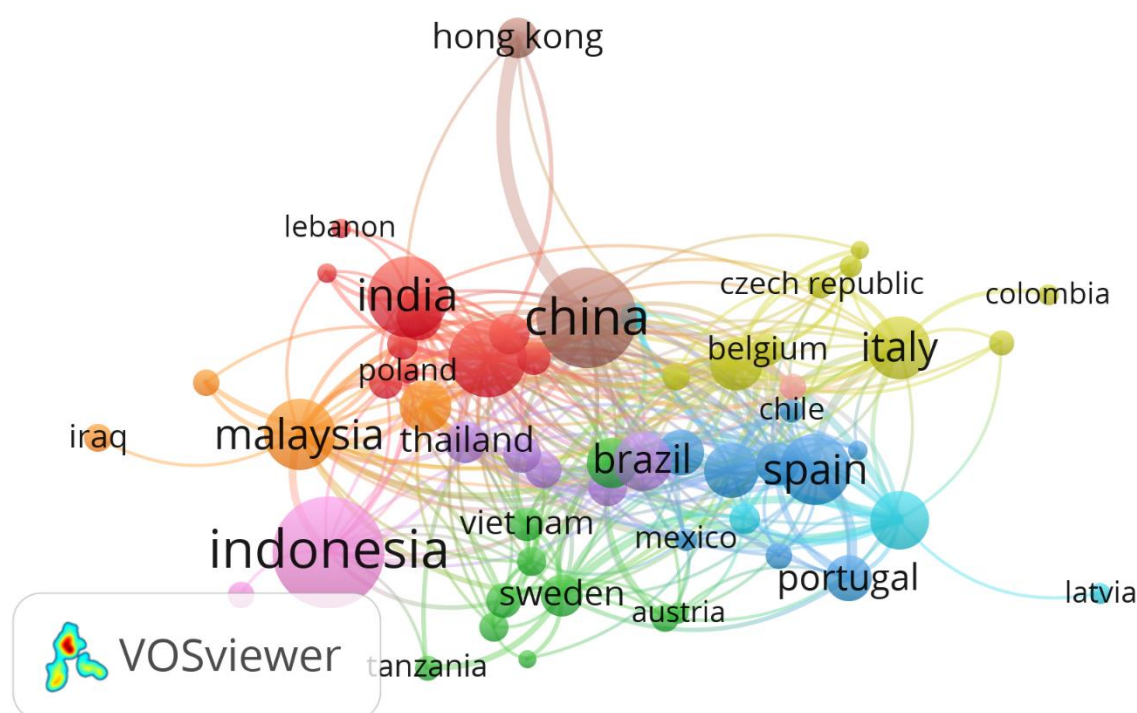
What Are Co-Authorship Countries' Collaboration?

Figure 4: The Countries Whose Authors Collaborate on Applying Waste Products to Fish Feed

The provided data from VOSviewer highlights global contributions to the research on utilising waste products as alternatives for fish feed, detailing the number of documents, citations, and total link strength for each country. Remarkably, China leads the research field with 149 documents, accumulating a significant 3,523 citations and demonstrating a strong collaborative network with a total link strength of 96. This dominant contribution reflects China's active engagement in aquaculture research and the exploration of sustainable feed practices, likely

driven by the country's large aquaculture industry and emphasis on food security. Other leading contributors include Indonesia, which has 183 documents, making it the second most prolific country, though it has fewer citations (790) compared to China. This discrepancy might indicate a more recent surge in publications or a focus on niche areas that have yet to receive wider recognition. The United States (US) also exhibits a high level of activity with 90 documents and an impressive 1,829 citations, tied for second in link strength (62) with Spain. This high citation count underscores the US's influence in this field, potentially due to robust research programs focused on sustainable aquaculture practices and adopting alternative feed sources.

Several European countries, such as Spain (75 documents, 2,114 citations) and Italy (58 documents, 1,838 citations), have strong representation in both document output and citations, indicating significant interest and impactful research in sustainable feed practices. Notably, countries like Australia, the United Kingdom (UK), and Norway also exhibit high levels of collaboration, with link strengths of 50, 50, and 56, respectively. Accordingly, these countries' active involvement reflects a growing global consensus on the significance of reducing reliance on traditional feed ingredients and exploring innovative, waste-derived alternatives to support sustainable aquaculture development.

Conclusion

Analysis of bibliometric data on waste products as fish feed alternatives reveals several key research trends and significant contributions that shape this field's current understanding and future direction. Research volume has increased over the past decade, peaking between 2021 and 2023. This increase indicates the growing demand for sustainable aquaculture and the need to find alternatives to conventional fishmeal, which is expensive and scarce. Notably, the consistent publication of key authors and researchers in the field of innovative feed ingredients derived from agricultural, industrial, and microbial waste indicates a well-established and growing scientific community. The diverse subject areas and documents published in this research—agriculture, environmental science, biochemistry, and engineering—reveal its interdisciplinary nature. Furthermore, this diversity emphasises a shared effort to address waste valorisation's environmental impacts, nutritional benefits, and processing technologies. Additionally, international collaboration between researchers and institutions emphasises a shared commitment to sustainable aquaculture practices worldwide. The high citation counts of key publications on aquaculture, bioconversion, and insect-based feeds' ecological footprint reduction demonstrate their influence and relevance. Thus, the findings suggest that waste-derived feed alternatives will continue to be studied due to a strong research network and increased awareness of aquaculture sustainability issues.

The bibliometric analysis indicates that resource efficiency and sustainability drive the use of waste products as aquaculture feed. VOSviewer's keyword analysis suggests that "animal feed," "waste management," "aquaculture," and "sustainability" are the most frequently cited and interconnected terms. Hence, the study of agricultural residues and biomass as fish feed ingredients should be prioritised. Meanwhile, the use of terms like "protein," "fermentation," and "digestibility" emphasises the need to evaluate waste materials' nutritional properties and processing methods to utilise them as feed alternatives. Moreover, the interconnected nature of these terms reflects researchers' multidisciplinary approach to developing circular economy models and environmentally sustainable aquaculture practices. With China's leading document output and citation count, the co-authorship analysis suggests significant international

collaboration. This emphasises sustainable aquaculture research. Indonesia and the US also contribute heavily to this field due to their high citation counts and research activity. Notably, Spain, Italy, and Norway have strong research outputs and collaboration, indicating a growing interest in sustainable feed practices in Europe. Active research networks in the UK and Australia support the global push for innovative feed solutions. This collective effort addresses fishmeal dependency and promotes waste-derived alternatives for a more sustainable aquaculture industry.

Acknowledgements

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