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An Exploration of Heavy Metals Research in Commonly Consumed Fish Species Across the Globe

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Abstract

Heavy metal contamination in fish species has become a major environmental and public health concern due to its potential effects on aquatic ecosystems and human consumers. This study presents a comprehensive bibliometric analysis of global research on heavy metals in selected fish species from 1947 to 2026. Data retrieved from the Scopus database yielded 9,317 documents published across 1,047 sources, with an annual growth rate of 7.47%. Original research articles dominated the literature (95.62%), highlighting the field's strong emphasis on primary data generation. Publication trends revealed two distinct phases: a period of limited growth (1947–1982) followed by rapid expansion from 1983 onwards, reflecting increased awareness of environmental pollution, food safety concerns, and advancements in analytical technologies. China emerged as the leading contributor, followed by Egypt, Brazil, the United States, and Thailand, while Chinese institutions and authors dominated productivity rankings. Keyword and thematic analyses demonstrated an evolution from early studies focused on fish physiology and histology to contemporary investigations emphasizing molecular biology, oxidative stress, gene expression, bioaccumulation, and environmental monitoring. Collaboration networks revealed extensive international partnerships spanning Asia, Europe, Africa, and the Americas. The synthesis of systematic reviews highlighted major concerns related to heavy metal accumulation, food safety risks, fish health, environmental contamination, and sustainable aquaculture practices. Overall, the field has evolved into a highly interdisciplinary research domain integrating toxicology, environmental science, molecular biology, and aquaculture, with increasing relevance for public health and ecosystem sustainability.

Keywords: Commercial fish; heavy metals; toxicity; human; ecosystem; cancer

Introduction

One of the major public and environmental concerns of the 21st century is the heavy metal contamination of aquatic ecosystems (Mishra et al., 2018, Singh et al., 2023). These concerns stem from the toxic, persistent and non-biodegradable nature of heavy metals (Jadaa and Mohammed, 2023). The release of heavy metals into the environment is largely driven by anthropogenic activities, including rapid industrialization, mining, petroleum exploration, and improper waste disposal (Jayakumar et al., 2021). Collectively, these activities have lead to the amplification of heavy metals, including lead (Pb), arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), nickel (Ni), zinc (Zn), and silver (Ag) in freshwater systems around the world (Edet et al., 2023; Jayakumar et al., 2021. Mishra et al., 2018). Unlike many pollutants that can be biodegraded over time, heavy metals have the outstanding ability too persist in the environment, including sediments and water column which now serve to seed aquatic food webs, where these metals eventually bioaccumulate and get biomagnified (Saidon et al., 2024; Wang et al.,, 2023). Fish species, including *Clarias gariepinu*s, *Heterobranchus*, and *Tilapia zillii* are widely cultivated in developing countries like Nigeria, due to their rapid growth, adaptability to varying environmental conditions, and commercial value in aquaculture industries (bin Mohd Khatib and Jais, 2021; Srikulnath et al., 2025). Given the public health importance of heavy metals in fish species and eventual consumption in humans, several studies exist that have examined various aspects of the heavy metal contamination in fish species.

Several bibliometric studies pertaining to the heavy metals and metalloids among aquatic seafood exists. Guo et al. (2025) examined heavy metalloid accumulation in aquatic organisms. In their study, they utilized Scopus and web of Sciences in the retrieval of studies. Their findings indicates that a rapid increase in studies from 2005, while fish dominated and sediment dominated the study subjects and reservoir of heavy metals in their study. In another study, Basmaci et al. (2023) conducted a bibliometric study aimed at the mapping of research trends, track research hot spots and determine future research directions. One of the strong findings from the study was an increased emphasis on risk assessment strategies in recent years. Ungureanu et al. (2023) examined health risks associated with heavy metals in food. Their findings noted that the retrieved articles focused mainly only certain foods, including fish, seafood, cereals, dairy, meat, and fruit/vegetables. On the other hand, Lopez-Celi et al. (2025) focused on heavy metal contamination on crabs, and revealed a growing interest in the field due to the public health implication of the heavy metals in food.

Irfan et al. (2023) in their study focused on heavy metal cadmium in freshwater and found that fish and vegetables posed the greater biological risk for humans as they accumulated cadmium the most. From these studies, none have focused on examination all the heavy metals in commonly consumed fish species around the world. At the moment, various gaps needs to be filled as none of the focused on commonly consumed fish species, including *Clarias gariepinus, Tilapia zillii and or Heterobranchus.* (1) What is the global trajectory of heavy metal research on fish ? (2) What is the rate of synthesis of primary studies to

secondary studies (3) Who are the prolific authors and affiliations ? (4) What outlets dominate the dissemination of evidence (5) What gaps exist in the current knowledge of heavy metals in fish and future prospects can be explored ?

Thus, the present bibliometric study seeks to critically evaluate the global scientific literature on heavy metal contamination in *Clarias gariepinus, Tilapia zillii and or Heterobranchus*, with emphasis on lead, arsenic, zinc, cadmium, chromium, mercury, silver, copper, and nickel. Our study aims to specifically examines publication growth trends, leading authors, influential journals, institutional productivity, international collaboration patterns, and dominant thematic clusters within the field. By focusing on species such as *Clarias gariepinus, Heterobranchus, a*nd *Tilapia zillii*, and the selected heavy metals, this study interrogates whether current research trajectories adequately address the realities of contamination in highly vulnerable regions where fish consumption remains essential for nutrition and economic survival. It further evaluates whether scientific outputs have translated into effective environmental policies, monitoring frameworks, and public health interventions, or whether the field remains largely descriptive and reactive. Ultimately, this work will contribute to a deeper understanding of how knowledge on heavy metal contamination in economically important freshwater fish species has evolved and how future research can better support evidence-based environmental management, aquaculture regulation, and sustainable public health protection in polluted aquatic ecosystems.

Methods

Study deisgn

The design for this study is a bibliometric study design. Bibliometric study is a type of that provides qualitative and quantitative insight into a field of study by mapping studies to reveal trajectory, gaps, prolific authors, and affiliations, preferred dissemination outlets, and collaborations.

Choice and screening of databases

For this study, Scopus and PubMed were searched. Our choice of PubMed was predicated on the fact that it is a dedicated database that indexes medical and related health studies globally. In contrast, Scopus as a database indexes studies covering all areas, including life, physical and social sciences from over 5000 publishers (Pranckutė, 2021).Our initial search was performed using both databases by applying the same set of search string. Scopus yielded a total of 4991 recorded, while PubMed yielded 9317 recorded. Given the huge difference, we decided to utilize PubMed alone as previous studies have shown a high degree of overlap between studies indexed in both PubMed and Scopus (Sember et al., 2010).

Retrieval of studies from PubMed and screening of study types

The PubMed was searched on May 23rd 2026. In performing the search, the following query was applied: “Heavy metal” OR “lead” OR “arsenic” OR “zinc” OR “cadmium” OR

"chromium" OR "mercury" OR "silver" OR "Copper" OR "Nickel" AND "Catfish" OR "*Clarias gariepinus"* OR "Tilapia" OR "*Tilapia zillii"* OR "Heterobranchus". The search year was set to cover 1947 to 2026, a period of approximately 80 years. Only documents in English were included with preprints also excluded. No restriction on document types were set. Using the advance search filters, document types were obtained and this also manually confirmed by two group of authors working differently to validate the automatic filtering of study types. In performing the screening, article mentioning heavy metals in the abstract, title and where applicable body of the study were retained for further analysis. The PubMed files were then retrieved for bibliometric and statistical analysis.

Bibliometric and statistical analyses of the data

Bibliometric analysis was performed as previously reported (Edet et al., 2026a; Ali et al., 2026). The analyses were performed using diverse tools, including VOSviewer (version 1.6.15) for Windows (Van Eckand and & Waltman, 2010), Biblioshiny (Aria and Cuccurullo, 2017), R version 4.5.2-(Team R Studio, 2021) and Datawrapper (https://www.datawrapper.de/) (Datawrapper, 2025) were used. Trajectory of studies were examined using an trend line plot with fitted polynomial equation and correlation coefficient in RStudio, to examine the relationship between the top ten authors, their keywords and outlets, the Sankey diagram was plotted in Biblioshiny in R Studio. Affiliation of authors, and outlets analysis using Bradford Law were done in Biblioshiny, while various aspects of keyword analyses were done using all the tools. Collaboration map was done in Biblioshiny tool.

Results

Summary of the search performed, study types and trajectory

The summary of the search conducted is presented in Figure 1. The results indicate that the time span (1947 to 2026), sources (1047) and a total of 9317 documents. Annual growth rate stood at 7.47%. The total number of authors was 24506, while the number of authors with single-authored document and percentage of international co-authored documents were 205 and 19.23%. The total number of author's keywords were 18223, while document age was 11.5 years.



Figure 1: Summary of the performed search

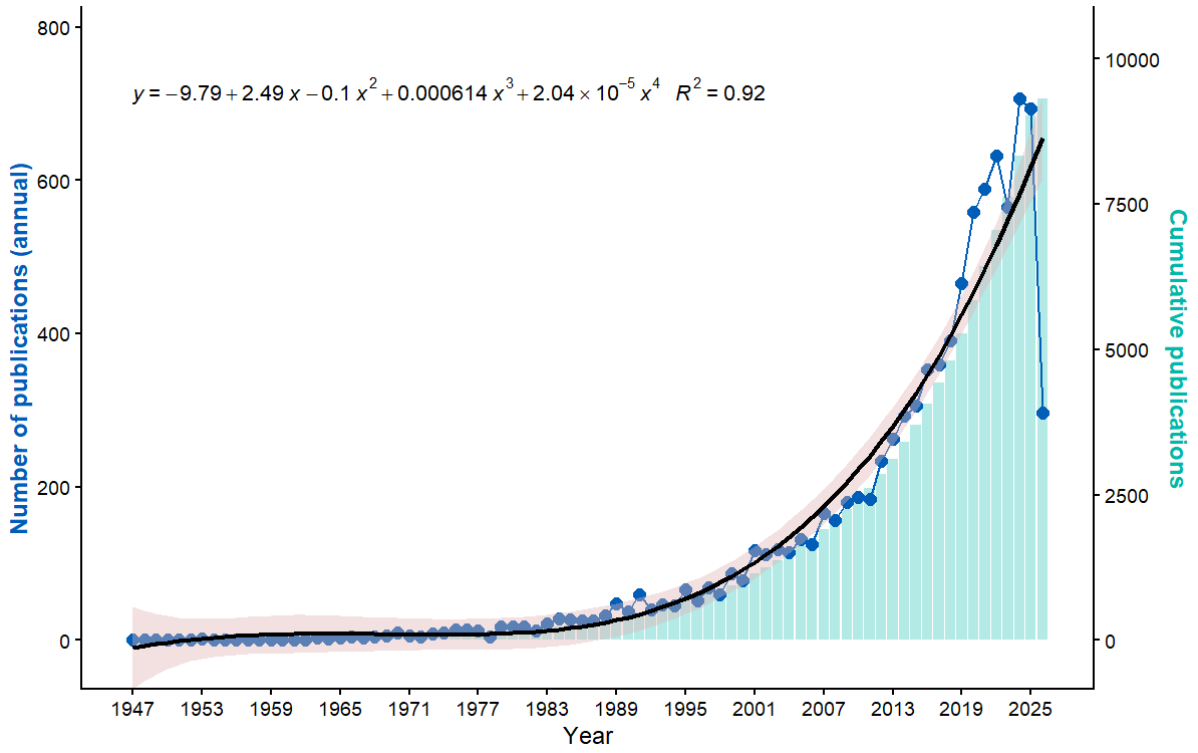

Figure 2: Annual and cumulative publication trends in heavy metals in selected fish species spanning 1947 to 2026. The blue connecting the blue dots indicate the trajectory of the publications, while turquoise bars represent cumulative publications. The fitted polynomial trend line returned a strong correlation indicating a strong model with a value of $R^2 = 0.92$.

The trajectory of the publication on heavy metals in the selected fish species is capture in Figure 2. The results trajectory indicate two distinct phases of growth. The period of little or stagnant growth which spanned 1947 to 1982 where output ranged from 1 to 17. The second distinct phase of growth spans 1983 to 2026, with volume of studies that ranged from 22 to 707, for 1983 and 2024, respectively. Despite the increase in the volume of publications observed, there was a drop in the volume of studies in 2025 with studies dropping to 693 in 2025.

Table 2 provides a breakdown of the different study types. The most dominant study type was of original research articles, which accounted for 8,909 publications (95.62%). This was followed by reviews with 218 publications (2.18%), while systematic reviews with or without meta-analysis were 23 (0.23%). Randomized controlled trials accounted for 123 publications (1.23%), and letters, editorials, and correspondence articles comprised 44 publications (0.44%).

Table 2: A summary of study types on heavy metals and diverse fish species

Types of study	Number of documents (%)
Original articles	8909 (95.62)

Reviews	218 (2.18)
Systematic reviews with or without meta-analysis	23 (0.23)
Randomized control trial	123(1.23)
Letter, editorial, correspondences	44(0.44)

Authors' and affiliation analyses

Various aspects of the authors analysis are presented in Figure 3 and Table 2

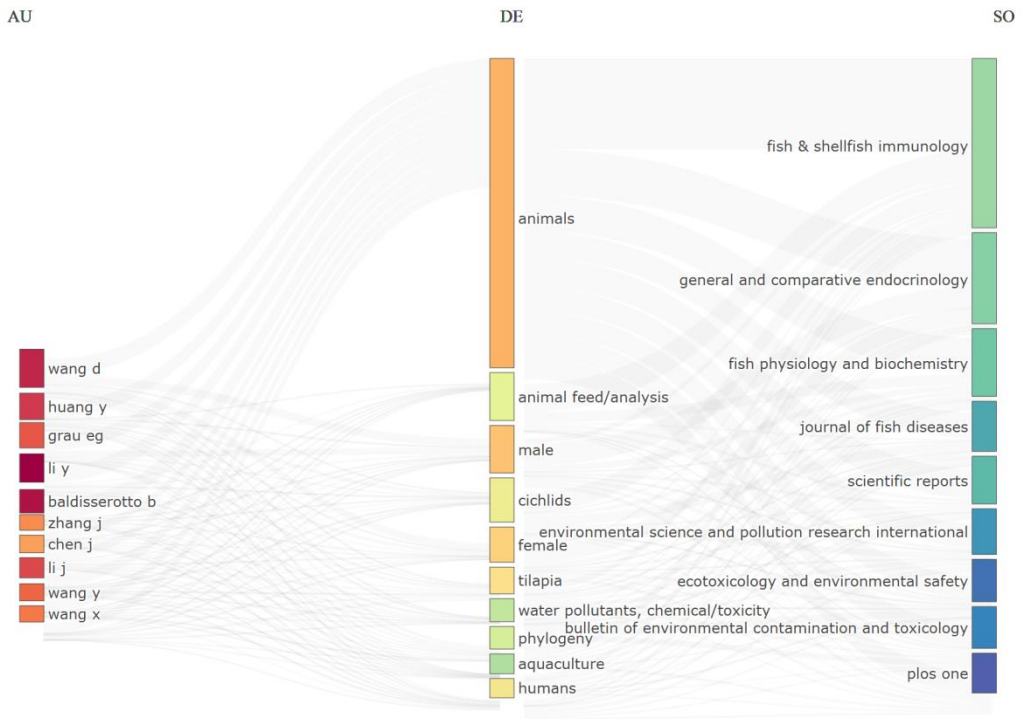

Figure 3: A three-field plot (Sankey diagram) showing the relationships among the top ten authors (AU) (left panel), author keywords/index terms (DE) (middle), and journals/sources (SO) (right). The light dark lines indicate relationships, while their thickness show strength or frequency of the relationships.

A summary of the number of articles and fractionalised articles is presented in Table 3 for the 20 authors. Between them top authors, the total number of articles they published stood at 1743, representing 18.71% of the total studies, while the number of studies ranged from 68 to 127. The top five most prolific authors were Li Y, Baldisserotto B, Wang D, Huang Y and Li

J, with 127, 125, 121, 111 and 104 studies, respectively. The etymology of the authors' names indicates that majority were of Chinese origin.

Table 3: Number of articles and fractionalised articles by the top 15 authors

Authors	Articles	Articles fractionalized
Li Y	127	16.77
Baldisserotto B	125	16.14
Wang D	121	16.49
Huang Y	111	14.76
Li J	104	14.87
Grau Eg	103	20.88
Wang Y	91	12.43
Wang X	89	13.07
Zhang J	79	10.41
Chen J	78	11.68
Hirano T	77	15.83
Liu Y	75	10.17
Liu Z	72	9.59
Wang J	72	10.15
Xu P	72	9.93
Zhang Y	72	10.36
Li M	70	9.87
Zhang X	69	8.97
Dawood Mao	68	11.11
Li C	68	8.65

The top ten authors, terms utilised in their study and preferred outlets are summarized in the three-field plot (Figure 3). The result indicate a dominance of China authors among the top ten authors, with the top two authors, Wang D and Huang Y being the most productive among the authors. The outputs of the top ten authors showed that their studies were mainly tied to animals, and fish species (particularly cichlids and tilapia) among others. Further analysis of the terms used by the various authors indicate that the field is strongly focused on the keyword "animals", as it had the highest band and also served as a link to the authors and outlets. Other equally important used terms included animal feed/analysis, male, female, cichlids, tilapia, aquaculture, water pollutants/chemical toxicity, and humans, indicating that the research of the top authors focuses largely on fish biology, aquaculture, toxicology, and environmental health. Their preferred outlet indicate that the journal, *Fish & Shellfish Immunology* was the leading journal, receiving the largest volume of outputs on associated with the dominant keywords. Other important outlets included *General and Comparative Endocrinology, Fish Physiology and Biochemistry, Journal of Fish Diseases, Scientific Reports, Environmental Science and Pollution Research International, Ecotoxicology and Environmental Safety, Bulletin of Environmental Contamination and Toxicology,* and *PLOS ONE*. Overall, the outlets indicates that the studies cover diverse areas, including fish health, endocrinology, physiology, environmental toxicology, and aquatic ecology.

Table 4: A summary of single country and multiple countries analysis

Country	Articles	Articles %	SCP	MCP	MCP %
China	1870	20.07	1644	226	12.09
Egypt	810	8.69	536	274	33.83
Brazil	662	7.11	555	107	16.16
USA	561	6.02	484	77	13.73
Thailand	363	3.90	226	137	37.74
India	347	3.72	300	47	13.54
Japan	250	2.68	231	19	7.60
Nigeria	242	2.60	184	58	23.97
Malaysia	165	1.77	102	63	38.18
Netherlands	156	1.67	146	10	6.41
South Africa	116	1.25	88	28	24.14
Canada	106	1.14	99	7	6.60
Israel	97	1.04	86	11	11.34
Belgium	92	0.99	65	27	29.35
Bangladesh	89	0.96	62	27	30.34
France	86	0.92	65	21	24.42
Germany	83	0.89	62	21	25.30
Portugal	71	0.76	58	13	18.31
Turkey	66	0.71	54	12	18.18
Spain	61	0.65	47	14	22.95

Key: SCP = MCP = Single country publication; Multiple country publication; % = Percentage

Table 4 provides a summary of the countries of authors with single country an multiple countries publications. The result indicates that China led with 1,870 publications, representing 20.07% of the total publications (SCP and MCP). This was followed by Egypt ranked second with 810 publications (8.69%), Brazil third (662; 7.11%), the United States fourth (561; 6.02%), Thailand fifth (363; 3.90%), and India sixth (347; 3.72%) for total publications (SCP and MCP). Other countries Japan, Nigeria, Malaysia, Netherlands South Africa, Canada, Israel, Belgium, Bangladesh, France, Germany, Portugal, Turkey and Spain in decreasing order of total volume of country-based publications. In terms of multiple country publications, Asian country led with China in pole position, while in Africa and Europe, Egypt and Belgium led. The MCP output for Africa and Asia was more than all of European countries.

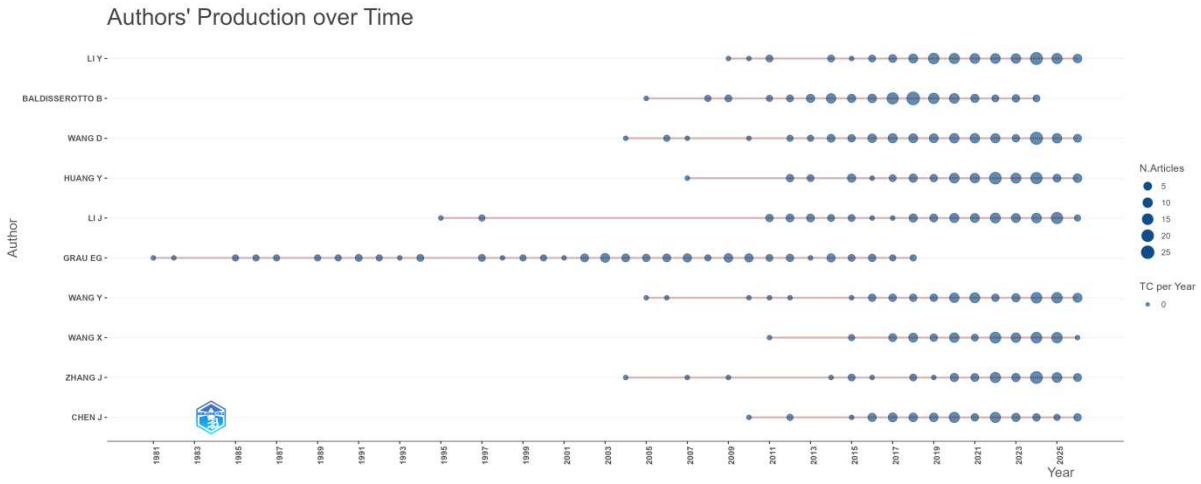

Figure 4: Productivity of the top ten authors over time (1981 to 2026). The legend indicates the number of production for each of the authors.

The productivity of the top ten authors is captured Figure 4. The result indicate that the earliest author Grau EG and was joined by Li J in 1995, 14 years after. The works of Grau EG who pioneer the field spans 1981 to 2018, a period of four decades approximately. Between 2014 and 2025, there has been a massive concentration of production activities. In all, the productivity of authors indicate a shift from a few authors that were pioneer to more authors joining the fray, indicating of growing interest in the field.

Affiliation's production over time

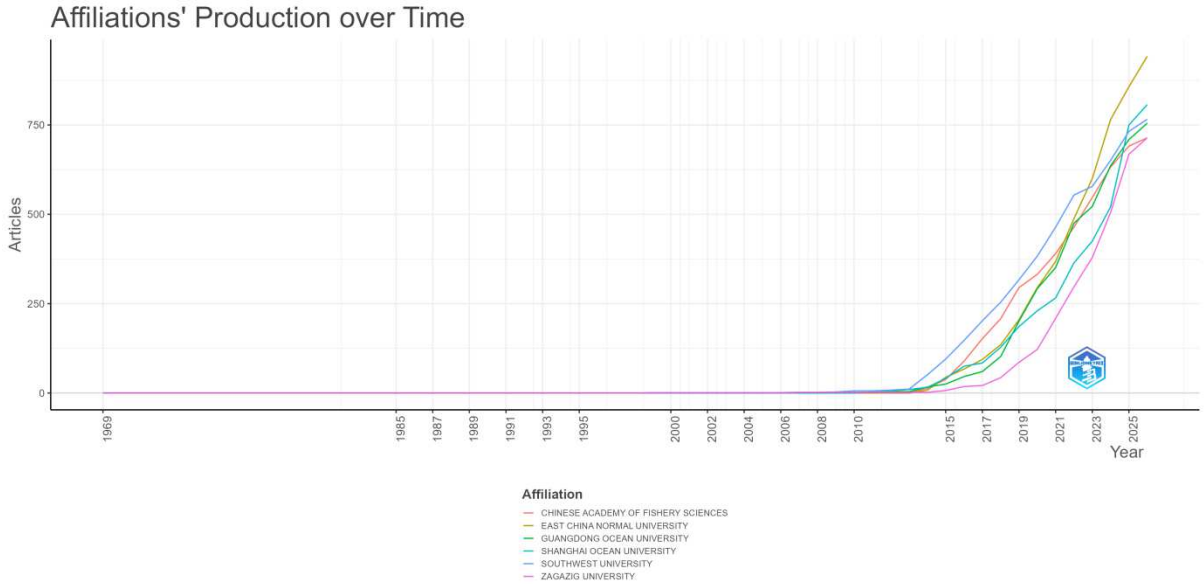

Figure 5: Top six affiliation of authors conducting research on heavy metals in diverse fish species over time (1969 to 2026). Differently coloured trend lines indicate different affiliations.

Figure 5 is a time-series plot of the top six affiliations conducting research on heavy metals in various fish species over time (1969 to 2026). The affiliations were based in China. Between 1969 and 2014, research productivity remained low but from 2015, to 2025 there was an exponential increase in the volume of studies. The affiliation, East China Normal University had the highest volume pf studies, while Zagazig University had the least.

Table 6 is a summary of the most productive affiliations (top twenty) and the number of articles. The top twenty affiliations are as shown in the table and the results indicates a clear dominance of China-based affiliations. Among the top ten affiliation, China affiliation accounted for nine of them with articles between them ranging from 518 to 942. Among the affiliations in the second half of the table, China-based affiliations also prominently featured with Huazhong Agricultural University, Pearl River Fisheries Research Institute and Nanjing Agricultural University. Three of the bottom half affiliations were from Egypt. Also, among them bottom half were affiliations from Thailand was Malaysia and Brazil. Agricultural and Fisheries related affiliations comprised three out of the top twenty. The number of articles within the bottom twenty affiliations ranged from 274 to 483.

Table 6: Most productive affiliations and the number of articles

Affiliation	Articles
East China Normal University	942
Shanghai Ocean University	807
Southwest University	766
Guangdong Ocean University	755
Chinese Academy Of Fishery Sciences	714
Zagazig University	714
Kasetsart University	674
South China Normal University	559
Sun Yat-Sen University	538
Hainan University	518
Universidade Federal De Santa Maria	483
Kafrelsheikh University	470
Pearl River Fisheries Research Institute	431
Nanjing Agricultural University	412
Universiti Putra Malaysia	362
Cairo University	319
Huazhong Agricultural University	289
Assiut University	287
Chiang Mai University	274
Chulalongkorn University	274

Table 7: Top dissemination outlets for studies on heavy metals and diverse fish species

Sources	Articles	IF
Fish & Shellfish Immunology	612	3.9
General and Comparative Endocrinology	311	1.7
Fish Physiology and Biochemistry	296	2.5
Scientific Reports	212	3.9
Journal of Fish Diseases	195	2.2
Environmental Science and Pollution Research International	166	-
Bulletin of Environmental Contamination and Toxicology	158	2.2
Ecotoxicology and Environmental Safety	156	6.1
PLOS One	151	-
Animals: An Open Access Journal from MDPI	143	2.7
Comparative Biochemistry and Physiology. Toxicology & Pharmacology : CBP	118	4.3
Chemosphere	116	-
Food Chemistry	114	9.8
Aquatic Toxicology (Amsterdam, Netherlands)	108	4.3
The Science of the Total Environment	108	-

Comparative Biochemistry and Physiology. Part B, Biochemistry & Molecular Biology	81	1.8
Journal of Fish Biology	80	2.0
BMC Veterinary Research	79	2.6
The Journal of Experimental Biology	79	2.4
Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology	77	2.2

Table 7 is a summary of the top twenty journal destinations. A total of 3360 articles were published within the top twenty outlets, comprising 36.06% of the total publications and ranged from 77 to 612 studies. Analysis of the various journals indicate the presence of outlets with various specialties, including Animal, Fishery/Fish/Shellfish, Veterinary, and multidisciplinary journals such as PLOS One, Scientific Reports. Also prominent among the top twenty journals were pollution and environmental-based journals such as *Environmental Science and Pollution Research International, Bulletin of Environmental Contamination and Toxicology, Ecotoxicology and Environmental Safety, The Science of the Total Environment and Aquatic Toxicology* (*Amsterdam, Netherlands*). The top five outlets were *Fish & Shellfish Immunology, General and Comparative Endocrinology, Fish Physiology and Biochemistry, Scientific Reports and Journal of Fish Disease*s had 612, 311, 296, 212 and 195 publications, respectively. All the outlet had impact factors, except for The Science of the Total Environment, Chemosphere and PLOS One. Bradford analysis of the core sources (indicated in grey colour) (Figure 6) indicates that the top twenty sources of journal formed the core sources.

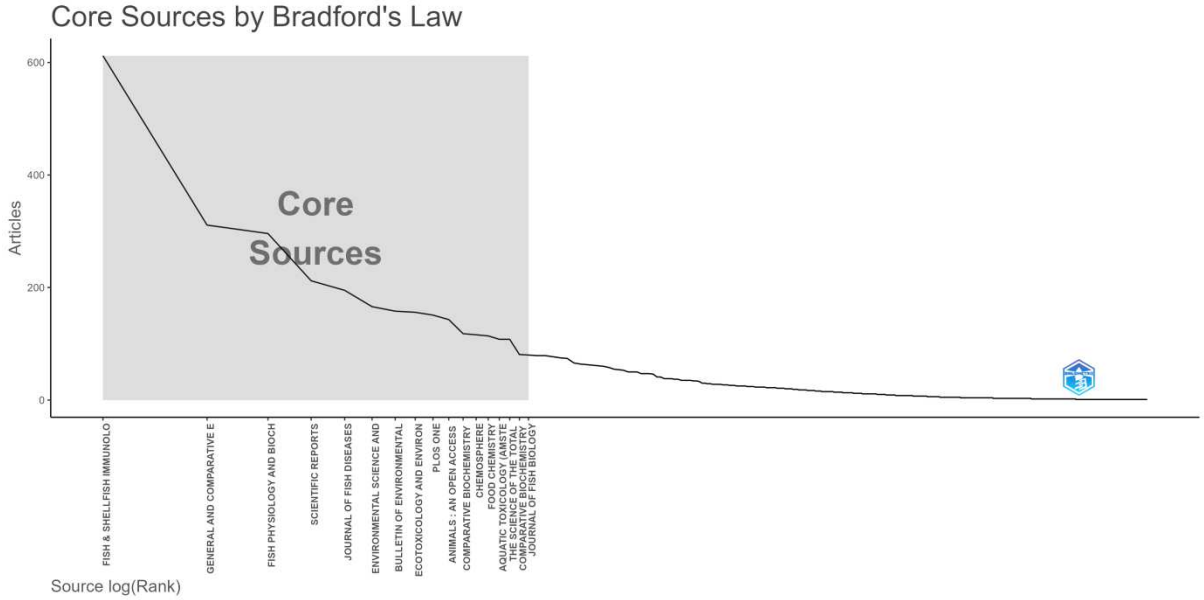

Figure 6: Bradford Law analysis of core sources of outlets.

Keyword analyses

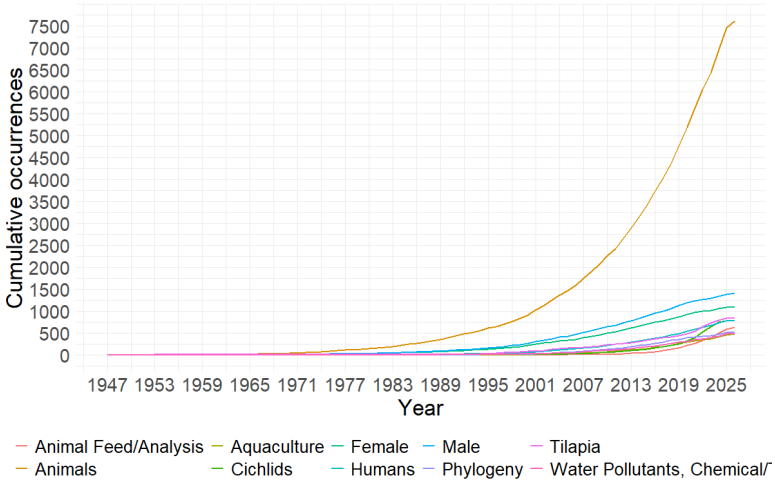

Figure 7A: A graphical representation of the cumulative occurrence of terms' frequency utilized in heavy metals research in various fish species over time (1947 to 2025). Each trend lines represent different keyword.

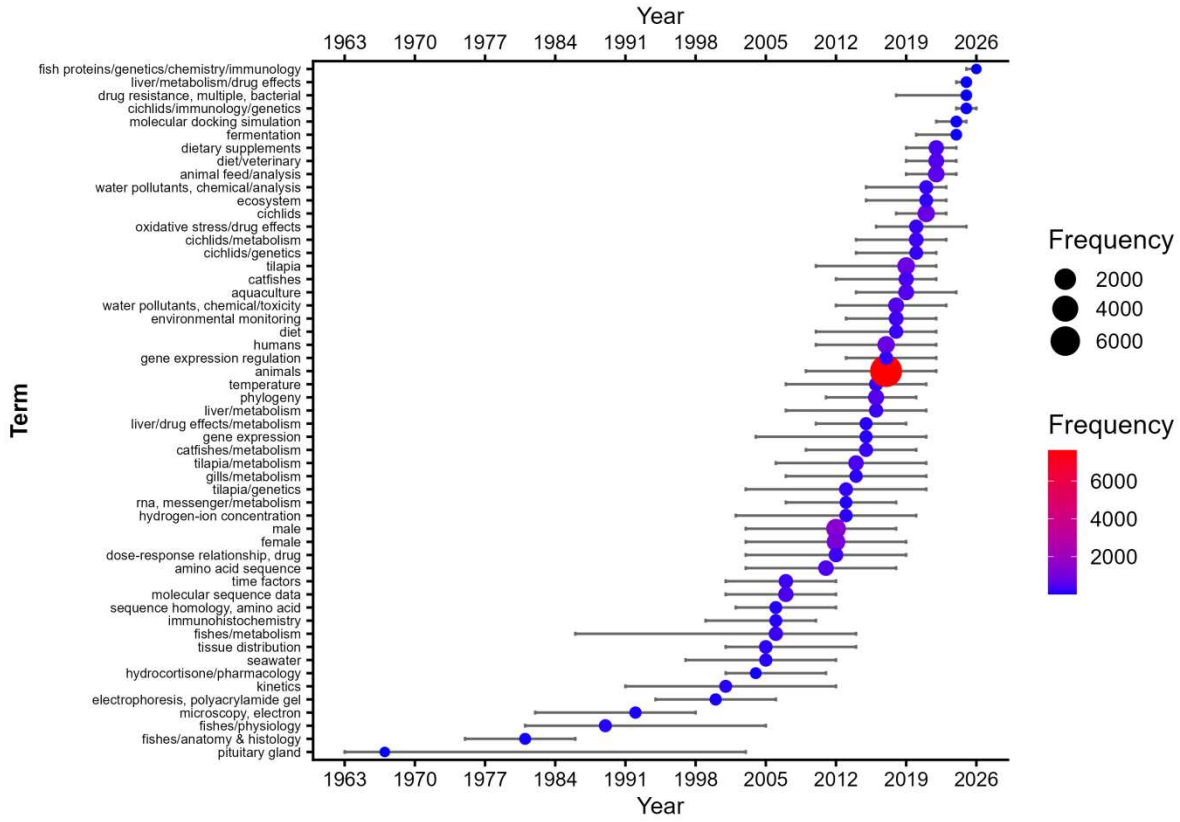

Figure 7B: A graphical representation of the trending topics in heavy metal research in selected fish species over time (1963 to 2026). The colour legend indicate the frequency of the terms, while the black spherical legend indicates the frequency of the terms.

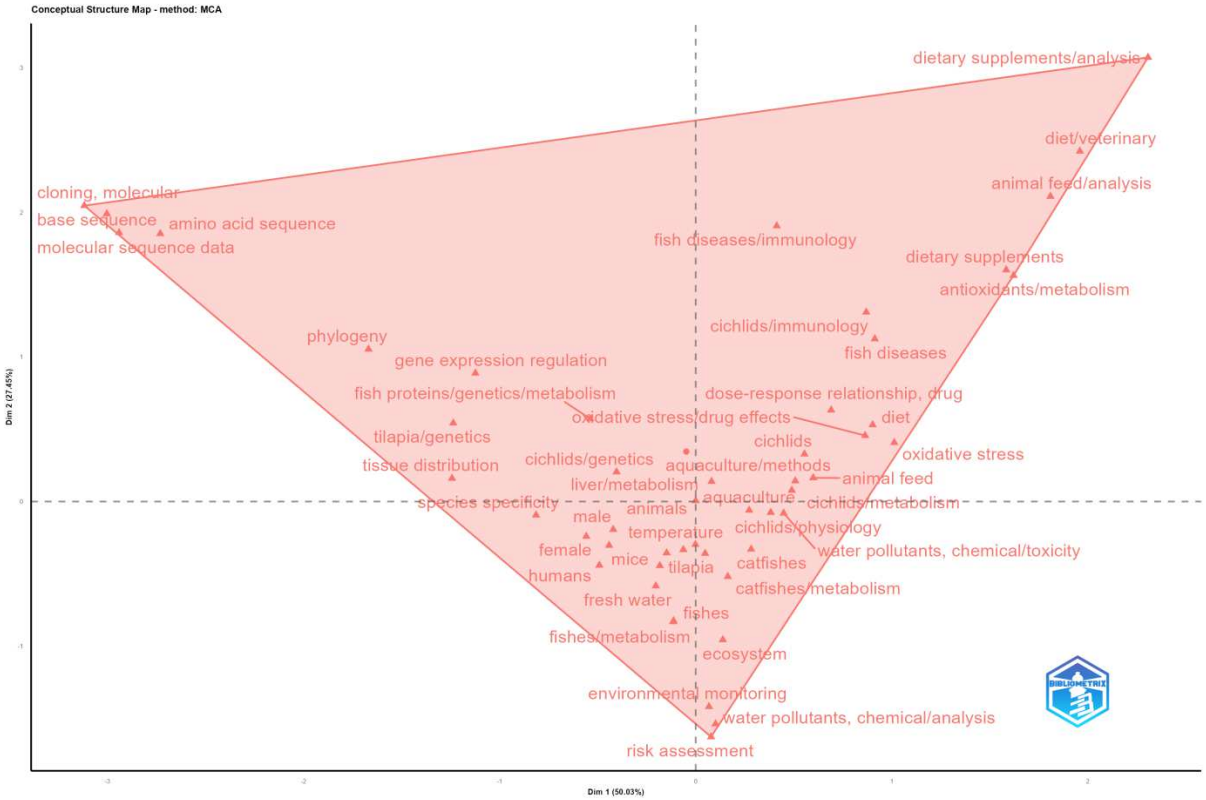

Figure 7C: A factorial analysis of the various terms used in heavy metal research in the selected fish species. The plot captures two dimensions (D1 = 50.03% and D2 - 27.45%), and these comprise of over 77.48% of the total variance. The plot divides the terms into 4 quadrants (two at the bottom and two at the top).

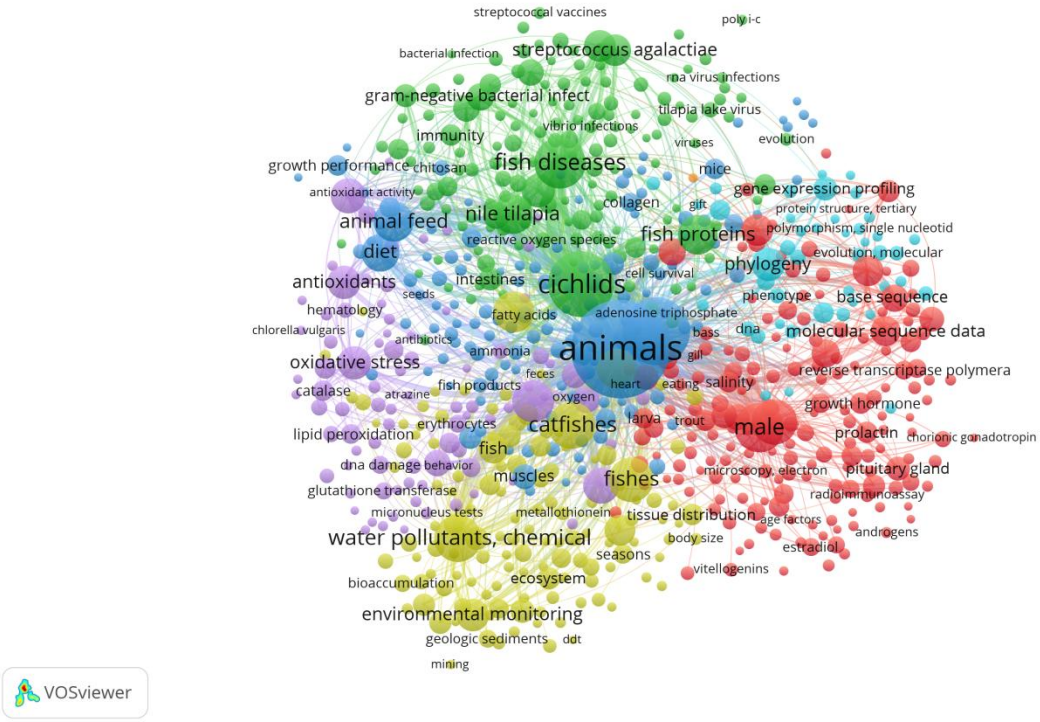

Figure 7D: A co-occurrence visualization of authors involved in heavy metals and selected fish species research. In achieving the plot, a threshold minimum of 20 keywords was used for network visualization using VOSviewer. The circular bubbles indicates influence or size of term in terms of usage.



Figure 7E: Top three keywords according to frequency of usage using a treemap. The different terms are indicated by sizes of the tiles and colours with the terms and its abundance embedded in each of the tile.

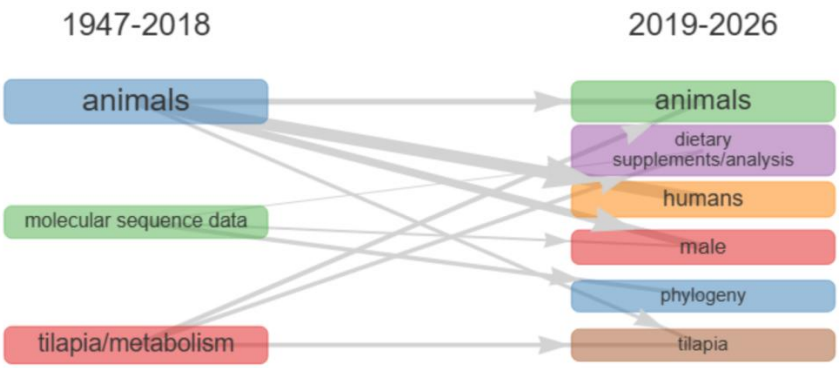

Figure 7F: Thematic evolution of terms used heavy metal in diverse fish species showing terms (left) and their evolution over time (right).

Figure 7A is a cumulative plot of the occurrence of the top ten terms used between 1947 to 2025. Cumulatively, the most used term animal, followed by male and female. Other terms were phylogeny, humans and tilapia. Trending terms from 1963 to 2026 used in heavy metals in selected fish species studies in this study is captured in Figure 7B. Older trending terms included microscopy, electrophoresis, polyacrylamide gel, kinetics, fishes/physiology, fishes/anatomy and histology, and pituitary gland. Figure 7C is a factorial analysis of terms. At the bottom, the terms include risk assessment, environmental monitoring water pollutant, chemical toxicity, fishes/metabolism, and terms associated with different fish species and models, including fishes, tilapia, cichlids, male, female, animals, mice, and humans to mention a few. Collectively, these terms indicate the focus or thematic focus was on the understanding of the chemical toxicity of heavy metals from various fish species (male and female) and environmental monitoring for these heavy metal pollutants. In the top half of the plot, on the right hand side, the terms tied to molecular biology, including cloning, base sequence, amino acid sequence, molecular sequence, phylogeny, gene expression regulation, and oxidative stress. Collectively, these indicate the focus of the studies aimed at understand the interactions of these pollutants at a molecular level. On the flip side of the top half, the terms encompassed drug, dose-response, immunology, dietary supplements, animal feed, and antioxidants, collectively indicating the focus of these terms were to understand the possible involvement of feeds and diets of the fish as a potential route for heavy metal contamination and immunology following exposure to various diets and its components.

Figure 7D is a co-occurrence visualization of authors involved in heavy metals and selected fish species research. The plot revealed various cluster displayed in various colours (blue, green, red, purple, and yellow). In the green cluster, the most influential term was fish diseases and terms associated with it, including bacteria infection, virus infection, *Streptococcus agalaactiae*, viruses, *Vibrio* infection, Gram-negative bacteria, among others. Analysis of the yellow cluster, showed a clear dominance of terms linked to pollution and environmental monitoring, including geologic sediments, ecosystem, seasons, bioaccumulation, mining, and tissue distribution. In the red cluster, the most used term was male, hormones related terms (prolactin, groeth hormones, androgens, chorionic gonadotropin, and estradiol), diagnostic terms (microscopy, electron microscopy, base sequence, reverse transcriptase polymerase chain reaction). In the purple cluster, oxidative stress and antioxidants dominated the cluster, and clustering terms included DNA damage, glutathione transferase, catalase, lipid peroxidation and hematology. Figure 7E is a treemap of the top 30 most used terms in heavy metal research in selected fish species across the globe. The most used term was animals with 7628 mentions, representing 36%, and this was followed by males, females and tilapia with 7, 5, and 4 %, respectively. Over the last seven decades, there has been an evolution of terms as indicated by the thematic evolution plot 1947-2018 to 2019-2026. The term animal evolved into diverse term, including animals, humans, male and tilapia. Molecular sequence data evolved into phylogeny, male and dietary supplements/analysis, while the term tilapia/metabolism evolved into dietary supplements/analysis, tilapia and animals.

Table 8: Country scientific production

Region	Frequency
China	14366
Brazil	4916
Egypt	4374
Thailand	2239
USA	2076
India	1722
Malaysia	1074
Nigeria	1058
Saudi Arabia	716
Japan	689
Mexico	584
Bangladesh	580
Israel	496
South Africa	443
France	419
Indonesia	381
Spain	370
Germany	369

Norway	361
Portugal	328
Belgium	319
Pakistan	319
Netherlands	311
South Korea	306
Italy	280
Ghana	269
Canada	252
Singapore	234
Iran	229
Australia	208

Table 8 shows the diverse countries and their respective productions over time. Among the top ten countries were China, Brazil, Egypt, Thailand, USA, India, Malaysia, Nigeria, Saudi Arabia and Japan with 14366, 4916, 4374, 2239, 2076, 1722, 1074, 1058, 716, and 689, respectively. Continent by continent analysis indicates that Africa had four countries, Nigeria Egypt, South Africa and Ghana, while Europe had France, Spain, Germany, Norway, Portugal, Belgium, Netherlands, Italy, and Australia. Those from Asia were Iran, South Korea, Pakistan, Singapore, Saudi Arabia, India, Thailand, Bangladesh and Malaysia. Those from America and South America included USA, Mexico, and Canada.

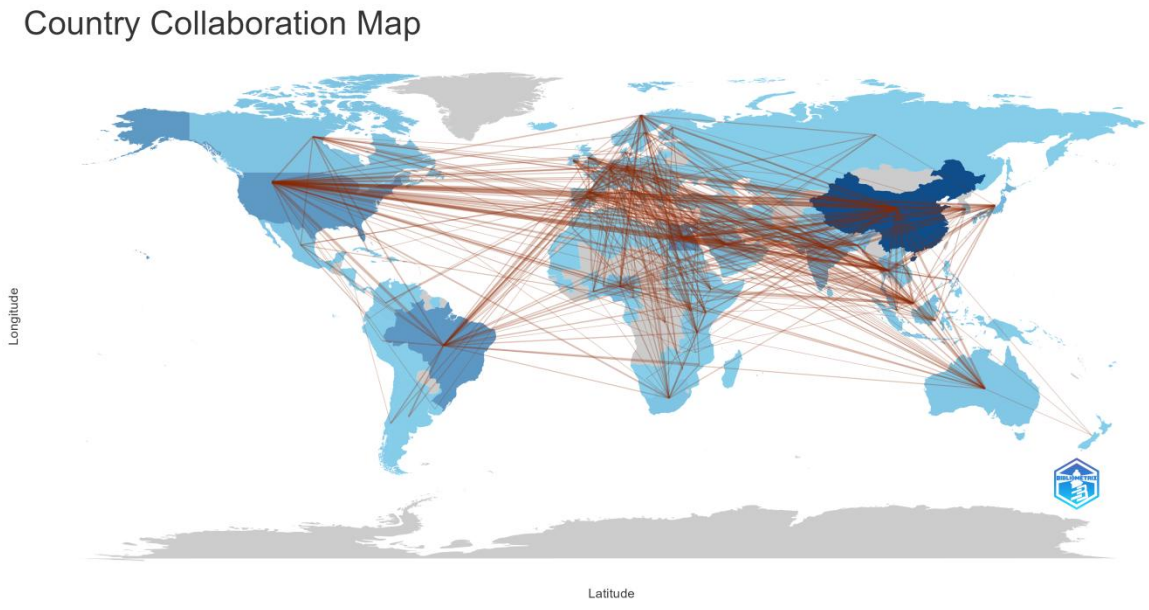

Figure 8: Country collaboration map showing collaborative research links across the globe. The red lines indicates the collaborations, while the different shades of blue indicates the intensities of individual volume of studies.

The collaborative map of the countries involved in heavy metals studies across the globe (Figure 8). The collaborations between the various countries demonstrates a highly interconnected global research network characterized by extensive international cooperation. China, Brazil and Egypt as indicated by the highest shades of blue indicates both high research productivity and strong international engagement. In addition, the United States and several European countries as indicated by the strong links across the globe also served as strong collaborative hubs. Overall, the dense collaborative pathways between Asia, Europe, North and South America and Africa highlight the global nature of research activities in the field.

Discussion

Our study aimed to provide a comprehensive bibliometric assessment of the research landscape of heavy metals in *Clarias gariepinus, Tilapia zillii and or Heterobranchus.*

Overview of the research landscape

The research landscape on heavy metals in selected fish species returned a total of 9,317 documents published between the seven decades examined in this study were distributed across 1,047 sources. Guo et al. (2025) examined 15,379 documents in their study of metal(loids) bioaccumulation in aquatic organisms. On other hand, Ungureanu et al. (2023), 573 studies were retrieved. The differences could be attributed to differences in the scope of the study. Overall, the field indicates a consistent level of increased productivity matched with an average growth rate of 7.47%, indicating sustained scientific interest over the seven decades. The number of contributing authors in the field were 24,506, indicating high global interest in the subject. International co-authorship rate and document age indicate expanding transboundary collaborative research and a balanced contribution from both foundational and contemporary studies shaping the field.

Study design characteristics

Evaluate of study types revealed diverse kinds of studies with a clear dominance original research articles. This align with previous bibliometric reports on vaccine uptake (Ezeani et al., 2025), the use of metagenomics as a diagnostics tool (Edet et al., 2026a) and diverse zoonotic pathogens (Edet et al., 2026b, Edet et al., 2026c). The dominance or original studies indicates a strong emphasis by authors in the field to generate empirical data. Reviews and systematic reviews accounted for combined 2.41%. This is sharp contrast to other fields that have reported reviews that comprised at least 10% of the total study volume. This suggest that there is less emphasis on synthesis of existing knowledge into reviews. A recent report on Lassa showed a constant conversion rate of 4:1 (Original articles to review) that have remained constant over four decades. Thus, there is an urgent need to convert existing primary studies into secondary studies, especially systematic reviews. Systematic reviews is the highest form of evidence and when well written can inform policies, guide funder and even future studies (Chien and Khan, 2023). In all, the field is largely driven by primary data generation as evident by the unparalleled number of primary studies compared to other study types. Thus, there is an urgent need for more integrative studies, especially systematic

reviews and meta-analyses, to consolidate existing evidence and guide future research directions.

Temporal evolution and publication trajectory

The temporal evolution and trajectory of publications revealed two distinct phases of growth, a period of low and stagnant output (1947 to 1982) and a phase of rapid and sustained growth (1983 to 2026). In previous bibliometric studies, phases of rapid growth are often time attributed to key event, such as outbreaks as noted for avian influenza virus (Meseko et al., 2025), Lassa fever virus (Edet et al., 2026b) and monkeypox (Edet et al., 2026c). However, in this case, the period of rapid growth could be attributed to increased need for and awareness from the scientific community and stakeholders of the public health risk of heavy metals to fish and consumers (humans) (Maghchiche and Meghchiche, 2024). In addition, the surge observed in the rapid growth phase aligns with increasing global concerns over environmental pollution of heavy metals, advancements in analytical methodologies, and expanding aquaculture and food safety research (Guo et al., 2025; Fajrianshah et al., 2024). The observed strong polynomial fitted equation ($R^2 = 0.92$) confirms a robust upward trajectory and validates the long-term growth trend observed in the field. The decline observed in 2025 in the volume of studies may be attributed to fluctuation in publication rather than decline in interest from the scientific community.

Authors, collaboration, and intellectual structure

A total of 24506 authors were involved in the research landscape, indicating a matured field. This explain the enormous scholarly output observed over time. Analysis of the prolific authors indicates that they were responsible for approximately 19% of the total volume of studies. This aligns with previous bibliometric studies, where the top ten or twenty most productive authors were responsible for approximately 15 to 25% of the total study volumes (Edet et al., 2026a, Edet et al., 2026b; Edet et al., 2026c). Etymologically, Chinese rooted authors dominated the scene, indicating strong interest in the field driven by access to funding, improved laboratory and infrastructure. Similar pattern of dominance by authors from income rich nations have been highlighted in previous studies (Meseko et al., 2025; Edet et al., 2026a). The three-field analysis further demonstrates strong linkages between the prolific authors, thematic keywords, and journals, highlighting a well-integrated intellectual structure. Prominent journal outlets such as *Fish & Shellfish Immunology*, *General and Comparative Endocrinology*, and *Fish Physiology and Biochemistry* emerged as key dissemination platforms, reflecting the interdisciplinary nature of the field, spanning toxicology, endocrinology, and aquatic biology.

Country-level productivity and collaboration patterns

Analysis of countries revealed China, followed by Egypt, Brazil, the USA, Thailand, and India as the top sixth countries. The dominance of income rich and poor countries indicate among the top twenty countries indicates strong interest in the discourse as the impact of heavy metals in aquaculture industry and public health is an issue that know no bound and affect us all. Multiple country publications was dominated by China, indicating strong international collaboration capacity and global leadership in research as indicated by previous report that have constantly shown China in lead research positions (Xing et al., 2023). African contributions were led by Egypt and Nigeria, while European output was distributed across Belgium, France, Germany, and Spain. The leadership shown Nigeria, South Africa,

Ghana indicate strong research commitment from these African countries, probably driven by the widespread cultivation of the selected fish species in these countries. The good ranking of Nigeria could be as a result of historical ties as fish farming started in Nigeria some 40 years ago (Miller et al., 2006) and it is yet to attain its full potential. The prolific Africa countries are among the populated countries across Africa (Abramova, 2022). The collaboration network further demonstrates a densely interconnected global research system, with China, Brazil, and Egypt serving as major hubs. In addition the observed strong intercontinental linkages between Asia, Europe, Africa, and the Americas highlight the global relevance of heavy metal contamination research in fisheries and aquatic ecosystems.

Institutional analysis revealed a strong dominance of Chinese universities and research institutes. East China Normal University (942 articles), Shanghai Ocean University (807), and Southwest University (766) were among the most productive institutions. Overall, Chinese affiliations occupied the majority of top-ranked positions, reflecting national research prioritization in aquaculture and environmental monitoring. Contributions from Egypt, Thailand, Malaysia, and Brazil were also evident, although at comparatively lower levels. Temporal analysis of institutional productivity indicates a sharp increase in output after 2015, suggesting intensified research investment and expansion of academic programs in aquatic toxicology and environmental sciences. This aligns with the submission of Osae et al. (2026) who stressed that heavy metal contamination is a global issue with significant public health risk.

Journal outlet choice by authors

Journal destination analysis revealed a clear dominance of some outlets compared to others. The top twenty outlets published slightly more than one third of the total outputs of studies in the field (36.06%). This is higher than the approximately 15% reported by Edet et al. (2026b) for Lassa among the top twenty outlets. The clear dominance shows preference by authors for these outlets and may have been driven by certain factors that include but are not limited to impact factors, publication models (open access or hybrid), individual factors such as gender, and scope among others (Amirkhanyan et al., 2023). The leading outlets included *Fish & Shellfish Immunology* (612 articles), *General and Comparative Endocrinology* (311), and *Fish Physiology and Biochemistry* (296). On the other hand, Environmental science journals such as *Environmental Science and Pollution Research* and *Ecotoxicology and Environmental Safety* also featured prominently, reflecting the environmental-health interface of the field. Our analysis of Bradford's law confirmed that the top twenty outlets dominated the field, indicating a well-defined publication ecosystem.

Thematic evolution and keyword dynamics

Keyword analysis serves to reveal temporal trending topics, thematic cluster, top keywords and thematic evolution and have been applied in previous bibliometric studies (Guo et al., 2025; Edet et al., 2026a, Edet et al., 2026b). Overall, temporal analysis showed a clear evolution of research themes over time. Studies pre-1980s focused on basic biological and histological concepts such as microscopy, physiology, and anatomy, suggesting emphasis at the time was on identification of the impact of the pollutant on the anatomy of fishes. On the other hand more, recent studies have focused on molecular mechanisms, gene expression, oxidative stress, and phylogenetic, indicating a shift toward at understanding of the impact of heavy metals from a molecular lens. Heavy metal contamination can induce oxidative stress, mitochondria dysfunction and endoplasmic reticulum change, and even changes in gene

expression levels (Koyama et al., 2024, Karri et al., 2018). This aligns with our finding as the terms gene expression, and oxidative stress strongly featured among the top keywords and trending topics, and thematic clusters revealed by factorial analysis. Factorial and co-occurrence analyses revealed four major thematic clusters: (i) fish diseases and pathogens, (ii) environmental pollution and bioaccumulation, (iii) molecular and endocrine regulation, and (iv) oxidative stress and antioxidant responses. These themes reveal that the field has evolved from descriptive toxicology toward a more mechanistic and interdisciplinary research domain, integrating environmental science, molecular biology, and aquaculture health. In addition to the themes, environmental and toxicological terms such as bioaccumulation, pollution, risk assessment, and water contaminants remained central across all periods. Clearly absent was the role of One Health in the heavy metal contamination. More studies using a One Health approach is urgently needed as these metals enter the food chain from the water and feed fed to the fish and and adversely affect human, animal, and environmental health, disrupting the balance required for One Health (Kaur and Pandey, 2026).

Synthesis of the key findings from included systematic reviews

From a total of 23 systematic reviews, their key findings were synthesized to provide insights into the research landscape. Maulu et al. (2021) reported that although considerable progress has been made in controlling streptococcosis in tilapia, no single intervention has proven completely effective. Similarly, Acosta-Pérez et al. (2022) found a notable prevalence of zoonotic parasitic infections in tilapia, with the highest burden occurring in Africa. Paredes-Trujillo and Mendoza-Carranza (2022) identified poor water quality, particularly elevated temperature, low dissolved oxygen, and high ammonia concentrations, as major drivers of pathogen outbreaks. Disease challenges were further highlighted by Fimbres-Acedo et al. (2025), who documented important bacterial, parasitic, fungal, and viral diseases affecting tilapia production systems.

Several studies emphasized the public health and environmental implications associated with tilapia culture and consumption. Jossefa et al. (2024) reported that aquaponic systems may harbour pathogenic bacteria, including Enterobacteriaceae and Shiga toxin-producing *Escherichia coli*, posing potential food safety risks. Environmental contamination was extensively documented by Oza et al. (2024), Dasmahapatra et al. (2024, 2025), and Dobaradaran et al. (2021), who demonstrated that microplastics, nanoplastics, parabens, and cigarette-butt-derived contaminants accumulate in fish tissues and can induce oxidative stress, endocrine disruption, neurotoxicity, impaired growth, and reproductive abnormalities. Likewise, Melake et al. (2023), Laoye et al. (2025), Mwebesa et al. (2025), and de Oliveira Novaes et al. (2025) reported widespread contamination of fish by heavy metals, mercury, and other pollutants, raising concerns regarding food safety, ecosystem health, and human exposure through fish consumption. The synthesized studies also highlights promising innovations for improving tilapia health, productivity, and sustainability. Pezantes-Orellana et al. (2024) demonstrated that essential oils possess antimicrobial, anti-inflammatory, antioxidant, and antiparasitic properties with potential applications in aquaculture. Similarly, Viagem et al. (2024) found that soybean-based diets improved growth performance, while seaweed-based diets may contribute to sustainable production. Biomedical applications were highlighted by Tozetto et al. (2026), Moraes et al. (2024), and Ibrahim et al. (2023), who showed that tilapia skin and skin-derived peptides significantly enhance wound healing and tissue regeneration. In addition, Barahona et al. (2026) emphasized the potential of genomic selection and gene-editing technologies for developing hypoxia-tolerant fish strains.

Collectively, these studies underscore the importance of integrating disease surveillance, environmental monitoring, pollution control, nutritional innovations, and genetic improvement strategies to support sustainable tilapia aquaculture and safeguard public health.

Conclusion

This bibliometric study provides a comprehensive overview of the global research landscape on heavy metal contamination in *Clarias gariepinus*, *Tilapia zillii*, and *Heterobranchus* species over nearly eight decades. The findings reveal a mature and rapidly expanding field characterized by sustained growth in scientific output, extensive international collaboration, and increasing interdisciplinary integration. Research has evolved from early descriptive studies focused on physiology and histopathology to more advanced investigations exploring molecular mechanisms, oxidative stress responses, gene expression, bioaccumulation, and environmental risk assessment. The dominance of original research articles highlights the field's strong emphasis on primary data generation, although the comparatively low number of reviews and meta-analyses indicates a need for greater synthesis of existing evidence.China emerged as the leading contributor in terms of authorship, institutional productivity, and international collaboration, while significant contributions from Egypt, Brazil, the United States, India, and several African countries underscore the global importance of heavy metal contamination in aquatic ecosystems. Thematic analyses identified environmental pollution, bioaccumulation, fish health, endocrine regulation, and oxidative stress as the major research domains. Furthermore, the synthesis of systematic reviews demonstrated that heavy metals, microplastics, nanoplastics, and other contaminants pose substantial risks to fish health, ecosystem integrity, aquaculture sustainability, and human health through food-chain exposure. Overall, the field is expected to continue expanding as concerns over environmental pollution, food safety, and sustainable aquaculture intensify. Future research should prioritize One Health approaches, advanced molecular tools, longitudinal monitoring, and evidence synthesis through systematic reviews and meta-analyses. Such efforts will strengthen understanding of contamination pathways, inform policy decisions, and support the development of effective mitigation strategies to protect aquatic ecosystems and public health.

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Contributions

MEI, UOE, and CM handled the study design; MEI, UOE and MZA collected data; CM and UOE supervised the study; UOE and MZA handled data, software and analyzed the data UOE. MZA and MEI handled manuscript writing. All authors read and approved the final manuscript.

Ethics declarations

Competing interests

The authors declare no competing interests.

Ethical approval and accordance

Not applicable

Consent to participate

Informed consent was obtained from all participants.

Consent to publish

Not applicable.

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