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GLOBAL TRENDS AND RESEARCH GAPS IN PESTICIDE TOXICOLOGY: A SCIENTOMETRIC ANALYSIS USING ZEBRAFISH (DANIO RERIO)

TENDÊNCIAS GLOBAIS E LACUNAS DE PESQUISA EM TOXICOLOGIA DE PESTICIDAS: UMA ANÁLISE CIENTOMÉTRICA USANDO PEIXE-ZEBRA (DANIO RERIO)

TENDENCIAS GLOBALES Y BRECHAS EN LA INVESTIGACIÓN SOBRE TOXICOLOGÍA DE PESTICIDAS: UN ANÁLISIS CIENCIOMÉTRICO CON PEZ CEBRA (DANIO RERIO)

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ABSTRACT

This scientometric review mapped research on pesticide toxicity in zebrafish (Danio rerio), focusing on the most relevant scientific publications in the field. The search was conducted on the Web of Science platform using the keywords “TS (Topic Search) = (“Danio rerio” OR “zebrafish”) AND (“pesticides” OR “herbicides” OR “fungicides”)”. After applying exclusion criteria, 159 articles (2004–2024) were analyzed, revealing a high citation index and growing impact of this research line, especially in the past two years (2021 and 2022). The most active countries include China, the USA, and Brazil, with significant international collaborations, highlighting the global importance of the topic. Co-citation analysis of sources revealed the influence of journals such as Chemosphere and Aquatic Toxicology as essential for advancing research. Furthermore, the results indicate that zebrafish (Danio rerio) has been established as a key model for studying the toxicological effects of pesticides, particularly during early developmental stages, contributing to environmental risk assessment. The study also highlighted interdisciplinarity and the use of classical methodologies, such as the Bradford Protein Assay, in modern contexts. Finally, research trends were observed, emphasizing oxidative stress parameters, cardiotoxicity, and neurotoxicity, as well as gaps related to long-term pesticide exposure and underlying molecular mechanisms.

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Keywords: Environmental. Ecotoxicology. Agriculture. Fish. 2,4-D.

RESUMO
Esta revisão cienciométrica mapeou a pesquisa sobre toxicidade de pesticidas em peixe-zebra (Danio rerio), com foco nas publicações científicas mais relevantes na área. A busca foi realizada na plataforma Web of Science usando as palavras-chave “TS (Topic Search) = (“Danio rerio” OR “zebrafish”) AND (“pesticides” OR “herbicides” OR “fungicides”)”. Após a aplicação dos critérios de exclusão, 159 artigos (2004–2024) foram analisados, revelando um alto índice de citação e crescente impacto desta linha de pesquisa, especialmente nos últimos dois anos (2021 e 2022). Os países mais ativos incluem China, EUA e Brasil, com colaborações internacionais significativas, destacando a importância global do tema. A análise de cocitação das fontes revelou a influência de periódicos como Chemosphere e Aquatic Toxicology como essenciais para o avanço da pesquisa. Além disso, os resultados indicam que o peixe-zebra (Danio rerio) se estabeleceu como um modelo fundamental para o estudo dos efeitos toxicológicos de pesticidas, particularmente durante os estágios iniciais de desenvolvimento, contribuindo para a avaliação de risco ambiental. O estudo também destacou a interdisciplinaridade e o uso de metodologias clássicas, como o Ensaio de Proteínas de Bradford, em contextos modernos. Por fim, foram observadas tendências de pesquisa, enfatizando parâmetros de estresse oxidativo, cardiotoxicidade e neurotoxicidade, bem como lacunas relacionadas à exposição prolongada a pesticidas e aos mecanismos moleculares subjacentes.

Palavras-chave: Ambiental. Ecotoxicologia. Agricultura. Peixes. 2,4-D.

RESUMEN
Esta revisión cienciométrica mapeó la investigación sobre la toxicidad de pesticidas en el pez cebra (Danio rerio), centrándose en las publicaciones científicas más relevantes en el campo. La búsqueda se realizó en la plataforma Web of Science utilizando las palabras clave “TS (Topic Search) = (“Danio rerio” OR “zebrafish”) AND (“pesticides” OR “herbicides” OR “fungicidas”)”. Tras aplicar los criterios de exclusión, se analizaron 159 artículos (2004-2024), lo que reveló un alto índice de citas y un impacto creciente de esta línea de investigación, especialmente en los últimos dos años (2021 y 2022). Los países más activos incluyen China, EE. UU. y Brasil, con importantes colaboraciones internacionales, lo que destaca la importancia global del tema. El análisis de cocitación de fuentes reveló la influencia de revistas como Chemosphere y Aquatic Toxicology como esencial para el avance de la investigación. Además, los resultados indican que el pez cebra (Danio rerio) se ha consolidado como un modelo clave para el estudio de los efectos toxicológicos de los pesticidas, especialmente durante las primeras etapas de desarrollo, lo que contribuye a la evaluación de riesgos ambientales. El estudio también destacó la interdisciplinariedad y el uso de metodologías clásicas, como el ensayo de proteínas de Bradford, en contextos modernos. Finalmente, se observaron tendencias de investigación, con énfasis en los parámetros de estrés oxidativo, cardiotoxicidad y neurotoxicidad, así como en las lagunas relacionadas con la exposición a largo plazo a pesticidas y los mecanismos moleculares subyacentes.

Palabras clave: Ambiental. Ecotoxicología. Agricultura. Pesca. 2,4-D.

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1 INTRODUCTION

Ensuring food security for a growing global population has been one of the main challenges of the 21st century (Lykogianni *et al*., 2021). In the quest to protect crops from pests, early pest control approaches began with the use of natural substances such as sulfur and ash. Over the centuries, this practice evolved into the development of synthetic pesticides, revolutionizing modern agriculture. Compounds such as Bordeaux mixture and lead arsenate marked the beginning of this era, followed by widely known substances like DDT, parathion, and malathion—pesticides that, while effective, brought a range of environmental implications still under discussion today (Van den Berg, 2009; Mansouri et al., 2017).

The use of pesticides remains essential for increasing agricultural productivity, but awareness and understanding of their effects on human health and the environment were slow to emerge and even slower to solidify (Zuanazzi *et al*., 2020; Tudi *et al*., 2021). Awareness of the risks associated with the indiscriminate use of these compounds led to the creation of regulations and a continuous scientific effort to assess their impacts on non-target organisms. In recent years, concerns about these unintended effects on aquatic ecosystems, have driven studies using bioindicator organisms such as zebrafish (*Danio rerio*), a widely accepted model due to its genetic relevance and environmental sensitivity (Wang et al., 2017; Severo et al., 2020; Guerra et al., 2021; Braga et al., 2024; Visentini et al., 2025).

Since the sequencing of its genome in 2013, which revealed approximately 70 % genetic similarity with humans, zebrafish (*Danio rerio*) has been a key model for toxicological analyses due to its ability to bioaccumulate pesticides even at low concentrations (Guerra et al., 2021). This model has been applied in studies involving contemporary pesticides, such as neonicotinoids, which are known for their implications for aquatic ecosystems and pollinators (Howe et al., 2013).

Given the importance of pesticides to global agriculture and the challenges they pose to environmental sustainability, this scientometric review aims to map the development of research involving pesticide toxicology in zebrafish (*Danio rerio*). The goal is to identify trends, leading research regions, the most studied compounds, and knowledge gaps that can guide future studies and regulatory policies to mitigate their impacts. Furthermore, this study will provide particularly useful data for fostering international cooperation networks, enhancing the potential for scientific advancements in the field.

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2 METHODS

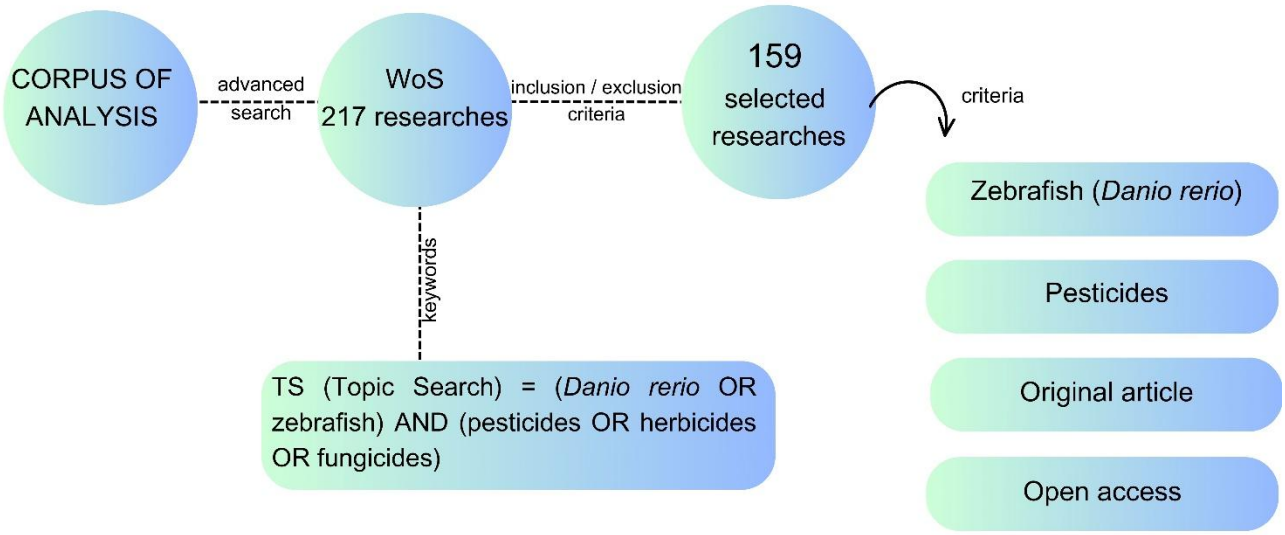
2.1 RESEARCH SOURCES, IDENTIFICATION, AND CRITERIA FOR INCLUSION OF STUDIES

Scientometric analysis is essential for evaluating the progress and research trends in specific areas of knowledge, providing a broad view of scientific and technological development (van Raan, 2019). In the present study, the approach focuses on the area of pesticide effects using zebrafish (*Danio rerio*) as a model organism, due to its relevance in toxicity research and environmental risk assessment. Through established qualitative and quantitative criteria, the analysis conducted allows for the identification of publication patterns, institutional collaborations, as well as the evolution and impact of studies in the field, providing a solid foundation to guide future investigations (Spinak et al., 1998).

The data were obtained from the Web of Science (WoS) platform's database through an advanced search using the terms “TS (Topic Search) = (“*Danio rerio”* OR “zebrafish”) AND (“pesticides” OR “herbicides” OR “fungicides”)” and Open Access and Article (Document Types) and Open Access and Article (Document Types) and Toxicology (Web of Science Categories) and Open Access and Article (Document Types). The search was conducted with no specific start date, and the keywords were searched in English. The search was performed on November 9, 2024, and returned 217 studies from 2004 to 2024. The studies were selected according to the pre-established exclusion criteria through manual refinement, which included reading titles and abstracts. The exclusion criteria were as follows: 1) use of pesticides; 2) zebrafish model (*Danio rerio*); 3) open access; 4) original article. After analysis, 11 studies were excluded for not using any type of pesticide, 43 studies were excluded for not involving *Danio rerio*, and 4 studies were excluded for being review articles. Only studies that met the aforementioned criteria and directly addressed the effects of pesticides on zebrafish (*Danio rerio*) were selected. After applying the exclusion criteria, the corpus for analysis was defined, resulting in 159 studies included in this review, as shown in the following flowchart (**Figure 1**):

Figure 1

Flowchart of the scientometric analysis corpus



2.2 DATA EXTRACTION

The data were analyzed using Microsoft Office Excel 365® and VOSviewer® software. The latter provides features to facilitate the understanding and interpretation of network patterns, including the identification of thematic areas, location of specific points, and labeling of selected terms. The software allows for mapping authors, journals (sources), and countries, helping to identify and visualize the key factors contributing to the evolution of knowledge in the field under study.

3 RESULTS AND DISCUSSION

3.1 CHARACTERISTICS OF THE PUBLICATIONS

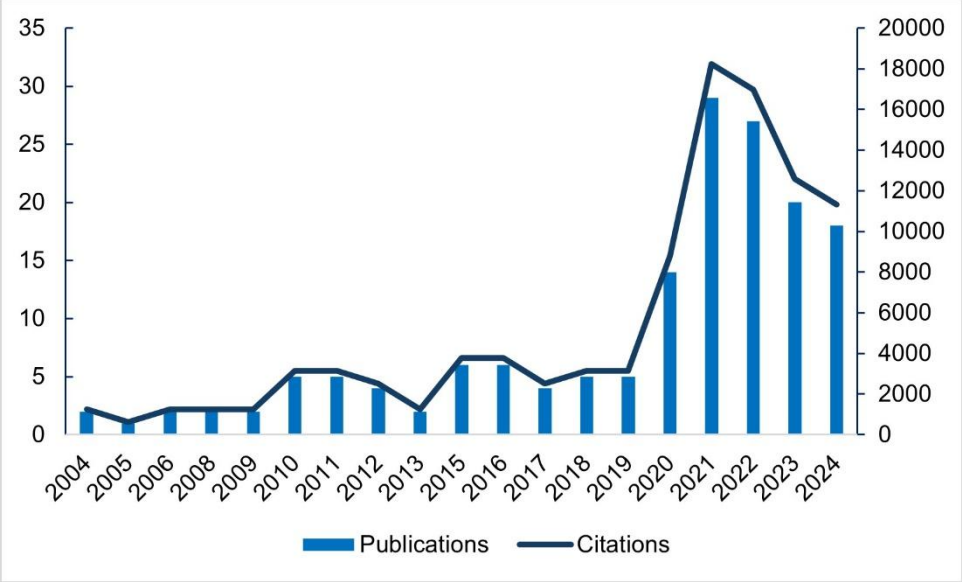
The first characteristic of the publications is that all 159 selected articles were published in English, regardless of the country of origin. This is an interesting finding, as it highlights the dominance of the English language in the scientific field. Additionally, the selected articles were cited 3,944 times, with an average of 24.81 citations per article, and the theme of this review had an H-index of 34. The H-index is a metric used to quantify both the productivity and impact of publications from a researcher, group, or research field. A high H-index, like the one obtained in the selected publications, reveals that the topic is highly relevant and is the subject of significant scientific research. An H-index value of 34 means that, in our dataset, 34 articles had at least 34 citations each. This analysis provides important insights into the scientific impact of research on the effects of pesticides on zebrafish (*Danio rerio*) (Hirsch, 2005). Furthermore, the analysis of the growth in the number of publications

over the years in the research field of this review is an important data point, as it provides an overview of the current relevance of the topic.

In this context, a mapping of the number of publications from the selected articles per year was carried out, as shown in **Figure 2**. Based on the data, an increase in the number of publications per year was observed, from the date of the first mapped publication (2004) up to 2024. This trend is consistent with the growing global concern about environmental issues. The highest number of publications occurred in 2021 and 2022, with 29 and 27 publications, respectively. Considering that the largest number of publications is recent, it can be inferred that the research area is currently relevant, and that research is still ongoing.

Figure 2

Quantitative mapping of 159 publications by year



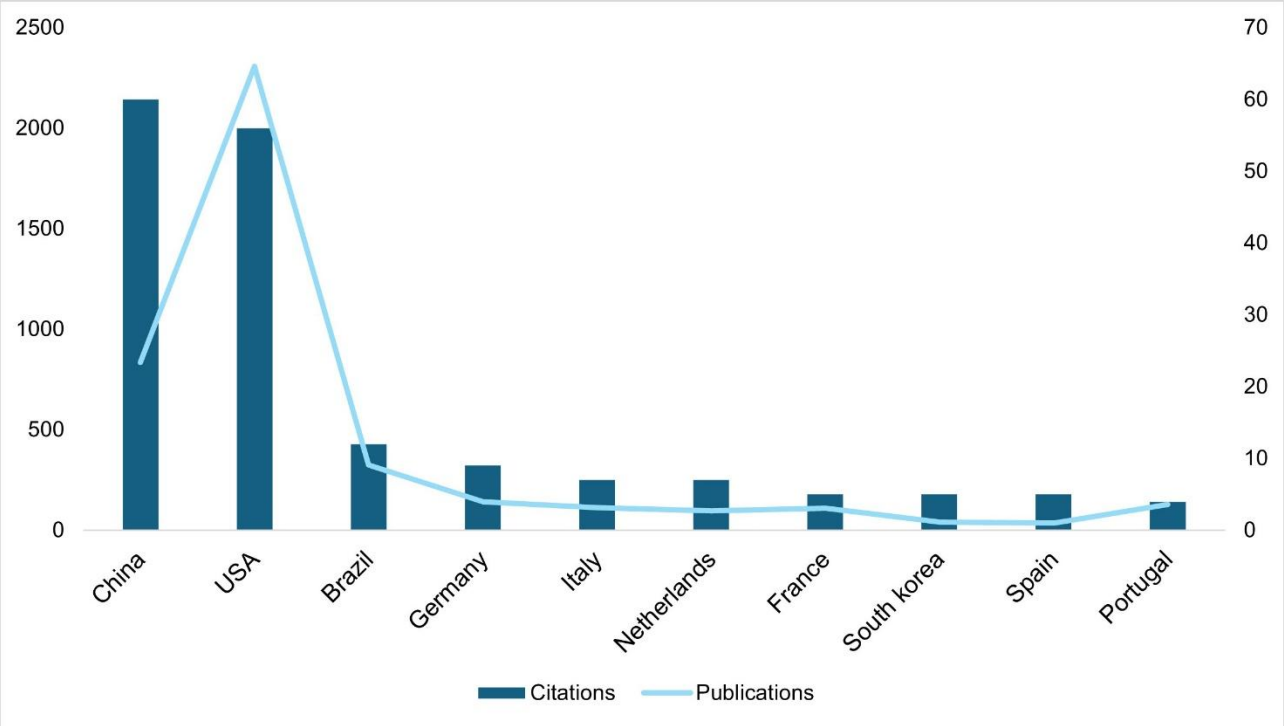
3.2 COUNTRIES

The analysis of the origin of scientific productions allows the identification of leading research regions in the field, as well as the cooperation networks among them. Based on the data extracted from the articles, the number of citations of the 10 countries with the most publications in this review was counted (**Figure 3**). The analysis showed that, in total, 33 countries have published on the topic of this review, with the theme being relevant even in countries with lesser scientific prominence It is interesting to note that, in terms of the number of documents, China leads with 60 publications. However, when the criterion is the number of citations, China ranks second, with only 836 citations. The United States (USA) holds second place in the number of publications, with 56 in the field. Nevertheless, it leads in citations, with 2,308, despite having fewer articles. Following this, the number of publications

per country decreases sharply, with Brazil ranking third, with 12 publications and 325 citations.

Figure 3

Ranking of the 10 countries with the highest number of published articles and their respective number of citations



To establish a complete visualization of the global development of research in the area, an important parameter is the analysis of the main co-authorship networks among these countries. Using the VOSviewer® software, it was possible to create a collaboration network by period, which can be seen in **Figure 4**. The criterion for forming the network was having at least one publication in the area. Countries with older publications are represented by the color purple, and the scale progresses from blue-green-yellow, representing the most recent contributions. It is important to mention that the size of the nodes (circles) in the network is proportional to the countries' contributions to the field, while the thickness of the lines represents the intensity of cooperation between countries. The network formed considered the existence of 13 clusters, with 7 cooperative clusters and 6 isolated countries. Of the total 33 countries that published in the field, 27 (81.8 %) have cooperation relations with other countries. The clusters were grouped as follows: Cluster 1 (Belgium, Iran, Italy, Kosovo, Norway), Cluster 2 (Czech Republic, France, Portugal, Saudi Arabia, Tunisia), Cluster 3 (Canada, Costa Rica, Israel, Spain), Cluster 4 (Egypt, Germany, Sweden, Switzerland), Cluster 5 (Japan, Malaysia, People's Republic of China), Cluster 6 (Brazil, Greece,

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Netherlands), and Clusters 7 to 13 consist of isolated countries (Argentina, Bangladesh, Croatia, India, Poland, Taiwan, respectively). Cluster 1 is made up of countries from different continents, suggesting significant transcontinental collaborations. Additionally, it represents a combination of countries with a historically stronger research presence (such as Italy and Belgium) and countries with developing scientific research (such as Kosovo, Norway, and Iran). Cluster 2 brings together European countries with countries from Africa and the Middle East. The inclusion of France, a traditionally influential country in scientific research, may act as a catalyst for collaborations within this group. Cluster 3 demonstrates geographic and infrastructure diversity, with Canada and Spain having robust research infrastructure, alongside Costa Rica, an emerging country in the field of environmental science. Cluster 4, with Germany and Switzerland leading as global scientific hubs, reflects the integration of emerging countries like Egypt with leaders in cutting-edge scientific production. Cluster 5 is focused on Asia and presents an interesting interaction between the massive production of China and Japan's technological advances, with Malaysia signaling a recent increase in its participation. Cluster 6 highlights Brazil's relevance as a leader in Latin America, collaborating with Greece and the Netherlands, known for their contributions in the environmental and biotechnological fields.

Additionally, it is possible to observe a larger collaboration network in the USA, indicating a strategy that favors scientific impact. Thus, although China produces a larger volume of research, its international relations are more restricted, which is a disadvantage in scientific development. The fewer international collaborations established by China directly affect its citation numbers, which amount to almost one-third of the citations received by the United States. Encouraging transnational collaborations may lead to better data standardization and more robust toxicological assessments applicable across different environmental conditions. Most countries have sought to promote international communication, even in less prominent regions, representing progress for the scientific community. Furthermore, the distribution of the network over time reveals that publications from the USA are older, highlighting its pioneering role in the field. In contrast, countries with less established scientific traditions, such as Malaysia, Iran, and India, are in the early stages of contributing, signaling the expansion of research into new territories.

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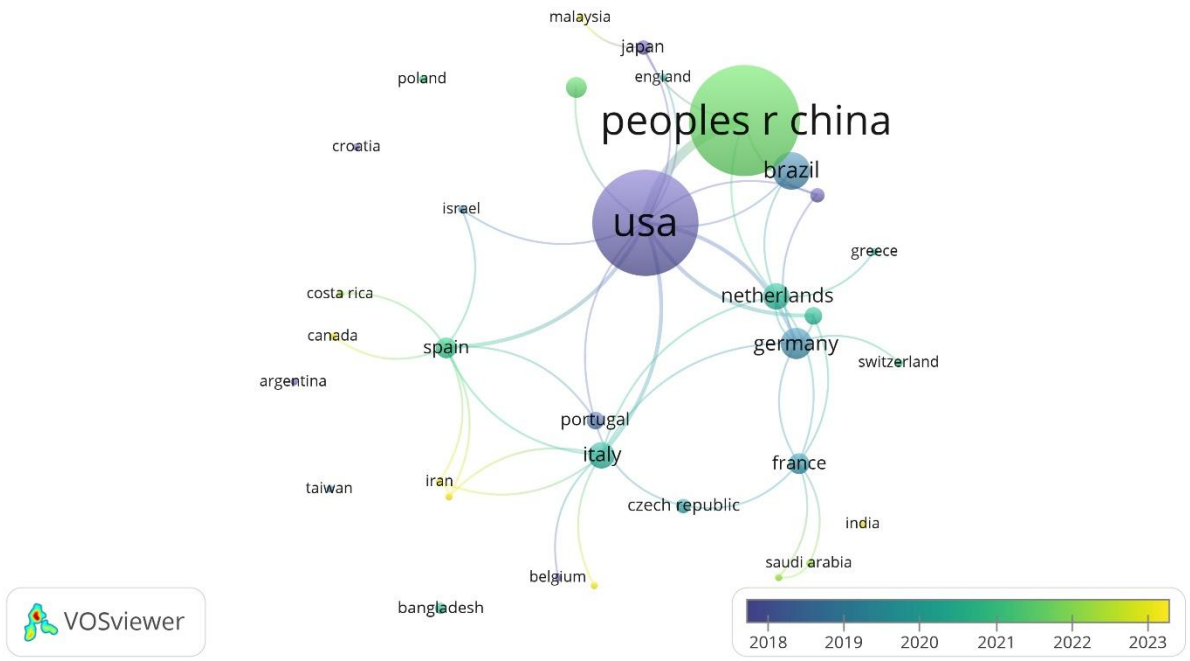
Figure 4

Co-authorship network among countries



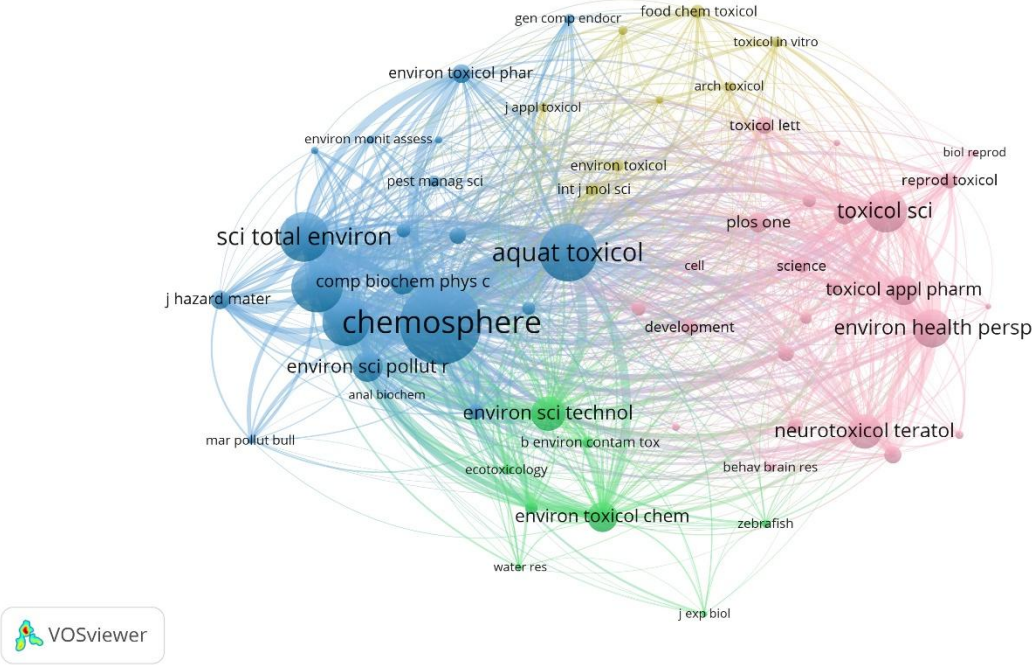
3.3 CO-CITATION ANALYSIS OF SOURCES

Co-citation networks of sources measure how frequently two sources are cited together within the same document. This analysis provides insights into the relationships among journals and their combined relevance in a research field. In this study, the co-citation network of sources was generated using the VOSviewer® software, considering a minimum of 20 citations per source. **Figure 5** illustrates the network, which consists of Clusters 1 to 4 (represented by pink, blue, yellow, and green colors, respectively). Cluster 1 includes journals related to cell and molecular biology, embryonic development, neuroscience, and the toxicological impacts on human health. Journals such as *Journal of Biological Chemistry*, *Development*, and *Endocrinology* focus on cellular mechanisms, while *Neurotoxicology* and *Neurotoxicology and Teratology* address neurotoxic effects. These journals reflect a common interest in understanding the molecular and biological effects of chemical substances on organisms. Cluster 2 encompasses journals that analyze toxicity in aquatic and terrestrial environments, as well as the impacts on ecosystems and environmental safety. Journals such as *Aquatic Toxicology*, *Environmental Pollution*, and *Science of The Total Environment* cover environmental pollution and toxicology, while *Fish & Shellfish Immunology* focuses on impacts on aquatic organisms. This cluster bridges toxicology and environmental conservation and includes the most cited journal, *Chemosphere*. Cluster 3 groups journals specializing in experimental toxicology, chemical substance evaluation, and their biological

impacts. Journals such as *Archives of Toxicology*, *Chemical Research in Toxicology*, and *Food and Chemical Toxicology* investigate the adverse effects of chemical compounds and strategies to assess toxicological risks in various contexts. Finally, Cluster 4 encompasses journals dealing with ecosystem monitoring and the use of experimental models, such as zebrafish (*Danio rerio*), to study pollution and toxicity. Journals like *Environmental Science & Technology* and *Environmental Toxicology and Chemistry* explore methodologies for assessing environmental contaminants, while *Zebrafish* highlights the use of this species as an experimental model in ecotoxicology.

Figure 5

Co-citation network of sources



The co-citation analysis revealed thematic clusters that align with the most pressing environmental and toxicological issues. Expanding this analysis to include emerging contaminants, such as microplastics and pharmaceuticals, could enhance the relevance of the studies. Exploring the interactive effects of pesticides with other environmental pollutants would more accurately reflect real-world exposure scenarios.

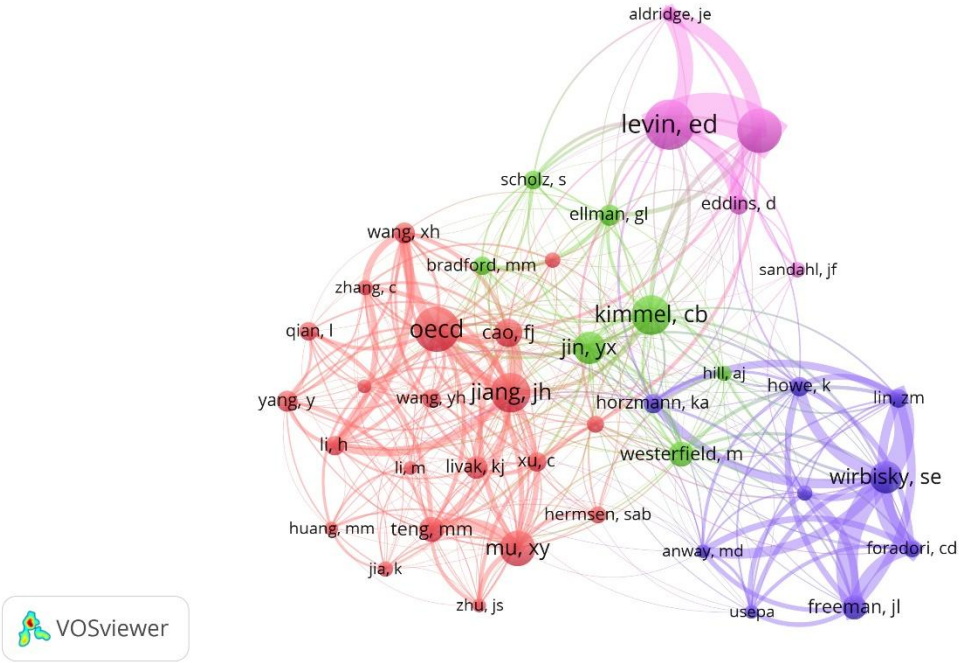
3.4 ANALYSIS OF AUTHOR CO-CITATION

Figure 6 illustrates the collaboration network for authors, highlighting the formation of four clusters as identified by VOSviewer®. In this network, each node represents a cited author. The co-citation analysis refers to the frequency with which two or more authors are

cited together in other documents. These data allow the identification of author groupings, suggesting thematic affinities or relevance in a specific field. This enables the mapping of key theoretical influences. Cluster 1 (red), is the largest cluster, indicating a core group of highly cited authors. The presence of OECD highlights the importance of regulatory standards for these authors. Cluster 2 (purple) includes a mix of researchers and institutions associated with environmental regulation (e.g., USEPA). The connections suggest an intersection between environmental regulation and experimental research. Cluster 3 (green) consists of authors associated with widely adopted methodologies in scientific studies, such as the Bradford Protein Assay and Ellman's Test for enzymatic activity. This cluster represents a solid methodological foundation and authors with historical contributions to the field. Finally, Cluster 4 (pink), comprises authors specializing in the neurotoxic and behavioral effects of chemical compounds, particularly in model organisms. The connections highlight a specific and emerging subfield.

Figure 6

Co-citation network authors



Regarding authors and their publications, **Table 1** from WoS presents the 10 most-cited articles in studies on pesticide toxicity in zebrafish (*Danio rerio*). The table also includes the total citation count and the annual average for each publication. The analysis of these documents is extremely relevant for researchers in the field. The listed articles investigate the toxicological impacts of various pesticides on the zebrafish experimental model. Other

prominent subtopics include pesticide neurotoxicity, endocrine disruptors, developmental impacts, behavioral changes, and morphological effects. Most studies focus on general effects, highlighting gaps such as the investigation of underlying molecular mechanisms, chronic exposure, exposure to mixtures, and cumulative effects. Exploring these gaps could lead to a deeper understanding of pesticide impacts and promote the development of more effective strategies for environmental risk regulation and mitigation.

Table 1

The 10 most-cited publications in studies on the toxic effects of pesticides on the zebrafish (Danio rerio) experimental model.

Publication	Citation Total	Average citation per year	Author / Year
Zebrafish provide a sensitive model of persisting neurobehavioral effects of developmental chlorpyrifos exposure: Comparison with nicotine and pilocarpine effects and relationship to dopamine deficits	12.8	192	Eddins et al, 2010
Thyroid endocrine disruption in zebrafish larvae following exposure to hexaconazole and tebuconazole	14.58	175	Yu et al., 2013
The developmental neurotoxicity of fipronil: Notochord degeneration and locomotor defects in zebrafish embryos and larvae	8.63	164	Stehr et al., 2006
Developmental Neurotoxicity of Pyrethroid Insecticides in Zebrafish Embryos	10.33	155	De Micco et al., 2010
Differential acetylcholinesterase inhibition of chlorpyrifos, diazinon and parathion in larval zebrafish	10.07	141	Yen et al., 2011
Glyphosate and Roundup® alter morphology and behavior in zebrafish	17	136	Bridi et al., 2017
Neurobehavioral impairments caused by developmental imidacloprid exposure in zebrafish	12.5	125	Crosby et al., 2015
Swimming impairment and acetylcholinesterase inhibition in zebrafish exposed to copper or chlorpyrifos separately, or as mixtures	8.57	120	Tilton et al., 2011
Developmental toxicity of the dithiocarbamate pesticide sodium metam in zebrafish	4.71	99	Haendel et al., 2004
Chlorpyrifos-Oxon Disrupts Zebrafish Axonal Growth and Motor Behavior	7	98	Yang et al., 2011

3.5 ANALYSIS OF CATEGORIES AND AUTHOR KEYWORDS

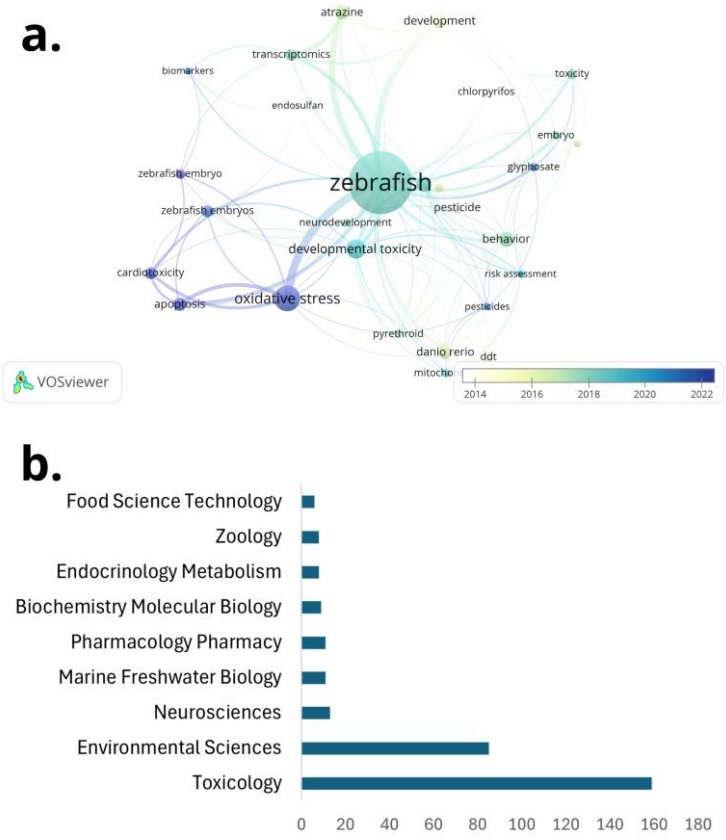
The most-cited keywords in the studies were mapped annually, and a network was created using the VOSviewer® software (**Figure 7A**). The network is represented by a gradient of white–blue–purple, reflecting the recency of terms in the field's research. A minimum occurrence threshold of four per term was set, resulting in a network with 28 author keywords grouped into 5 clusters. Cluster 1indicates a molecular and cellular approach, emphasizing studies on the toxic impact of substances on biomarkers and critical processes such as apoptosis and neurodevelopment. Terms like endosulfan and cardiotoxicity suggest a focus on specific pesticides and their toxic effects, particularly on zebrafish embryos, providing insights into toxicity during early developmental stages. Cluster 2 highlights a behavioral and functional focus, with studies examining pesticide impacts on neuromuscular and behavioral systems, particularly those involving the enzyme acetylcholinesterase and pesticides like chlorpyrifos and glyphosate. Cluster 3 focuses on developmental toxicity and neurotoxic risks, with special attention to the role of mitochondria and the impact of pyrethroids. Cluster 4 emphasizes the use of genomic tools, such as transcriptomics, to study the effects of pesticides on zebrafish development. Transcriptomics enables the understanding of gene expression and molecular-level changes. Finally, Cluster 5 focuses on understanding the impacts of DDT, a banned pesticide that still persists in the environment. Overall, the network demonstrates growing interest in zebrafish embryo toxicity research and biomarkers like oxidative stress and cardiotoxicity. Furthermore, the prevalence of terms such as oxidative stress, zebrafish embryo, apoptosis, and cardiotoxicity in recent years provides insights into current research developments. These trends suggest the expansion of aquatic toxicology toward more sensitive approaches and the use of zebrafish (*Danio rerio*) as a model organism for studying toxic effects during critical developmental stages and in environments exposed to multiple pollutants.

In addition to the keyword network, the co-occurrence of subject categories on the WoS platform was analyzed. These data highlight central areas of research on pesticide toxicity in zebrafish (*Danio rerio*), as shown in **Figure 7B**. This analysis allows for the establishment of a relationship between the main subjects provided by WoS and the author keywords, revealing research trends. The most prominent category is Toxicology, which encompasses 100% of the works. Toxicology is related to keywords such as zebrafish, toxicity, developmental toxicity, neurotoxicity, cardiotoxicity, apoptosis, and glyphosate. This relationship pertains to the investigation of the toxic action mechanisms of substances at the cellular level, focusing on apoptosis and the development of physiological functions, using zebrafish (*Danio rerio*) as a model. The second most prominent category is Environmental

Sciences, found in 53.5 % of the documents. This category is linked to keywords such as atrazine, chlorpyrifos, glyphosate, zebrafish, toxicity, behavior, and oxidative stress. The focus here is on analyzing the effects of pesticides and other environmental pollutants on aquatic species, investigating oxidative stress and behavioral changes in zebrafish in natural or simulated environments. The relationships between categories and keywords reveal a complex, interdisciplinary research network where zebrafish serves as a model to understand the environmental and toxicological effects of substances on the health of aquatic organisms and, by extension, the potential impacts on human and environmental health.

Figure 7

Co-occurrence network of author keywords; B. Categories listed in WoS. Source: derived from the articles selected in this review



Although the emphasis on oxidative stress, neurotoxicity, and cardiotoxicity in zebrafish research provides valuable insights into the acute and sublethal effects of pesticides, broader investigations into immune responses and endocrine disruption remain limited. The integration of advanced methodologies, such as CRISPR-based gene editing and high-resolution imaging, could enhance the understanding of how pesticides disrupt biological systems at the molecular level.

4 CONCLUSIONS

The analysis of scientific publications on the effects of pesticides on zebrafish revealed a significant increase in scientific production since 2004, reflecting growing global environmental concerns. The research has a global reach, with a particular emphasis on China and the USA, and an expanding international collaboration network. The journal co-citation analysis identified key sources, such as *Chemosphere* and *Aquatic Toxicology*, while thematic clusters revealed connections between authors and methodologies. Zebrafish have proven essential for understanding the toxic effects of pesticides, especially at critical developmental stages. The study highlights advancements in aquatic toxicological approaches, with an increasingly integrated and multidisciplinary approach. Despite these advances, there are still significant gaps, such as the need for more in-depth investigations into immune responses, endocrine disruption, and the interactive effects of pesticides with other environmental pollutants to provide a more comprehensive understanding.

REFERENCES

Braga, A. P. A., Souza, L. R. D., Lima, M. G. F., Cruz, J. M., Souza, A. C. Z. D., Costa, M. S., & Marin-Morales, M. A. (2024). The zebrafish as an alternative animal model for ecotoxicological research and testing. Brazilian Archives of Biology and Technology, 67, e24220968. https://doi.org/10.1590/1678-4324-2024220968

Bridi, D., Altenhofen, S., Gonzalez, J. B., Reolon, G. K., & Bonan, C. D. (2017). Glyphosate and Roundup® alter morphology and behavior in zebrafish. Toxicology, 392, 32–39. https://doi.org/10.1016/j.tox.2017.10.007

Crosby, E. B., Bailey, J. M., Oliveri, A. N., & Levin, E. D. (2015). Neurobehavioral impairments caused by developmental imidacloprid exposure in zebrafish. Neurotoxicology and Teratology, 49, 81–90. https://doi.org/10.1016/j.ntt.2015.02.006

DeMicco, A., Cooper, K. R., Richardson, J. R., & White, L. A. (2010). Developmental neurotoxicity of pyrethroid insecticides in zebrafish embryos. Toxicological Sciences, 113(1), 177–186. https://doi.org/10.1093/toxsci/kfp258

Eddins, D., Cerutti, D., Williams, P., Linney, E., & Levin, E. D. (2010). Zebrafish provide a sensitive model of persisting neurobehavioral effects of developmental chlorpyrifos exposure: Comparison with nicotine and pilocarpine effects and relationship to dopamine deficits. Neurotoxicology and Teratology, 32(1), 99–108. https://doi.org/10.1016/j.ntt.2009.08.005

Haendel, M. A., Tilton, F., Bailey, G. S., & Tanguay, R. L. (2004). Developmental toxicity of the dithiocarbamate pesticide sodium metam in zebrafish. Toxicological Sciences, 81(2), 390–400. https://doi.org/10.1093/toxsci/kfh220

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. Proceedings of the National Academy of Sciences, 102(46), 16569–16572. https://doi.org/10.1073/pnas.0507655102

Lykogianni, M., Bempelou, E., Karamaouna, F., & Aliferis, K. A. (2021). Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. Science of the Total Environment, 795, 148625. https://doi.org/10.1016/j.scitotenv.2021.148625

Mansouri, A., Cregut, M., Abbes, C., Durand, M. J., Landoulsi, A., & Thouand, G. (2017). The environmental issues of DDT pollution and bioremediation: A multidisciplinary review. Applied Biochemistry and Biotechnology, 181(1), 309–339. https://doi.org/10.1007/s12010-016-2214-5

Sánchez-Bayo, F., & Wyckhuys, K. A. (2019). Worldwide decline of the entomofauna: A review of its drivers. Biological Conservation, 232, 8–27. https://doi.org/10.1016/j.biocon.2019.01.020

Severo, E. S., Marins, A. T., Cerezer, C., Costa, D., Nunes, M., Prestes, O. D., & Loro, V. L. (2020). Ecological risk of pesticide contamination in a Brazilian river located near a rural area: A study of biomarkers using zebrafish embryos. Ecotoxicology and Environmental Safety, 190, 110071. https://doi.org/10.1016/j.ecoenv.2019.110071

Spinak, E. (1998). Scientometric indicators. Ciência da Informação, 27(2), 141–148.

Stehr, C. M., Linbo, T. L., Incardona, J. P., & Scholz, N. L. (2006). The developmental neurotoxicity of fipronil: Notochord degeneration and locomotor defects in zebrafish embryos and larvae. Toxicological Sciences, 92(1), 270–278. https://doi.org/10.1093/toxsci/kfj008

Tilton, F. A., Bammler, T. K., & Gallagher, E. P. (2011). Swimming impairment and acetylcholinesterase inhibition in zebrafish exposed to copper or chlorpyrifos separately, or as mixtures. Comparative Biochemistry and Physiology C-Toxicology & Pharmacology, 153(1), 9–16. https://doi.org/10.1016/j.cbpc.2010.07.008

Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., & Phung, D. T. (2021). Agriculture development, pesticide application and its impact on the environment. International Journal of Environmental Research and Public Health, 18(3), 1112. https://doi.org/10.3390/ijerph18031112

van den Berg, H. (2009). Global status of DDT and its alternatives for use in vector control to prevent disease. Environmental Health Perspectives, 117(11), 1656–1663. https://doi.org/10.1289/ehp.0900785

van Raan, A. (1996). Advanced bibliometric methods as quantitative core of peer review based evaluation and foresight exercises. Scientometrics, 36(3), 397–420. https://doi.org/10.1007/BF02129602

Visentini, A. E., & et al. (2025). Do estágio embrio-larval ao adulto: Uma revisão narrativa sobre a toxicidade do ácido 2,4-diclorofenoxiacético em peixe-zebra (Danio rerio). In Open science research VIII (pp. 275–288). Cientifica Digital. https://doi.org/10.37885/241218515

Wang, Y., Lv, L., Yu, Y., Yang, G., Xu, Z., Wang, Q., & Cai, L. (2017). Single and joint toxic effects of five selected pesticides on the early life stages of zebrafish (Danio rerio). Chemosphere, 170, 61–67. https://doi.org/10.1016/j.chemosphere.2016.11.130

Yang, D. R., Lauridsen, H., Buels, K., Chi, L. H., La Du, J., Bruun, D. A., Olson, J. R., Tanguay, R. L., & Lein, P. J. (2011). Chlorpyrifos-oxon disrupts zebrafish axonal growth and motor behavior. Toxicological Sciences, 121(1), 146–159. https://doi.org/10.1093/toxsci/kfr028

Yen, J., Donerly, S., Levin, E. D., & Linney, E. A. (2011). Differential acetylcholinesterase inhibition of chlorpyrifos, diazinon and parathion in larval zebrafish. Neurotoxicology and Teratology, 33(6), 735–741. https://doi.org/10.1016/j.ntt.2011.10.004

Yu, L., Chen, M. L., Liu, Y. H., Gui, W. J., & Zhu, G. N. (2013). Thyroid endocrine disruption in zebrafish larvae following exposure to hexaconazole and tebuconazole. Aquatic Toxicology, 138, 35–42. https://doi.org/10.1016/j.aquatox.2013.04.001

Zuanazzi, N. R., de Castilhos Ghisi, N., & Oliveira, E. C. (2020). Analysis of global trends and gaps for studies about 2,4-D herbicide toxicity: A scientometric review. Chemosphere, 241, 125016. https://doi.org/10.1016/j.chemosphere.2019.125016