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Causes and effects of contamination of water sources due to excessive use of agrochemicals and pesticides: bibliometric analysis

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ABSTRACT

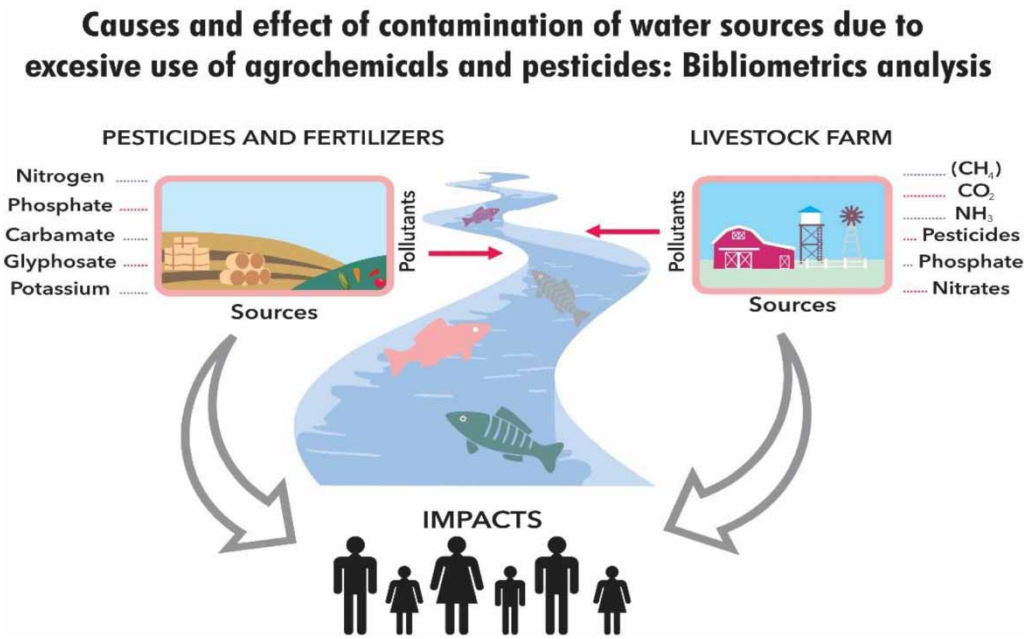
This article conducts a bibliometric analysis of water pollution caused by agricultural pesticides, focusing on theoretical and methodological trends. The analysis uses Scopus databases and Bibliometrix and VOSviewer software tools to analyze 2,330 documents from 2013 to 2022. The research highlights the importance of environmental, agricultural, and biological sciences in addressing water pollution. The study suggests improving pesticide use, reducing fertilizer applications, and addressing the harmful impacts of contaminated fish on human health. The restriction of glyphosate use in the European Union caused economic losses for companies, and a follow-up on glyphosate use in crop applications was proposed. The study also evaluates chemical concentrations and recommends addressing aquatic ecotoxicological risks. Future research trends include increasing water use efficiency and quality, hydrogeological studies, watersheds and land use, and climate modeling and impacts. The research is unique in addressing both research trends and knowledge gaps in water pollution research in various aspects.

Key words: Bibliometrics, Conflicts, Pesticides, Rivers, Sustainability, Water pollution

HIGHLIGHTS

- This article generates information for future agricultural and environmental research.
- Livestock and crop production produce one-third of the N and P that pollute water.
- Consumption of fish contaminated by pesticides and fertilizers affects human health.
- There are gaps in knowledge about the behavior of agricultural pollutants over time.
- China is the country that produces the most scientific papers on water pollution.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The river basin is the main source of drinking water supply for human and industrial consumption in large cities, where the water source has comparative advantages, especially in terms of infrastructure, allowing favorable conditions for human settlements and the development of tourism and agricultural and livestock activities of different kinds, which leads to imbalances in the production processes and normal recovery of natural resources. This raises the need to generate and put into practice integrated water resource management strategies, in coordination with the different stakeholders involved: territorial entities, regional autonomous corporations, organized civil society, academia, and production associations, which propose water management and use as an articulating axis.

Environmental deterioration in watersheds is due, among other reasons, to the application of state policies promoted for the agricultural sector, generating eco-systemic and cultural impacts that have accelerated the unsustainable use of natural resources, causing immense conflicts in the distribution of natural wealth. Agriculture has predominantly been identified as the primary source of water pollution in many countries globally, particularly affecting vulnerable ecosystems such as lakes, rivers, and streams. The concept of vulnerability to aquifer contamination refers to the inherent qualities determining how susceptible an aquifer is to negative impacts from introduced pollutant loads (Foster *et al.*, 2002). Different methods can be considered to measure this environmental impairment, including spatial, statistical, process-based, or hybrid index simulation models.

Contemporary agricultural practices result in substantial discharge of agrochemicals, organic materials, sediments, and salts into water bodies. This contamination adversely impacts billions of individuals and leads to annual economic costs reaching billions of dollars in the United States alone. Agriculture stands as the primary contributor to wastewater generation, with livestock producing notably higher volumes of excreta compared to humans. This level of pesticide use is a major source of contaminants found in air, water, soil, and agricultural products, and these chemicals have been shown to cause acute and chronic illnesses (Lai, 2017).

The main agricultural contaminants that pose significant risks to human health are pathogens in livestock, pesticides, nitrates in groundwater, small amounts of metals, and new contaminants such as antibiotics and antibiotic-resistant genes, which are discharged by livestock. The intensification of livestock production, which has tripled since 1970, has led to a new class of contaminants: antibiotics, vaccines, and hormonal growth promoters that travel through water from farms to ecosystems and into our drinking water.

The most efficient approach to mitigating harm to aquatic and rural ecosystems is to restrict the release of pollutants from farms by implementing measures to contain and reduce emissions before they can reach vulnerable ecosystems. Achieving this goal necessitates the development of policies and incentives that promote the adoption of more sustainable diets, while also curbing the demand for food with significant environmental footprints.

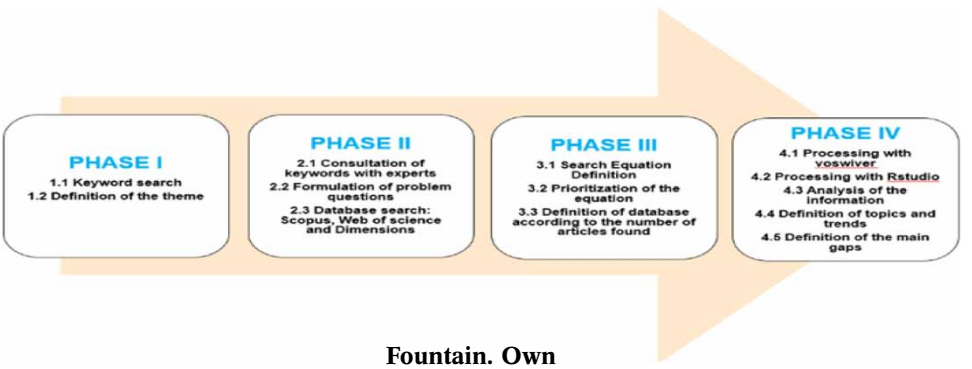
Research has shown that the nitrogen and total phosphorus contained in the waters of the rivers that flow into the Maracaibo Lake system (Venezuela) are constituents of fertilizers used on crops; in addition, the detergents and domestic and industrial wastewater that flow into the lake contribute to the irrigation of cereal and bread crops due to their richness in organic matter (Rivas *et al.*, 2009).

This paper reviews the different research studies carried out from 2013 to 2022 on water pollution due to the effects of agricultural pesticides. In addition, it examines research trends and identifies knowledge gaps by constructing networks using VOSviewer and R software. This facilitates the identification of correlations and behavioral patterns within the literature concerning the topic.

This analysis will enable the academic and scientific community to pinpoint primary publications and topics related to water pollution. Moreover, it aids in identifying research gaps for exploration, key authors, and research institutions delving into these topics, as well as countries leading in research efforts. Furthermore, it sheds light on collaboration among researchers aimed at addressing critical gaps in research concerning such a vital global issue as water pollution.

2. MATERIALS AND METHODS

Initially, a search for keywords was carried out to configure the search equation, and the following sequence was used to process the information:



Fountain. Own

Subsequently, the guiding questions were constructed, which are listed below.

- Which subject areas and countries conduct the most current research on water pollution?
- What are the key descriptors related to water pollution due to pesticide effects?
- What are the research trends on water pollution from pesticides?
- What is the relationship between countries, authors, and journals on water pollution?
- Which sources have received the highest number of citations?

Based on the above questions, a quantitative analysis was carried out to identify trends and research topics associated with water pollution. A bibliometric analysis was conducted using databases such as Scopus, Web of Science, and Dimensions. The Scopus database was given priority due to the higher number of documents available. Initially, a search was conducted using relevant keywords related to water pollution in the academic Google database. This helped identify the main descriptors, such as water pollution, water bodies, water consumption, and wastewater. Five equations were constructed, which are described in Table 1.

Concerning the search of the documents, some search criteria were considered to achieve greater veracity of the information, as follows: use of keywords in English to have more information on the documents from other countries, different documents including articles, secondary documents, as well as a search range of 2013–2022, without considering the year 2023 due to the lack of information. The selected search equation most appropriate to our work is the following: (water AND pollution AND pesticides AND agricultural).

A database was organized with the documents extracted from Scopus to be used with VOSviewer to carry out the analysis of co-occurrence and co-authorship, where the authors with the most publications and the different keywords pertinent to the topic of water pollution were identified. In addition, R software was used to review other aspects such as publication index, collaboration between authors, documents published by the author, annual publication dynamics, and annual citations. Moreover, an analysis was conducted using a tri-field graph, with countries listed in the left field, authors in the middle field, and journals that have published on the subject of study in the right field.

Subsequently, the citations per document were analyzed considering a minimum of 10 citations, and the citations registered in the journals were also considered, considering a minimum of five documents per journal.

3. RESULTS AND DISCUSSION

It was decided to work with search equation 1, where 2,330 documents were found for the years analyzed, the criterion for selection being that the publications found in the database were more closely related to the subject of the study.

With the Scopus database, 5,144 results were initially found, and with the 10-year re-profiling, it gave 2,330 results: 77.1% are research articles, 9.1% reviews, 7.9% book chapters, 4.5% conference papers, 0.3% notes, 0.3% books, and the remaining 0.3% in other documents. It is also found that the area where most documents are published is environmental, followed by agricultural and biological sciences and engineering, chemistry, medicine, earth, and planetary sciences. It is noteworthy that there are also publications on the subject of study in the area of social sciences; this is because water pollution problems become social problems, if there are not good water health conditions, this will generate health problems and increase the social crisis (Figure 1).

The countries that have scientific production regarding water pollution due to the effect of agricultural pesticides are mainly China, the United States, and India, as shown in Figure 2.

Table 1 | Search equations (Scopus database original research in 2022).

Equation	Search Equation	Results
Equation 1	(water AND pollution AND pesticides AND agricultural)	5,144
Equation 2	(water AND pollution AND agrochemicals)	1,045
Equation 3	(rivers AND pollution AND agrochemicals)	282
Equation 4	(water AND pollution AND bodies AND agrochemicals)	96
Equation 5	(water AND pollution AND bodies AND pesticides)	1,466

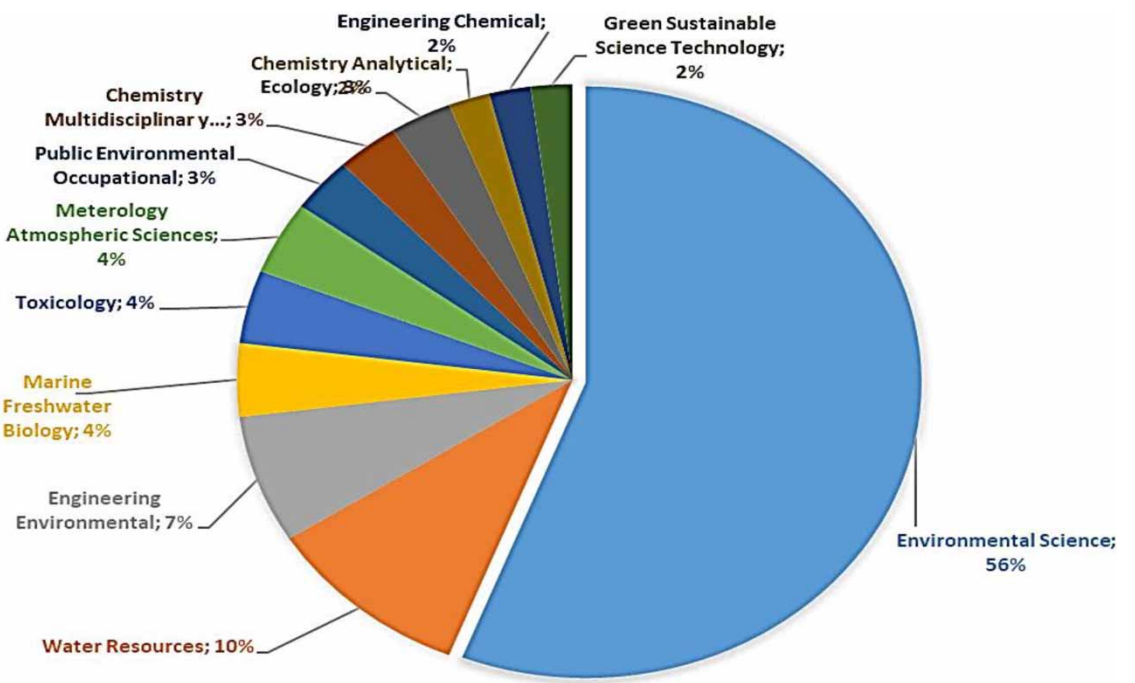


Fig. 1 | Documentation by thematic area (own research with data from the database Scopus).

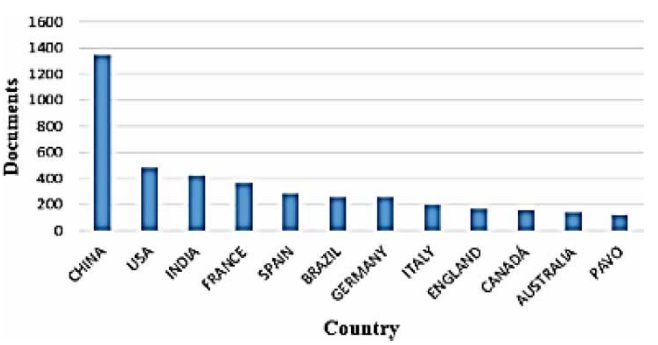


Fig. 2 | Documents by country (own research with data from the Scopus database).

According to the bibliometric analysis, 130 countries have published papers related to water pollution, and 90 countries have published at least five papers in the last 10 years. China with 434 documents, the United States with 340, and India with 274 documents are the countries with the highest number of publications, and they are also among those with a high presence of cooperation for publication. China, the United States, and India have been investigating the issue of water pollution by pesticides for a long in their agricultural sector; this is a consequence of being developed countries where there is very high pollution due to overpopulation, industrialization, and, conversely, the presence of highly trained scientists to provide solutions to the problems we are studying.

The analysis of the bibliometric co-occurrence networks using the VOSviewer tool allows us to observe that the words pesticides, contamination, soil contamination, insecticides, herbicides, groundwater, fertilizers, biodegradation, agriculture, environmental monitoring, crops, and water are the most investigated by scientists to solve an existing problem. It was observed that pesticides have the highest number of publications, and this is intertwined with citations related to water pollution, water treatment, organophosphorus pesticides, groundwater, river pollution, nitrogen, oxidation, and wastewater, with its research related to others in 999 links. A total of 34,626 strong links were found with other words in the pesticide water pollution group and several co-occurrences of 1,078. A total of 1,000 words were found in the five groups of the bibliometric network analysis for the word pesticides used in the agricultural sector (Figure 3).

The authors with the most published papers are Li Y., Wang Y., Liu Y., Zhang Y., Wang X., Liess M., Schafer R., Li H., Wang J., Wang I., Rodriguez-Cruz M., Sanchez-Martin M., and Zhang Z., among others, with 27, 25, 22, 19, 18, 18, 17, 17, 16, 16, 15, 15, and 14 published papers on pesticide water pollution with different numbers of links to other researchers. According to the number of publications, these have been grouped into 12 clusters with 18, 15, 14, 14, 14, 13, 13, 12, 11, 10, 7, 6, and 4, and 3 researchers per group out of a total of 127 researchers working on the topic of pesticide water pollution in the agricultural sector. This indicates that the authors from China, the United States, and India are the ones who produce the most publications on the selected topic as a consequence of being developed countries with high agricultural pollution and a very high overpopulation (Figure 4).

However, with the analysis of Scopus results, the institutions that produce the most publications are the Chinese Academy of Science, National Council for Scientific and Technical Research, Centre National de la Recherché Scientifique – CNRS, Ministry of Education of the People's Republic of China, University of Chinese Academy of Sciences – CAS, Spanish National Research Council (CSIC), and University Koblenz-Landau, among

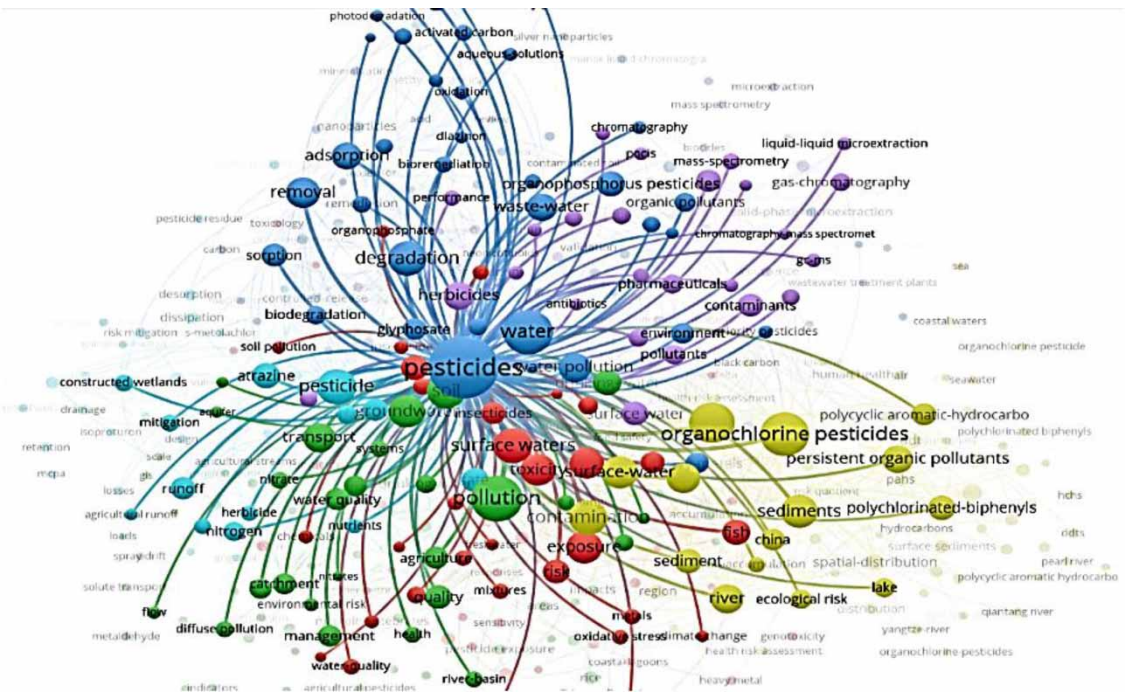


Fig. 3 | List of keywords declared by the author (own research with Scopus database).

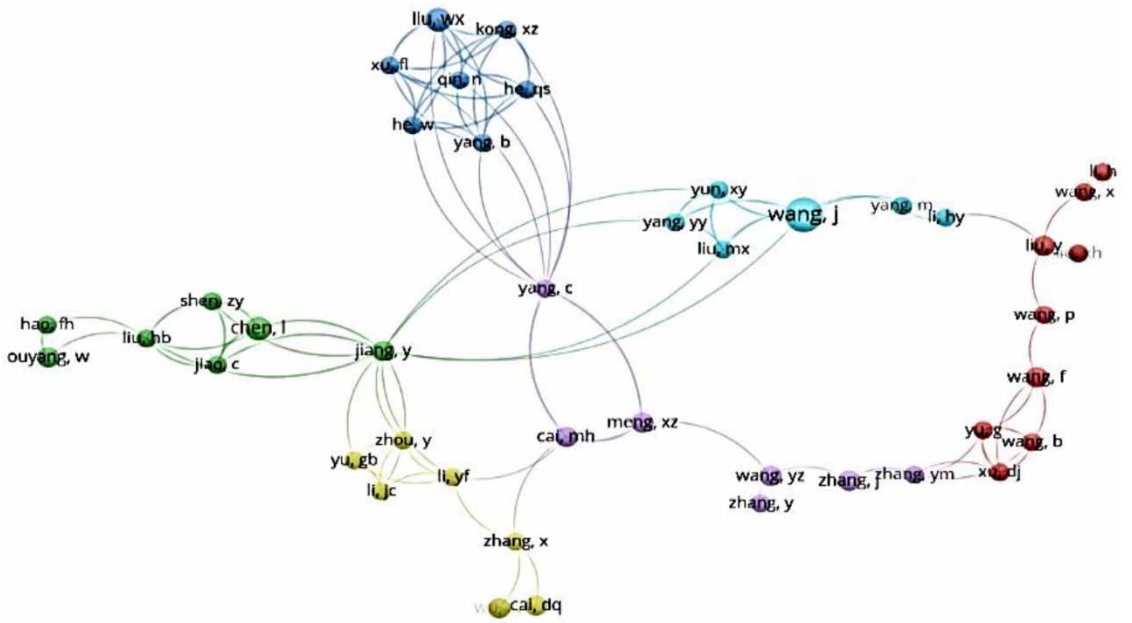


Fig. 4 | List of scientists with their publications about the selected topic.

others, with publications of 98, 61, 56, 40, 37, 36, and 34, respectively. This allows us to affirm that Chinese universities are the ones that produce the most scientific articles on water pollution due to the effect of pesticides, taking into account only 10 institutions (Figure 5).

The analysis performed with R software found 2,307 documents with an average citation per document of 26.56, from 766 sources (journals, books, etc.), and the number of co-authors per document of 5.28. It also found 114 single-authored documents, 1 reference, and the number of authors found in the bibliometric analysis was 9,134, with the average age of the document being 4.69.

In front of the annual scientific production, a downward growth is observed in the years 2013 and 2014 (177–156), with a reduction of 21 articles per year. From 2014 to 2022, the growth in the production of scientific articles was ascending, highlighting the year 2022 with a total of 372 publications. Despite the global pandemic situation due to COVID-19, research and scientific production continued to increase (Figure 6).

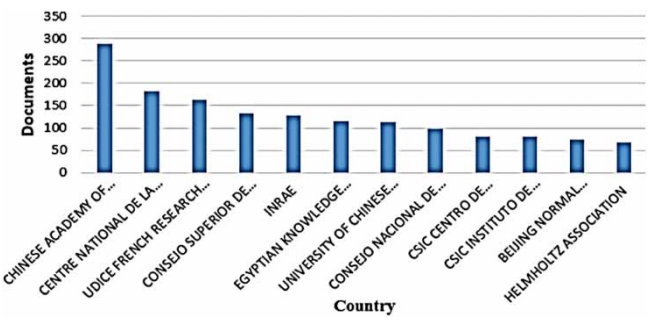


Fig. 5 | List of institutions that publish the most scientific documents.

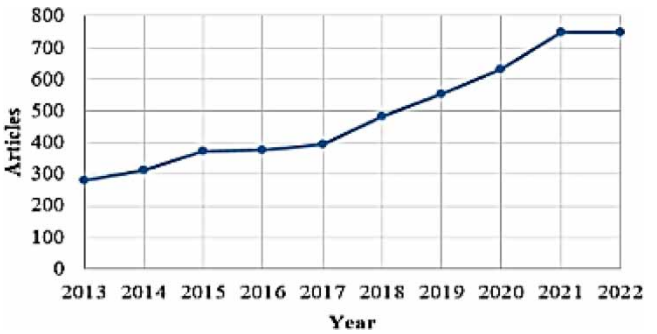


Fig. 6 | Number of publications per year (own research with data from Scopus).

Figure 7 shows the average citation per year, where it can be observed that from 2013 to 2014, there was a downward growth and then rises until 2015, and so on until 2018, with a decrease in the average number of citations per year. From 2018 onwards its average appointment growth is ascending until 2021, where it begins a decrease in the production of average appointments per year until the year 2022. This indicates that the average citation production per year of the scientists is irregular during the study period for water pollution due to the effects of agricultural pesticides (Figure 7).

The analysis of the three databases and considering the field of countries, authors, and sources shows that the country that produces the most scientific papers is China, with 20 authors producing papers on water pollution by pesticides in the agricultural sector. This is followed by smaller quantities of scientific articles from the United States, United Kingdom, Australia, France, Spain, Portugal, Italy, Denmark, and Germany (Figure 8).

Regarding journals, authors from China publish especially in *Science of the Total Environment*, *Environmental Science and Pollution Research*, *Environmental Pollution*, *International Journal of Environmental Research and Public Health*, *Ecotoxicology and Environmental Safety*, *Marine Pollution Bulletin*, *Water Research Chemical Engineering Journal*, *Chemosphere*, and other journals. It is also observed that authors from the United States, Australia, France, Portugal, and the United Kingdom publish their scientific articles on water pollution by pesticides in the agricultural sector in these journals.

The most relevant authors in the production of scientific articles are Zhang Y., Li Y., Wang Y., Liu X., Wang H., Liu H., Zhang X., Zhang H., and Zhang H., among others from China. This indicates that China leads the scientific research on water pollution by pesticides used in the agricultural sector, which is a major problem in industrialized countries.

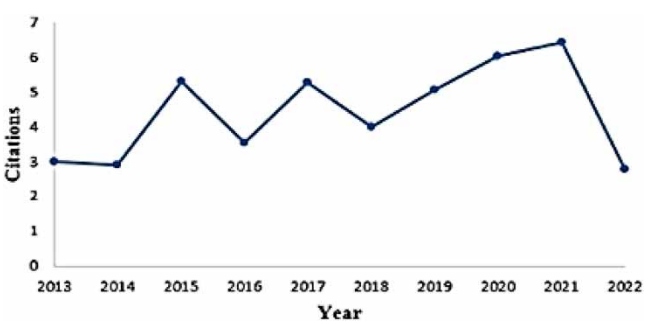


Fig. 7 | Number of citations per year (Publications with Scopus data).

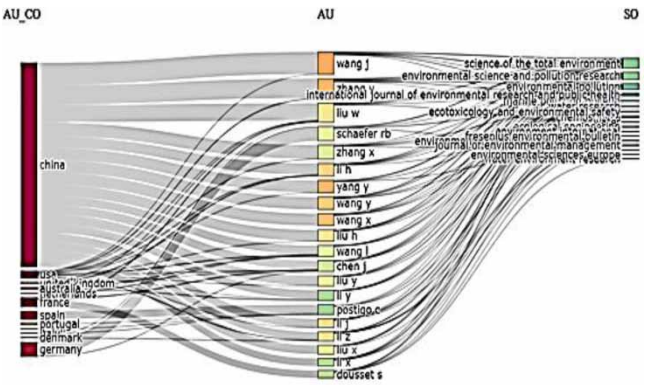


Fig. 8 | Analysis of the three data (Research with Scopus data).

3.1. Volume of agricultural chemicals in developed and developing countries by 2022

When comparing developed countries such as Spain, the United States, and China with developing countries like Colombia and Argentina, it is observed that among developed nations, the United States uses the greatest amount of chemical products for its crops (approximately 46 million tons/year), compared to Spain and China, which apply the least amount of chemical inputs. In comparison to developing countries, Colombia is the country that uses the largest amount of chemical inputs in agriculture (approximately 135 million tons/year) compared to the other countries analyzed. This indicates that Colombia is the country that most heavily pollutes surface and groundwater with chemical inputs used on farms, in addition to bovine excrement generated on these farms that pollutes the environment (water, air, fauna, soil, and flora), thereby impacting human beings (Table 2) (FAO, 2024a).

Chemical fertilizers such as sulfates, urea, potassium chloride, phosphates, and minor and foliar elements applied to the soil and crops are being used without control, generating environmental pollution and causing

Table 2 | Volume of agricultural chemicals in developed and developing countries by year 2022.

	Developed countries			Developing countries	
Chemicals	**Spain Volume (ton/year)**	**United States Volume (ton/year)**	**China Volume (ton/year)**	**Colombia Volume (ton/year)**	**Argentina Volume (ton/year)**
Insecticides	142.89	7,797.54	63,747.26	27,846	3,353.76
Fungicides and bactericides	32,094.32	15,074.68	61,711.88	19,858	4,404.34
Herbicides	12,186.18	405,497.1	97,662.81	29,949.65	249,796.29
Growth regulators	0	0	2,479.32	559.8	98.15
Rodenticides	0	0	47.38	17.3	0
Other pesticides	0	39,307.28	10,111.7	0	4,854.39
Chemical fertilizers	89,169.13	42,542,110	932,354	134,872,513	4,552,510
Total	**133,592.52**	**46,009.786.6**	**1,168,114.35**	**134,950,744**	**4,815,016.93**
Pesticide use per area of land under cultivation (kg/ha)	3.61	3.02	1.83	16.02	5.94

Source: Own with FAO data support, 2024.

economic losses for farmers. Once again, Colombia and the United States are the countries that use the greatest amounts of chemical fertilizers, especially potassium chloride (KCl). The chemical fertilizers used by these countries reach approximately 134.8 and 42.5 million tons per year, respectively, in various crops such as corn, rice, coffee, sugarcane, fruit trees, and flowers (Table 2) (FAO, 2024b).

With respect to pesticides (fungicides, herbicides, insecticides, growth regulators, rodenticides, and others), the United States is the leading user, applying 467.6 million tons per year, which generates significant contamination of surface and groundwater. Argentina and China follow with 262.5 and 235.7 million tons per year, respectively. These figures show that the most commonly used pesticide in these countries is herbicides, employed to protect crops from weeds (Table 2) (FAO, 2024a).

The table also reveals that when comparing pesticide use per hectare, Colombia applies the most with 16.02 kg/ha, followed by Argentina with 5.94 kg/ha and Spain with 3.61 kg/ha. In conclusion, developing countries apply more pesticides to protect their crops, causing significant environmental contamination (water, air, flora, fauna, and soil), which, in turn, impacts human health and generates diseases (Table 2) (FAO, 2024a).

3.2. Research trends in water pollution due to the effects of pesticides

In the analysis of citations for water pollution due to the use of pesticides in the agricultural sector, there are 2,330 documents, including research that evaluated the rates of voluntary reduction of pesticides and fertilizers by farmers as proxies for the willingness of farmers to prevent and control agricultural pollution from diffuse sources. The study found that pesticides are a significant production factor for farmers, and any decrease in pesticide use would cause significant production fluctuations. An ordinal regression analysis revealed lower risk associated with reducing fertilizers, and farmers' attitudes differ significantly between pesticide and fertilizer reduction (Lin & Pan, 2020). In another study, research shows that pesticide use boosts agricultural output, reduces grain losses, and improves human well-being. However, it can leave residues that can contaminate food, ecosystems, and organisms. Even at lethal concentrations, pesticides can disrupt fish physiology. The extent of pesticide assimilation into fish and the food chain, potentially causing adverse health effects, is debated (Ray & Shaju, 2023). According to Koppenberg *et al*. (2023), this research work analyzed the glyphosate controversy in the European Union (EU) from 2015 to 2017 in the stock prices of pesticide-producing companies. Providing the first insights into the implications of the pesticide ban discussions on the pesticide industry, Antier *et al*. (2020) conducted a study examining pesticide usage in agricultural practices and the associated risks. They gathered data on glyphosate sales and application in Europe from 2013 to 2017. Glyphosate serves various agronomic purposes, encompassing weed control, crop desiccation, cover crop removal, temporary grassland clearance, and permanent grassland renovation. The study introduces a framework aimed at precisely monitoring glyphosate usage, which involves identifying the cropping systems employing it, specifying its agronomic objectives, determining the dosage administered, and providing justification for its diverse applications. Another study by Buah-Kwofie *et al*. (2018) indicated that the accumulation of these pesticides in two common fish species, *Oreochromis mossambicus* and *Clarias gariepinus*, surpassed the maximum residue limits set by the European Commission. A health risk assessment identified potential dietary hazards associated with exposure to heptachlor, heptachlor epoxide, and dieldrin. These findings emphasize the necessity for further comprehensive research into the bioaccumulation and ecotoxicological impacts of these contaminants within the food web, as well as their implications for local ecosystems and human health (Buah-Kwofie *et al*., 2018). A study conducted in Costa Rica sought to evaluate the risk of groundwater contamination in the Maravilla-Chiz and Quebrada Honda rivers, crucial water sources for agricultural purposes reliant on groundwater. The research categorized potential contamination sources into point, linear, and diffuse types. Findings revealed that 7% of the area exhibited elevated pollutant

levels attributed to pesticide application, while 55% showed moderate contamination stemming from sugar cane and coffee cultivation, as well as urban development lacking proper sanitary sewage systems (Fonseca *et al.*, 2019). In the study conducted by Tauchnitz *et al.* (2020), it was discovered that pesticides pose a threat to aquatic ecosystems and contribute to environmental contamination. The research aimed to evaluate the pathways through which pesticides enter the Querne/Weida catchment in central Germany to facilitate the implementation of monitoring measures. Surface water and soil samples revealed the presence of common pesticide compounds such as glyphosate, α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA), diflufenican, and tebuconazole. Surprisingly, the study found that urban sources significantly influence water quality within the catchment area, despite the anticipated agricultural sources of these pollutants.

3.3. Research trends in water pollution due to pesticide effects in livestock production

The study by Selvam *et al.* (2023) assessed nitrates and fluorides in groundwater in the livestock sector, revealing high contamination levels. The groundwater contamination index (GIP) classified 21% of samples as high to very high, mainly due to fluoride levels exceeding WHO guidelines. The findings highlight the need for sustainability in groundwater availability and supply in a country with the largest population and significant groundwater utilization, amid increasing risks from population growth, climate change, and industrial development. A study in Wujin, China, found that pesticides like carbendazim and imidacloprid are prevalent in surface water, with severe contamination in Gehu Lake and Sanshangang River. The study also found that wastewater discharge is a significant anthropogenic factor affecting urban river water quality. Over 1,500 suspected organic pollutants were screened, with silafluofen being a prominent contributor. A negative correlation was observed between fish diversity and the combined toxicity of organic contaminants, indicating a potential ecological risk in these urban rivers (Zhou *et al.*, 2020). A study found that wastewater discharge is a significant anthropogenic factor affecting urban river water quality. The study collected water samples from two urban rivers and analyzed pollutant composition. Compound toxicity prediction and concentration addition models were used to forecast changes in pollutant toxicity. Over 1,500 suspected organic pollutants were identified as major contributors to toxicity. A negative correlation was observed between fish diversity and mixed toxicity of organic contaminants, indicating potential ecological risks in the two urban rivers (Liu *et al.*, 2023a, b, c). Emerging contaminants (ECs) in surface water aquaculture ponds pose ecological and health risks. Monitoring data on ECs in rural China is limited, prompting further investigations into their presence in surface water, aquaculture ponds, and wastewater treatment facilities. The study found 29 compounds in water samples from aquaculture ponds, with 13 detected in all three ponds. While EC removal efficiencies in wastewater treatment facilities were generally limited, notable removal rates were observed for certain compounds, such as valsartan (82–86%), nobiletin (100%), and dodecyl phthalate (100%) (Cheng *et al.*, 2023). The research investigates groundwater contamination in rural Argentina attributed to agricultural and livestock practices. It unveils that urban regions exhibit higher contamination levels compared to rural areas, primarily stemming from waste disposal from sludge systems and animal corrals. The analysis employs isotopic analysis and multivariate statistical techniques to elucidate the correlation between land usage and contamination levels (Blarasin *et al.*, 2020).

3.4. Research trends on water pollution due to agricultural activities

Among the research on water pollution by agricultural actions, one study evaluated the nitrogen balance at the national, regional, and/or farm levels in agricultural production. Finding large changes in Polish agriculture, this nitrogen surplus decreased from 90 kg ha^{-1} in 1989 to 60 kg ha^{-1} in 1991. Of the surplus nitrogen, approximately 30% is volatilized into the atmosphere as ammonia, while comparable amounts infiltrate into water bodies,

notably groundwater (Sapek & Sapek, 1993). Other works of importance are related to the increase of nitrates in surface and groundwater that has become a problem in agricultural areas. Therefore, attempts to reduce agricultural nitrate pollution of aquatic systems by nitrates must consider the long-term legacy of past applications of synthetic fertilizers in agricultural systems and the nitrogen retention capacity of these same soils (Sebilo *et al*., 2013). The rise of nitrates in both surface and groundwater within agricultural regions of Serbia presents a considerable concern. In efforts to mitigate water pollution, a study was conducted to evaluate the vulnerability of agricultural soil in Pančevo utilizing the LOS index method. The findings indicated that implementing closed fertilizer use periods, adhering to soil application standards, practicing balanced fertilization, optimizing production structures, employing contour plowing, adopting conservation tillage techniques, and maintaining buffer strips represent the most effective nitrogen management practices for agricultural activities, thereby safeguarding water resources (Vuković *et al*., 2018). The study evaluated nitrate risk in groundwater in Sicily, Italy, using intrinsic vulnerability methods. The increase in agrochemical consumption and manure consumption led to increased nitrate levels, contaminating surface and groundwater sources. The Agricultural Nitrate Hazard Index (IPNOA) parametric modeling method and intrinsic aquifer vulnerability methods (SINTACS and DRASTIC) were used, along with Geographical Information System (GIS) analysis. The SINTACS method was found to be most suitable for creating a risk map (Pisciotta *et al*., 2015). Research has revealed notable shifts in agricultural practices stemming from negotiations between farmers and water suppliers. Within water catchment areas, efforts have been made to enhance water quality, with a primary focus on mitigating diffuse pollution arising from intensive agriculture. This objective aligns closely with one of the key priorities outlined in the EU Water Framework Directive (Heinz *et al*., 2002). A study on farm-level water pollution management strategies, focusing on nutrient guidance systems, found that practices vary depending on factors like farm type, educational background, and nutrient utilization orientation. The study suggests that water companies could use upstream land management approaches and invest in targeted extension services to encourage the adoption of on-farm guidance systems, aligning with the EU Water Framework Directive. The findings highlight the need for improved agricultural pollution control (Wilson, 2014). A similar study was conducted in China, which included groundwater quality monitoring along with isotopic analysis. The study used Markov Chain Monte Carlo modeling to determine the riverine flux proportions of NO_3 from four potential sources: atmospheric deposition, nitrogenous chemical fertilizers, soil nitrogen, manure, and sludge. Nitrification was found to dominate nitrogen transformation in surface waters of the basin and it was found in groundwater, and a new index was constructed to characterize the uncertainties of nitrogen source identification (Ji *et al*., 2017).

3.5. Research trends in pollutant removal from water bodies

There are many ways to remove pollutants from water bodies, whereby it is intended in this research that biochar produced by the thermal decomposition of biomass under oxygen-limited conditions has received increasing attention as a cost-effective sorbent to treat metal-contaminated waters. The biosorption technique was used (Li *et al*., 2017). Additional research indicates that biochar derived from rice straw and herbal plants can successfully immobilize metals present in fish pond sediments, thereby rendering them suitable for use as fertilizers. Indeed, while these sediments are abundant in organic carbon and nutrients, they frequently harbor toxic elements. Biochar has demonstrated its efficacy in managing these elements, thereby enriching the sediment with macronutrients and rendering it suitable for utilization as fertilizers for plants. This makes fish pond sediments valuable resources for soil improvement (Mehmood *et al*., 2022). Another approach involves utilizing biochar derived from rice straw and swine manure, modified with phosphoric acid (H_3PO_4), for the sorption of tetracycline (TC) as a means to control water pollutants. It was observed that, under the same conditions, biochar derived from swine manure showed lower TC sorption capacity than

rice straw biochar, but still could be a good material for TC sorption. The following models were considered: Freundlich and Langmuir (Chen *et al.*, 2018). Heavy metal contamination in river sediments is a global environmental concern, affecting ecology and human health. With the development of continuous studies on the immobilization of heavy metals in sediments, a variety of curing agents have been reported. At present, several composite curing agents have been proposed to improve the curing effect of heavy metals to some extent. Key challenges in solidifying heavy metals in sediments have been identified, and suggestions for innovative future research directions have been proposed (Liu *et al.*, 2023a, b, c). Another study explores the use of $Ca(OH)_2$-modified rice straw biochar for immobilizing lead (Pb) in river sediments. The biochar, derived from agricultural by-products, was treated with calcium hydroxide to produce modified biochar (BCC). The immobilization mechanism focused on adsorption targeting Pb(II) in aqueous solutions. The effectiveness of immobilization was assessed using the Toxicity Characteristic Leaching Procedure and a modified method for river sediments. Adsorption studies showed BCC had a maximum adsorption capacity of up to 913.0 mg/g for Pb(II) (Liu *et al.*, 2023a, b, c). Floodplain forests play a crucial role in protecting riverbeds by facilitating surface runoff and preventing pollutants from entering water systems as they pass through agricultural areas. The absence of these forests can lead to erosion, soil loss, and high nitrogen concentrations in the water, as well as the presence of other pollutants (Soto, 1998). Studies highlight the various impacts of chemical contaminants on ecosystems and human health, emphasizing the urgent need for sustainable waste management practices. The widespread use of chemical contaminants, such as organochlorines, poses significant risks to biodiversity, water quality, and food safety. Exposure to these contaminants has been linked to increased risks of Hodgkin's lymphoma, Parkinson's disease, and antimicrobial resistance in microbes. A shift toward sustainable practices, including integrated waste management, improving standards, and educating users, can significantly contribute to sustainable agriculture by reducing reliance on chemicals and promoting ecological balance (Zhou *et al.*, 2025). Pesticides, such as organochlorines, parathion-ethyl, methamidophos, and some organophosphates and synthetics, are a global public and ecological health concern. A study conducted in Ankobra, Ghana, investigated the exposure levels and risks of these contaminants in groundwater and surface water. The results indicated that concentrations of banned contaminants ranged from less than Limit of Detection (LOD) to 0.110 μg/L, while non-banned contaminants ranged from less than LOD to 2 μg/L (Affum *et al.*, 2018). A study assessing the ecological risk of 25 pesticides in surface waters found a high risk associated with insecticides, particularly cypermethrin, permethrin, and chlorpyrifos. The probabilistic risk assessment method provided more comprehensive results than the conventional deterministic approach (Risk Performance (RQ)), highlighting the need for a regulatory framework to assess and mitigate pesticide risks in aquatic ecosystems (Rodríguez-Bolaña *et al.*, 2024). Research conducted near Guatemala City examined contamination from organochlorine and organophosphorus pesticides in water used for hydroponic production. Water samples were analyzed using liquid chromatography coupled with mass spectrometry and gas chromatography with selective detectors (Toj Juárez, 2024). In addition, new materials like BM-TB, made from aluminized tourmaline and biochar beads, have been developed with high adsorption capacities for heavy metals in aqueous solutions. BM-TB showed an adsorption capacity of 142.6 mg/g for Cd2+ at pH 4.0 and above, and it can also adsorb As, Cd, Cu, and Pb from groundwater. This material significantly reduces the bioavailability of these metals, making it effective for soil remediation and improving soil nutrient content (Zhu *et al.*, 2025).

3.6. Gaps in knowledge regarding wastewater contamination

A comprehensive strategy that connects hydrogeology and ecotoxicology is crucial for positively impacting sustainable water resource management on a worldwide scale.

Novel methods are urgently required to pinpoint sources, routes, and pertinent potential consequences, facilitating the adoption of suitable remedial actions and source management measures. Enhanced ecological and chemical analyses are essential for comprehensively investigating surface water sources.

Furthermore, it is imperative to delineate the responsibilities of sewage service providers and to incentivize and ensure funding for water treatment. This involves coordinating various funding sources, including allocations from the national budget. In addition, strategies need to be devised for controlling diffuse contamination, particularly within the agricultural sector, encompassing the management of wastewater and runoff from farming and breeding zones, as well as the storage and handling of agrochemicals.

Examinations of river, lake, and stream contamination have primarily concentrated on measuring physicochemical parameters. However, there is a pressing need to employ diverse bioindicators for a more holistic understanding of water pollution. Moreover, there are notable gaps in understanding contaminant behavior over time, with minimal retrospection on past water body conditions for present-day comparisons. There is a growing call for more comprehensive research that integrates advanced statistical methodologies with geospatial technologies to thoroughly assess water pollution levels (Machiwal *et al*., 2018).

The importance of investigating organic contaminants is underscored in the study by Gwenzi & Chaukura (2018). The study emphasizes the necessity to delve into areas such as identifying reservoirs of contamination hotspots, understanding the behavior and environmental fate of contaminants, exploring ecotoxicology and epidemiology, and developing interventions to mitigate health risks (Gwenzi & Chaukura, 2018).

Another aspect regarding the gaps in scientific research concerning water bodies is the correlation between climate change and these ecosystems. A study on the impacts of climate change on water and dependent ecosystems highlights a significant level of uncertainty, particularly concerning management techniques and numerical modeling aimed at understanding this relationship (Kløve *et al*., 2015).

4. CONCLUSIONS

Globally, agricultural land receives approximately 115 million tons of mineral nitrogen fertilizers each year. Of this, about 20% of nitrogen inputs are retained in soils and biomass, while approximately 35% are deposited into the oceans. Interestingly, developing countries utilize 25% of the world's pesticides in agriculture, yet they unfortunately account for 99% of global pesticide-related deaths (FAO, 2018). Farmers use fertilizers and pesticides to stimulate growth and mitigate harm caused by pests. These compounds are also used in golf courses, as well as in lawns and residential gardens. The chemical residues of these products can be filtered into groundwater, and the extent of contamination is determined by the nature and quantity of chemicals applied, as well as by local environmental conditions, such as soil type, precipitation, and seasonal snow.

Furthermore, it is imperative to delineate the responsibilities of sewage service providers and to incentivize and ensure funding for water treatment. This requires the coordination of diverse funding sources, including allocations from the national budget. Moreover, strategies must be developed to control diffuse contamination, especially within the agricultural sector. This involves managing wastewater and runoff from farming and breeding areas, as well as implementing effective measures for the storage and handling of agrochemicals.

Examinations of river, lake, and stream contamination have primarily concentrated on measuring physicochemical parameters. However, there is a pressing need to employ diverse bioindicators for a more holistic understanding of water pollution. Moreover, there are notable gaps in understanding contaminant behavior over time, with minimal retrospection on past water body conditions for present-day comparisons. There is a call for more exhaustive research integrating advanced statistical methodologies with geospatial technologies to assess water pollution levels comprehensively.

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AUTHOR CONTRIBUTIONS

JAHB Contributed to data curation, analysis of data, drafting, preparation of the original draft and editing the article. GYFY contributed to the conceptualization, methodology, software, supervision, and validation. DH contributed to display, investigation, software, and supervision.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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