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Bacteria with potential use in the bioremediation of water contaminated with pesticides: A systematic review and scientometric analysis

Bacterias con potencial uso en la biorremediación de aguas contaminadas con plaguicidas: Una revisión sistemática y análisis cienciométrico

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ABSTRACT

Among the most harmful contaminants to the environment and human health are various types of pesticides widely used in agriculture, which exhibit genotoxic and cytotoxic effects. Bioremediation emerges as a promising solution to mitigate these adverse effects. In this systematic review and scientometric analysis, the PRISMA model (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was employed to identify the bacterial species most commonly used in the bioremediation of water bodies contaminated with pesticides. SCOPUS database and tools such as R Studio and VOSviewer were used for the analysis.

The results reveal that organophosphate pesticides, particularly chlorpyrifos are the most commonly studied for microbial degradation, mainly with bacterial genera such as *Pseudomonas*, *Enterobacter*, and *Bacillus*. Furthermore, the scientometric analysis highlights the high scientific output from countries like China, Denmark, and Egypt, providing a comprehensive overview of key contributions and collaborations in this field. Additionally, the analysis identified leading researchers, the most impactful scientific communities, and the leading research centers, creating a detailed map of contributions and international collaborations in this critical area of biotechnology.

KEY WORDS: Chlorpyrifos, Bacteria, Pesticides, Bioremediation, Water.

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RESUMEN

Entre los contaminantes más dañinos para ambiente y la salud humana se encuentran diversos tipos de plaguicidas utilizados ampliamente en la agricultura, los cuales presentan efectos genotóxicos y citotóxicos. La biorremediación se perfila como una solución prometedora para mitigar estos efectos adversos. En esta revisión sistemática y análisis cienciométrico, se empleó el modelo PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) para identificar las especies bacterianas más utilizadas en la biorremediación de cuerpos de agua contaminados con plaguicidas. Se utilizó la base de datos SCOPUS y herramientas como R Studio y VOSviewer para el análisis. Los resultados revelan que los plaguicidas organofosforados, especialmente el clorpirifos, son los más investigados para la degradación microbiana, destacando el uso de especies bacterianas como *Pseudomonas, Enterobacte*r y *Bacillus*. Además, el análisis cienciométrico resalta la alta producción científica en países como China, Dinamarca y Egipto, proporcionando una visión integral sobre las contribuciones y colaboraciones clave en este campo. También se identificaron los principales investigadores, las comunidades científicas con mayor impacto y los centros de investigación líderes, generando un mapa detallado de las contribuciones y colaboraciones internacionales en este ámbito crítico de la biotecnología.

PALABRAS CLAVE: Clorpirifos, Bacterias, Plaguicidas, Biorremediación, Agua.

Introduction

Agricultural practices developed to meet the growing global demand for food are proving unsustainable, causing significant negative impacts on ecosystems and human health. The intensification of agriculture, with its reliance on large-scale pesticides and fertilizers, has led to widespread water contamination, affecting biodiversity and the quality of water resources available for human consumption (Leyva-Morales *et al*., 2017; Smith *et al*., 2017; Ouyang *et al*., 2019; Singh *et al*., 2023). Recent reports from the International Water Management Institute (IWMI) emphasize that agriculture is the largest wastewater producer by volume, exacerbating the crisis through the use of synthetic inputs (FAO, 2022).

It is estimated that approximately 35% of all agrochemicals used globally in agricultural production end up contaminating water systems, which eventually flow into rivers and seas (Rad *et al*., 2022). This runoff, primarily caused by agricultural drainage associated with intensive irrigation techniques, represents one of the greatest threats to human health and aquatic ecosystems, underscoring the urgent need for effective mitigation strategies (FAO, 2022). Additionally,

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contaminants in water bodies such as nitrates and certain pesticides have been linked to the loss of up to 30% of global biodiversity, highlighting the extensive ecological damage caused by these agricultural practices (ONU, 2015; EPA, 2021).

Annually, it is estimated that approximately three billion kilograms of pesticides are used worldwide. The primary objective of this massive use is to enhance agricultural yield and minimize crop losses (Sharma *et al*., 2020). However, since these agrochemicals are non-biodegradable and possess recalcitrant characteristics, they persist in the environment for extended periods, posing a continuous risk to ecological and human health (Hossain *et al*., 2022). Human exposure to these toxic residues often occurs through the food chain, potentially triggering a range of adverse health effects, including chronic illnesses and developmental issues (Hakeem *et al*., 2016; Singh *et al*., 2023; Rincón-Rubio *et al*., 2024).

Pesticides are classified according to their function (herbicides, fungicides, insecticides, rodenticides, among others) and the specific species they target for extermination (Niaoumakis *et al*., 2017). These chemicals include compounds that act as acetylcholinesterase inhibitors and organochlorines, commonly used in their formulation (Bertero *et al*., 2020).

Within the broad range of pesticides, categories such as carbamates, pyrethroids, organochlorines, organophosphates, and phosphonoglycines (glyphosate and derivatives) can be identified (Gauicha & Bolívar, 2015). Among these, organophosphates stand out for being less recalcitrant in the environment, although they exhibit more severe toxic effects on vertebrates. These compounds account for 36% of the total pesticides used globally, with their presence consistently observed in the market since the 1970s (Badii & Varela, 2015; Briceño *et al*., 2020; Singh *et al*., 2023).

Numerous studies have confirmed that pesticides can cause significant health impacts, including genotoxic and cytotoxic effects, in addition to causing serious environmental issues (Hernández-Toledano *et al*., 2020; Sánchez-Alarcón *et al*., 2021; Girón-Pérez *et al*., 2022; Robles *et al*., 2022; Costa *et al*., 2024). In response to these challenges, several mitigation strategies have been developed, with soil and water bioremediation emerging as one of the most promising. This technique utilizes biological organisms (fungi, bacteria, or plants) to decompose or neutralize hazardous contaminants in the environment, offering a sustainable and effective solution to reduce the toxic burden of pesticides in various ecosystems (Passatore *et al*., 2014; Saeed *et al*., 2021; Giri *et al*., 2021; Bhalla *et al*., 2022; Mali *et al*., 2023).

Bioremediation is an advanced technology that employs biological systems to reduce, eliminate, or transform contaminants in soil, substrates, water, and air into less toxic or harmless compounds (Passatore *et al*., 2014 Saeed *et al*., 2021; Dash & Osborne, 2023).

- *Aerobic bioremediation*: Utilizes aerobic microorganisms, such as bacteria and fungi, to degrade organic pollutants like hydrocarbons in the presence of oxygen.

- *Anaerobic bioremediation*: Employs anaerobic microorganisms to break down

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contaminants without oxygen, ideal for compounds like heavy metals and complex organic pollutants.

• *Phytoremediation*: Involves using plants to absorb and store contaminants, leveraging their natural ability to accumulate heavy metals and other organic compounds in their tissues.

• *Assisted bioremediation*: Combines bioremediation techniques with other technologies, such as organic amendments and aeration, to optimize the efficiency of the process.

Applying bioremediation in aquatic environments such as rivers, lakes, ponds, and aquifers requires a meticulous evaluation of environmental conditions and an appropriate selection of organisms and technologies to ensure efficient pollution reduction.

In contaminated soils, various bacteria capable of degrading organophosphate pesticides have been identified, including genera such as *Bacillus*, *Pseudomonas*, and *Flavobacterium* (Lara, 2021). These bacteria are crucial for the biodegradation of chemical compounds in the soil, facilitating the effective removal of pesticides through several biochemical mechanisms (García, 2022). These include:

• *Hydrolysis*: They produce enzymes that break the chemical bonds of pesticides. In organophosphates, these enzymes hydrolyze phosphate groups, resulting in less toxic products.

• *Demethylation*: Involve enzymes that can remove methyl groups from pesticides, reducing their toxicity and facilitating their degradation.

• *Oxidation*: Involve enzymes such as oxidases and peroxidases to oxidize pesticides, transforming them into more soluble and less harmful compounds.

• *Cleavage*: Involve enzymes that break the aromatic rings of compounds, promoting their decomposition.

• *Co-metabolism*: Some bacteria use pesticides as a secondary carbon or energy source, incidentally transforming these contaminants during their growth.

This study aims to identify and analyze the bacterial species used in the bioremediation of water bodies contaminated with pesticides through a systematic review based on the PRISMA methodology to determine trends, usage patterns, and innovative approaches in this scientific field.

Materials and Methods

This research methodology is based on the PRISMA model (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). This methodology requires reporting each step of the article selection process (identification, inclusion, and exclusion). It includes constructing a flow diagram that documents the number of studies evaluated at each stage. The results are validated by comparing patterns identified in the generated network maps with key publications, ensuring consistency between quantitative and qualitative data. This reproducible methodological design ensures that other researchers can replicate the selection and analysis steps to confirm or contrast the findings (Page *et al*. 2021).

The investigation is guided by the key question: What species of bacteria have been used in the bioremediation of water bodies contaminated with pesticides according to scientific literature? This question ensures that the review is specific and addresses a well-defined problem. To explore this emerging field, mathematical and statistical methods were employed to analyze publications using the SCOPUS database. This platform indexes articles hosted in journals with impact factors listed in the Journal Citation Report (JCR) across various quartiles and covers a ten-year period (2014–2024).

This scientometric analysis was conducted using open-source software, such as R Studio, Bibliometrix, and VOSviewer. The inclusion of these tools minimizes human bias in data extraction and analysis. Additionally, tools like density mapping in VOSviewer suggest probabilities of co-occurrence between key terms, while network analysis using metrics such as centrality degree and modularity are used to determine the relevance of certain terms or nodes within the generated information networks (Dervis, 2019).

We focused on including articles with a DOI and excluded bioremediation studies not directly related to water.

The network maps analysis provides an innovative and valuable perspective on how pesticides and other contaminants are distributed and persist in aquatic ecosystems. These maps aid identify dispersion patterns and concentration of contaminants, guiding more effective monitoring and control strategies. By integrating data from different sources, network maps not only help understand the environmental impact of pesticides but also their interactions, offering a holistic approach that improves water resource management

Results and Discussion

The search yielded a total of 180 articles. The inclusion and exclusion criteria were applied based on a review of the abstracts of each article, focusing on those that reported both the pesticide and the bacteria used in the bioremediation study in water (Figure 1). The results were generated from articles that included a DOI, resulting in a total of 24 publications (Table 1). The analysis of these publications showed that most of the scientific output originated from China, followed by Denmark and Egypt.

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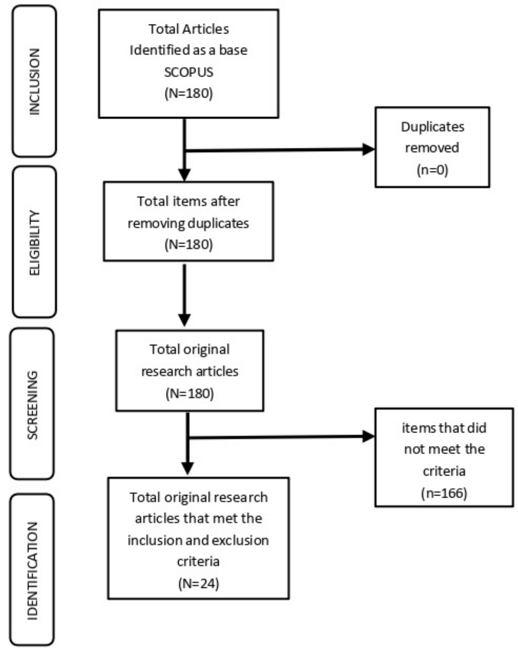

Figure 1. Diagram of the search process for research articles.

Source: Authors' elaboration.

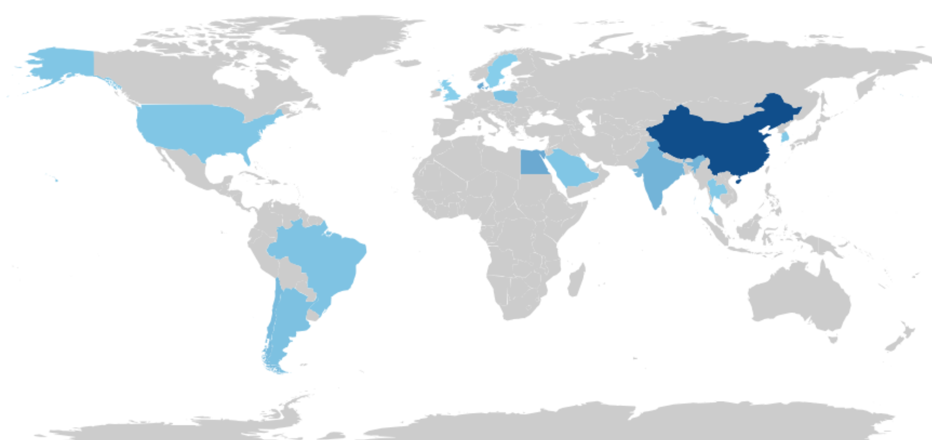

Figure 2. Scientific production of related documents by country.

Source: Authors' elaboration based on bibliometrix with data from SCOPUS

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Figure 2 presents the geographical distribution of scientific production on the studied topic. Notably, China stands out as the leading contributor, reflecting its growing dominance in global research, followed by countries such as Denmark and Egypt, which also show significant activity in this field. The trend highlights the increasing interest and diversification of research worldwide, where even nations with emerging research systems are starting to make significant contributions (Bin *et al*., 2024).

Main Pesticides which Degradation by Bacteria in Water Bodies was studied

Organophosphates

Organophosphate (OP) compounds are the most widely used pesticides globally and pose a significant environmental risk due to their high toxicity. Santillán *et al*. (2020) developed a bioreactor for the remediation of OPs-polluted wastewater. Their research identified and isolated bacteria from contaminated soils, highlighting two effective genera: *Sphingomonas sp.* and *Brevundimonas sp.* The degradation efficiency of OPs was evaluated based on variables such as temperature, pH, and tolerance to different substrates, with high degradation rates observed at 60 °C, a pH of 10, and in the presence of large OPs such as coroxon, coumaphos, and chlorpyrifos.

Abdel-Razek *et al*. (2019) explored using microalgae and cyanobacterial consortia for bioremediation in water bodies. The results showed that *Spirulina platensis* effectively removed the pesticide malathion and heavy metals like cadmium, lead, and nickel from wastewater. Talwar *et al*. (2014) isolated the bacterial strain *Ochrobactrum sp.* Strain HZM from pesticide-contaminated soils. This strain demonstrated the ability to utilize various OPs as carbon sources, highlighting its capacity to mineralize quinalphos and suggesting its potential utility in the bioremediation of contaminated soils and water.

Chlorpyrifos

A wide variety of microorganisms have been shown to degrade chlorpyrifos (CP), including cyanobacteria, *Bacillus*, *Streptomyces*, *Enterobacter*, *Streptococcus*, *Pseudomonas*, and *Achromobacter*, among others (Table 1). Some of these genera can degrade CP at high concentrations, such as the PC2 strain of *Bacillus cereus* and the SP1 strain of *Streptomyces praecox*, isolated from agricultural drainage wastewater in El-Khairy, Egypt (Elzakey *et al*., 2023).

Lourthuraj *et al*. (2022) identified bacteria capable of degrading OPs, particularly CP, by locating the activity of bacterial organophosphate hydrolase. *Enterobacter aerogenes* CP2 and *Streptococcus pyogenes* CP11 removed 77 ± 1.8 % and 74.2 ± 3.1 % of the pesticide, respectively. These strains produced organophosphate hydrolase activity and localized enzyme biosynthesis. The CP2 strain demonstrated the fastest OP degradation rate among *Enterobacter* species. However, in similar studies, *Cupriavidus nantongensis* X1T, a strain of the *Cupriavidus* genus, efficiently degraded 200 mg/L of CP in 48 hours—approximately 100 times faster than *Enterobacter* species. The X1T strain tolerated high CP concentrations (500 mg/L) across a wide range of temperatures (30-42 °C) and pH values (5-9). RT-qPCR analysis revealed that organophosphate

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hydrolase (OpdB) in the X1T strain is an inducible enzyme, and the crude enzyme isolated *in vitro* retained 75 % degradation activity (Fang *et al*., 2021; Shi *et al*., 2019).

In other studies, the C1 strain of *Achromobacter sp.* exhibited a CP removal of 0.72–0.147/day, a half-life of 4.7 to 9.7 days, and a maximum metabolite concentration of 2.10 mg/L at 120 hours (Briceño *et al*., 2020). Other microorganisms isolated from brackish water using the enrichment culture technique, such as the psychrophilic bacterium *Shewanella sp.* BT05, showed significant tolerance and growth at different CP concentrations (10–50 mg/L). Furthermore, BT05 degraded 94.3 %, 91.8 %, 87.9 %, 82.6 %, and 80.5 % of CP at 10, 20, 30, 40, and 50 mg/L, respectively, within 24 hours (Govarthanan *et al*., 2020).

Subsanguan *et al*. (2020), using a consortium of five bacteria belonging to the genera *Pseudomonas*, *Klebsiella*, *Stenotrophomonas*, *Ochrobactrum*, and *Bacillus* in a mixed culture system, efficiently degraded CP in an aqueous media. Combining a mixed bacterial population with a biosurfactant significantly improved the CP degradation rate in soil without accumulating toxic intermediates. This environmentally benign biosurfactant can be produced *in situ* and may replace toxic synthetic surfactants commonly used in bioremediation.

Lakshmipathy *et al*. (2018) cultured and identified pesticide-degrading bacteria using biochemical tests. They determined that *Pseudomonas aeruginosa* was the predominant strain, capable of degrading up to 200 ppm of CP within 240 hours of incubation, equivalent to 80 %. These results indicated its effective use in the bioremediation of contaminated soils and water. CP degradation using a genetically engineered strain of *Pseudomonas putida* that displayed bacterial laccases on its surface demonstrated that this system could completely degrade the pesticide without generating any toxic metabolites. Bioassays with the model organism *Caenorhabditis elegans* as an indicator demonstrated the complete detoxification of CP degradation products (Liu *et al*., 2016).

Table 1. Degradation of pesticides by different bacteria.

Pesticide	Bacterial Species	References
Chlorpyrifos	*Bacillus cereus* and SP1 of *Streptomyces praecox*, *Enterobacter aerogenes* CP2 and *Streptococcus pyogenes* CP11, *Cupriavidus nantongensis*, *Pseudomonas* and *Achromobacter*, *Shewanella sp.*, *Cupriavidus nantongensis* CX1, *Pseudomonas aeruginosa* pF1, 4R3-M1, *Pseudomonas sp.* 4H1-M3, *Rhizobium sp.*, *Pseudomonas*, *Klebsiella*, *Stenotrophomonas*, *Ochrobactrum*, and *Bacillus*, *Pseudomonas putida*	(Elzakey *et al.*, 2023), (Lourthuraj *et al.*, 2022), (Fang *et al.*, 2021), (Briceño *et al.*, 2020), (Govarthanan *et al.*, 2020), (Shi *et al.*, 2019), (Lakshmipathy *et al.*, 2018), (Liu *et al.*, 2016), (Singh *et al.*, 2016)
2,6-dichlorobenzamide	*Aminobacter niigataensis* MSH1, *Aminobacter sp.*	(Schostag *et al.*, 2022), (Hylling *et al.*, 2019)
Pyridine	*Pseudomonas aeruginosa* PAO1, *Enterobacter cloacae complex sp.* BD17, and *Enterobacter sp.* BD19	(Niu *et al.*, 2023), (Nie *et al.*, 2021)
Sulfoxaflor (SFX)	*Synechocystis salina* and *Microcystis aeruginosa*	(Łukaszewicz *et al.*, 2023)
Triazophos (TAP), metamidophos (MAP), and carbofuran (CF)	*Enterobacter sp.* Z1	(Zhang, B. *et al.*, 2020)
Organophosphates	*Sphingomonas sp.* and *Brevundimonas sp.*, *Spirulina platensis*, *Ochrobactrum sp.*	(Santillán *et al.*, 2020), (Abdel-Razek *et al.*, 2019), (Talwar *et al.*, 2014)
Simazine	*Pseudomonas stutzeri*	(Zhang, B. *et al.*, 2020)
Atrazine	*Pseudomonas* and *Arthrobacter*	(Zhao *et al.*, 2019)
Profenofos	*Pseudomonas plecoglossicida*	(Subsanguan *et al.*, 2020)
Organochlorines	*Paenibacillus sp.*	(Belal *et al.*, 2018)
Triazines	*Leucobacter sp.*	(Liu *et al.*, 2018)
Pyrethroids	*Kocuria sp.* CBMAI 135, *Kocuria sp.* CBMAI 136, *Kocuria marina* CBMAI 141, and *Kocuria sp.* CBMAI 145	(Birolli *et al.*, 2016)

Organochlorines

Organochlorine pesticides (OCPs), being highly recalcitrant, persist in the environment for extended periods. Belal *et al.* (2018) conducted a study monitoring OCP concentrations in three agricultural drainage water sources in the Kafr El-Sheikh Governorate, Egypt. They discovered numerous bacteria capable of significantly degrading various pesticides. They isolated and identified *Paenibacillus* sp. strain 10, which exhibited high efficiency in the biodegradation of these pesticides, ranging from 24.4 % to 98 % of these compounds.

Other experiments on the biodegradation of pyrethroid pesticides, such as esfenvalerate, utilized a consortium of microorganisms isolated from the sea (Kocuria sp. CBMAI 135, Kocuria sp. CBMAI 136, Kocuria marina CBMAI 141, and Kocuria sp. CBMAI 145). These bacterial strains accelerated the contaminant's degradation and increased the concentrations of its metabolites (Birolli *et al*., 2016).

Other Pesticides

Groundwater contamination by pesticide residues poses a threat to drinking water quality. One way to remediate drinking water containing microcontaminants is by using sand filters bioaugmented with contaminant-degrading bacteria such as *Aminobacter niigataensis* MSH1 (Schostag *et al*., 2022) and *Aminobacter* sp., which degrades 2,6-dichlorobenzamide (Hylling *et al*., 2019).

Stenotrophomonas maltophilia J2 is a highly efficient bacterium for pyridine degradation. Niu *et al*. (2023) isolated it from an aerobic tank in a pesticide-contaminated wastewater treatment plant. The J2 strain achieved a pyridine degradation rate of 98.34 % ± 0.49 % within 72 hours at a pyridine concentration of 1100 mg/L, 30 °C, a pH of 8.0, and a NaCl concentration of 0.5 %. These results provide a basis for the effective use of immobilized strains in treating recalcitrant pesticide-contaminated wastewater. Similarly, *Enterobacter cloacae* complex sp. BD17 and *Enterobacter* sp. BD19 demonstrated efficiency in pyridine degradation, also isolated from an aerobic tank in a wastewater treatment plant (Nie *et al*., 2021).

The use of neonicotinoid pesticides, such as Sulfoxaflor (SFX), is widespread in modern agriculture. Due to its high water solubility and environmental mobility, SFX significantly impacts aquatic ecosystems. According to recent studies, SFX degradation in the environment leads to the formation of amide (M474), which may be more toxic to aquatic organisms than the original molecule. Łukaszewicz *et al*. (2023) evaluated the potential of two common unicellular bloom-forming cyanobacteria species (*Synechocystis salina* and *Microcystis aeruginosa*) to metabolize this pesticide.

ZhanG, Y. *et al*. (2020) designed and compared various immobilization materials and compositional combinations to improve the functional durability of *Pseudomonas stutzeri* sp. Y2 for the degradation of simazine, one of the most commonly used herbicides found in industrial wastewater and cornfields in Hefei, China. They provided an immobilization strategy to stabilize bacteria and prolong their functional capabilities in treating water and soil contaminated with pesticides.

Pseudomonas and *Arthrobacter* are among the bacterial genera that degrade atrazine, demonstrating high adaptability. These genera are used for bacterial bioaugmentation in constructed wetlands. Results showed that this practice significantly improved pesticide degradation from 5 mg/L to below the threshold value within 43 days by increasing the presence of functional bacteria (Zhao *et al*., 2019).

The network visualization of the most co-occurring terms, generated using VOSviewer (Figure 3), revealed that "biodegradation" emerged as a significant keyword in the graph. Hovering over the terms highlights their relationships with others, with notable terms including "article," "non-human," "pesticide," "bacterium," and "chlorpyrifos." This indicates that research in this field is primarily related to these terms.

Figure 4 shows the co-occurrence of the most frequently used terms over the past 10 years, analyzing the most cited publications each year to determine research trends. The term "microorganisms" stands out starting in 2018 as a search driver, transitioning to the use of the keyword "wastewater treatment" by 2021. This shift reflects changes in research trends within the topic.

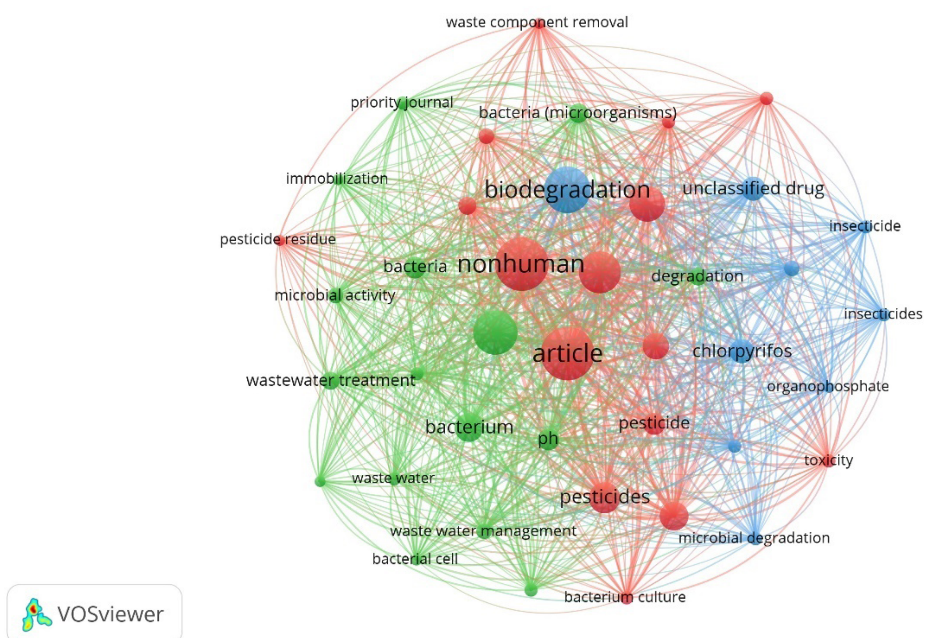

Figure 3. Network visualization resulting from the co-concurrence of keywords between publications.

Own elaboration from data generated by SCOPUS after being processed by VOSviewer.

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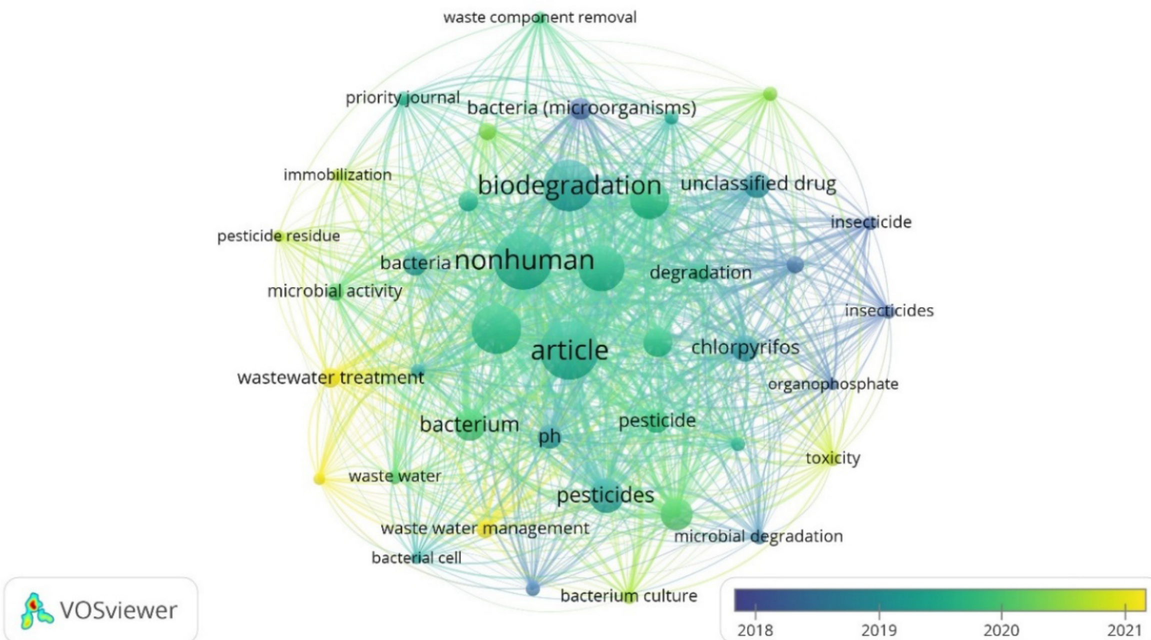

Figure 4. Network visualization resulting from the co-concurrence of the most used keywords in each year from 2014 onwards.

Source: Authors' elaboration based on data generated by SCOPUS after being processed by VOSviewer.

The results of author co-citation, using a selection criterion of at least 13 citations, are presented in Figure 5. A network visualization of three clusters was generated, highlighting authors Aamand J, and Zhang Y as the most cited.

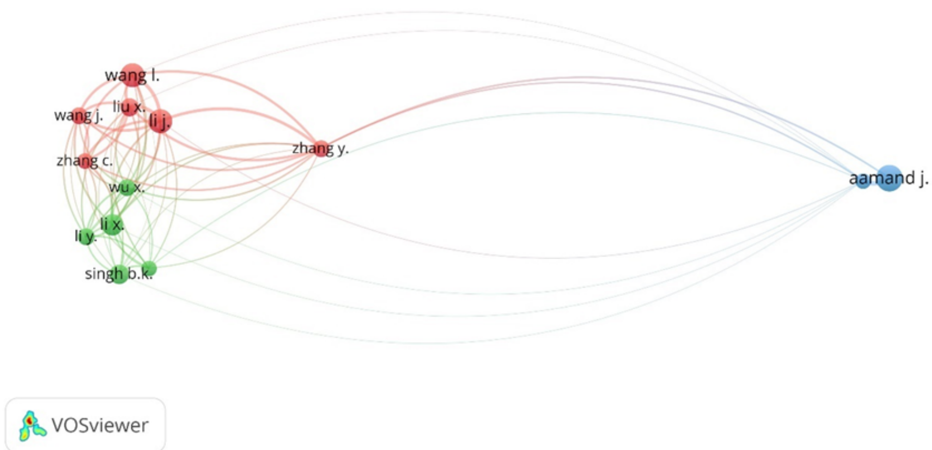

Figure 5. Visualization of co-citation networks in scientific publications.

Source: Authors' elaboration based on data generated by SCOPUS after being processed by VOSviewer.

The literature identifies organophosphates (OPs) as the most widely used pesticides in agriculture, with notable examples including dichlorvos, fenitrothion, dimethoate, parathion, chlorpyrifos, diazinon, and malathion (Silveira *et al*., 2018). The results demonstrate that the most studied OPs in terms of microbial degradation are chlorpyrifos, fenamiphos, tributyl phosphate, malathion, methyl parathion, and fenitrothion, which aligns with the findings of Cycoń *et al*. (2013). Our systematic review reveals that research trends on pesticides, specifically in water bodies, highlight studies related to chlorpyrifos (Liu *et al*., 2016; Singh *et al*., 2016; Lakshmipathy *et al*., 2018; Shi *et al*., 2019; Briceño *et al*., 2020; Govarthanan *et al*., 2020; Fang *et al*., 2021; Lourthuraj *et al*., 2022; Elzakey *et al*., 2023).

Various OP-degrading microorganisms have been reported, including species from the *Lactobacillus* genus and bacteria such as *Serratia liquefaciens*, *Serratia plymuthica*, *Pseudomonas putida*, and *Pseudomonas radiora* (Zhao & Wang, 2012). However, the microorganisms identified in this study predominantly belong to the genera *Pseudomonas*, *Enterobacter*, and *Bacillus* (Liu *et al*., 2016; Singh *et al*., 2016; Lakshmipathy *et al*., 2018; Shi *et al*., 2019; Zhao *et al*., 2019; Subsanguan *et al*., 2020; Zhang, Y. *et al*., 2020; Lourthuraj *et al*., 2022; Elzakey *et al*., 2023).

Conclusions

The success of employing various bacteria in the degradation of pesticides in water bodies is influenced by multiple factors, including microorganism resistance, the concentration and type of contaminant, humidity, pH, and temperature. The analyzed studies reveal that microbial consortia offer superior degradation potential, with three bacterial genera standing out: *Pseudomonas*, *Enterobacter*, and *Bacillus*.

The results of the bibliometric analysis provide valuable insights into current research trends in this field. Our study highlights the prominence of countries such as China, Denmark, and Egypt in scientific production related to this topic. Additionally, the analysis identified leading researchers, scientific communities with the highest output, and research centers at the forefront of the field, offering a detailed map of contributions and international collaborations in this critical area.

Author Contributions

"Conceptualization of the work, I.M.F., L.D.O.M.; Methodology development, I.M.F., L.D.O.M., V.R.S.; Software management, I.M.F., L.D.O.M., J.J.C.A.; Results analysis and data management, L.C.M., J.B.L.M.

All authors of this manuscript have read and approved the published version."

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Conflict of Interest

The authors declare no conflict of interest.

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