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MAPPING THE SCIENTIFIC LANDSCAPE OF ENVIRONMENTAL POLLUTION RESEARCH: A BIBLIOMETRIC APPROACH

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Abstract
This bibliometric analysis maps global research on the impacts of environmental pollution on biodiversity from 1990–2024. Using Scopus data processed with VOSviewer, Bibliometrix, and OpenRefine, the study identifies major publication trends and thematic structures. Research output surged after 2015, mirroring rising concern about ecosystem degradation. The United States and China dominate publication volume and collaboration networks. Core themes include heavy metals, microplastics, and persistent organic pollutants, with increasing focus on bioaccumulation, biomagnification, and ecosystem health risks. Thematic evolution shows a transition toward interdisciplinary and risk-oriented studies. Findings highlight geographic and funding disparities, underscoring the need for broader international participation. Despite database and keyword limitations, this study offers insights into how scientific communities respond to pollution-driven biodiversity loss and provides an evidence base for policy, education, and coordinated global research.

Keywords: Bibliometrics, biodiversity, environmental pollution, global research, publication trends

Introduction

Environmental pollution is one of the most critical global challenges of the 21st century, threatening ecosystems, human health, and the stability of the biosphere. Industrialization, urbanization, and intensive agriculture have raised concentrations of heavy metals, persistent organic pollutants (POPs), plastics, and airborne toxins across multiple ecosystems (Lee *et al.* 2023). These pollutants disrupt ecological processes, degrade habitats, and trigger bioaccumulation and biomagnification, which reduce species survival and reproductive success (Zhang *et al.* 2024, Schoenke *et al.* 2025). Pollution affects not only biodiversity but also ecosystem services and socio-economic stability. Contaminants such as pesticides and heavy metals accumulate along food chains, damaging trophic interactions and increasing extinction risks. Growing research attention since the *Aichi Biodiversity Targets (2010–2020)* and *Paris Agreement (2015)* illustrates the escalating global response to pollution-driven biodiversity loss (Okedele *et al.* 2024). Bioaccumulation denotes the gradual buildup of substances such as pesticides or metals within organisms, while biomagnification reflects their increasing concentration within trophic levels—especially relevant to Persistent Organic Pollutants (POPs) that persist in the environment and threaten wildlife and humans through reproductive and immunological disruption. Anchored in socio-ecological and sustainability frameworks, this study views pollution, biodiversity loss, and human health as intertwined within a complex adaptive system. Rising anthropogenic pressures on air, water, and soil disturb ecological balance and trigger cascading impacts. Scientific research both documents and mediates these impacts; bibliometric analysis provides an evidence-based lens to trace how global science conceptualizes and addresses these challenges (Bettencourt & Kaur 2011, Judijanto & Muhtadi 2024). Accordingly, this work conducts a comprehensive bibliometric study of global literature on environmental pollution and biodiversity (1990–2024). It identifies major publication trends, influential contributors, thematic structures, and collaboration patterns, while integrating cross-links with human health and ecosystem services to deliver a holistic picture of research evolution.

Materials and Methods

Study period and location. The analysis was performed from December 2024 to January 2025 at the *National Research and Innovation Agency (BRIN)*, Cibinong, Bogor, Indonesia. The period 1990–2024 was chosen because the volume of relevant research increased sharply after 1990. Earlier records were sparse and inconsistent, providing limited insight into modern research trajectories.

Sources of data and approach to searching. *Scopus* was selected as the primary database for its broad coverage, metadata standardization, and robust citation tracking widely adopted in bibliometric research. The search query—TITLE-ABS-KEY (pollution) AND (environmental AND contamination) AND (air AND pollution) AND (water AND pollution) AND (soil AND pollution)—was executed on 10 February 2025, yielding 2,026 records. After screening and filtering for relevance and eligibility, 1,200 articles remained for analysis. The data retrieval and screening workflow is summarized in Figure 1. The use of multiple AND operators intentionally captured studies integrating several pollution dimensions (air, water, soil), though it may have excluded single-domain investigations—a limitation acknowledged during interpretation.

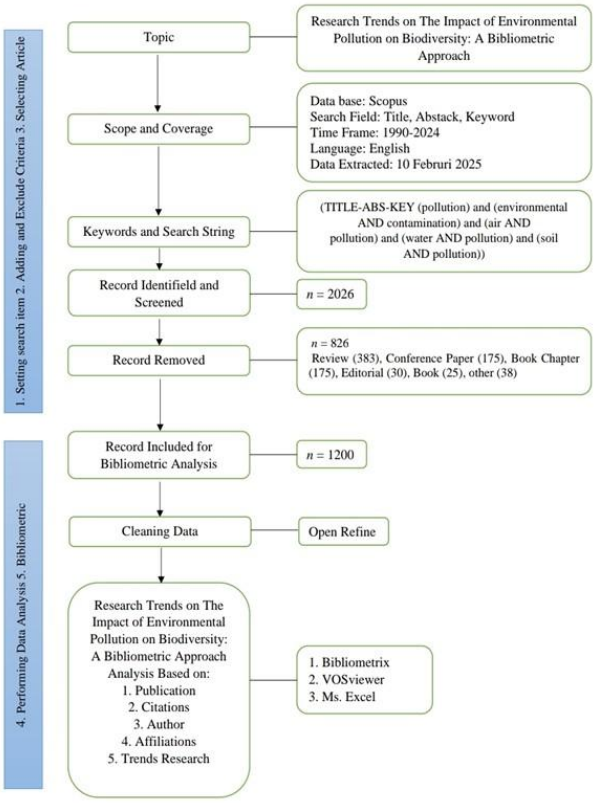

Figure 1. Data retrieval flow diagram for bibliometric analysis

Exclusion criteria and data cleaning. Eligible publications met the following conditions: indexed in Scopus, English-language, peer-reviewed articles (1990–2024), and directly related to environmental pollution. Conference proceedings, book chapters, editorials, letters, and non-English materials were excluded (Fahimnia *et al.* 2015, Prihambodo *et al.* 2025). Data refinement was performed with OpenRefine, ensuring uniform author names and keyword harmonization through key-collision and nearest-neighbour clustering (e.g., “Wang Y.”, “Y. Wang”, “Wang, Y.” merged). Synonyms such as “environmental pollution” and “pollution, environmental” were unified to prevent fragmentation. These procedures improved accuracy in co-authorship and co-occurrence analyses.

Bibliometric analysis. Two analytical platforms were applied:

1. VOSviewer (v1.6.18)—for constructing visual networks of co-authorship, keyword co-occurrence, citations, and bibliographic coupling (Van Eck & Waltman 2018).
2. Bibliometrix (v4.2.1) in R Studio—complemented by Excel for statistical exploration—covering publication growth, citation performance, H-index, author productivity, and thematic evolution (Aria & Cuccurullo 2017).

VOSviewer excels in generating intuitive distance-based visualizations but lacks advanced statistical flexibility, whereas Bibliometrix enables quantitative and conceptual mapping from structured metadata. Their combined use allowed robust visualization and interpretation of global research trends.

Analysis of publication trends. Publication frequency (1990–2024) was analysed to track the evolution of scholarship on pollution impacts on biodiversity. Annual outputs, document types, and disciplinary distribution were examined using descriptive statistics, revealing patterns of growth and variability. Time-series analyses were employed to detect turning points and rates of increase, visualized through graphs.

Thematic mapping and co-word analysis. Co-word relationships were analysed via *Correspondence Analysis (CA)* to identify conceptual structures. Two dimensions were extracted:

- **Dm1:** centrality—keyword relevance within the field.
- **Dm2:** density—maturity or development of each theme. High Dm1 keywords (e.g., *risk assessment*, *heavy metals*) represent core, well-integrated themes, while low Dm2 values (e.g., *groundwater pollution*) indicate emerging or underexplored areas (Sup. Table 3).

Results

Publication trends and total citations. From 1990 to 2024, 1,200 documents from 407 sources were identified (Sup. Table 1). Research output grew at 11.38 % per year, with an average of 42.48 citations per paper and a total of 5,099 authors, signifying strong global collaboration. Publications rose from 3 in 1990 to 117 in 2024, illustrating a sustained expansion in scholarly interest (Figure 2). While recent articles show lower citation rates due to lag effects, the overall trend demonstrates increasing visibility and relevance of the field. The near-zero citations observed in 2024 likely reflect the typical citation lag for newly published studies rather than a decline in research influence. This indicates that many papers published in 2023–2024 have not yet had sufficient time to accumulate citations, and their citation performance will only become evident in subsequent years.

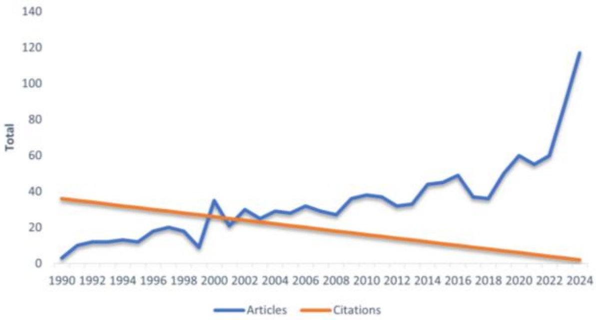

Figure 2. Annual count of scientific publications and citations (1990–2024)

The average citation rate per article (0.55) suggests a phase of rapid growth where publication quantity is increasing faster than long-term impact. The thematic mapping (Figure 3) provides a detailed visualization of the conceptual structure of the field across four quadrants. Soil pollution and environmental monitoring are positioned in the upper-right quadrant as core or "motor" themes, indicating high centrality and maturity, meaning they are well-developed and play a driving role in shaping the research landscape.

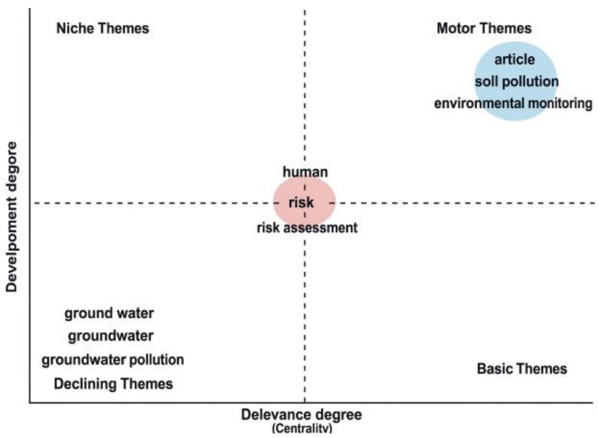

Figure 3. Thematic map of centrality and density of research themes

The central cluster containing risk assessment and human represents basic themes with strong relevance but moderate development, serving as foundational topics that support broader research directions. Groundwater, groundwater pollution, and related terms appear in the lower-left quadrant, signifying emerging or declining themes depending on their recent evolution; in this context, their positioning suggests emerging themes with potential for future exploration. The size of each bubble reflects the frequency of keyword occurrence, demonstrating the relative weight of each theme within the field. Overall, the thematic map highlights how established topics continue to dominate while simultaneously revealing areas where new research opportunities are beginning to grow.

Country scientific production. Country-level analysis (Sup. Table 2) shows that the United States and China dominate global output, each accounting for ≈ 19 % of co-authorship frequency (Figure 4). Italy (6 %), India (5 %), and France and Canada (4 % each) follow. Because multi-country papers are counted per affiliation, the totals exceed the unique document count. This distribution reflects both scientific capacity and policy investment: the U.S. and China lead due to funding initiatives and robust environmental networks. European nations (Italy, France, Germany) maintain strong regional programs under EU sustainability mandates. Biodiversity-rich countries such as Brazil and India remain underrepresented relative to their ecological importance, revealing a persistent geographical research imbalance.

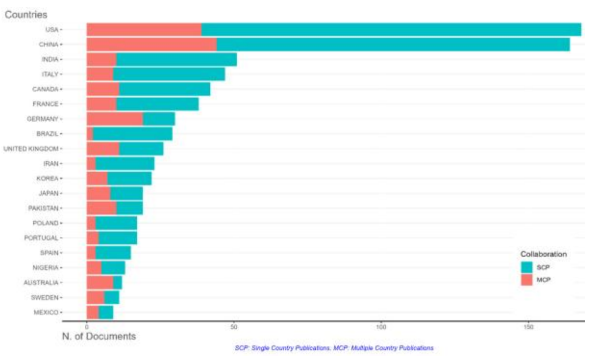

Figure 4. Countries of origin of corresponding authors in pollution–biodiversity research

Researchers with the highest publication output. The most productive authors include Huanhuan Zhang (13 papers), Xinxin Wang and Yuxing Wang (11 each), followed by Yingming Li (10) and Ziye Wang (9). Their collective output constitutes 1.4 % of total articles. H-index analysis reveals Yang Y as most influential (H = 8), followed by Li Y, Ma M, and Zhang X (H = 6–7). These relatively modest H-index values indicate that individual scholarly impact in this field is still developing, reflecting the emerging and rapidly expanding nature of the research area rather than the presence of highly established contributors.

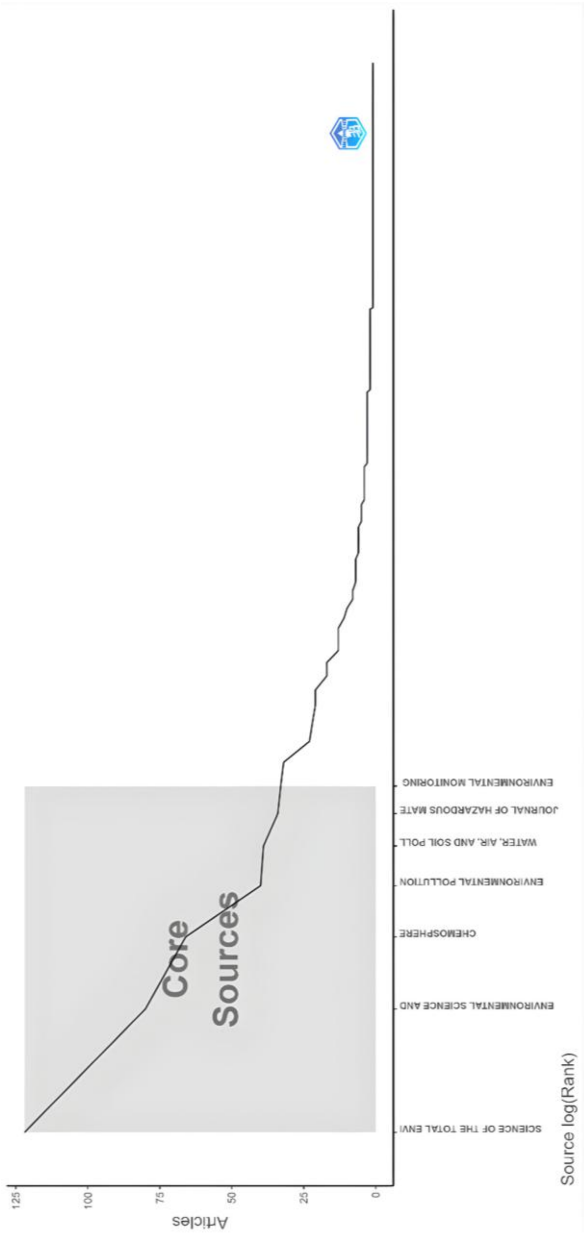

Figure 5. Core sources identified using Bradford's Law

Organizations producing the most publications. Institutional analysis identifies the Chinese Academy of Sciences as the top producer, followed by Beijing and Tsinghua Universities, and the Institute of Geochemistry. U.S. Indian, and European universities also rank highly. These patterns mirror national outputs and reflect strong research funding for pollution control and biodiversity studies. Institutions focused on *microplastics*, *heavy metals*, and *risk assessment* serve as major nodes linking interdisciplinary research themes.

Core sources and influential journals. Bradford's Law (Figure 5), which describes how scientific literature is distributed across journals by identifying a small core set that produces the highest number of relevant articles, shows that a few key journals dominate publication output. These core outlets include Science of the Total Environment, Environmental Science & Technology, Chemosphere, Environmental Pollution, Water, Air & Soil Pollution, and Journal of Hazardous Materials. Influence, as measured by H-index, ranks Environmental Science & Technology highest (H = 44), followed by Science of the Total Environment (39) and Chemosphere (29). Together, these journals serve as the primary communication channels for research on pollution and biodiversity.

Keyword clusters and thematic structure. Keyword co-occurrence (Figure 6) identifies five thematic clusters representing major research directions.

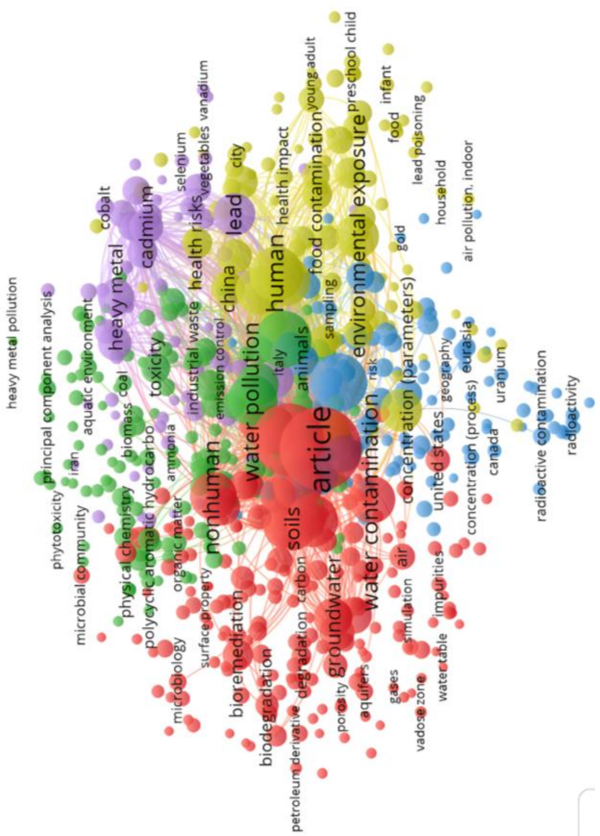

Figure 6. Co-occurrence network of author keywords showing five major clusters

The red cluster focuses on water–soil contamination and biological remediation processes. The yellow cluster captures themes related to human exposure and associated health risks. The green cluster reflects microbial and chemical interaction pathways. The purple cluster centers on heavy metal toxicity, while the blue cluster highlights radioactive and air pollution topics. Conceptual structure analysis (Figure 7) reveals three principal thematic groups. The purple cluster represents core environmental contamination topics air and water pollution, environmental impact, and monitoring showing high conceptual connectivity. The red cluster includes heavy metals, human exposure, and health hazards, which (Sup. Table 3) confirms as high-centrality concepts (Dim1 > 0.8). In contrast, the green and turquoise clusters covering soil pollutants, groundwater, and chemical contaminants—correspond to low-density themes (Dim2 < –0.8), indicating underdeveloped areas with future research potential. Together, these clusters highlight the field's multidisciplinary character across toxicology, environmental chemistry, and human health.

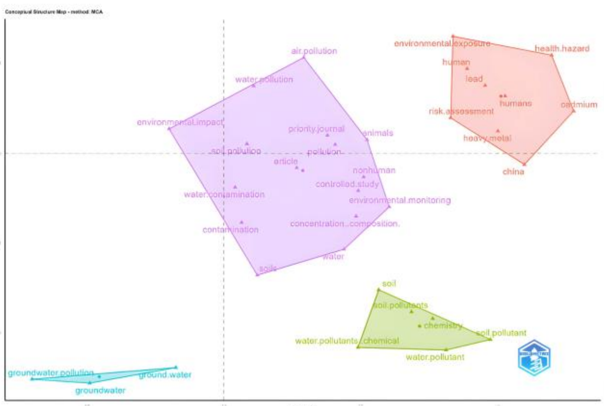

Figure 7. Dendogram impact of environmental pollution

Institutional affiliations, author networks, and collaborations. This is visualized through the three-field plots (Figure 8), which link institutions, authors, and dominant keywords. The Chinese Academy of Sciences exhibits strong connections to themes such as air pollution and soil contamination, while institutions in Europe and North America engage more with climate change, health risks, and ecological assessment. Core journals including Science of the Total Environment and Environmental Pollution serve as primary publication outlets for these highly connected institutions. Together, these visualizations demonstrate increasingly intensive cross-institutional collaboration across Asia, Europe, and North America, confirming the global and interconnected nature of pollution research.

Discussion

This analysis reveals a strong growth trajectory in global research on pollution's impact on biodiversity since 1990. The post-2015 surge aligns with international policy frameworks and increased public concern over environmental crises. Keyword trends indicate a progression from traditional pollution domains to emerging chronic contaminants (Akdogan & Guven 2019). China and the U.S. lead in productivity and collaboration (Wang B. 2024, Wang Q. *et al.* 2023). Global events such as the *Deepwater Horizon oil spill* (2010) and *Amazon wildfires* (2019) correlate with publication spikes, illustrating how ecological disasters drive scientific response.

Recent research emphasizes molecular-level assessment of pollutant impact, integrating genetic and biochemical markers (Singh *et al.* 2023, Sigmund *et al.* 2023, Winter 2024). This shift from ecosystem-scale to cellular analysis signals a more mechanistic approach to ecotoxicology. Persistent pollutants continue to reduce ecosystem productivity and affect health via endocrine and carcinogenic pathways (Johnston *et al.* 2015, Doyle *et al.* 2020, Edo *et al.* 2024). Cross-national collaboration networks—particularly China-U.S.-Germany—underscore increasing integration of scientific resources (Pan *et al.* 2024, Virú-Vásquez *et al.* 2024, Kennes 2023). Bibliometric patterns also reflect policy-driven research investment: China's *ecological civilization strategy* and the U.S. EPA and NSF programs have stimulated major research growth. The coinciding expansion of open-data platforms and advanced analytical tools has enhanced transparency and collaboration in pollution studies.

Soil pollution and chemical contaminants emerge as critical themes for agricultural sustainability and terrestrial biodiversity (B.K. Singh *et al.* 2014). Heavy metals and POPs alter microbial communities, reduce nutrient availability, and cascade through trophic chains. Groundwater pollution presents a rising concern linked to industrial effluents and agricultural runoff, posing risks for both ecosystem and human health (Andreas *et al.* 2021, Anjaria & Vaghela 2024).

The application of Bradford's Law verifies the dominance of a few key journals that shape research trajectories. These core sources not only disseminate high-impact findings but also set standards for methodology and policy translation. Concurrently, keyword evolution points to new paradigms in molecular ecology and risk evaluation, marking a shift toward quantitative, multi-level assessment of pollution effects.

Research Gaps and Future Directions. This bibliometric mapping reveals major progress in global studies on environmental pollution and biodiversity, but also clear knowledge gaps. *Groundwater contamination* and *soil pollutants* occupy the low-centrality, low-density quadrant of the thematic map, indicating underdeveloped yet vital areas. These themes demand more field-based and modelling studies that integrate terrestrial and subsurface systems, which remain overshadowed by surface-water and atmospheric research.

Although topics such as *microplastics* and *risk assessment* have surged since 2018, they require deeper interdisciplinary inquiry linking exposure pathways, trophic transfer, and cumulative ecological effects. Geographic imbalance persists: most publications originate from high-income countries (China, U.S., EU), whereas biodiversity-rich but underfunded regions—Africa, Southeast Asia, South America—remain under-represented. This asymmetry constrains the global perspective necessary for equitable policy frameworks.

To bridge these gaps, future work should:

1. Investigate neglected pollutant types such as emerging organics, nanomaterials, and groundwater toxins.
2. Conduct longitudinal impact assessments capturing chronic and synergistic pollution effects on biodiversity.
3. Enhance regional participation by expanding research infrastructure and open-access data in biodiversity hotspots.
4. Foster transdisciplinary networks combining ecology, toxicology, chemistry, and social sciences to co-produce actionable knowledge.

Interdisciplinary Nature of the Research Landscape. The keyword co-occurrence network and three-field plots confirm the inherently interdisciplinary nature of pollution–biodiversity research. Environmental toxicology, public health, ecology, and conservation biology converge through shared terms such as *heavy* *metals*, *toxicity*, *ecosystem services*, and *habitat loss*. Emerging associations with *climate change*, *urbanization*, and *policy* underscore integration with climate and governance studies (Najicha *et al.* 2023).

Institutional linkages show that environmental-engineering departments collaborate increasingly with life-science faculties, reflecting the convergence of technological mitigation and ecological restoration. Cross-disciplinary authorship patterns (Aria & Cuccurullo 2017) illustrate that biodiversity is now one pillar within a broader environmental-health continuum. Global co-authorship networks (Clayton *et al.* 2016, Davelaar 2010) demonstrate exchange across continents, reinforcing that solutions to pollution-driven biodiversity loss depend on shared data and hybrid methodologies. These patterns highlight that future advances will rely on maintaining open collaboration, standardized metrics, and synthesis between quantitative environmental modelling and socio-ecological resilience frameworks.

Conclusion. This study provides a three-decade bibliometric overview (1990–2024) of global research on the effects of environmental pollution on biodiversity. Output has grown steadily, peaking in 2024, with China and the United States leading production and collaboration. Dominant themes include *heavy metals*, *microplastics*, *risk assessment*, and *toxicity*, revealing the field's pivot toward chronic pollutants and health-linked ecological risks. Co-word and thematic analyses delineate mature domains (soil pollution, monitoring) and emerging frontiers (groundwater pollution, molecular biomarkers). Institutional and authorship mapping demonstrate extensive international cooperation and the convergence of environmental sciences, ecology, toxicology, and policy studies. Future research should expand into under-represented geographies, address soil and subsurface pollution, and promote cross-disciplinary collaboration to translate scientific insight into effective biodiversity and pollution-management policy. The findings offer a quantitative foundation for directing global research investments and educational strategies toward mitigating biodiversity decline.

Limitations. The Boolean query—TITLE-ABS-KEY (pollution) AND (environmental AND contamination) AND (air AND pollution) AND (water AND pollution) AND (soil AND pollution)—used multiple AND operators, potentially excluding studies on single-domain pollutants. Reliance on **Scopus** alone may omit non-indexed or regional literature, introducing language and database bias. Keyword variability can also distort thematic clustering despite harmonization efforts. Moreover, bibliometric indicators assess productivity and connectivity rather than research quality or policy impact. Thus, results should be viewed as reflective of publication behaviour, not a direct measure of scientific merit. Future analyses should integrate multiple databases (e.g., Web of Science, Dimensions), adopt inclusive multilingual search strategies, and complement quantitative mapping with qualitative review of policy influence and methodological rigor to construct a more nuanced global synthesis.

Author contributions

RM, WW conceptualized the study and designed the search strategy; RM, NQ collected the data and performed the bibliometric analysis using Bibliometrix and VOSviewer; AS, AE interpreted the data and contributed to the writing of the results and discussion; IGN, YY, RM reviewed the manuscript critically for intellectual content and assisted with revisions.

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Supplemental data

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