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Scientometric analysis on persistent organic pollutant in aquatic system from 1984 -2025

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Abstract

Persistent organic pollutants (POPs) are long-lasting synthetic chemicals that contaminate aquatic systems through agricultural runoff, industrial effluents, atmospheric deposition, and wastewater discharge. Their persistence, lipophilicity, and resistance to degradation enable long-range transport and extensive bioaccumulation in aquatic organisms, ultimately exposing humans through seafood consumption. These pollutants are linked to reproductive disturbances, metabolic disruption, neurological impairment, and elevated chronic disease risks. This scientometric analysis examines global POP research in aquatic environments from 1984 to 2025 (data retrieved from scopus and WOS) evaluating publication growth, influential authors and institutions, collaboration patterns, and keyword evolution. Research output rose sharply after 2001, driven by increasing environmental awareness and advancements in analytical technologies. Keyword mapping highlights major themes such as bioaccumulation, toxicity, environmental monitoring, and emerging contaminants like microplastics. Collaboration trends show strong contributions from small and medium research groups, with citation impact influenced more by publication quality than quantity. Overall, POP research exhibits rapid interdisciplinary expansion and growing global relevance.

Keywords: Persistent Organic pollutant, scientometric analysis, Scopus, WOS, R packages, VOSviewer, Network

Introduction

Persistent organic pollutants (POPs) are a group of synthetic organic components which are capable of environmental contaminating matters that distributed all over the ecosystem. These contaminants are produced variety of paths, involving agricultural run -offs, direct release from industrial effluent, atmospheric overthrows and unintentional by products [1, 2]. Effective control of POPs remains challenging, as ongoing research into technologies and methodologies struggles to fully counteract their destructive environmental and health effects [3]. Direct releases from manufacturing, such as PCBs used in electrical equipment or OCPs in pesticides, contribute to point-source pollution in rivers and estuaries [4]. In urban and estuarine environments, proximity to human activities like urbanization and industrialization amplifies inputs, with wastewater treatment plants (WWTPs) serving as hotspots for POPs and related emerging contaminants due to incomplete removal during treatment [5, 6].

POPs are transported for long distances through prevailing wind currents before being deposited into aquatic systems via atmospheric deposition. This long-range transport is a defining characteristic of POP conduct, enabling these chemicals to reach and contaminate remote oceanic regions far removed from their original emission sources. In addition to atmospheric inputs, POPs enter marine environments through riverine discharge and wastewater effluents originating from industrial and agricultural activities, leading to direct contamination of coastal waters [7–10].

The degree of this pollutant to transfer into multiple biotas by bioaccumulation and magnification due to its unique properties like lipophilic nature and resistant to breakdown [11–13]. For instance,

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Persistent Organic Pollutants (POPs), including polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs), polychlorinated biphenyls (PCBs), and dichloro-diphenyl-trichloroethane (DDT), demonstrate high resistance to natural breakdown, necessitating 3.5 hours of UV irradiation at 254 nm in hexane for complete degradation [14]. The synergetic effects between nanosized microplastics and POPs underscore the increased bioaccumulation risks in environments where both pollutants coexist [12].

Human exposure to persistent organic pollutants (POPs) occurs mainly through the consumption of contaminated seafood. Fish, shellfish, and marine mammals at higher trophic levels accumulate significant POP concentrations, placing coastal populations and communities dependent on seafood at greater risk [15–17]. Over the last two decades, these pollutants have been linked to multiple metabolic and physiological disorders. POPs disrupt reproductive health, with studies showing endocrine interference, reduced sperm quality, and negative effects on fertility in both men and women [18–22]. Cardiovascular impacts include altered lipid metabolism, inflammation, and increased risks of myocardial infarction and stroke, with prenatal exposure posing long-term metabolic consequences [23, 24]. Furthermore, POPs weaken the immune system, increasing susceptibility to infections and autoimmune disorders. The elimination of POPs is really tough and understanding the mechanism is major concern. The scientometric analysis of POPs will reproduce all the necessary clarity and this study provides the combined data and insights of the research from extracting different databases.

Methodology

The present study' research plan is illustrated in (Fig. 1). The initial phase, as depicted in fig, was data acquisition for creation of dataset for mining the literature articles. Among the most popular database available including PubMed, Google Scholar, EBSCO Applied Science and Technology, CiteseerX, ISI Web of Science, Scopus, Dimension and Lens, Scopus and ISI Web of Science (WOS) were used to extract bibliometrix data on persistent organic pollutant in aquatic life from 1984 to 2024 for this study. The multiple relevance database of science and technology sector, Scopus and WOS is most reliable sources of information spinning between diverse publication encompassing research articles, review, conference paper, editorial and notes [25].

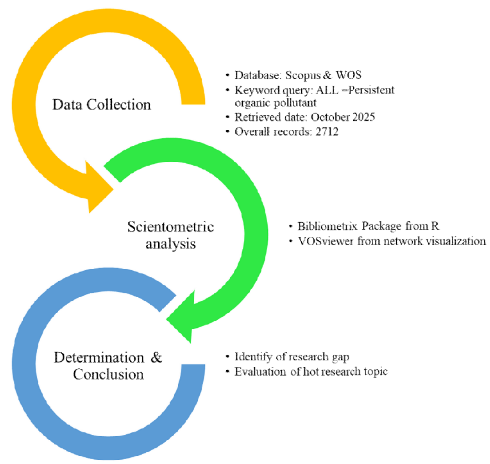

Fig. 1: Research Flow design of present study

The query search keywords “Persistent Organic Pollutant AND Aquatic” was employed in the advance search mode of both the database scopus and WOS collection for this investigation. The datasets were meticulously verified to ensure the correctness of the data gathered. The range of publication, documentation type, language used, authorship and source collaboration relevant to the topics were summarized with R package These data were documented by exporting from WOS as “Plain text” and scopus as “Common Separated Values”, and further analysis were carried out with application such as VOSviewer, BibExcel and R biblioshiny package [26–28].

The citation data was analysed using BibExcel Software [29]. CitNetExplorer, VOSviewer and Citespace are some handy visualization software available for access to

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generate the concept maps and image representations from author level contribution to country level collaborations [30]. This study elucidated the biblio-coupling, co- citation analysis, citation and co-occurrence using the java based VOSviewer application and constructed network visualization [31, 32]. Biblio-coupling measures the degree of connection between two entities (such as journals, authors, institutions, or countries) based on the number of shared references they cite. The strong point of their relationship is classically assessed by the number of shared citations. Co-citation is used to compare between two items with third publication and if two of them are cited in the same source, the co- citation links are formed. The specific keywords appear in together in different articles with high frequencies indicates the robust association between the research trend in particular sector is described with co – occurrence analysis [33, 34].

Annual data entities in Microsoft excel quantified the measurement of the collaborative index, which depicts the approx. count of author per publication, and collaborative degree indicating the ratio of articles with single author and multiple authors [35, 36]. Further, the study calculated the overall global citation value and overall local citation score. These values represent the number of publications cited with local datasets or throughout the scopus and web of science records at the time data collection [37, 38].

Results

Basic Information extracted

In the June 2025, the Web of Science yielded a sum of 1838 unique papers in text format and 1840 articles from scopus as common separated files for the present study using the query terms as mentioned earlier. There were almost 884 common publications in this study field which were merged to get 2712 unique article data, hence the database search revealed findings from 1984 to 2025, a 41 -year duration.

Document types of publication

The total paper related to Persistent organic pollutant, were categorised into 10 distinct document formats. The most common was research articles accounting for 71.3% (n= 1932) of all document category, followed by review papers about 461 (17.02 percent), book chapters (n= 178, 6.5%), proceeding (n=91, 3.36 percent), conference paper (n=27, 0.99 %), editorial (n =11, 0.4%), notes (n= 11, 0.4%) and others (4, 0.1%). Within this document classification, about 97.7% papers were man scripted in English. Followed by, Chinese (39, 1.4 percent), French (6, 0.22 percent) and German (0.07 percent) and other non- English language like Arabic were also contributed to this study.

Annual publication trends

Global evolution in the research of persistent organic pollutant can be elucidated by seeking the findings which have been diverged through durations. The graph displays the annually and total of papers along with citations per year of cumulative of all publication on that period from 1984 to 2025. Two major phases are apparent from the bar chart in (Fig. 2 a & b):

1. Determinative phase (from 1984-2003): Till 1989, the number of publications were less than 10 per year were documented on specified subject topic, identifying a declined activity in publications. Prior to 2000, less than a fifty document were made public. This depicts that this importance of study has not gained much consideration in the academical community. Since the years after 2004, this graph shows a steady increase in the study area, indication a strong attention in the field of research.
2. Exponential Phase (from 2004 to 2024): The year 2004 marks a clear turning point in the research trajectory, as reflected by the sharp upward shift in the cumulative publication curve. Annual publication yield amplified hastily, rising from fewer than 30 articles in the mid-2000s to over 100 by 2015. This accelerating trend continued into the following decade, with yearly publications consistently exceeding 150 and eventually surpassing 250 articles by 2021–2024.

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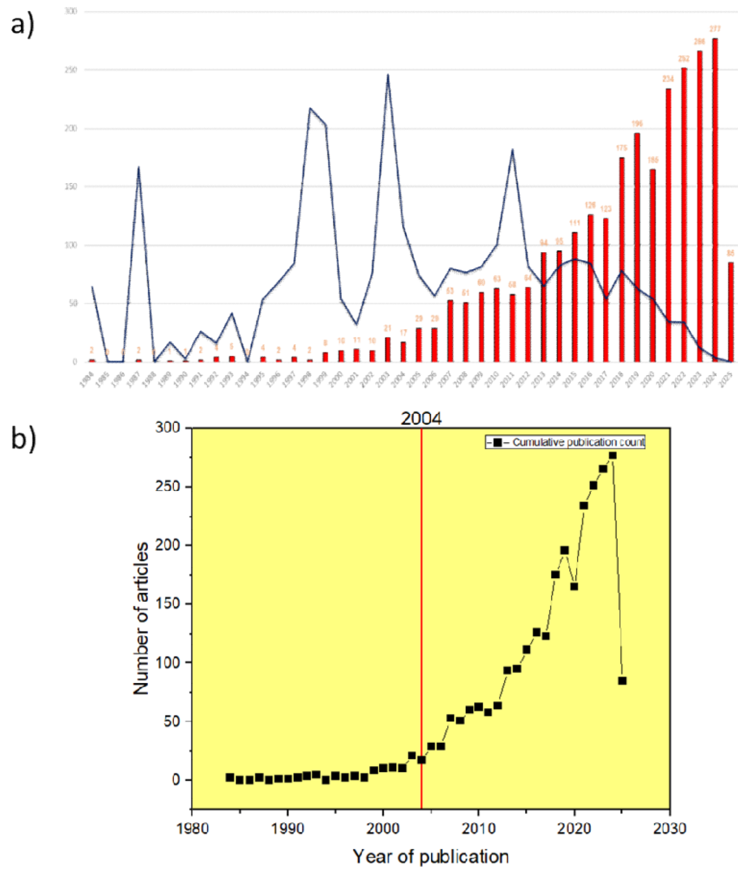

Fig. 2: (a) Number of articles published over a definite period (1984-2025), (b) Cumulative count of documentation with exponential progress design

Journal Category Analysis

The bibliometric study has crucial requirement to understand the dispersal of article produced in varying categories related to a specified topic's outcomes [39]. Persistent organic pollutant may always get categorized in the matter of the domain in which specific topics are highly predominant. RStudio tools was used to evaluate the combined data from scopus and WOS on the scientific categories, and depicted in (Fig. 3). "Environmental Science," "Engineering, environment," "Toxicology," "Marine and Freshwater biology" and "Water Resources" were the most prevalent categories, with 1305, 301, 257, 203 and 150 publications,

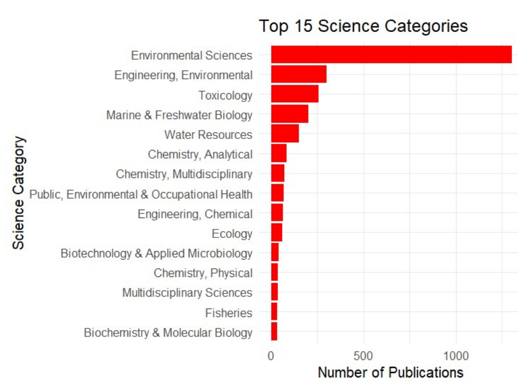

Fig. 3: Top 15 science categories with at least 30 publications

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accordingly. Field of research such as chemistry, marine and freshwater biology, environment science and biotechnology is major contributors in highest portion of whole study in this initial study area.

Publications (journal) that scientifically discussing the concern on persistent organic pollutant have been helping the researchers to deeply understand these topics and further researching. Over 1200 articles are published on persistent organic pollutant. Based on Table 1, we observe 20 uppermost cited publications on this topic (until 2025). Starting from Science of the total environment with 331 publications, and Chemosphere with 163 articles, Environmental pollution journal has highest publications (153). The citation per paper (CPP_{2025}) till 2025 was calculated by average citation of papers published in specific journal to the overall publication paper count. The most cited articles were recorded in Environment international (CPP_{2025} = 170.57), followed by Water research with 145.85, Environmental science and technology (128.66) and Marine pollution bulletin (122.714) among all productive journals. The CPP_{2025} for marine and freshwater biology articles was 43.474. Further, the toxicology studies (128.66) are predominant research area.

The VOSviewer tool analysis of bibliographic coupling networks were constructed to determine the linking strength among the sources (Fig. 4).

Country based analysis

The author contribution of minimum one person from a nation were estimated basedon affiliations in this current title. Almost, count of all 2526 papers in RStudio evaluation revealed research performance of author(s) affiliated to 87 countries. The geographical distribution of publications demonstrated clear regional variation, with Asia contributing the highest research output across 23 countries, accounting for 1033 publications. Europe followed with 862 publications from 31 countries, reflecting strong scientific productivity across Germany, Italy, France, Spain, Switzerland, the Netherlands, Belgium, and the United Kingdom. The Americas collectively produced 485 publications, largely dominated by the United States, Canada, and Brazil. Among the top 20 most productive countries globally, there was broad regional diversity, with multiple Asian (China, India, Korea, Japan), European (Germany, Italy, France, Spain, Switzerland, the Netherlands), and American nations (USA, Canada, Brazil) represented. Countries such as the United States, Canada, Germany, France, Italy, Japan, and the United Kingdom consistently ranked among the global leaders in scientific productivity.

A total of 618 publications from China place it as the most productive country in terms of total papers, reflecting 22.95% of global output. However, its 28,162 citations rank it lower in citation impact, with a CPP_{2025} of 45.57. The Netherlands, despite producing only 45 papers, stands out remarkably with 12,640 citations, giving it an exceptionally high CPP_{2025} of 280.89, the highest among all listed countries. In contrast, several countries with smaller publication counts exhibit exceptional citation influence. The Netherlands, with only 45 papers, has accumulated 12,640 citations, resulting in an outstanding CPP_{2025} of 280.89, the highest among all nations listed. Similarly, England (35 papers) and Switzerland (35 papers) demonstrate high citation efficiency with CPP_{2025} values of 163.4 and 121.57, respectively. These counts suggest that although their research volume is limited, the scientific impact of each publication is considerably higher. On the lower-impact end, India, despite being one of the more productive contributors with 139 publications, registers only 2,209 citations, resulting in a considerably low CPP_{2025} of 15.89—the lowest among the top-listed countries. Other nations such as Brazil (CPP 24.48) and South Africa (CPP 33.79) also exhibit modest citation performance relative to their publication outputs (Table 2).

The publication linkages that have published more than ten articles are linked through citation networks and bibliographic

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Table 1: Top 20 most prolific sources that have published the most on persistent organic pollutant

Journal	Tp	Tc	Norm. Citations	CPP_{2025}	Scientific Category
Science Of the Total Environment	331	17533	84.542	52.970	Environmental Sciences
Chemosphere	163	10873	52.428	66.706	Environmental Sciences
Environmental Pollution	153	12913	62.265	84.399	Environmental Sciences
Environmental Science and Pollution Research	91	3009	14.509	33.066	Environmental Sciences
Environmental Science & Technology	87	7521	36.265	86.448	Engineering, Environmental
Marine Pollution Bulletin	84	10308	49.704	122.714	Environmental Sciences
Aquatic Toxicology	78	3391	16.351	43.474	Marine & Freshwater Biology
Water Research	71	10356	49.935	145.859	Engineering, Environmental
Journal Of Hazardous Materials	70	3364	16.221	48.057	Engineering, Environmental
Environmental Toxicology and Chemistry	63	3617	17.441	57.413	Environmental Sciences
Environmental Science and Technology	50	6433	31.019	128.660	Toxicology
Ecotoxicology and Environmental Safety	46	3486	16.809	75.783	Environmental Sciences
Environment International	40	6823	32.900	170.575	Environmental Sciences
Environmental Research	36	1392	6.712	38.667	Environmental Sciences
Environmental Monitoring and Assessment	28	636	3.067	22.714	Environmental Sciences
Archives Of Environmental Contamination and Toxicology	21	287	1.384	13.667	Environmental Sciences
Water Air and Soil Pollution	19	534	2.575	28.105	Environmental Sciences
Water Environment Research	17	260	1.254	15.294	Engineering, Environmental
Ecotoxicology	16	426	2.054	26.625	Ecology

Tp- total publications, Tc- total citation of all documents till 2025, Norm. citation- citation normalized value for all documents, CPP_{2025}- citations per publication (total citation per total publications)

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Table 2: Top 20 most productive countries related to persistent organic pollutant

Country	TP	TP (%)	Citation	Norm. Citations	CPP2025
China	618	22.95	28162	46.626	45.57
Netherlands	45	1.67	12640	20.927	280.89
United States	101	3.75	10767	17.826	106.6
Canada	158	5.87	10366	17.162	65.61
Germany	115	4.27	9708	16.073	84.42
Italy	101	3.75	6242	10.334	61.8
England	35	1.3	5719	9.469	163.4
France	86	3.19	5148	8.523	59.86
Spain	102	3.79	4315	7.144	42.3
Switzerland	35	1.3	4255	7.045	121.57
Australia	58	2.15	3962	6.56	68.31
Belgium	42	1.56	3589	5.942	85.45
Norway	52	1.93	2984	4.94	57.38
Sweden	40	1.49	2779	4.601	69.47
United Kingdom	24	0.89	2323	3.846	96.79
India	139	5.16	2209	3.657	15.89
Portugal	24	0.89	1853	3.068	77.21
Brazil	75	2.78	1836	3.04	24.48
Malaysia	16	0.59	1274	2.109	79.62
South Africa	33	1.23	1115	1.846	33.79

TP-Total publications, Norm. citations- normalized number of citations received by the articles, CPP_{2025} - citations per publication (TC_{2025}/TP)

coupling, which is depicted in (Fig. 5 a & b). Figure 5a, contributed to the distribution among all the countries and intensity in the color shows higher number publication from that particular region. 44 Nations were classified into 13 clusters based on biblio-coupling. Cluster 21(yellow) including 26 countries or nodes which was dominated by Asian countries, in which China being the predominant producers. The other clusters where interlinked with minimum of only one to five articles in each cluster (Fig. 5 b).

Institutes

For postdoctoral assignments, research discussion programs, and academic study tours, institutional performance analysis is essential for recognizing leading research hubs within a specific domain. In the context of POPs-related research, the period under review highlights several institutions that have demonstrated notable impact based on total publications (TP), citation volume, CPP_{2025}, citation percentage, and normalized citations. As shown in Table 3, although each of the top-listed institutions contributed only a single publication (TP = 1), their citation influence varied substantially. North Carolina State University ranked first in citation performance with 5,770 citations and a CPP_{2025} value of 2,885, accounting for 4.02% of total citations—indicating exceptionally high

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research influence despite minimal publication count. The Omegam Environmental Research Institute, with 4,075 citations and the highest CPP_{2025} score (4,075), also showed strong impact, contributing 2.84% of global citations.

Similarly, institutions such as VU University (2,468 citations), University of Cambridge (1,776 citations), and Jiangsu University (1,724 citations) were among the notable contributors, each demonstrating substantial citation strength relative to their

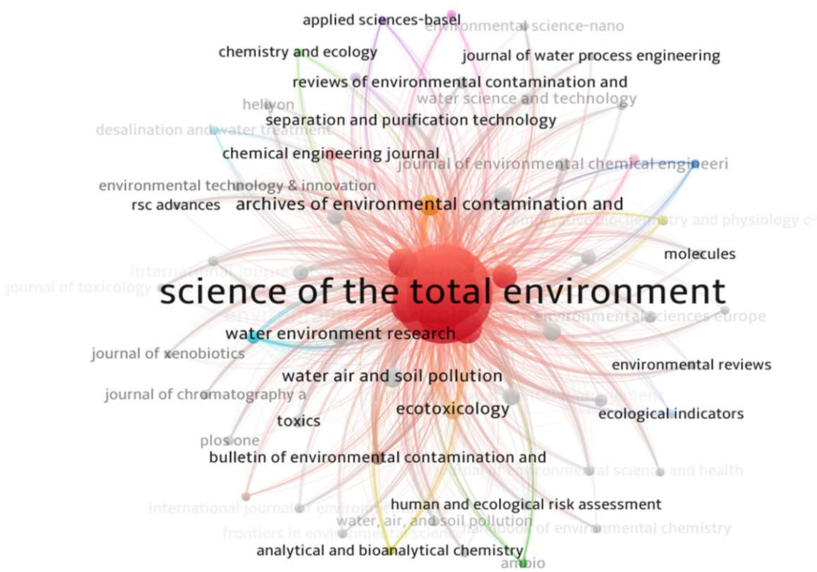

Fig. 4: VOSviewer network visualization of bibliographic coupling between sources

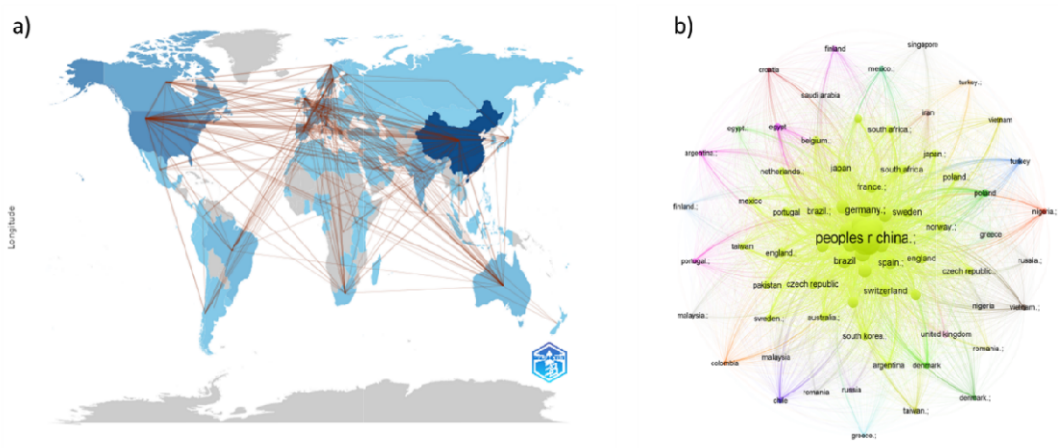

Fig 5: (a) Geographic distribution of the persistent pollutant detection research outputs and the cooperative network among the countries. Intense colors specify the country's largest productivity. (b) Network visualization of bibliographic coupling between countries

Scientometric analysis

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Table 3: Top 15 most cited institutes related to persistent organic pollutant

Institution	Total Citation	TP	CPP_{2025}	Citation (%)	Norm. Citations
North Carolina State University	5770	2	2885	4.02	92.354
Omegam Environ. Research Institute	4075	1	4075	2.84	65.224
Vu University	2468	1	2468	1.72	39.503
University Of Cambridge	1776	1	1776	1.24	28.427
Jiangsu University	1724	1	1724	1.2	27.594
Universite Gustave-Eiffel	1608	1	1608	1.12	25.738
Swiss Federal Institutes of Technology Domain	1363	1	1363	0.95	21.816
Griffith University	1172	1	1172	0.82	18.759
University Of Antwerp	1169	1	1169	0.81	18.711
Hong Kong Baptist University	1163	1	1163	0.81	18.615
Lancaster University	1137	1	1137	0.79	18.199
Wageningen University	1132	1	1132	0.79	18.119
Marche Polytechnic University	979	1	979	0.68	15.67
University Of Plymouth	974	1	974	0.68	15.59
Ghent University	961	1	961	0.67	15.382

single publication. European and Asian institutions including Université Gustave-Eiffel, the Swiss Federal Institutes of Technology Domain, Hong Kong Baptist University, and University of Antwerp also achieved moderate to high normalized citation values, indicating well-recognized scientific contributions within the field. Other universities, including Lancaster University, Wageningen University, Marche Polytechnic University, University of Plymouth, and Ghent University, each recorded citation counts ranging from 961 to 1,137, reflecting consistent but comparatively lower citation influence. Overall, the analysis shows that even institutions with minimal publication counts can exert significant scientific impact if their research outputs are highly cited (Fig. 6). This indicates that, within persistent organic pollutant studies, the quality and influence of individual publications often outweigh the quantity, making these institutions attractive for advanced research training and academic collaborations.

Most productive cited articles and authors

The influence of authors within the selected research area varies significantly, as reflected by differences in publication counts, citation impact, and collaborative links. Authors such as Covaci Adrian, Gobas Frank A.P.C., and Loos Robert show high research visibility, supported by strong citation counts (1917, 1323, and 2408, respectively) and extensive co-authorship connections. Several researchers, including Ahrens Lutz, Braunbeck Thomas, and Zeng Eddy Y., also demonstrate notable contributions with consistently high citation averages and strong normalized citation scores. In contrast,

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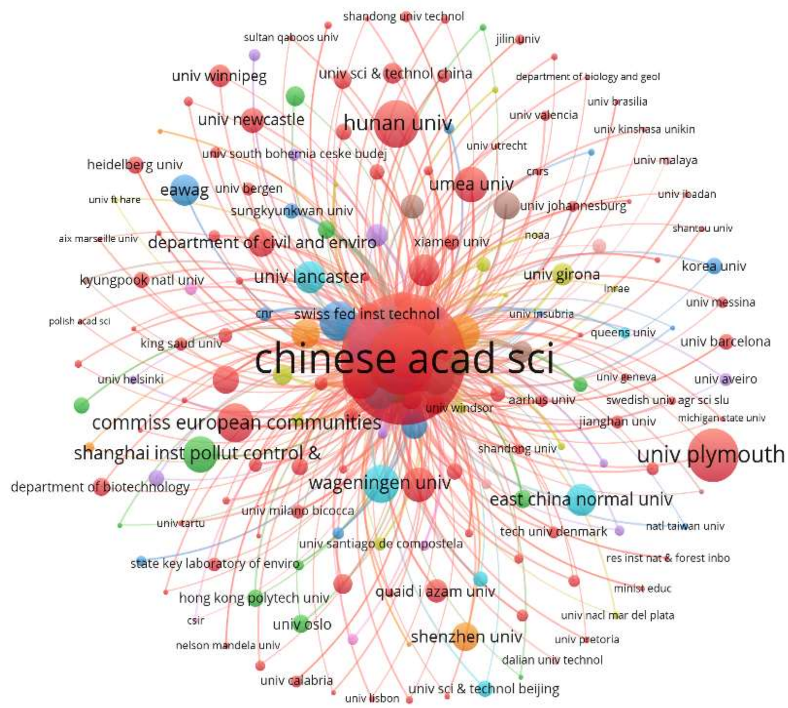

Fig. 6: VOSviewer network visualization of bibliographic coupling between institutes

emerging authors such as Miao Jingjing, Pan Luqing, and Zhao Yan have more recent publication years, indicating the entry of new contributors into the field. Overall, the findings reveal that both long-established researchers and newly active authors play important roles, with high-performing individuals distinguished by stronger link strengths, higher citation averages, and greater normalized impact (Table 4).

Author keyword analysis

A potential keyword datasets supports the enhancement of search strategies, enabling researchers to identify emerging themes and research frontiers in the field of persistent organic pollutants (POPs) [40, 41]. Using VOSviewer, a comprehensive co-occurrence map was constructed from the data's, revealing a strong network of interconnected terms that define the scientific landscape of POP-related studies networked in 12 Clusters. The analysis identified 241 occurrences of "Persistent Organic Pollutants", which also exhibited the highest link strength (609), highlighting its centrality in the research domain. Closely following this were keywords such as "Microplastics" (156 occurrences, 354 link strength) and "Bioaccumulation" (148 occurrences, 372 link strength), signifying the growing concern around contaminant transfer and trophic-level accumulation. POP-related abbreviations and subgroups such as "POPs", "PCBs", "PAHs", and "PBDEs" also appeared frequently, reflecting the diversity of pollutant classes investigated (Table 5).

Environmental matrices and biological indicators were strongly represented, with keywords such as "Sediment" (89 occurrences), "Fish" (81 occurrences), and "Wastewater" (48 occurrences), showing the emphasis on monitoring and ecological risk evaluation in aquatic environments. Keywords related to noxious effects and risk analysis—

Table 4: Top 10 most cited articles related to persistent organic pollutant

Title	Authors	Source	Year	Total citation
Microplastics in the marine environment	Andrady A	Marine Pollution Bulletin	2011	5769
Fish bioaccumulation and biomarkers in environmental risk assessment: a review	Van D O R;Beyer J;Vermeulen N	Environmental Toxicology And Pharmacology	2003	4075
Phosphorus flame retardants: properties, production, environmental occurrence, toxicity and analysis	Van D V I;De B J	Chemosphere	2012	2468
Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs	Eerkes-Medrano D;Thompson R;Aldridge D	Water Research	2015	1776
A critical review on the treatment of dye-containing wastewater: ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety	Al-Tohamy R;Ali S;Li F;Okasha K;Mahmoud Y;Elsamahy T;Jiao H;Fu Y;Sun J	Ecotoxicology And Environmental Safety	2022	1724
Advanced oxidation processes in water/wastewater treatment: principles and applications. A review	Oturan M;Aaron J	Critical Reviews In Environmental Science And Technology	2014	1608
Global water pollution and human health	Schwarzenbach R;Egli T;Hofstetter T;Von G U;Wehrli B	Annual Review Of Environment And Resources, Vol 35	2010	1363
Microplastics in wastewater treatment plants: detection, occurrence and removal	Sun J;Dai X;Wang Q;Van L M;Ni B	Water Research	2019	1172
Novel brominated flame retardants: a review of their analysis, environmental fate and behaviour	Covaci A;Harrad S;Abdallah M;Ali N;Law R;Herzke D;De W C	Environment International	2011	1169
Pharmaceuticals and personal care products (PPCPs): a review on environmental contamination in china	Liu J;Wong M	Environment International	2013	1163

including “Toxicity,” “Risk Assessment,” “Biomagnification,” and “Bioaccumulation”—further reinforce the scientific focus on understanding exposure pathways and health implications of these pollutants. Analytical methodologies are also well characterized, with recurring mentions of adsorption studies, chemical profiling, and pollutant quantification methods, underscoring their role in tracking contaminant fate and transport.

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Table 5: Top 25 Author Keywords in publications related to persistent organic pollutant based on occurrences and total link strength

Keywords	Occurrences Frequency	No. of Links	Total Link Strength
Persistent Organic Pollutants	241	229	609
Microplastics	156	158	354
Bioaccumulation	148	165	372
POPs	100	120	238
Pesticides	94	136	335
Risk Assessment	92	121	201
Sediment	89	112	224
PCBs	86	109	254
Fish	81	112	211
Toxicity	76	125	202
Pharmaceuticals	70	97	272
Organochlorine Pesticides	64	74	149
Adsorption	62	58	117
Persistent Organic Pollutants (POPs)	61	81	121
PAHs	59	84	151
Emerging Contaminants	56	69	125
Heavy Metals	55	92	154
Persistent Organic Pollutant	55	94	155
Metals	51	98	245
Polychlorinated Biphenyls	51	68	115
Polycyclic Aromatic Hydrocarbons	50	64	101
Wastewater	48	69	184
Biomagnification	45	75	138
Organic Pollutants	44	61	84
PBDEs	41	63	117

Moreover, the presence of terms such as “Pesticides,” “Organochlorine pesticides,” “Pharmaceuticals,” and “Emerging Contaminants” suggests the expanding breadth of POP-related research beyond traditional industrial pollutants to include newer classes of environmental contaminants. Collectively, the dominance of pollutant categories, environmental compartments, biological species, and assessment-related keywords within the top 20 highlights an integrated research approach—one that spans contaminant characterization, ecological risk assessment, and environmental monitoring. This pattern confirms that POP research continues to evolve toward understanding complex pollutant mixtures, multi-source contamination, and their long-term ecological impacts.

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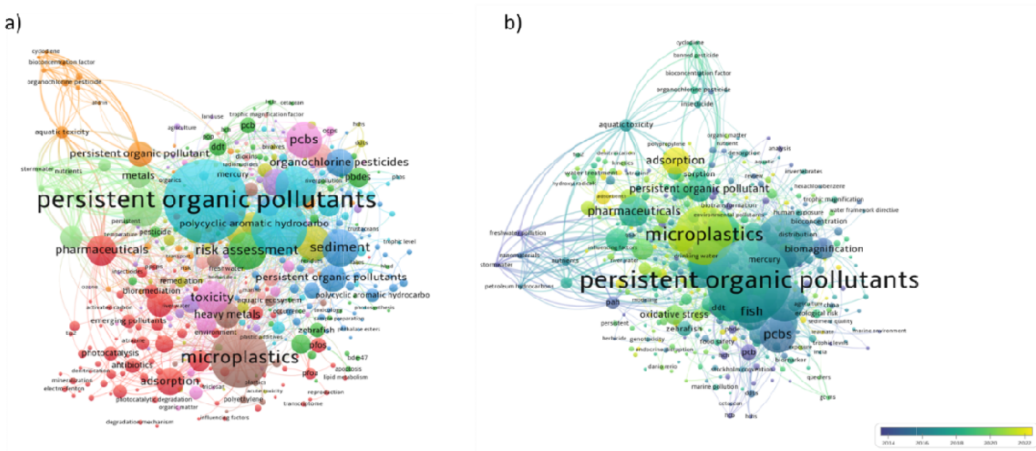

Fig. 7: Author keyword VOSviewer analysis: Co-occurrence visualization network (a) Time-wise overlay visualization (b)

Based on the VOSviewer co-occurrence mapping (as ca be seen in Fig. 7 a & b), Cluster 1 (Red) emerges as the largest and most influential group within the persistent organic pollutant (POP) research landscape. This cluster predominantly contains terms related to bioconcentration processes, aquatic exposure pathways, and ecological interactions, such as "bioconcentration," "marine environment," "aquatic organism," and "aquatic ecosystem." The appearance of keywords like "bioaccumulation," "biomagnification," "trophic transfer," "food chain," and "marine organisms" suggests that the red cluster is heavily oriented toward understanding how POPs move through food webs and accumulate across trophic levels. In addition, terms such as "arctic," "antarctica," and "marine mammals" indicate a strong focus on long-range transport and contamination in remote ecosystems, reinforcing the global-scale relevance of POPs. Cluster 2 (Green) is positioned toward the left region of the map and includes a diverse range of chemical contaminants and environmental matrices. Prominent terms such as "pesticides," "metals," "wastewater," "PAH," "endocrine disruptors," "freshwater pollution," and "nanomaterials" demonstrate that this cluster represents pollutant diversity, with emphasis on industrial inputs, urban discharges, agricultural runoff, and emerging contaminants. The coexistence of chemical pollutant groups with environmental compartments (e.g., freshwater, wastewater, stormwater) reflects cross-media contamination and mixed-pollutant scenarios. Cluster 3 (Blue) contains terms related mainly to environmental monitoring, regulatory assessment, and analytical frameworks. The presence of keywords such as "monitoring," "environmental pollution," "environmental contamination," "water," "contaminants," "passive sampler," and "Water Framework Directive" indicates that this cluster is associated with large-scale surveillance programs, pollutant quantification, and policy-driven environmental standards. Methodological terms like "modelling," "QSAR," "trophic magnification factor," and "analytical techniques" further indicate a methodological and prediction-oriented focus. Other medium and smaller clusters include terms like "PCBs," "toxicity," "microplastics," "sorption," "mixture toxicity," and "organic matter," representing specialized research niches. These address toxicological mechanisms, pollutant–particle interactions, sediment–water exchange processes, and

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the influence of natural organic matter on POP behavior.

Discussion and future perspectives

The scientometric assessment of persistent organic pollutants highlights a strong global research trajectory shaped by increasing environmental concerns and advancements in analytical technologies. The dominance of English-language publications reflects the global shift toward English as the primary medium of scientific communication, enabling broader visibility and citability [42]. Publication trends show that although research on POPs began in the 1980s, a significant rise occurred after 2001, coinciding with intensified environmental monitoring, emerging contaminant identification, and the development of modern analytical platforms. Countries with strong scientific infrastructure, particularly China, contributed most prominently to this growth.

Keyword mapping indicates that POP research has become increasingly interdisciplinary [43, 44].

Initial studies focused on broad pollution descriptors, whereas contemporary research expands across chemical behavior, toxicology, environmental transport, risk assessment, and emerging contaminants. High-frequency keywords such as persistent organic pollutants, microplastics, bioaccumulation, sediment, and toxicity underscore concerns about ecological exposure pathways, trophic transfer, and long-term environmental persistence. The presence of terms linked to sediments, marine organisms, wastewater, and atmospheric processes indicates that research now encompasses multiple environmental compartments. Cluster analysis shows that the largest cluster (Red) is centred on exposure pathways such as bioconcentration, trophic transfer, and ecological interactions. Other clusters highlight pollutant diversity (Green), monitoring and regulatory frameworks (Blue), and specialized domains such as sorption behavior, mixture toxicity, and chemical modelling. This clustering pattern demonstrates that POP research has broadened from basic contamination studies to complex environmental behavior and risk assessment frameworks [45, 46]. The institutional and authorship networks further show that quality often outweighs publication quantity. Institutions producing fewer but high-impact studies contributed disproportionately to citation strength. Despite broad global engagement, collaboration levels remain modest in some regions, with most outputs generated by small research groups. Nevertheless, increasing interdisciplinary journals and emerging collaborations suggest a growing convergence of environmental science, chemistry, toxicology, and ecological modelling.

Research paper keywords precisely and systematically represent the scientific content of each publication, and the keyword analysis clearly highlights the major thematic directions within POP research. The co-occurrence patterns reveal that terms such as “persistent organic pollutants,” “microplastics,” “bioaccumulation,” “pesticides,” “PCBs,” “PAHs,” “PBDEs,” “sediment,” “fish,” “wastewater,” “toxicity,” and “risk assessment” dominate the field. These recurrent keywords demonstrate the scientific community’s strong focus on pollutant distribution, ecological exposure pathways, and associated human and environmental risks [47–54].

“Persistent organic pollutants” emerged as the most frequent term, reflecting its central role in defining the research domain. Keywords linked to environmental compartments—including sediment, freshwater, wastewater, stormwater, marine environment, and aquatic organisms—show that studies commonly examine how POPs move through air–water interfaces, accumulate in aquatic habitats, and persist over long timescales. Terms such as bioaccumulation, biomagnification, trophic transfer, food chain, and marine organisms emphasize the importance of understanding the transport of POPs through biological systems and their amplification across trophic levels [55–60].

Overall, POP research displays continuous expansion, shaped by evolving environmental challenges, advances in detection techniques, and rising awareness of chemical risks. Research gaps identified through keyword and trend analysis suggest the ongoing need for studies on mixture toxicity, emerging POPs, long-range transport, and human exposure pathways—ensuring that this field will continue to develop rapidly in the coming years.

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