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# Investigating the research landscape of chlorinated paraffins over the past ten decades

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Chlorinated paraffins (CPs) are classified as emerging persistent organic pollutants (POPs). Due to their associated environmental and health impacts, these groups of chemicals have been a subject of interest among researchers in the past decades. Here we used a scientometric approach to understand the research landscape of CPs using literature published in the Web of Science and Scopus database. RStudio and VOSviewer programs were employed as scientometric tools to analyze the publication trends in global CP-related research from 1916 to 2024. A total of 1,452 articles were published over this period, with a publication/author and co-author/publication ratio of 0.43 and 5.49, respectively. China ranked first in publication output ( $n = 556$ , 43.3%), and the highest total citations ( $n = 12,007$ ), followed by Sweden ( $n = 90$ ), Canada ( $n = 77$ ), and Germany ( $n = 75$ ). Publications from developing countries were limited, with most contributions from Africa originating from Egypt ( $n = 7$ ), South Africa ( $n = 5$ ), and Nigeria ( $n = 3$ ), primarily through international collaborations. The average annual growth rate of 4.3% suggests a significant future article output. This scientometric analysis allowed us to infer global trends in CPs, identify tendencies and gaps, and contribute to future research. Despite having similar toxicity to short-chain chlorinated paraffin (SCCP), long-chain chlorinated paraffin (LCCP) has received less attention. Therefore, future research should prioritize studying LCCP bioaccumulation and toxicity in diverse food webs, focusing on aquatic species vulnerable to CPs and effective toxicological models. Additionally, collaborative research with developing countries should be encouraged to enhance meeting the Stockholm Convention's demand.

## KEYWORDS

persistent organic pollutants (POPs), chlorinated paraffin, scientometric analysis, short-chain chlorinated paraffin, medium-chain chlorinated paraffin, long-chain chlorinated paraffins

## 1 Introduction

Persistent organic pollutants (POPs) might remain near their sources or travel long-range in the atmosphere or oceans. Therefore, emissions from one country can contaminate another country (Jones, 2021; Ohoro et al., 2022); consequently, they are regulated globally (Gong et al., 2021). Due to their inability to biodegrade, they may persist in the environment for long. They can also bioaccumulate in plants, aquatic organisms, and humans, where they can become potentially harmful (Aravind Kumar et al., 2022). Chlorinated paraffins (CPs), categorized as emerging POPs (Huang et al., 2023) are one of the most prevalent challenges

in current analytical chemistry (Fernandes et al., 2022a). Due to their widespread use, persistence, and long-range atmospheric transport, they are prevalent in the environment, particularly in the oceans where they are transformed (Lyu and Zhang, 2023). For ages, these anthropogenic compounds have been extensively utilized in the manufacturing of rubber, textiles, leather goods, pigments, sealing agents, adhesives, plasticizers, fluids for welding, lubricant additives, thermal regulators for metalworking, and flame retardants (Huang et al., 2023; Fernandes et al., 2022a; Vetter et al., 2022; Chen C. et al., 2022; Yuan S. et al., 2021; Guida et al., 2020; Mu et al., 2023).

An estimated 1,000,000 tonnes of CPs are produced annually (Mézière et al., 2021), with China being the major producer (Pan et al., 2021), followed by India (Guida et al., 2020). Carbon-chain length categorizes CPs into three groups: short-chain (SCCP,  $C_{10-13}$ ), medium-chain (MCCP,  $C_{14-17}$ ), and long-chain (LCCP,  $C_{18-30}$ ) (Mu et al., 2023; Chen et al., 2023). Sources of CPs include the leaching and release of marine plastic litter (Lyu and Zhang, 2023), discharges from manufacturing and consumption (Xia et al., 2021), polyvinyl chloride curtains, ovens, and window glass (Beloki Ezker et al., 2024). The two main ways of exposure to CPs are by ingestion and inhalation of contaminated dust and air (Yuan B. et al., 2021b), others include dermal exposure (Liao et al., 2023; Gao et al., 2021; Zhu et al., 2024; Yuan et al., 2022a), nail and hair contact, breastfeeding (Mu et al., 2023; Chain et al., 2020), and exposure during pregnancy (Chen et al., 2023). CPs may result in diabetes, asthma, immunological dysfunction, endocrine disruptions, neurotoxicity, developmental toxicity, liver and kidney toxicity, mutagenicity, carcinogenicity, and reproductive toxicity (Huang et al., 2023; Mu et al., 2023; Yuan B. et al., 2021; Liao et al., 2023; Zhu et al., 2024; Tahir et al., 2024a). They have been detected in various matrices such as water and sediment (Guan et al., 2023; Tahir et al., 2024b), plants (Wang et al., 2021), seawater (Hu et al., 2022), groundwater (Wu et al., 2021), municipal solid waste incineration (Han et al., 2024), soil and sediment (Wu et al., 2020; Wang K. et al., 2020), foodstuff (Ding et al., 2021; Lee et al., 2020; Cui et al., 2020; Perkons et al., 2022; Han et al., 2021; Li et al., 2020), biota samples (Yuan et al., 2022b; Wang W. et al., 2020; Girones et al., 2023; Lee et al., 2022; Tomasko et al., 2021), cow milk and feed (Dong et al., 2020), serum (Ding et al., 2020), human blood (Niu et al., 2023), breastmilk (Krätschmer et al., 2021; Xu et al., 2021; Wang et al., 2024; Zhou et al., 2020), placenta (Liu et al., 2020), and toys (Zhang et al., 2023). From this we can see that CPs have been widely studied; hence there is a need to investigate the research progression over the years.

Despite having the same toxicity as SCCP, MCCP, and LCCP were used as substitutes but not as well-studied (Ding et al., 2020; McGrath et al., 2021; He et al., 2023; South et al., 2022; McGrath et al., 2022); and might not be a reliable replacement for SCCPs, leaving gaps in safety assurance (Chen et al., 2023). Owing to their growing health concern, SCCPs were added to the Stockholm Convention's POPs list in 2017, and recently, MCCPs have been proposed for inclusion as POPs under the Stockholm Convention, with the formal decision anticipated in 2025 (UK Government Department of Environment Food and Rural Affairs, 2024). While MCCPs and LCCPs receive less attention and have limited regulations in place for their management, SCCPs are extensively studied and regulated (Huang et al., 2023; Liao et al., 2023; Zhou et al., 2020; Jain et al., 2022).

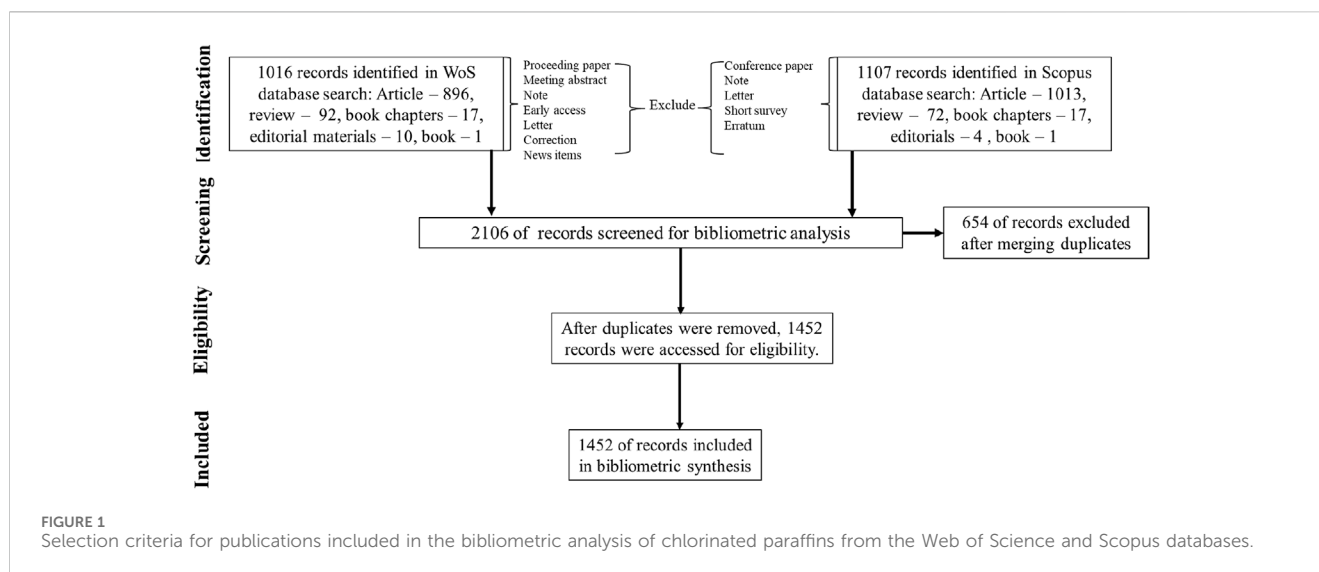
SCCPs and MCCPs have been widely studied due to their growing industrial use and environmental and health implications. Given the consistent research outputs and regulation of this pollutant category under the Stockholm Convention on POPs, a bibliometric review of global research on CPs is necessary. Such review can map global publication trends, inform policy, foster research collaboration by highlighting networks and funding sources, and guide future studies, particularly around LCCPs that have been understudied. Their limited research could be due to analytical difficulties, such as the requirement for advanced detection techniques, appropriate standards, and low volatility that limits their atmospheric dispersion (South et al., 2022); as a result, exposure risk may be less of a concern. Research funding and attention are being discouraged because there is a limit to global regulations addressing their rising emissions, particularly their persistence, bioaccumulation, and possible toxicity in the marine environment (Lyu and Zhang, 2023). Their low solubility and high molecular size can also reduce their uptake and absorption by aquatic organisms (Adetunji et al., 2022); consequently, less motivation to investigate their occurrences in aquatic environments.

A bibliometric analysis is a branch of scientometrics that employs statistical methods to evaluate scientific output, identifying trends, key contributors, and knowledge gaps while assessing research productivity (Olisah et al., 2024; Joshi, 2016; Aria and Cuccurullo, 2017). This evaluation tracks research trends, publication impact, and key topics (Siamaki et al., 2014; Tomy and Boer, 2010), using indicators such as annual scientific production, most cited articles, collaboration networks, total citations per country, most productive authors, most cited authors, most relevant sources, and most relevant keywords. To date, no scientometric study on CPs has been conducted based on available information. Therefore, this study presents the first scientometric evaluation of CP research over the past century, providing insights into the field's evolution and major themes. It aims to analyze global research on CPs from January 1916 to October 2024 using bibliometric tools to analyze articles indexed in WoS and Scopus, and addressing seven key research questions (1): What are the research outputs on CPs in ecosystems before and after the ban? (2) How has collaboration influenced CP research output? (3) What are the citation and authorship patterns? (4) What are the publication trends over the past 10 decades? (5) What thematic areas related to CPs have been most studied? (6) Are these themes potential drivers for future research? (7) Which CP classes have drawn the most research attention? This study helps researchers identify gaps and opportunities in the field.

## 2 Methodology

### 2.1 Data collection and inclusion criteria

In this bibliometric study on chlorinated paraffins (CPs), we collected and analyzed publications from two major academic databases: the Web of Science Core Collection and Scopus. The Web of Science was chosen for this study because of its rich dataset of physical and biological science articles. The Scopus database, launched by Elsevier in 2004, was also selected for its comprehensive



coverage of literature, enriched citation metrics, and detailed abstract sources (Reth and Oehme, 2004). The data collection aimed to provide a comprehensive understanding of the research landscape on CPs by examining publication patterns, document types, and research trends over time. The search term “chlorinated paraffin\*” was used in the Web of Science Core Collection topic and the “Article Title, Abstract, Keyword” fields in Scopus. The search spanned all available years in each database, covering publications from 1 January 1990, to 4 October 2024, in Web of Science, and from 1 January 1916, to 4 October 2024, in Scopus. An initial search in the Web of Science Core Collection yielded a total of 1,070 documents related to CPs. These documents were categorized into several types: articles, review articles, proceeding papers, book chapters, meeting abstracts, editorial materials, notes, early access items, letters, corrections, news items, and books (Figure 1). To maintain a focus on peer-reviewed and substantial academic content, we excluded certain document types from the analysis. Excluded items included proceeding papers, meeting abstracts, notes, early access items, letters, corrections, and news items, resulting in a refined dataset of 1,016 Web of Science Core Collection documents. Similarly, a search in Scopus yielded 1,196 documents on CPs, which were also categorized by type: articles, review articles, conference papers, book chapters, notes, editorials, erratum, letters, short surveys, and books (Figure 1). Consistent with the criteria applied to the Web of Science dataset, certain document types were excluded from the Scopus dataset, including conference papers, notes, erratum, letters, and short surveys. This resulted in a total of 1,107 documents from Scopus. After excluding duplicate entries and merging the results from both databases using R (Version 1 April 1,106 © 2009–2021 RStudio, PBC), a total of 1,452 unique documents were identified and used for the bibliometric analysis.

## 2.2 Scientometric analysis

This final dataset provided a robust foundation for evaluating trends in CP research, allowing for a more detailed exploration of

publication patterns, research focus, and key contributors within the field. Data from both databases were imported into RStudio (Version 1 April 1,106 © 2009–2021 RStudio, PBC) for bibliometric analysis. Key bibliometric indicators analyzed included the number of documents and authors, annual scientific productivity, top authors by productivity, most-cited manuscripts, corresponding authors’ countries, total citations by country, most relevant journals, and frequently used keywords. Codes with slight modifications used to analyze these indicators were adopted from Aria and Cuccurullo (Krätschmer and Schächtele, 2019). Additionally, thematic area classification and the country collaboration network were analyzed using VOSviewer (version 1.6.15 © 2009–2022).

## 3 Results and discussions

### 3.1 Literature demographics

This study analyzed 1,452 documents on CPs retrieved from the WoS and Scopus databases, covering January 1916 to October 2024. Articles made up most publications, accounting for 89.7% ( $n = 1,299$ ), followed by Reviews (7.5%,  $n = 108$ ), Editorials (0.1%,  $n = 2$ ), and Book Chapters (0.8%,  $n = 12$ ). Only 113 were single-authored papers, with ratios of 0.43 publications/author, and 5.49 co-authors/publication. The citation/publications and citation/year averages for these documents were 2.86 and 25.05, respectively. A high level of co-authorship participation is revealed by the study’s collaboration index, which is roughly 17.49 per article (van Mourik et al., 2016). About 3,353 authors contributed to the literature, with 83 authors producing single-authored works and 7,968 author appearances, retrieved from 443 journal and book sources. The publication output was low from 1916 to 1977 (Figure 2), likely due to the analytical challenges posed by CPs. The extreme complexity of CP mixtures, comprising thousands of stereoisomers, presents substantial difficulties for gas chromatography separation, hindering congener-specific analysis and limiting research on CP composition in environmental samples (Guida et al., 2020;

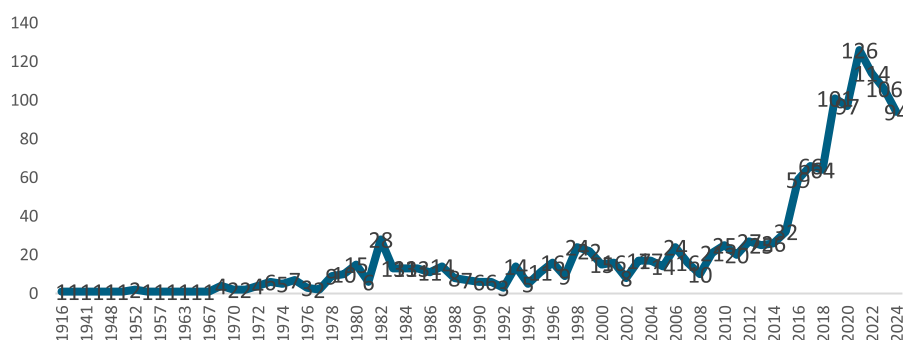


FIGURE 2

The annual publication frequencies on CPs globally published between 1916 and 2024. The annual growth rate was 4.3%.

Fiedler and Boer, 2010; Vorkamp et al., 2019; Glüge et al., 2016; Feo et al., 2009). There was a rapid increase in 1982 which could be a result of the 1980s production boom spurred on by the plastics and paint industry's high demand for the use of SCCP as additives (Chen C. et al., 2022; Lipnick and Muir, 2000; Chen L. et al., 2022). This could also be similar to the rapid increase in Europe and Japan in 1977 (Alipour Parvizian et al., 2024), having growing concern due to the awareness of the widespread persistence, bioaccumulation, toxicity, and vast industrial use (UNEP, 2017; UNEP, 2015). Consequently, toxicological information regarding MCCP and LCCP was generated during this time (Liao et al., 2023), and biotransformation research was conducted (Arko et al., 2024). The output of articles decreased after that, but it increased again in 2015 ( $n = 32$ ), and it has remained as such since then. There has been an upsurge in publications related to CPs ( $n = 768$ , 53%), since SCCPs were listed in the Stockholm Convention (2017–2024), compared to 235 articles generated before the listing (2009–2016).

### 3.2 Geographical distribution of publications and collaboration patterns

Table 1 lists the top 25 corresponding author countries and citations for research regarding CPs conducted globally between 1916 and 2024, directed via publication and citation indices. The four countries with the highest publication rate were China ( $n = 556$ , 43.3%), Sweden ( $n = 90$ , 7%), Canada ( $n = 77$ , 6%), and Germany ( $n = 75$ , 5.8%). Collaboration has a very strong influence on the research into CPs. Asia, North America, and Europe show strong collaborative ties in CP research, particularly between countries like China, the USA, Canada, Sweden, Switzerland, Norway, and Germany (Figure 3). This cooperation may stem from the inclusion of SCCPs in international agreements, such as the United Nations Economic Commission for Europe (UNECE) Long-Range Transboundary Air Pollution (LRTAP) Convention, Aarhus Protocol on POPs (adopted on 18 December 2009), which has continued to track these contaminants and continues to monitor and regulate these contaminants globally (Lipnick and Muir, 2000). Additionally, Environment and Climate Change Canada and the US EPA released a joint risk management strategy in 2021 for SCCP control in the Great Lakes, enforcing federal policies to limit

contaminant release (UNEP. SC-8/11). South Africa has engaged in CP-related research collaborations with European countries such as Sweden, Germany, Denmark, Norway, and France (Figure 3), likely due to its recognition as a CP producer under the Stockholm Convention (Guida et al., 2020). Support from various institutions has contributed to the growth of research in developed countries. On 26 July 2006, the European Community and its Member States proposed SCCPs for inclusion in Annexes A, B, or C of the Stockholm Convention as Parties to the Convention (UNEP/POPS/POPRC.2/INF/6 and compiled in UNEP/POPS/POPRC.2/14). Environment Canada and the UK's Department for Environment, Food & Rural Affairs (DEFRA) also prepared risk assessment documents. International collaboration has expanded in Europe, Asia, and North America since this nomination, which has contributed to boosting awareness of CPs as hazardous compounds across the globe. These collaborations involved significant institutions that focused on various aspects of SCCPs, including their classification as possible carcinogens (Group 2B) by the International Agency for Research on Cancer (IARC), and their designation as contaminants of very high concern under the EU's Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) guideline due to their impact on the liver, thyroid, and kidneys. The UNECE Aarhus (POPs) Protocol to the Convention on LRTAP also recognized SCCPs as POPs, and the Oslo-Paris (OSPAR) Commission regulated their main uses and sources through Decision 95/1 for the safeguarding of Marine Environment of the North-East Atlantic. In November 2007, SCCPs were further included in the Baltic Sea Action Plan by the Baltic Marine Environment Protection Commission (HELCOM), aiming to restrict the use of hazardous substances, including SCCPs, in the Baltic Sea region by 2008 (UNEP, 2022; Glüge et al., 2018; Krättschmer et al., 2023; Schächtele et al., 2023). The global campaign to regulate SCCPs extended to the UK, EU, Switzerland, Australia, and Canada, with attention also being drawn to MCCPs due to their persistent, bioaccumulative, and toxic properties (Yuan et al., 2023); although their bioaccumulative behaviours are still unclear (Nevondo and Okonkwo, 2021). Given these collaborations, it is unsurprising that research from these countries has contributed to a substantial number of publications. Most of the research on human exposure involved collaborations among eighty-two United Nations member states, with fifty nations participating in multiple studies

TABLE 1 Top 25 corresponding author countries on research conducted on the assessment of CPs across the globe from 1916 to 2024 ranked based on publication and citation indices.

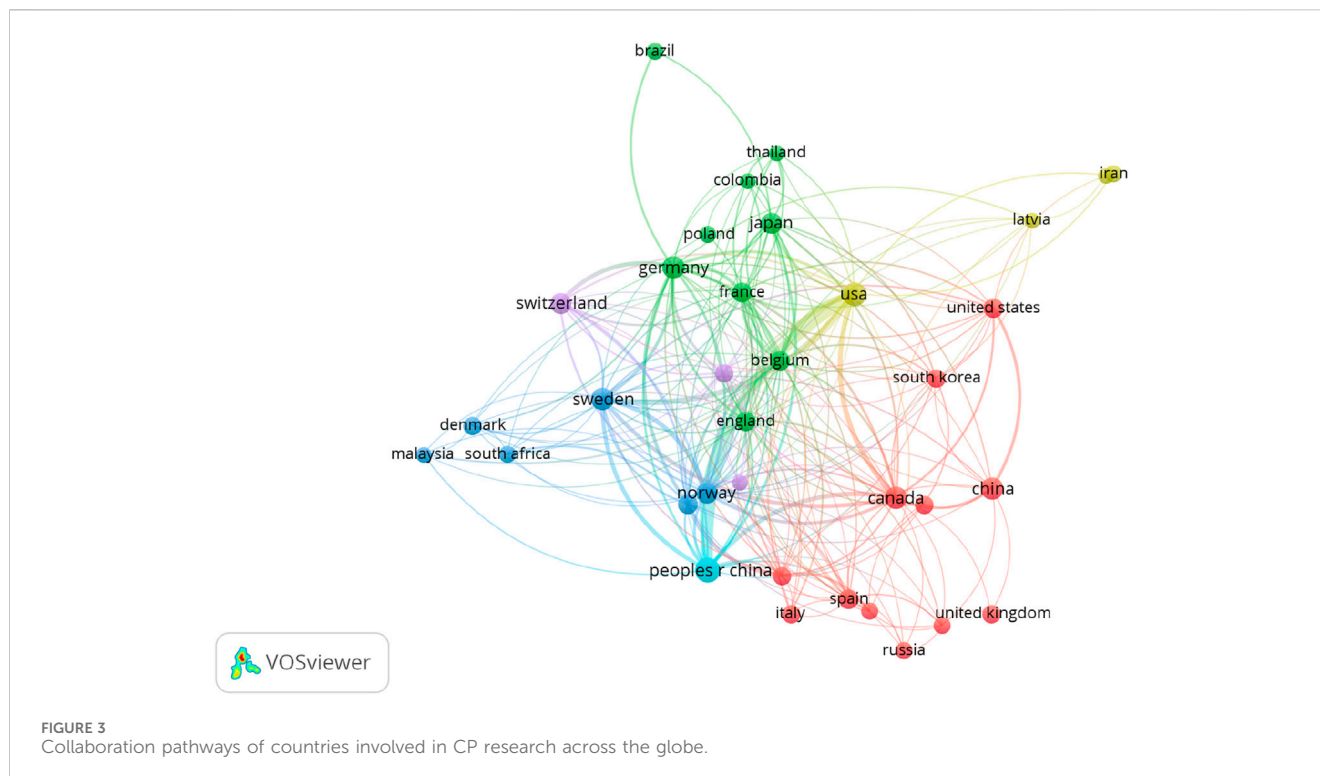
Most productive countries								Total number of citations per country			
Rank	Countries	Articles	% of 1,425	Freq	SCP	MCP	MCP/P ratio	Rank	Country	Total citations	Citation average
1	China	556	43.268	0.432	484	72	0.130	1	China	12,007	21.6
2	Sweden	90	7.004	0.070	63	27	0.300	2	Canada	3,899	50.64
3	Canada	77	5.992	0.060	59	18	0.234	3	Sweden	3,024	33.6
4	Germany	75	5.837	0.058	64	11	0.147	4	Switzerland	3,017	52.93
5	Switzerland	57	4.436	0.044	42	15	0.263	5	United Kingdom	2,482	56.41
6	United States	47	3.658	0.036	38	9	0.192	6	United States	2,329	49.55
7	United Kingdom	44	3.424	0.034	37	7	0.159	7	Germany	1,750	23.33
8	Japan	38	2.957	0.030	30	8	0.211	8	Spain	1,023	36.54
9	France	31	2.412	0.024	27	4	0.129	9	Australia	785	49.06
10	Spain	28	2.179	0.022	25	3	0.107	10	Japan	695	18.29
11	Norway	26	2.023	0.020	10	16	0.615	11	Norway	649	24.96
12	India	18	1.401	0.014	16	2	0.111	12	Netherlands	538	29.89
13	Netherlands	18	1.401	0.014	9	9	0.500	13	France	523	16.87
14	Australia	16	1.245	0.012	6	10	0.625	14	Denmark	345	31.36
15	Belgium	16	1.245	0.012	10	6	0.375	15	Czech Republic	334	25.69
16	Italy	15	1.167	0.012	15	0	0.000	16	Italy	304	20.27
17	Czech Republic	13	1.012	0.010	11	2	0.154	17	India	186	10.33
18	Korea	12	0.934	0.009	10	2	0.167	18	Korea	180	15
19	Denmark	11	0.856	0.009	10	1	0.091	19	Saudi Arabia	161	161
20	Russia	10	0.778	0.008	10	0	0.000	20	Belgium	146	9.12
21	Iran	9	0.700	0.007	6	3	0.333	21	Egypt	107	15.29
22	Egypt	7	0.545	0.005	7	0	0.000	22	Iran	106	11.78
23	Pakistan	6	0.467	0.005	2	4	0.667	23	Brazil	93	23.25
24	Poland	6	0.467	0.005	6	0	0.000	24	South Africa	82	16.4
25	South Africa	5	0.389	0.004	3	2	0.400	25	Singapore	72	72

SCP, single country publications; MCP, multiple country publications.

from 2000 to 2019. These efforts focused on assessing the effectiveness of the Stockholm Convention in reducing or eliminating emissions of chlorinated POPs. These exposure studies on human milk were carried out at the State Institute for Chemical and Veterinary Analysis of Food (CVUA) in Freiburg, Germany, under the direction of the World Health Organization and the United Nations Environment Programme (WHO/UNEP) (Nipen et al., 2022; Babayemi et al., 2022), and human biomonitoring and exposure collaborative research between Sweden and Norway (Wang and Gao, 2016). Other top countries in CP collaboration studies include Switzerland (n = 57, 4.4%), the USA (n = 47, 3.7%), the UK (n = 44, 3.4%), Japan (n = 38, 3%), France (n = 31, 2.4%), and Spain (n = 28, 2.2%). These countries also

dominated citation metrics, except for France, which was replaced by Australia. The top six countries with the highest citation metrics were China (12,007), Canada (3,899), Sweden (3,024), Switzerland (3,017), the UK (2,482), and the USA (2,329). Most of the collaborating countries with high citation metrics were from Europe and Asia. Research from this region is well-supported with funding and equipped with the necessary facilities. In contrast, publications from Africa were scarce, with contributions from Egypt (n = 7), South Africa (n = 5), Nigeria (n = 3), Kenya (n = 1), and Liberia (n = 1), most of which were the result of international collaboration. Despite the relatively high concentrations of CPs detected in indoor dust in South Africa (Guida et al., 2020; Chen et al., 2020), human milk (Krätschmer et al., 2021), air and soil





(Klaunig et al., 2003) compared to other countries, data from African countries remain limited. This scarcity of information on CPs in Africa could be due to a lack of production in most African countries, except South Africa and Egypt. Production, importation, and use of CPs are still restricted in Nigeria. However, there have been reports of unregulated and undocumented importation of large quantities of unlabelled products containing SCCPs (Zhang and Horrocks, 2003). Consequently, African and developing countries might not prioritize research on CPs since they have more pressing needs and few resources to fund the project, especially being aware that these chemicals are restricted. Moreover, Africa as a developing continent, faces challenges in collaboration and funding for research. However, projects like the Field and mechanism-based toxicity research on pesticides in Africa (ToRePs) funded by Africa-Japan Collaborative Research (AJ-CORE) in collaboration with the National Research Foundations (NRF), have advanced pesticide research in countries like South Africa, Ghana, and Zambia. These initiatives illustrate how funding and international partnerships can enhance research. Expanding such support from more institutions on CP projects could foster further collaborations between developed nations and African research bodies, empowering contributions from scientists and diverse stakeholders.

### 3.3 Publication outlets

The top 25 journals for CP research output throughout the evaluation period are shown in Table 2. Chemosphere was the leading journal, publishing 116 articles and accounting for 13.1% of the total collection. Following closely were Environmental Science & Technology and Science of the Total Environment,

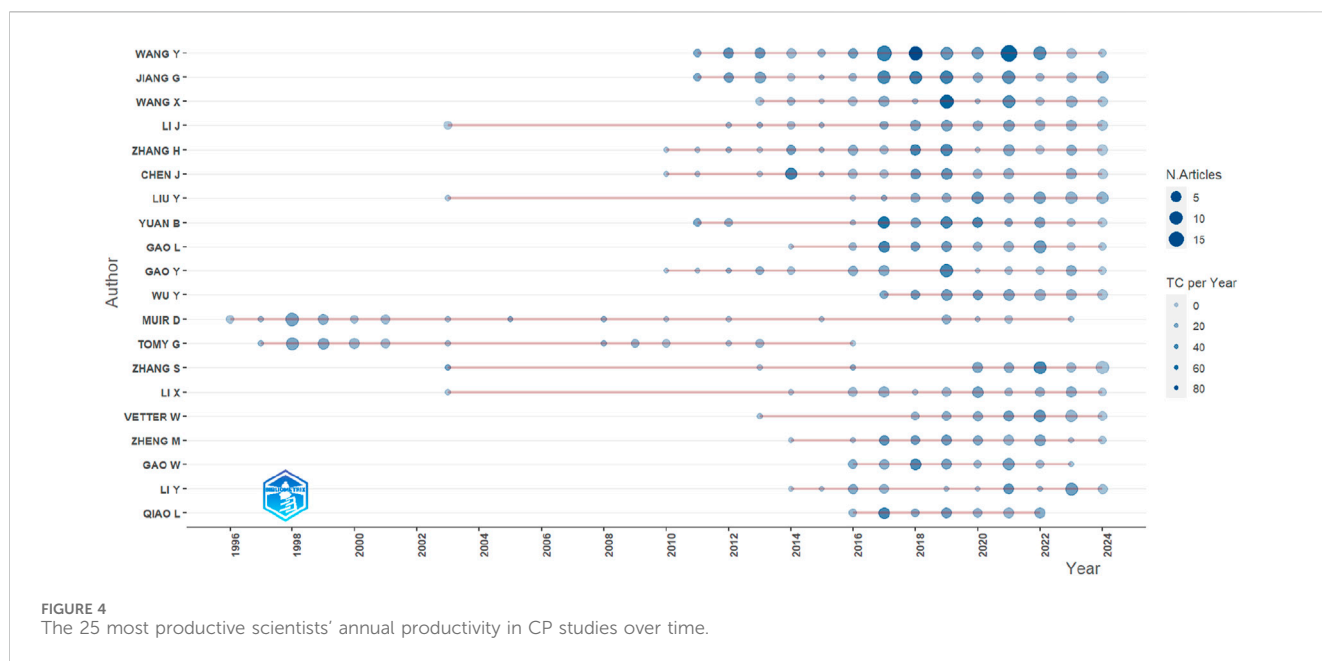
which ranked second and third with 114 (12.9%) and 104 (11.7%) articles, respectively. Environmental Pollution ( $n = 90$ , 10.2%) and Environment International ( $n = 42$ , 4.7%) occupied the fourth and fifth positions respectively. Between 1916 and 2024, a total of 443 journal sources featured publications on CPs. The multidisciplinary focus of these journals which publish work on chemical detection, behaviour, toxicology, and remediation across the biosphere, hydrosphere, lithosphere, and atmosphere, probably accounts for their prominence. While advocating for solutions to critical environmental issues, they investigate environmental contamination and its consequences on ecosystems and human health. These publications cover a wide range of issues, including environmental chemistry, toxicology, public health, risk assessment, and environmental technology. They are aimed towards an international readership of scientists, policymakers, and environmental professionals. The Journal of Hazardous Materials has the highest impact factor (12.2), followed by Environmental Science & Technology (10.8), Environment International (10.3), Chemosphere (8.1), and Environmental Pollution (7.6). Significantly, the primary focus of all these prominent journals is on the impact of chemicals on the environment.

### 3.4 Citation records and author distribution patterns

We analyzed citation metrics to identify the most significant articles in the collection. Highly cited literature is often recognized as groundbreaking in a research field for its original contributions and lasting impact, with frequent citations underscoring its influence.

TABLE 2 The top 25 cited publications on the assessment of CP across the globe from 1916 to 2024 ranked based on their citation frequencies.

Top manuscript per citation						Most relevant sources	
Rank	First author, initials, and year of publication	Journal Title	DOI	TC	TC/year	Sources	Articles
1	Klaunig J, 2003	Crit Rev Toxicol-A	10.1080/713,608,372	544	24.73	Chemosphere	116
3	Zhang S, 2003	Prog Polym Sci	10.1016/j.progpolymsci.2003.09.001	480	21.82	Environmental Science & Technology	114
4	Shaw S, 2010	Rev Environ Health	10.1515/REVEH.2010.25.4.261	459	30.6	Science Of the Total Environment	104
5	Braune B, 2005	Sci Total Environ	10.1016/j.scitotenv.2004.10.034	324	16.2	Environmental Pollution	90
6	Hallgren S, 2002	Toxicology	10.1016/S0300-483X(02)00,222-6	295	12.83	Journal Of Hazardous Materials	43
7	Van M L, 2016	Chemosphere	10.1016/j.chemosphere.2016.04.037	241	26.78	Environment International	42
8	Glüge J, 2016	Sci Total Environ	10.1016/j.scitotenv.2016.08.105	234	26	Journal Of Chromatography A	25
9	Tomy G, 1997	Anal Chem	10.1021/ac961244y	222	7.93	Environmental Toxicology and Chemistry	21
10	Houde M, 2008	Environ Sci Technol	10.1021/es703184s	214	12.59	Analytical Chemistry	16
11	Reth M, 2005	J Chromatogr A	10.1016/j.chroma.2005.05.061	204	10.2	Environmental Science and Pollution Research	16
12	Brown S, 2004	Environ Toxicol Chem	10.1897/03-242	204	9.71	Environmental Science and Technology	16
13	Bayen S, 2006, Environ Int	Environ Int	10.1016/j.envint.2006.05.009	199	10.74	Polymer Degradation and Stability	16
14	Jansson B, 1993	Environ Toxicol Chem-A	10.1002/etc.5620120704	196	6.12	Ecotoxicology And Environmental Safety	12
15	Tomy G, 1998	Rev Environ Contam Toxicol	10.1007/978-1-4612-1708-4_2	187	6.93	Journal Of Applied Polymer Science	11
16	Smith S, 2009	Philos Trans R Soc A-Math Phys Eng Sci	10.1098/rsta.2009.0154	179	11.19	Wear	11
17	Gluege J, 2018	Environ Sci Technol	10.1021/acs.est.7b06459	171	24.43	Analytical And Bioanalytical Chemistry	10
18	Alcock R	Chemosphere-A	10.1016/S0045-6535(98)00,444-5	168	6.46	Trac-Trends in Analytical Chemistry	10
19	Ma X, 2014	Environ Sci Technol	10.1021/es500940p	161	14.64	Ambio	9
20	Seleiman M, 2020	Resour Conserv Recycl	10.1016/j.resconrec.2019.104647	161	32.2	Archives Of Toxicology	9
21	Chen M, 2011	Environ Sci Technol	10.1021/es202891a	160	11.43	Environmental Science \and Technology Letters	9
22	Gao Y, 2012	Environ Sci Technol	10.1021/es2041256	153	11.77	Chinese Journal Of Chromatography	8
23	Zeng L, 2011	Environ Sci Technol	10.1021/es103740v	151	10.79	Emerging Contaminants	8
24	Friden U, 2011	Environ Int	10.1016/j.envint.2011.04.002	149	10.64	Environmental Research	8
25	Alcock R, 1999	Chemosphere	10.1016/S0045-6535(98)00444-5	149	5.73	Food Chemistry	8



Such works also reflect trending topics and core issues within the field, highlighting their continued relevance (Shaw et al., 2010; Kwon, 2018). The top 25 most cited publications are listed in Table 2. Articles focusing on toxicology, health effects, applications, usage, toxicity, and effectiveness of CPs as flame retardants received higher citations than other topics. The article published by Klaunig et al. (2003) leads the list, with 544 citations and an average of 24.73 citations per year. This invited review article comprehensively explored the toxicology of CPs and their health effects, noting that exposure to CPs caused kidney and thyroid tumours in rats and mice. Zhang and Horrocks (2003) ranked second with 480 citations and an annual average of 21.82. Their study reviewed the application of CPs as flame retardants, highlighting how CPs lower the destabilization temperature of polypropylene. In third place is the study of Susan Shaw (Sukhareva et al., 2010), which examined the use, toxicity, and effectiveness of organohalogen fire retardants, originally thought to replace phased-out chemicals. Shaw's research recorded 459 citations, averaging 30.6 citations per year. Her findings revealed that these fire retardants produced toxic by-products and raised environmental concerns. Of the total papers reviewed, 59% (n = 859) were published between 2015 and 2024, while 14.9% (n = 216) were published between 2003 and 2013. Figure 4 shows the productivity of the top 25 authors throughout the study period. The size of the blue bubbles represents the total number of articles, while the visibility of the bubbles reflects cumulative citations. Gaps between bubbles indicate periods of inactivity in these authors' contributions. Among the top contributors shown in Table 3, Wang Y. (96 publications, TC = 3,243) and Jiang G. (71 publications, TC = 2,339) from the Chinese Academy of Sciences had the most papers and citations, with their work appearing between 2012 and 2024. The most recent author, Wu Y., from Sun Yat-Sen University, Guangzhou, China began publishing in 2017, amassing 37 articles by 2024. Earlier authors, such as Muir D. from Environment Canada, National Water

Research Institute, Ontario, Canada (1996–2023) and Tomy G. with h-index of 29 (1997–2016) from Fisheries and Oceans Canada Freshwater Institute, Winnipeg, Canada, published 36 articles with 2,584 citations and 33 articles with 2,478 citations, respectively. Qiao L. from the University of Chinese Academy (2016–2022) had a shorter period of publication but accumulated 28 citations. Table 4 shows the top 25 authors from 1916 to 2024 ranked by authorship frequency. Only a few of these authors had single-authored articles, including Darnerud P (3) and Tomy G (1); implying that they single-handedly conceptualized and contributed to the articles. However, 97% of Tomy G's total papers were multi-authored. All other authors contributed to multi-authored and first-authored articles. While Yuan B did not have any single-authored papers, he was the first author of 47% of his total articles. These highly referenced authors have collaborated and will likely continue to collaborate.

### 3.5 Keyword analysis and thematic domain

Author keywords are terms authors select to summarize and represent the content of scientific publications. They are key in data retrieval, bibliometrics, and knowledge arrangements (Li et al., 2023; Yan et al., 2023). The Top 25 most relevant keywords (DE) (2,893) and keywords-plus (ID) (5,067) based on research on CP are shown in Table 5 in a ranking of occurrence and prevalence. These search terms were applied to analyze trends in the CP literature. With 221 and 262 articles for relevant keywords (DE) and keywords-plus (ID), respectively, chlorinated paraffins and paraffin have the highest percentage of the two categories. A keyword network map (Figure 5) was generated to identify the research hotspots. Four research thematic areas of CPs were identified: Material Science, Environmental Fate and Behaviour, Animal Physiology and Toxicity, and Exposure Science.



TABLE 3 Bibliometric evaluation of the top 25 most productive authors on research conducted on the assessment of CPs across the globe from 1916 to 2024 ranked based on publication, citation indices, and frequency of articles.

	Most productive authors				Author index						
	Authors	Articles	Authors	Article fractionalized	Element	h_index	g_index	m_index	TC	NP	PY_start
1	Wang Y	96	Wang Y	14.12	Bleiner D	7	13	1.00	177	17	2018
2	Jiang G	71	Jiang G	10.57	Bogdal C	17	17	1.42	1,436	17	2013
3	Wang X	46	Darnerud P	9.07	Cariou R	8	15	0.89	253	17	2016
4	Li J	45	Tomy G	8.41	Chen J	22	36	1.47	1,298	43	2010
5	Zhang H	44	Muir D	7.94	Darnerud P	13	21	0.29	683	21	1980
6	Chen J	43	Vetter W	7.6	Fisk A	16	18	0.55	1,507	18	1996
7	Liu Y	41	Yuan B	7.29	Fu J	13	22	1.00	605	22	2012
8	Yuan B	40	Coelhan M	6.92	Gao L	18	32	1.64	1,039	37	2014
9	Gao L	37	Wang X	6.39	Gao W	18	29	2.00	890	30	2016
10	Gao Y	37	Anon A	6	Gao Y	19	32	1.27	1,041	37	2010
11	Wu Y	37	Na N	6	Geng N	14	18	1.40	627	18	2015
12	Muir D	36	Li J	5.71	Heeb N	12	18	1.50	350	20	2017
13	Tomy G	33	Zhang H	5.67	Jiang G	29	47	2.07	2,339	71	2011
14	Zhang S	33	Chen J	5.65	Knobloch M	8	13	1.14	183	18	2018
15	Li X	32	Gao Y	5.59	Li	11	17	0.85	437	17	2012
16	Vetter W	32	Oehme M	5.52	Li H	16	25	1.23	632	27	2012
17	Zheng M	32	Li X	5.19	Li J	17	32	0.77	1,085	45	2003
18	Gao W	30	Liu Y	5.07	Li Q	11	19	0.69	465	19	2009
19	Li Y	29	Zitko V	5	Li X	15	21	0.68	486	32	2003
20	Qiao L	28	Zhang S	4.68	Li Y	14	23	1.27	554	29	2014
21	Li H	27	Camino G	4.67	Liu J	10	22	0.37	543	22	1998
22	Zhou Y	26	Costa L	4.67	Liu W	12	19	0.43	611	19	1997
23	Xu C	25	Gao W	4.64	Liu X	6	15	0.50	231	17	2013
24	Wang Z	23	Wu Y	4.61	Liu Y	15	25	0.68	656	41	2003
25	Zeng L	23	Sprengel J	4.45	Luo X	12	19	0.86	658	19	2011

The mixed-colour lines that link the two phrases indicate their degree of collaboration. The use of cluster analysis which classifies items into several groups with related themes depending on their similarity was employed to describe the keyword network map (Darnerud and Bergman, 2022). With keywords like lubricants, composites, additives, and rubber, the golden cluster (cluster 1) in Figure 5 focuses on material science. CPs have been used in these materials to improve qualities like flexibility, fire resistance, and chemical resistance, which makes them important for industrial applications (He et al., 2023; Yang et al., 2021; NTP, 1986; Chen et al., 2024). Cheap commercial production of chlorinated paraffins and their huge industrial applications in various fields started in the 1920s and 1932 without restrictions on the use of MCCPs and LCCPs (Vetter et al., 2022; Guida et al., 2020), with an estimated

33 million metric tons of CPs generated and consumed worldwide by 2020 (Chen C. et al., 2022), and predicted production increase in the foreseeable future (Yuan S. et al., 2021). The enormous applications would have encouraged researchers to further their investigation in material science.

The blue cluster (cluster 2) is depicted as Animal Physiology and Toxicity with keywords such as microsomes, mice, support, animal experiment, female, chicken, non-human, rat, and liver. However, little research exists in this niche compared to other POPs (Chen et al., 2023), and there is currently no metabolic scheme provided, and the metabolic transformations of CPs are not well-explored (Fernandes et al., 2022b). Over the past few years, studies on the toxicity of SCCPs to zebrafish and their cells have employed metabolomics based on high-resolution mass spectrometry, which provides a quantitative

TABLE 4 The top 25 cited publications on the assessment of CPs across the globe from 1916 to 2024 ranked based on their authorship pattern.

Rank	Author	Dominance factor	Tot articles	Single-authored	Multi-authored	First authored	Rank by articles	Rank by DF
1	Knobloch M	0.611	18	0	18	11	35	1
2	Darnerud P	0.556	21	3	18	10	25	2
3	Fisk A	0.556	18	0	18	10	35	2
4	Sprengel J	0.529	17	0	17	9	41	4
5	Xia D	0.500	18	0	18	9	35	5
6	Yuan B	0.475	40	0	40	19	7	6
7	Li H	0.444	27	0	27	12	18	7
8	Zhang Z	0.412	17	0	17	7	41	8
9	Zeng L	0.391	23	0	23	9	21	9
10	Liu L	0.375	16	0	16	6	46	10
11	Van Ml	0.368	19	0	19	7	31	11
12	Sun Y	0.333	21	0	21	7	25	12
13	Li Q	0.316	19	0	19	6	31	13
14	Chen C	0.313	16	0	16	5	46	14
15	Wang X	0.304	46	0	46	14	3	15
16	Tomy G	0.281	33	1	32	9	11	16
17	Wu Y	0.243	37	0	37	9	8	17
18	Geng N	0.222	18	0	18	4	35	18
19	Zhang Y	0.217	23	0	23	5	21	19
20	Gao W	0.200	30	0	30	6	15	20
21	Xu C	0.200	25	0	25	5	20	20
22	Zhou Y	0.192	26	0	26	5	19	22
23	Chen X	0.188	16	0	16	3	46	23
24	Liu X	0.176	17	0	17	3	41	24
25	Liu Y	0.171	41	0	41	7	6	25

research methodology. However, many of the physiological mechanisms in zebrafish differ significantly from those in mammals, posing challenges for direct comparisons (107). The green cluster (cluster 3), focused on Exposure Science with keywords such as child, inhalation, urban area, health risks, environmental exposure, soil, China, octanol, and cluster analysis. However, most studies on health and exposure were conducted *in vitro* as epidemiological research is scarce; therefore, future studies on human exposure and adverse effects of CPs should use more exposure methodologies (Huang et al., 2023; Xu et al., 2021). Environmental Fate and Behaviour are the red clusters (cluster 4), with the keywords that include source apportionment, CP production, Shanghai, plant, indoor, sediment, distribution, temporal trends, tropical chain, chlorinated paraffin, GC-MS, extraction, and quantification. This focuses on publications that promote the study of harmful substances and their interactions with the environment. A

significant toxicology study on CPs, conducted by the US National Toxicology Program, NTP (1986), demonstrated carcinogenic effects on the kidneys, liver, and thyroid in rodents. CP toxicology research from 1900 to 2023 reported by Chen et al. (2023) reveals that only 13% of studies focused on the analytical chemistry of CPs, while 7% addressed toxicology. Notably, just 26% of the toxicological research was published between 2014 and 2023, suggesting a significant gap in both toxicology and analytical chemistry data for CPs. The study further suggests that computational toxicology could serve as a more cost-effective alternative to traditional *in vivo* experiments. Most of these studies were conducted in China, considering their position in Table 1. This could probably be due to their involvement in mass production (Pan et al., 2021). Recently, there has been a growing interest in very short CPs (vSCCPs, C < 10), which are environmental byproducts produced during the manufacture of CPs (Chen et al., 2024).

TABLE 5 Top 25 most relevant keywords (DE) and keywords-plus (ID) on research conducted on the assessment of CP across the globe from 1916 to 2024 ranked based on publication.

Rank	Author keywords (DE)	Articles	% Of 1,640	Articles keywords-plus (ID)	Articles	% Of 1,640
1	Chlorinated paraffins	221	15.252	Paraffin	262	18.081
2	Short-chain chlorinated Paraffins	80	5.521	Chlorinated paraffins	176	12.146
3	SCCPs	75	5.176	China	169	11.663
4	Chlorinated paraffin	65	4.486	Paraffins	153	10.559
5	Bioaccumulation	43	2.968	Bioaccumulation	147	10.145
6	Persistent organic pollutants	39	2.692	Environmental monitoring	146	10.076
7	MCCPs	36	2.484	Article	128	8.834
8	Risk assessment	35	2.415	Polychlorinated biphenyls	122	8.420
9	Short-chain chlorinated paraffins	31	2.139	Environmental samples	119	8.213
10	Distribution	30	2.070	Polybrominated diphenyl ethers	115	7.937
11	SCCP	28	1.932	Chain chlorinated paraffins	111	7.660
12	Short-chain chlorinated paraffins (SCCPs)	28	1.932	Hydrocarbons	111	7.660
13	Polychlorinated n-alkanes	27	1.863	Polychlorinated n-alkanes	109	7.522
14	Chlorinated paraffins (CPs)	24	1.656	Chlorinated	104	7.177
15	Human exposure	24	1.656	Chlorinated hydrocarbon	103	7.108
16	Sediment	22	1.518	Sediments	96	6.625
17	Analysis	21	1.449	Exposure	94	6.487
18	Short-chain chlorinated paraffin	21	1.449	Flame retardants	92	6.349
19	Biomagnification	20	1.380	N-alkanes	89	6.142
20	Polychlorinated alkanes	20	1.380	Mass spectrometry	83	5.728
21	Soil	20	1.380	Short-chain	81	5.590
22	Mass spectrometry	17	1.173	Fish	80	5.521
23	Medium-chain chlorinated paraffins	17	1.173	Risk assessment	77	5.314
24	Fish	16	1.104	Temporal trends	76	5.245
25	MCCP	16	1.104	Toxicity	76	5.245

## 4 Future perspectives and recommendations

Since CPs were designated as POPs under the Stockholm Convention due to their harmful environmental and health effects, research interest has surged globally. This scientometric analysis indicates a steady annual increase in CP-related publications, with an average growth rate of 4.3%, reflecting a significant rise in article output. It went from just one publication in 1916 to 106 in 2023, suggesting continued growth in future research. This growth would be enhanced by the vast collaborations and funding that these studies have attracted.

Compared to legacy POPs like polychlorinated biphenyls (PCBs), dioxins, and DDT, global CP production is considerably higher, with an estimated 32.5 million tons produced in 2020, and CPs continue to be manufactured and used in some developing countries (Lyu and Zhang, 2023; Mu

et al., 2023). This increasing production and usage leads to an increasing risk of environmental pollution and adverse effects on human health. Therefore, regulatory bodies should enhance monitoring and implement stricter controls on CP emissions. In this regard, special attention is needed for developing countries that lack funding, analytical capacity, and waste management techniques, as these gaps may worsen pollution (Guida et al., 2020). Also, the regulation of CPs should be expedited by international cooperation and partnerships in tackling the global health and environmental concerns relating to these chemicals through information transfer (Krätschmer et al., 2023). Additionally, the Stockholm Convention's restrictions on recycling SCCP-containing products pose significant challenges to waste management, particularly for developing countries with limited disposal and analytical capacities. This is because SCCP recycling may lead to the release of other hazardous substances such as PCBs and



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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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