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The "forever" per- and polyfluoroalkyl substances (PFAS): A critical accounting of global research on a major threat under changing regulations

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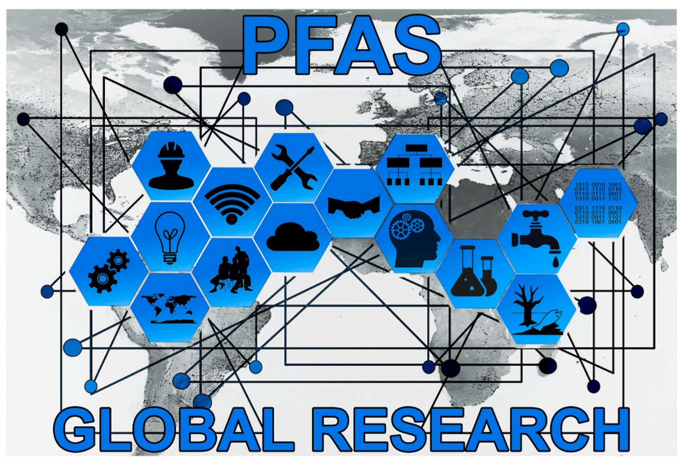
HIGHLIGHTS

- Currently, China has the most publications, ahead of the USA and European countries.
- Research focuses are strictly separated into ecological and material science topics.
- Russia and Ukraine are among the frontrunners with a clear focus on materials science.
- The focus in PFAS research is shifting toward ecological issues.
- A national imbalance can be observed that leaves the low economies behind.

GRAPHICAL ABSTRACT



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ABSTRACT

The European Commission's current efforts to launch the largest proposal to restrict per- and polyfluoroalkyl substances (PFAS) in history reflect the dire global plight of PFAS accumulation in the environment and their health impacts. While there are existing studies on PFAS research, there is a lack of comprehensive analysis that both covers the entire research period and provides deep insights into global research patterns, incentives, and barriers based on various parameters. We have been able to demonstrate the increasing interest in PFAS research, although citation numbers are declining prematurely. Policy regulations based on proving and establishing the toxicity of PFASs have stimulated research in developed countries and vice versa, with increasing emphasis on ecological aspects. China, in particular, is investing increasingly in PFAS research, but without defining or implementing regulations - with devastating effects. The separation of industrial and environmental research interests is clear, with little involvement of developing countries, even though their exposure to PFAS is devastating. It, therefore, requires increased globally networked and multidisciplinary approaches to address PFAS contamination challenges.

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Abbreviations

AIST	National Institute of Advanced Science and Technology Japan
CAS	Chinese Academy of Science (please note: not for Chemical Abstract Service)
CHL	Cited-Half-Life
Corp	Corporation
EPA	US Environmental Protection Agency
BRS	Basel, Rotterdam and Stockholm
DEMP	Density Equalizing Map Projections
EU	European Union
GDP	Gross Domestic Product
NASU	National Academy of Sciences of the Ukraine
NewQIS	New Quality and Quantity Indices in Science
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctyl Sulfonate
ppb	parts per billion
R_{GDP}	Number of articles on PFAS/Gross Domestic Product in 10 billion dollars
R_{POP}	Number of articles on PFAS/Population size of publishing country in millions
RAS	Russian Academy of Sciences
SCIE	Science Citation Index Expanded
SVHC	Substances of Very High Concern
WoS	Web of Science

1. Introduction

Per- and polyfluoroalkyl substances (PFAS), formerly referred to as PFCs, are synthetic chemicals that are now ubiquitous, having accumulated in the environment and biosphere for decades (McCarthy et al., 2021). The identification of new classes of PFAS in the environment has caused worldwide concern (Nakayama et al., 2019). They are widely used and found in the environment on every continent – except for Antarctica. Therefore, human exposure is inevitable (Liu et al., 2020). PFAS denote a large group of chemical compounds of more than 4700 substances widely used in industry and everyday products due to their unique properties (Gluge et al., 2020). They are characterized by a carbon-fluorine structure that is one of the strongest bonds in nature, which is why PFAS are known for their exceptional stability and resistance to heat, chemicals, and biological degradation or that of their degradation products. Once released into the environment, it is extremely difficult to remove them. That is why they are also called "forever chemicals" (Wackett, 2022). PFAS are therefore extremely difficult to degrade and, insofar, as highly bio-accumulative and bio-magnifying (McCarthy et al., 2021). They are also easily transportable and insofar extremely widely found. Consequently, they can have long-term effects on ecosystems worldwide (ECHA, 2023b).

PFAS are both hydrophobic and oleophobic, which makes them water and grease-repellent and therefore very interesting for the textile and food packaging industry (EPA, 2021). More than 1400 individual PFAS have been identified for use in more than 200 categories, and thus in a wide variety of other products, including Teflon coatings, flame retardants, insecticides, non-stick cookware, foams for fire extinguishers, and many other applications, including those not scientifically described, such as munitions and soil remediation (Gluge et al., 2020; Naidu et al., 2020).

Because of their many uses and their characteristics, PFAS are widely distributed in the environment and can be detected in air, water, soil, and biota. It is estimated that about 4.4 million tons of PFAS will accumulate in the environment over the next 30 years unless their release is minimized.

Some PFAS have already been shown to be extremely toxic to humans and linked to developmental, liver, kidney, and hormonal disorders. They are also carcinogenic, immuno-toxic, and hemotoxic (Anderko and Pennea, 2020; Bil et al., 2023). Human biomonitoring has already detected PFAS concentrations in the blood of highly exposed citizens that exceeded the proposed levels for adverse health effects (EEA, 2019).

Concerning environmental hazards, some PFAS compounds have also been associated with adverse effects on animal reproduction, growth, and development, thus affecting wildlife biodiversity in any ecosystem (Reid et al., 2019). But not only individual chemicals but also mixtures pose enormous risks that are mostly unknown (McCarthy et al., 2021). PFAS have already been detected in human blood (Kotlarz et al., 2020), breast milk (Tao et al., 2008), hair (Ruan et al., 2019), and tissue (Perez et al., 2013).

In addition to these potential risks of PFAS to humans and the environment, the most comprehensive restriction proposal in history for the European Union (EU) was published in February 2023, targeting bans and concentration limits (ECHA, 2023a). The European REACH proposal poses a major challenge as it relates to more than 10,000 substances (ECHA, 2023a). In this context, the USA is also considering disclosure requirements for certain PFAS products (EPA, 2023).

Many countries have already taken steps to restrict the use of PFAS, e.g., through the Basel, Rotterdam, and Stockholm (BRS) Conventions on Persistent Organic Pollutants (IISD, 2019). However, an immediate ban is not always realistic due to the lack of applicable alternatives for products for human health or those necessary for the stability of society. Nevertheless, priority must be given to the development and marketing of PFAS-free products and methods of removal from the environment (Kucharzyk et al., 2017; Gluge et al., 2020). For some applications, e.g., where oil-repellent properties are not required, some kerosene, silicone, dendrimer, and polyurethane-based impregnating agents are considered acceptable. However, it should be noted that there is often insufficient information available for these alternative products on the identity of the substances and their data on health and environmental properties (OECD, 2015; Leinala, 2022).

Nevertheless, as long as PFAS have been manufactured, they have been the subject of scientific study. Nevertheless, epidemiological and toxicological data, and thus understanding of their toxicology, are limited, not only for the individual chemicals but especially for their mixtures. Therefore, the potential risk they pose remains unclear but many experts declared PFAS as an emerging major health threat (Abunada et al., 2020; Bell et al., 2021). Moreover, industrial substitution and removal methods are compelling topics for future research. The overall needs, drivers, and barriers to PFAS research must be known to plan and implement projects that address the pressing needs of a sustainable future. For this reason, we have analyzed global research efforts, measured as publication output, using a variety of parameters to provide a comprehensive picture of what has been done and by whom. The results provide considerable background knowledge for all stakeholders, decision-makers, and funders to meet the scientific requirements of a global, environmental, and social approach in dealing with PFAS. In this way, potential goals, partners, and requirements can be identified not only for the national research strategy but also for balanced global cooperation.

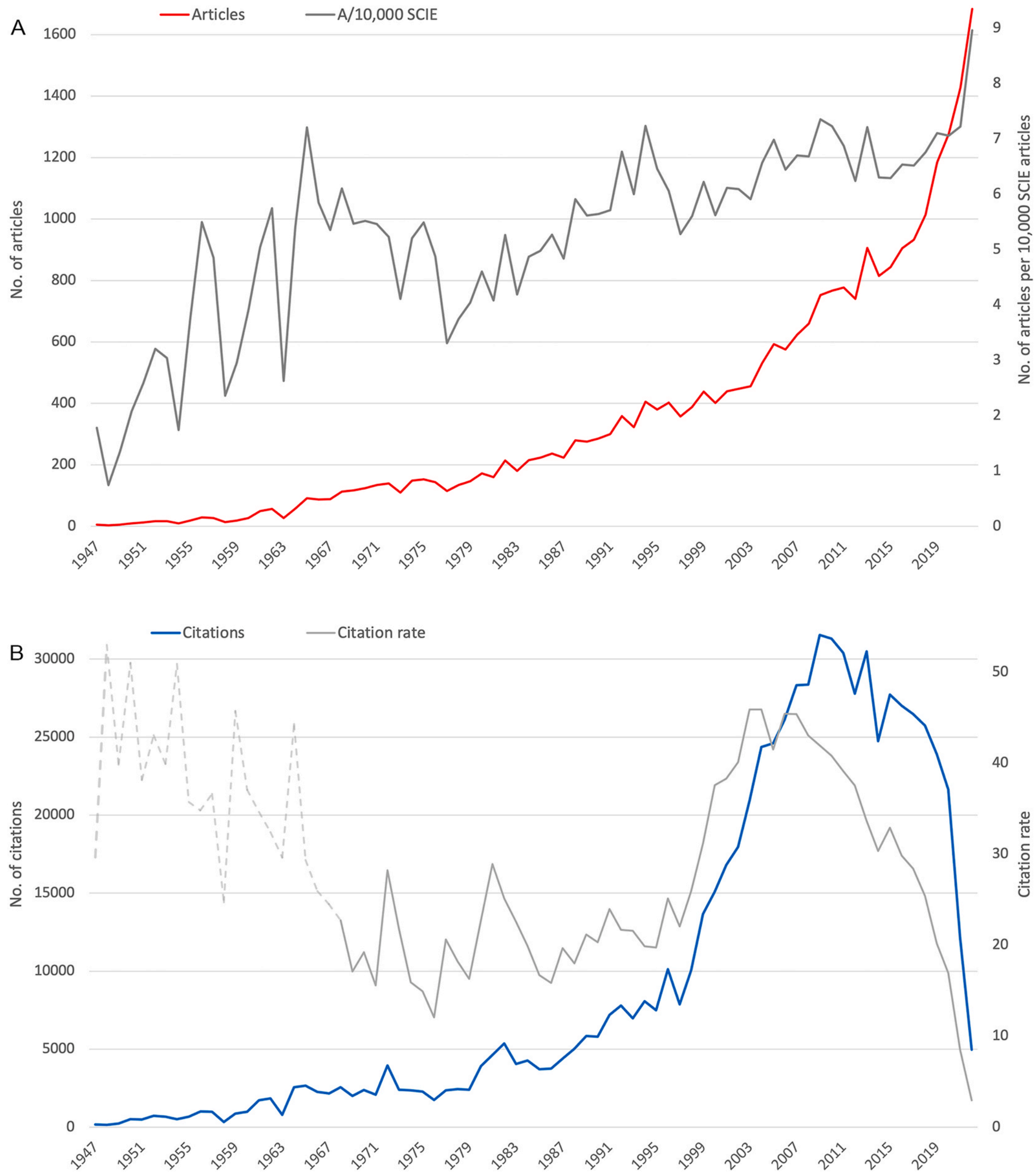

Fig. 1. Chronological analyses from 1947 to 2022. A) Number of articles on PFAS and Number of articles on PFAS per 10,000 SCIE (Science Citation Index Expanded) articles. B) Number of citations and average citation rate, dotted line = number of articles > 100 articles per year (citation rate not as meaningful).

2. Methods

2.1. Database generation

This study is based on the advanced methodology of the *New Quality and Quantity Indices in Science* (NewQIS) bibliometric platform (Groneberg et al., 2019) that was established to perform analyses on scientific fields related to, among others, ecologically important areas with global impact. The default database for all NewQIS studies is the Core Collection of Web of Science (WoS), one of the most recommended online literature databases for bibliometric studies. To ensure the generation of a representative analysis database, an explicit search term must be created to increase the number of topic-related entries and reduce the number of spurious ones.

The data were retrieved on 04/25/2023. A bilateral strategy was chosen for the search of PFAS publications, combining concrete term fragments (Search 1) with non-concrete abbreviations, which, on their own, would lead to incorrect entries linked to terms from the field of PFAS research (Search 2). Subsequently, the entries thus found were filtered by the document type “article” to include only original studies in the analysis (Supplementary Fig. 1). The meta-data of the entries were stored in an MS Access database and sorted according to the analyzed parameter.

2.2. Analysis and visualization

The data were analyzed in terms of global temporal and geographical patterns by determining the number of articles and citations and the resulting citation rate. National and institutional key players in PFAS research were identified. Each country of origin specified in the information of an article counts for its respective publication number so that a multinational article is assigned to more than one country. Occurring keywords and title words were analyzed, clustered, and evaluated according to their temporal association and citations received. In combination with the analysis of research areas according to the listed WoS categories, this allowed us to evaluate the publication priorities.

Table 1
Most-cited articles, Data of 04/25/2023, * Impact Factor of Clarivate's Journal Citation Report 2021, ** co-authoring countries: China, Netherlands, Poland, Russia.

Authors (Country)	Year	Citations	Title	Source	Impact Factor*
Giesy, J.P., Kannan, K. (USA)	2001	1927	Global distribution of perfluorooctane sulfonate in wildlife	Environmental Science & Technology	11.357
Gierke, T.D., Munn, G.E., Wilson, F.C. (USA)	1981	1440	The Morphology in Nafion Perfluorinated Membrane Products, as determined by Wide-Angle and Small-Angle X-Ray Studies	Journal of Polymer Science	3.046
Olsen, G.W. et al. (USA)	2007	1359	Half-life of serum elimination of perfluorooctanesulfonate, per-fluorohexane-sulfonate, and perfluorooctanoate in retired fluoro-chemical production workers	Environmental Health Perspectives	11.035
Nair, R.R et al. (UK**)	2010	1052	Fluorographene: A Two-Dimensional Counterpart of Teflon	Small	15.153
Lindstrom, A.B., Strynar, M. J., Libelo, E.L. (USA)	2011	980	Polyfluorinated Compounds: Past, Present, and Future	Environmental Science & Technology	11.357
Higgins, C.P., Luthy, R.G. (USA)	2006	916	Sorption of perfluorinated surfactants on sediments	Environmental Science & Technology	11.357
Zawodzinski, T.A. et al. (USA)	1991	886	Determination of Water Diffusion-Coefficient in Perfluorosulfonate Ionomeric Membranes	Journal of Physical Chemistry	4.173
Giesy, J.P., Kannan, K. (USA)	2002	832	Perfluorochemical surfactants in the environment	Environmental Science & Technology	11.357
Hsu, W.Y., Gierke, T.D. (USA)	1983	822	Ion-Transport and Clustering in Nafion Perfluorinated Membranes	Journal of Membrane Science	10.53
Hall, M.B., Fenske, R.F. (USA)	1972	822	Electronic-Structure and Bonding in Methyl(Pentacarbonyl)Manganese and Perfuoromethyl(Pentacarbonyl)Manganese	Inorganic Chemistry	5.436

For socioeconomic weighting, the population per country and the gross domestic product (GDP) (UIS.Stat, 2022) were related to national publication output. This normalization is important for the comparison of national research contributions, as population size weights the available human resources and GDP the economic resources for the countries' scientific output. The results were visualized in part using Density Equalizing Map Projections (DEMPs), cartograms created using an algorithm by US physicists Gastner and Newman (2004) to build up target geographic values by skewing country sizes. In this process, countries with a high value concerning the parameter to be analyzed are enlarged, while countries with a low value are reduced in size. The keyword analyses were displayed using the bibliometric network construction and visualization tool VOSviewer (van Eck and Waltman, 2010).

2.3. Methodological limitations and strength

Although the study's approach is based on an established and successfully applied method (Groneberg et al., 2019), some limitations should be mentioned. All bibliometric analyses are susceptible to the characteristics of the source used. In the NewQIS studies, WoS serves as the data source, taking advantage of one of the largest online scholarly databases but with its associated limitations. One to mention is the English bias of WoS, which favors English literature and biases the results in that direction. On the other hand, the journals listed in WoS are limited according to the requirements, so not all related articles could be included in the analysis database. The number of entries found is also limited by the search term, which must be a weighed concept to find a maximum of related articles but also a minimum of unrelated articles. Since the principle of representativeness of the generated database is mandatory, a reduction of entries has to be accepted.

3. Results

By the application of the search procedure and the inclusion criteria, 27,442 original articles (n) could be identified and their metadata included in the database.

3.1. Timeline patterns

Although the first three articles (n) found in WoS were published as early as 1900, subsequently, no article on PFAS was found until the end of World War 2 in 1947. From then on, there was a steady increase in the annual publication numbers, leading to the peak of 1683 articles by the time of the evaluation in 2022. Compared with the trend of all articles listed in the *Science Citation Index Expanded* (SCIE), calculated as the number of articles on PFAS per 10,000 SCIE articles, the ratio shows a fluctuating slightly increasing trend with a remarkable increase in the last year (Fig. 1A).

The annual citation numbers (c) increased slightly until 1996 when a 5-digit value was reached for the first time. One year later, the citation numbers started to increase significantly until they reached their maximum of c = 31,550 in 2009. Only two years later, in 2011, a drastic decline in annual citation counts began until today. The calculation of the average annual citation rate shows several peaks over time, which are particularly meaningful when the respective article numbers exceed a minimum value of 100 articles/year. In 1972 and 1981, intermediate highs were reached at about cr = 28. In 2003/2004 and 2006/2007, citation rates reached values above 45 citations per article. From then on, the citation rate dropped sharply, except in 2015, which saw another small interim peak (Fig. 1B).

The most frequently cited articles are listed in Table 1. Of these ten articles, only one is not exclusively written by US scientists.

3.2. Research areas

The analysis of the occurring keywords shows four thematic clusters of PFAS research: 1) material and polymer sciences, 2) human exposure and toxicity, 3) environmental contamination, and 4) removal from the environment (Fig. 2A). The temporal analysis of these clusters shows that the topics related to environmental and human exposure are more recent in terms of their publication date (Fig. 2B). In terms of citations received, it can be shown that, despite their short time since publication, these topics are the most cited (Fig. 2C).

Analysis of the title words of PFAS articles separates equal thematic clusters of material and polymer and human and environmental exposure, which are rarely combined and are far apart in theme and intent (Supplementary Fig. 2).

Looking at the distribution of the WoS category "research areas," the most frequently assigned areas are "Chemistry" (n = 12,956), "Environmental science & Ecology" (n = 4720), "Engineering" (n = 2843), "Materials science" (n = 2422), and "Polymer science" (n = 2172). The temporal development of the research areas shows a relative increase in topics related to human and environmental exposure and a decrease in material-related topics that include chemical and physical scopes. In the case of "Chemistry", the proportion of the number of articles among the

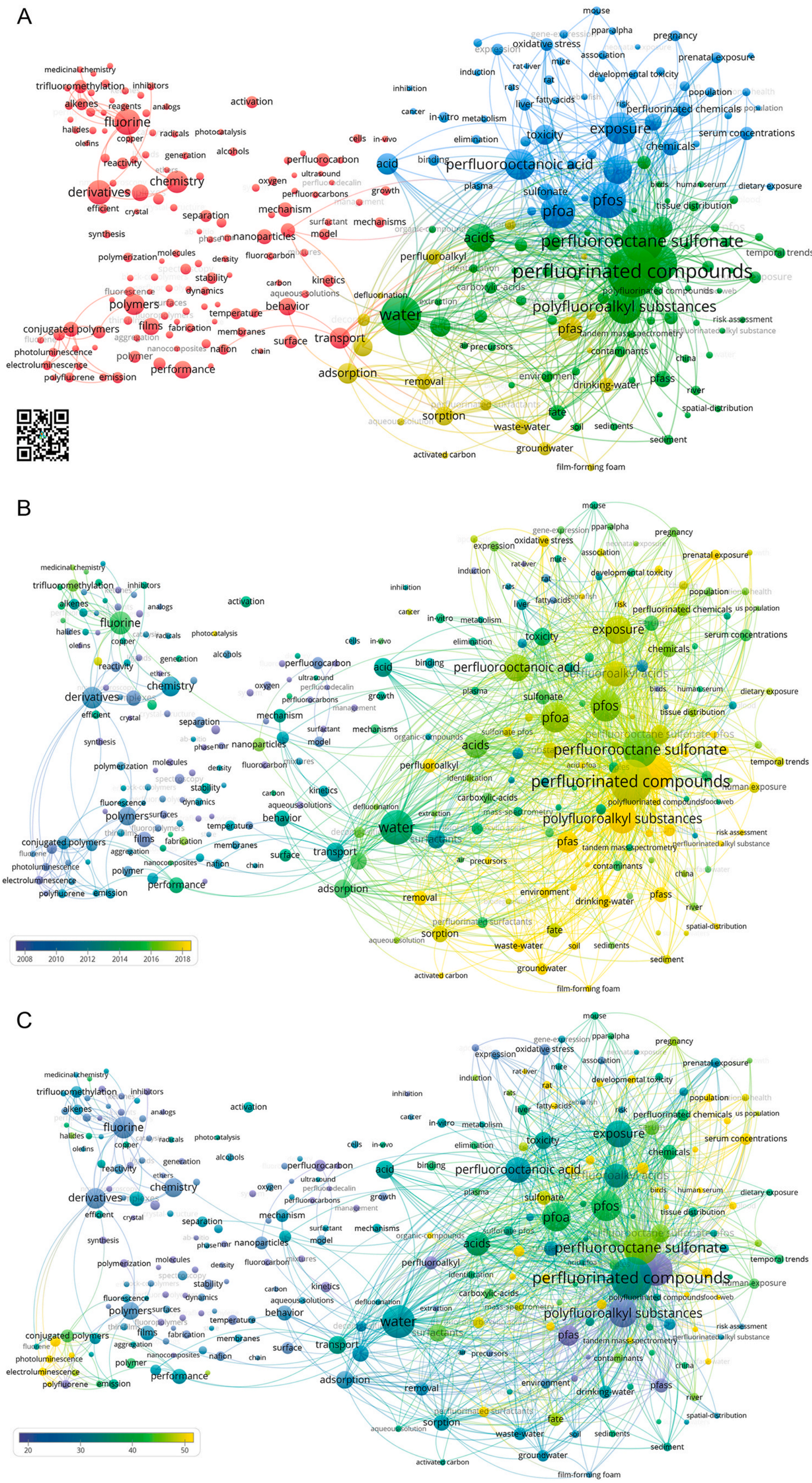

Fig. 2. Cluster analysis of keywords of PFAS articles (threshold: 100 occurrences), QR code for interactive display. A) Red cluster: material, polymer sciences; blue cluster: human exposure; green cluster: environmental pollution, yellow cluster: removal from the environment. B) Publication date of articles with the respective keyword. C) Citations of articles with the respective keyword.

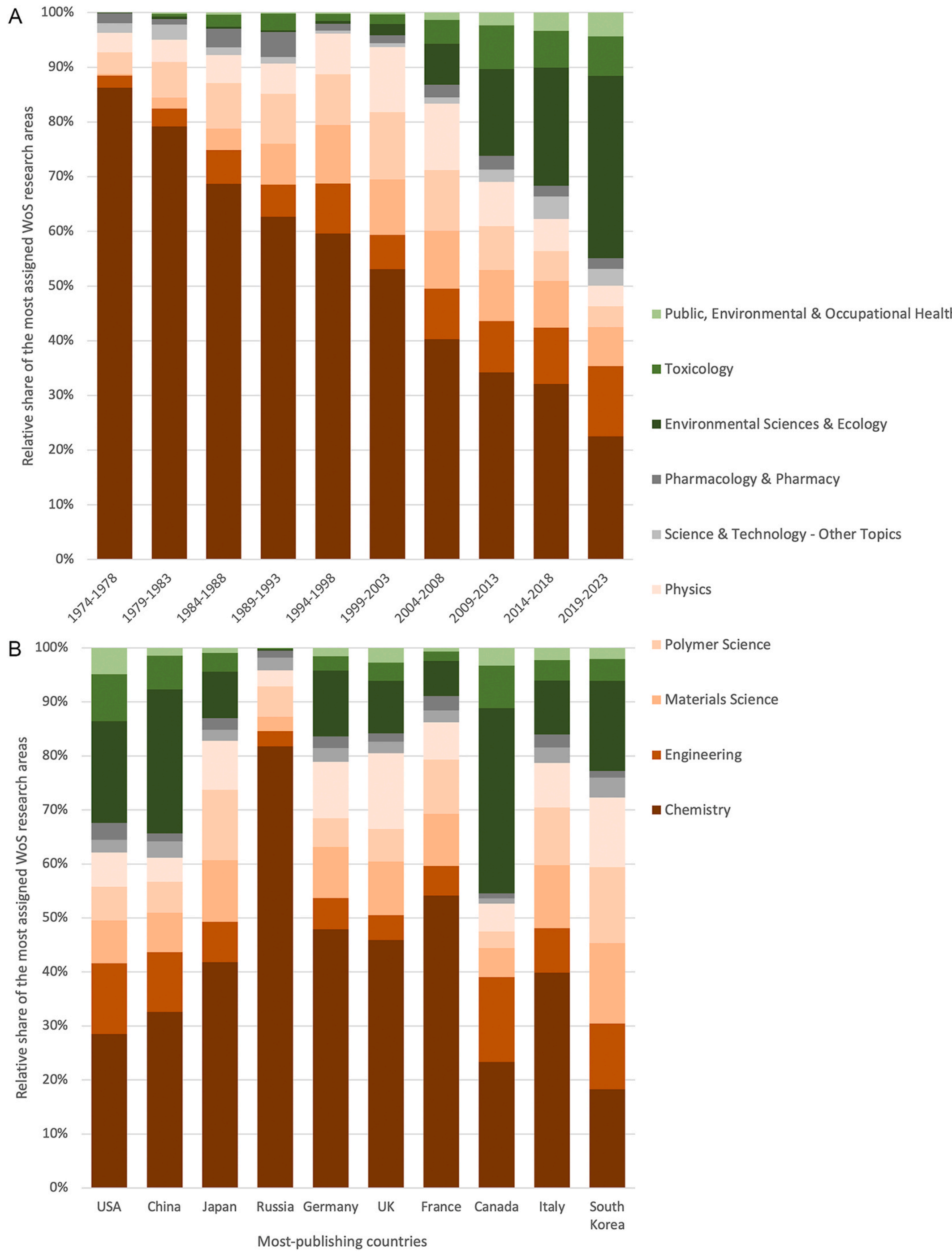

Fig. 3. WoS research area categories. A) Development of the most assigned research areas in 5-year intervals from 1974 to 2023. B) Relative share of the most assigned research areas in the PFAS output of most-publishing countries.

ten most frequently assigned research areas decreased from 86.62% (1974–1978) to 22.53% (2012–2023), while "Environmental Science & Ecology" increased from 0.15% to 33.32% during the same period, reaching the first place in the last evaluation interval (Fig. 3A).

In terms of the thematic distribution of the countries with the most publications, we find that the countries with the highest proportion of "environmental science and ecology" are Canada (34.33%), China (26.70%), and the USA (18.79%). Russia had the lowest percentage (0.26%) but the highest for "Chemistry" (81.79%). Of the European countries, France had relatively the most chemical and material articles (Fig. 3B).

3.3. Publishing countries

For 26,024 articles, at least one country of origin could be determined. Thus, 94.83% of the total analysis data could be included in the geographical analysis. Of these, the USA could be identified as the main contributor with n = 7014 articles on PFAS. China ranked second with n = 5601 articles, followed by Japan (n = 2802), Russia (n = 2382), and Germany (n = 1914) (Fig. 4A). These absolute numbers are average for 50 years (1973–2023) in which country mappings can be drawn from the WoS metadata.

It is also interesting to note the evolution of national performance over time (Fig. 4B), which shows that China reached first place in the

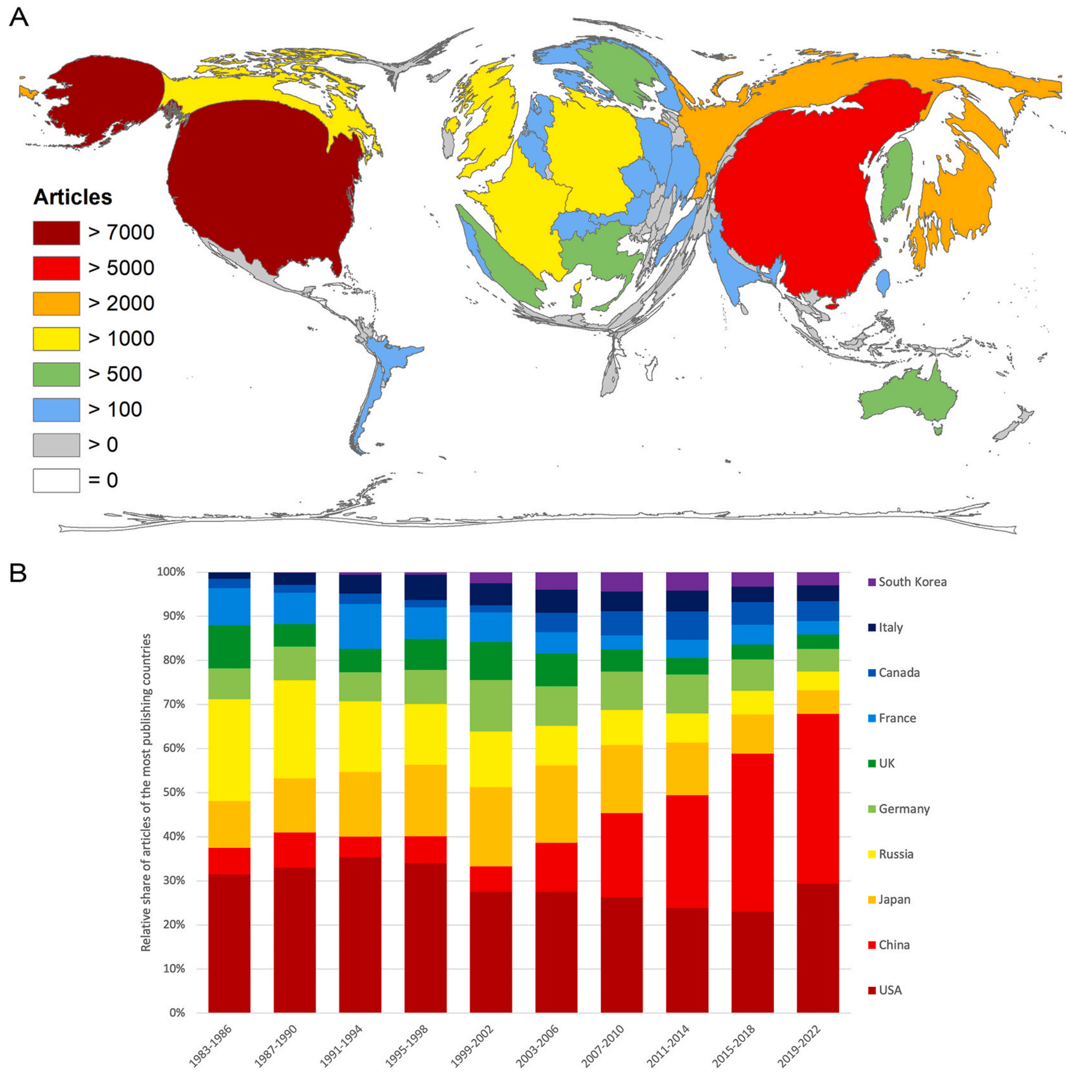

Fig. 4. Country analysis of global PFAS articles. A) Number of articles on PFAS per country. B) Relative share of the number of articles of the most publishing countries on PFAS in 4-year intervals from 1983 to 2022.

last two evaluation intervals from 2015 to 2018 and from 2019 to 2022 placed the USA second. It is also worth mentioning the ranking of Ukraine, which achieved a place in the top ten in the first two time intervals with about 30 articles. This number has stagnated except in the last few years when the number of PFAS articles declined. Without a clear upward trend, Ukraine was unable to maintain its ranking and was, therefore, no longer included in the top ten. On average, Ukraine ranks 15th (n = 334).

The national citation numbers (c) essentially follow the distribution of articles, except for Russia, which drops to 11th place (c = 17,415). The top-ranked country is the USA (c = 259,684), followed by China (c = 138,748), Japan (c = 76,634), Germany (c = 56,584), and Canada (c = 50,150) (Supplementary Fig. 3A). The cartogram of the average citation rate (threshold > 30 articles) shows a different picture. Here, Denmark leads (cr = 49.95), followed by Sweden (cr = 48.86), Canada (cr = 46.44), the Netherlands (cr = 45.94), and Austria (cr = 43.22) (Supplementary Fig. 3B).

The institutions that publish the most on PFAS are listed in Table 2, with the Russian (RAS), Chinese (CAS), and Ukrainian Academies of Sciences (NASU) publishing the most. Industrial companies DuPont Corp (USA), Sovay Solexis Corp (Italy), and 3 M Corp (USA) are also among the institutions with the most publications. In addition to Japan's National Institute of Advanced Science and Technology (AIST) and the US Environmental Protection Agency (EPA), many universities are also major contributors to PFAS research.

3.4. Socio-economic patterns

The ranking of the socioeconomic structure of PFAS research includes the ratio of the number of articles to the countries' population (R_{POP}) and the ratio of the number of articles to the countries' GDP (R_{GDP}).

The five leading countries in terms of R_{POP} per 10 million inhabitants are Sweden (R_{POP} = 648.62), Norway (R_{POP} = 536.04), Denmark (R_{POP} = 462.75), Switzerland (R_{POP} = 291.45), and Singapore (R_{POP} = 286.08) (Fig. 5A).

If R_{GDP} per 10 billion US-$ is considered, Ukraine is in the lead (R_{GDP} = 16.69), followed by Russia (R_{GDP} = 13.41), Sweden (R_{GDP} = 10.50), Tunisia (R_{GDP} = 7.68), and the Czech Republic (R_{GDP} = 6.94) (Fig. 5B).

3.5. Collaboration networks

A total of n = 4658 collaborative articles involving at least two countries of origin were published on PFAS, most of which were binational works (n = 3713). An international cooperation network has been established in recent decades, with the USA as the core. They have

Table 2
Most-publishing institutions. Corp = Corporation, AIST = National Institute of Advanced Science and Technology, Japan, US EPA = United States Environmental Protection Agency.

Institution	Country	Articles	Citations	Citation rate
Russian Academy of Science	Russia	1644	12,857	8.40
Chinese Academy of Science	China	1473	45,853	31.13
DuPont Corp.	USA	300	15,506	51.69
National Academy of Science Ukraine	Ukraine	290	3024	10.43
AIST	Japan	274	14,143	51.62
Kyoto University	Japan	237	8173	34.49
US EPA	USA	231	14,469	62.64
Nankai University	China	205	6760	32.98
University of Stockholm	Sweden	198	13,049	65.90
Shanghai Jiao Tong University	China	191	2513	13.16
University of Toronto	Canada	190	12,856	67.66
Harvard University	USA	189	7653	40.49
Tokyo Institute of Technology	Japan	185	4361	23.57
Solvay Solexis SpA	Italy	183	3717	20.31
Tsinghua University	China	182	7766	42.67
3 M Corp.	USA	177	15,451	87.29
Lomonosov Moscow State University	Russia	159	1457	9.16
Kyushu University	Japan	156	5766	36.96
Durham University	UK	156	5230	33.53
Nanjing University	China	154	5739	37.27

collaborated with China on n = 535 articles on PFAS, which is the most frequent research between two countries, followed by joint work with Canada (n = 223), Japan (n = 203), the UK (n = 178), and Germany (n = 174). In the case of PFAS research, Russia even has notable Western collaborations: with Germany (n = 103) and with the USA (n = 57) (Supplementary Fig. 4A).

Not surprisingly, collaborations between research institutions were mainly at the national level. Here, the joint work of the Russian RAS and Novosibirsk State University on PFAS is noteworthy (n = 87), followed by the number of collaborations between the Chinese Academy of Science and Shanghai University (n = 64). International PFAS research was conducted between Harvard University (USA) and Danish Universities Southern Denmark (n = 46) and Copenhagen (n = 24). The City University of Hong Kong has international partnerships with AIST (Japan) (n = 48), the University of Saskatchewan (Canada) (n = 23), and the Michigan State University (USA) (n = 28). Another PFAS research link was established between Stockholm University (Sweden) and the Swiss Federal Institute of Technology (n = 22) (Supplementary Fig. 4B).

4. Discussion

Consistent with previous study results (Wu et al., 2022), our findings show that the number of articles published annually on PFAS has increased significantly. We show that the trend of PFAS articles runs steeper than the trend of SCIE-indexed articles, indicating a relatively higher interest from the beginning of research activity. The first three articles found via the applied search strategy were published in 1900 by French chemist and pharmacist Henri Moissan on the chemistry of perfluorides (Moissan and Lebeau, 1900) who won the Nobel Prize for the first isolation of fluorine (Fechete, 2016).

The chemistry of PSAF was discovered in the late 1930s. They have been manufactured since the 1940s (ITRC; Gluge et al., 2020). In the 1950s, PFOA (perfluorooctanoic acid) and PFOS (perfluorooctyl sulfonate) were used for the Teflon production process (ITRC, 2022). Therefore, the actual beginning of PFAS research can be placed in this time frame, as consistent research publications occurred in the postwar period after 1945. Concern about PFAS began in the late 1960s and early 1970s when some chemicals were found in the human serum of people who were not occupationally exposed (Guy et al., 1976; Buck et al., 2011). Concerns about PFAS began in the 1970s when some chemicals were found in the blood of workers. They peaked in the 1990s when, due to the development of techniques and tools for detection, PFAS were found in the blood of the general population and the environment (Sunderland et al., 2019). However, more than 20 years had to pass between initial concerns and appropriate academic research and regulatory action (Grandjean, 2018).

In 2000, 3 M, the main global and only PFOS manufacturer in the USA, voluntarily abandoned the production of some perfluorooctanyl chemicals (EPA, 2003).

Six years later, in 2006, the US Environmental Protection Agency (EPA) launched the PFOA Stewardship Program (EPA, 2006), in which eight manufacturing companies pledged to reduce PFOA, other longer-chain PFCA (perfluorocarboxylic acid), and related precursors (EPA, 2017).

In 2009, PFOS were included in the list of persistent organic pollutants of the Stockholm Convention on Persistent Organic Pollutants. The EU classified other PFOS as candidate substances of very high concern (SVHC) (Naidu et al., 2020). As a result, more attention was paid to limiting PFAS production and more researchers investigated the source, fate, and effects of PFAS (Abunada et al., 2020). Accordingly, the number of publications has increased significantly since then.

As expected, 2009 was also the year with the highest number of annual citations for the articles on PFAS. The fact that the sharp decline in citation numbers started already two years later shows the premature waning of scientific interest in the articles published later, as they already had enough time to reach their maximum citation count, expressed as cited half-life (CHL), which is about 7–8 years in biomedical research (Martín-Martín et al., 2014).

The peak values of the citation parameters essentially correspond to the publication years of the most frequently cited articles. In this context, a separation of the research foci can be seen, as the articles published before are mainly focused on materials science, while later articles mainly deal with environmental and ecological issues. An earlier study of the titles and keywords used in PFAS research after 2000 also showed that the emphasis was on environmental science, toxicology, and environmental engineering (Wu et al., 2022).

When addressing ecological issues before 2000, studies generally focused on major releases of PFAS by manufacturers. After that, there was more and more focus on the occurrence of PFAS in the environment. PFOA and PFOS are the best studied and, therefore, best known PFAS (Abunada et al., 2020), so these chemical designations are also the most important keywords from studies dealing with human exposure. The greater awareness of environmental and human exposure research is also reflected in the higher citation frequency of these articles, even though they were published later. Nonetheless, the relationship between PFAS exposure and risks remains one of the evolving areas of research that warrants urgent investigation (Abunada et al., 2020).

The separation of the two main research foci, material and ecological sciences, could be made clear by the occurrence of title words in this study. There are few links between substance-related and ecologically-oriented research.

This separation is also reflected in the focus of the publishing countries. The leading countries, the USA and China, have focused equally on materials science and ecological sciences, with a tendency toward the latter. Canada focuses more on ecological sciences, while Russia stands out for its emphasis on chemistry research. This also corresponds to the research priorities of Ukraine (not among the top ten). It should be noted that the number of Ukrainian articles may be low because they belonged to the USSR, as the country affiliation until 1990 is usually not taken into consideration. Russian influence is certainly present in this regard. Ukraine and Russia are at the top of the economic ranking that calculates the ratio of article count to GDP (R_{GDP}), which shows the high involvement in the development of PFAS for industrial purposes. Their research was mainly carried out by the countries' Academies of Science.

In general, China's research efforts on PFAS have increased, lifting

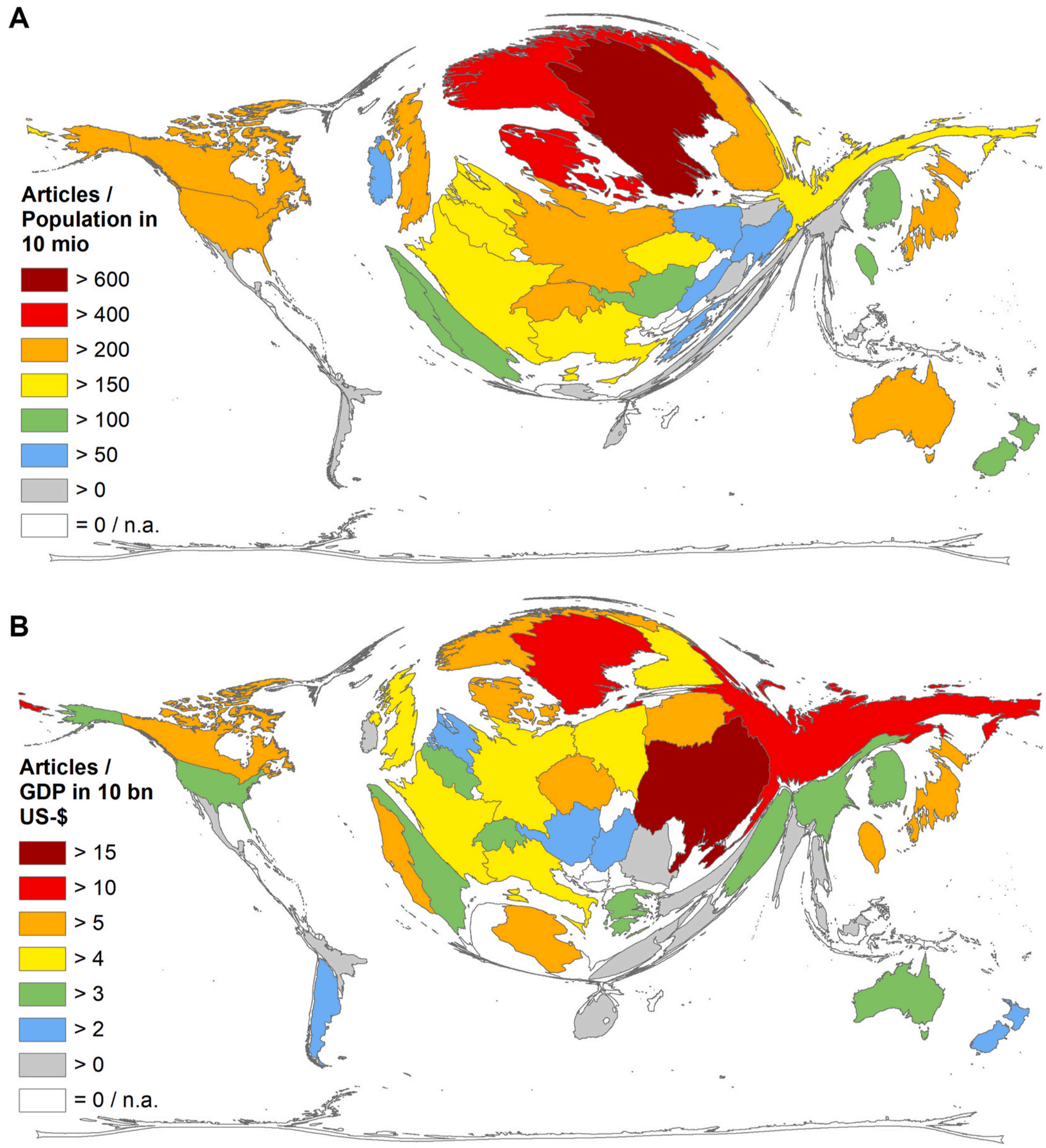

Fig. 5. Socio-economic ratios (threshold ≥ 30 articles on PFAS). A) Number of articles/population in 10 million (R_{POP}), Singapore is not shown because physical constraints prevent the country from being enlarged. B) Number of articles/gross domestic product (GDP) in 10 billion US-$ (R_{GDP}).

the country ahead of the USA in terms of item numbers. The USA has steadily increased its efforts to restrict or ban PFAS compounds, resulting, for example, in a steady decline in detected PFAS concentrations in human blood after 2000 as a result of policy regulations requiring PFAS manufacturers to phase out their production (EPA, 2017). China, on the other hand, is increasing pollution, which continues to skyrocket without restrictions. A comparison of pollution in Chinese and European rivers showed that PFC (perfluorocarbons) concentrations in the Xiaoqing River were more than 6000 times higher than in the Scheur River near a DuPont production plant in the Netherlands (Heydebreck et al., 2015). Also, the highest PFAS level in human blood was found in a Chinese employee at 31,400 ppb (DeWitt, 2015). The most regulated substances, in line with their high research interest, are PFOA and PFOS. For them, a decrease in environmental concentrations could be observed in the European countries (EEA, 2019).

All this underscores the need for policy regulations, which have already resulted in guidelines for action levels for drinking water and bans on certain uses, especially in industrialized countries (ECHA, 2023a). It is not surprising that developed countries are more involved in PFAS research than developing or emerging countries (Abunada et al., 2020) where PFAS are still used and approved indiscriminately (Das and Janardhanan, 2022). The development of the international PFAS research network confirms this state of affairs, which urgently needs to be changed.

The USA, for example, invested $91.57 billion through the Department of Defense in 2022, nearly half of which went toward the destruction and degradation of PFAS accumulated in the environment (Statista, 2023).

5. Conclusions

Despite the partial commitment at the national level to ban and regulate, the release of PFAS and their accumulation in environmental compartments is still increasing tremendously worldwide. In this respect, further progressive steps need to be taken and backed up by scientific efforts. It has already been shown that there is a lack of diverse information, which leads to problems in the detection of PFASs and poor understanding of risks that limit the urgently needed policy measures. Basically, the fate of PFAS residues in the environment, exposure pathways, and toxicity assessment are still poorly documented (Naidu et al., 2020). Therefore, real field data studies and long-term monitoring are needed (Abunada et al., 2020). This needs to be done in a more globally linked and more multidisciplinary, as our results show.

CRediT authorship contribution statement

Doris Klingelhöfer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Markus Braun:** Writing – review & editing, Writing – original draft, Investigation. **David A. Groneberg:** Writing – review & editing, Validation, Supervision, Methodology. **Dörthe Brüggmann:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2024.141694.

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