A research synthesis of humans, animals, and environmental compartments exposed to PFAS: A systematic evidence map and bibliometric analysis of secondary literature

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Type of review

Systematic map of reviews

Highlights

- This systematic evidence map includes 175 systematic reviews addressing human, animal, and environmental PFAS exposure across 35 compounds.
- Discussion focuses on literature content, reviews' methodological quality, and research biases.
- A bibliometric analysis unveils reviews' network, independence, and connectedness.
- Users can access the map’s database via an interactive, publicly available web page, which simplifies data navigation and literature reviews.

Abstract

Background

Per- and polyfluoroalkyl substances (PFAS) are a class of widely used anthropogenic chemicals. Concerns regarding their persistence and potential adverse effects have led to multiple secondary research publications. Here, we aim to assess the resulting evidence base in the systematic secondary literature by examining research gaps, evaluating the quality of reviews, and exploring interdisciplinary connections.

Methods

This study employed a systematic evidence-mapping approach to assess the secondary literature on the biological, environmental, and medical aspects of exposure to 35 fluorinated compounds. The inclusion criteria encompassed systematic reviews published in peer-reviewed journals, pre-prints, and theses. Comprehensive searches across electronic databases and grey literature identified relevant reviews. Data extraction and synthesis involved mapping literature content and narrative descriptions. We employed a modified version of the AMSTAR2 checklist to evaluate the methodological rigour of the reviews. Furthermore, we conducted bibliometric data analysis to uncover patterns and trends in the academic literature. A research protocol for this study was

previously pre-registered (osf.io/2tpn8) and published (Vendl et al., Environment International 158 (2022) 106973). The database is accessible for free on the online, interactive, and user-friendly systematic evidence map at https://hi-this-is-lorenzo.shinyapps.io/PFAS_SEM_Shiny_App/.

Results

Our map includes a total of 175 systematic reviews that met the eligibility criteria. Over the years, there has been a steady increase in the annual number of publications, with a notable surge in 2021. The majority of reviews focused on human exposure, whereas environmental and animal-related reviews were fewer and often lacked a rigorous systematic approach to literature search and screening. Review outcomes were predominantly associated with human health, particularly focusing on children's reproductive and developmental health. Animal reviews primarily focused on studies conducted in controlled laboratory settings, and wildlife reviews were characterised by a taxonomic bias. Recent reviews increasingly incorporated quantitative synthesis methodologies. The methodological strengths of the reviews included detailed descriptions of study selection processes and disclosure of potential conflicts of interest. However, weaknesses were observed in the critical lack of detail in reporting methods. A bibliometric analysis showed a bias in research toward certain geographical areas. Some regions were highly productive in terms of research, mainly with authors from within the country, but they had limited and clustered international collaborations.

Conclusions

In this overview of the available systematic secondary literature, we map literature content, assess reviews' methodological quality, highlight data gaps, and draw research network clusters, aiming to guide future research initiatives, facilitate literature reviews, and enhance opportunities for cross-country collaboration. Furthermore, we discuss how this systematic evidence map and its publicly available database benefit scientists, regulatory agencies, and other stakeholders by providing access to current systematic secondary literature on PFAS exposure.

Keywords

PFOA, PFOS, Ecotoxicology, Systematic review, ROSES, Contamination

1. Background

1.1. Rationale

Per- and polyfluoroalkyl substances (PFAS) are a vast group of anthropogenic organic chemicals manufactured since the 1950s (OECD, 2015a). Although some are regulated or no longer manufactured, many are still produced in significant quantities today (Glüge et al., 2020). They share a common aliphatic carbon composition in which some (prefix: poly-) or all (prefix: per-) of the hydrogen atoms have been substituted with fluorine atoms (ITRC, 2022). PFAS have amphipathic properties and high thermostability, which make them highly resistant to heat, stains, grease, and water. The chemical and physical properties that make PFAS useful in industrial applications also make them problematic in the environment and biological systems. PFAS are highly polar, and their strong carbon-fluoride bonds prevent them from breaking down entirely in the environment (Cordner et al., 2019), earning them the nickname "forever chemicals". Their extensive and unregulated manufacture, use, and disposal in the second half of the 20th century resulted in exposure and bioaccumulation in both humans (Olsen et al., 2017) and wildlife (Routti et al., 2015; Smithwick et al., 2005). Traces of PFAS have been found in even the remotest environments (Miner et al., 2021; Bossi et al., 2015), suggesting their worldwide transport in the air (Shoeib et al., 2006; Taniyasu et al., 2013) and water (Yamashita et al., 2005; Ahrens & Bundschuh, 2014).

In both humans and animals, PFAS compounds can attach to proteins (mainly albumin) in the blood (Forsthuber et al., 2020) and tend to bioaccumulate in body tissues (Shi et al., 2018). Biomagnification of highly fluorinated compounds has been observed across diverse wildlife taxa, including birds (Haukås et al., 2007) and aquatic and terrestrial mammals (Boisvert et al., 2019). Emerging research suggests PFAS could impact human development, fertility, hormone regulation, cholesterol, immune function, vaccine efficacy, and cancer risk (Bach et al., 2015; Grandjean et al., 2017; Vélez et al., 2015). The estimated cost of PFAS-associated diseases in the USA amounted to $5.52 billion (Obsekov et al., 2023). Consequently, the production and disposal of fluorinated compounds, and persistent organic pollutants (POPs) in general, are significant environmental and public health concerns (Wang et al., 2017). Driven by concerns about the potential harmful impacts of certain PFAS on both the environment and human health, various initiatives have been implemented to reduce exposure to long-chain perfluoroalkane sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs) (OECD, 2015b). Several international regulatory frameworks have imposed restrictions on the production and use of long-chain PFCAs and PFSAs, with some substances, like perfluorooctane sulfonic acid (PFOS) in 2009, perfluorooctanoic acid (PFOA) in 2019, and perfluorohexane sulfonic acid (PFHxS) in 2022, being added to the restricted list under the Stockholm Convention on Persistent Organic Pollutants (Pinas et al., 2020) and others, including C_{11}–C_{14} PFCAs, designated as Substances of Very High Concern for Authorization under the European chemicals regulation, REACH (ECHA, 2012; ECHA, 2013; ECHA, 2015).

In 2016, the International Agency for Research on Cancer (IARC) categorised PFOA as a Group 2B substance, deeming it potentially carcinogenic to humans (IARC, 2017). At the end of 2023, the IARC finalised their judgment on PFOA and PFOS, which were classified as “carcinogenic to humans” (Group 1) and “possibly carcinogenic to humans” (Group 2B), respectively. The classification specifically pertains to prostate, testicular, liver, and kidney cancers. It is worth noting that while IARC regulation is significant, PFAS are also subject to regulation under various other regulatory frameworks (e.g., legislation such as the Safe Drinking Water Act and the Clean Water Act in the United States, the Stockholm Convention on Persistent Organic Pollutants (POPs), and regulations set by agencies like the Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA)). In response to the continued need for chemicals with similar properties to these compounds, new PFAS have been developed and produced, including supposedly less-harmful shorter-chain analogues (Guo et al., 2019). Nonetheless, when evaluating toxicokinetics, the toxic potency seems similar between fluorinated alternatives and their predecessors (Gomis et al., 2018; Chappell et al., 2020).

The risks posed to human and animal health and the environment emphasise the need for action against persistent chemicals (Usman & Hanna, 2023), as well as increased scientific investigation. Consequently, the increasing concern about the hazardous nature of PFAS has led to a growing number of primary studies (i.e., empirical studies) and secondary studies (e.g., evidence syntheses and reviews). Primary studies are crucial in measuring the extent of PFAS exposure and assessing their toxicological effects, typically through experiments or observational studies. Such studies form the building blocks of knowledge in this field and support formulating hypotheses about PFAS impacts across larger scales. As the volume of primary literature addressing the impacts of PFAS continued to rise, an opportunity emerged to synthesise such a body of literature.

Systematic evidence reviews (commonly known as 'systematic reviews') adhere to a rigorous and transparent methodology aimed at addressing a particular research question. This process involves identifying pertinent studies, conducting a thorough evaluation of each study's quality, extracting data, analysing and synthesising the evidence, and reporting findings according to a predetermined protocol. For these reasons, systematic reviews are generally considered the most trustworthy evidence review (Haddaway et al., 2015). Nevertheless, the scope of systematic reviews can vary significantly, meaning that the overarching patterns and emerging evidence reported differ across scales and disciplines. The high heterogeneity of reviews' subjects, methods, terminology, and reliability of conclusions can make it difficult to appreciate the evidence base fully. However, this challenge can be effectively addressed by systematic evidence mapping, a relatively new tool used to summarise the available primary or secondary research.

A systematic evidence map (SEM) is an overview of the distribution and abundance of evidence about multifaceted elements of a broad question of policy or management relevance (Wolffe et al., 2019). Consequently, SEMs are a valuable instrument for maximising the efficient utilisation of present research in managing chemical risks (Wolffe et al., 2019). SEMs can enhance transparency, the effectiveness of research, and regulatory efforts by becoming a starting point for further evidence synthesis via targeted systematic reviews and meta-analyses. PFAS-related evidence originates from various disciplines, subject areas, and methodologies, and their dependability varies significantly. The large volume of available systematic secondary literature on PFAS exposure presents an unprecedented opportunity to aggregate and elucidate the current evidence.

1.2. Objectives

In this study, we assess the systematic secondary evidence base on the exposure of humans, animals, and the environment to 35 PFAS (according to the list of PFAS of emerging importance published by Kirk et al. (2018) and Pelch et al. (2019); Supplementary Table 1). Our approach involves combining systematic evidence mapping with critical appraisal and bibliometric analysis (Fig. 1), commonly called 'research weaving' (Nakagawa et al., 2019). Research weaving is a powerful approach that goes beyond the traditional compilation of evidence and enables the research questions of greater complexity and depth to be addressed. Our main research questions are three-fold:

1) What areas of health and environmental research related to PFAS have been systematically synthesised?

(2) How robust and reliable are systematic reviews of PFAS exposure evidence?

(3) How interdisciplinary and connected are PFAS-related reviews?

To address these questions, we have three primary objectives: (1) Identifying the areas where systematic evidence syntheses are lacking. Specifically, we analyse whether the reviews have an exclusive focus on PFAS or a broader focus on persistent organic pollutants in general, whether they concentrate on one or several types of PFAS, the type of main topic, the main review subject type (e.g., humans, animals, or environmental compartments) and whether the authors focus on single or multiple species. (2) Critical appraisal, where we assess the reporting quality and potential bias of existing reviews. We utilise various pieces of information, including the AMSTAR2 checklist scores

(Shea et al., 2017), the type of review funding sources, and the availability of raw data and code. (3) Bibliometric analysis, where we assess the interdisciplinary nature and connections within the PFAS research field by analysing bibliographic data. We look at publication time and place, co-authorships, inter-jurisdictional collaboration, co-word analysis, and patterns in cited references. Lastly, bibliometric coupling analysis of the references cited in the included secondary studies provides information on their connectedness by primary papers. Addressing these objectives highlights research patterns across different disciplines, as well as the specific questions and topics explored and the overall reliability of the research.

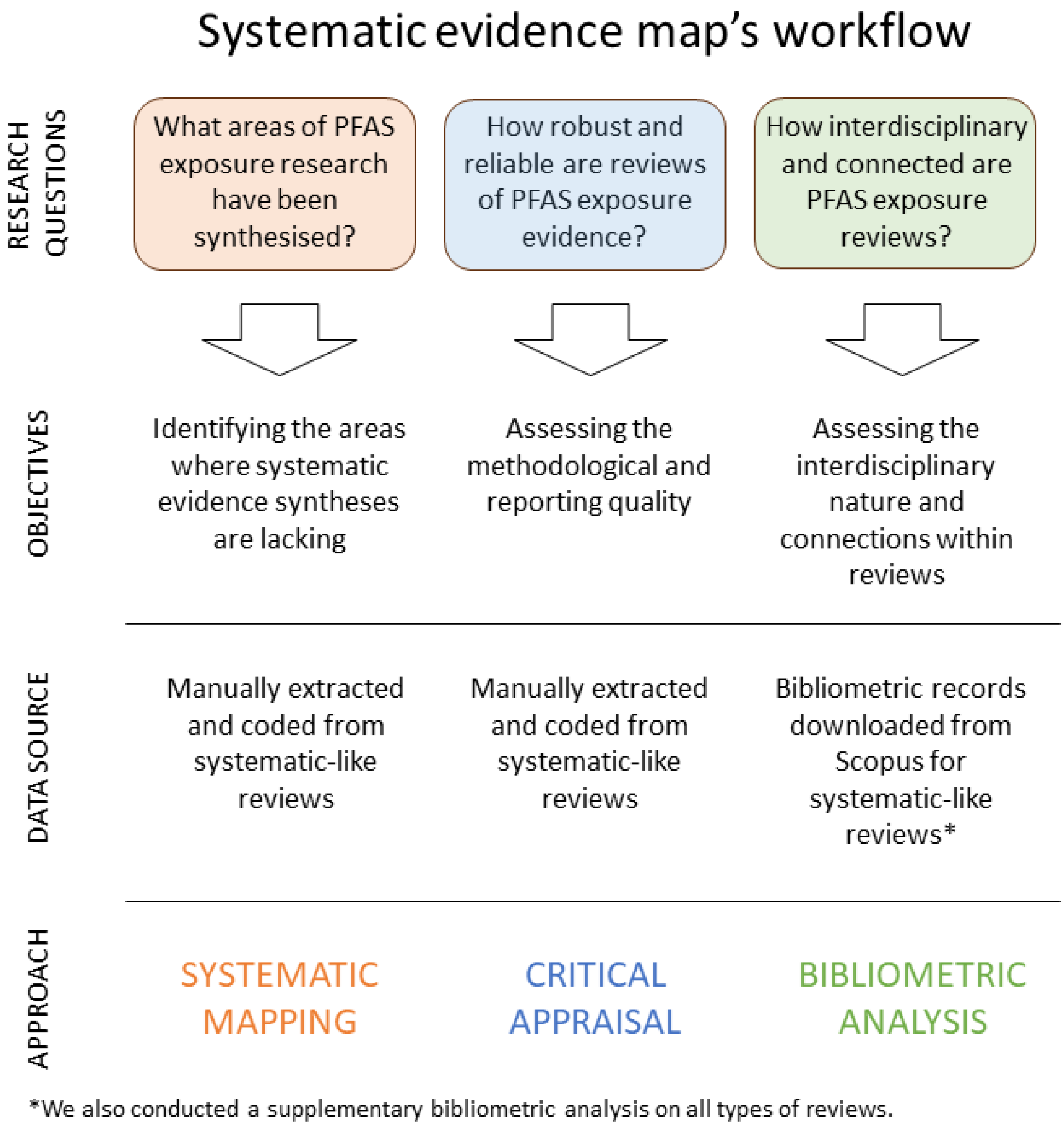

Fig. 1. Workflow illustrating the main research questions, objectives, data sources, and analysis approaches.

2. Methods

This systematic evidence map (SEM) adopts a systematic data analysis approach, comprising five fundamental procedural steps. First, we registered and published the project plan to ensure transparency and facilitate replication. Second, we conducted an extensive literature search in multiple databases to collate available systematic reviews on the research topic. The third step involved extracting and mapping pre-registered data items from the literature, followed by an analysis of the results. The fourth step entailed the development of a browsable and interactive version of the database, aimed at enhancing its usability and navigational ease. Finally, we discussed the implications of our findings for policy-making and scientific research, thereby advancing the current state of knowledge on the research topic.

2.1. Protocol and reporting

Our SEM adhered to the highest standards of reporting guidelines for systematic evidence syntheses in environmental research. Specifically, we followed the *RepOrting standards for Systematic Evidence Syntheses* (ROSES) in environmental research, as per the adapted version for mapping secondary literature (Haddaway et al., 2018) (Supplementary Table 1). We registered a pre-protocol plan on the Open Science Framework and made it publicly accessible through a provided link (osf.io/2tpn8). Furthermore, we published an *a priori* plan for our methods as a protocol to ensure transparency and consistency in our methodology (see Vendl et al., 2022). These measures ensured the study was conducted rigorously and transparently, allowing for greater scrutiny and replication by the broader scientific community. Thirteen deviations and additions to the protocol were applied in our SEM and are reported in Section 2.9: "Deviations and Additions to the Protocol".

2.2. Eligibility criteria

Complying with the PECO framework, the eligibility criteria were defined as:

- Population: Peer-reviewed journal articles, pre-prints, grey literature, or theses. Reviews must identify themselves as one of the review types considered part of the systematic-like review family by Moher et al. (2015), or they must include a systematic method of search and screening of the literature reviewed and/or quantitative analysis (meta-analyses) (note: to simplify, the reviews that meet the eligibility criteria are referred to as "systematic reviews" within this map). Eligible review types from the systematic review family include, but are not limited to: systematic reviews, scoping reviews, critical reviews, rapid reviews, realist reviews, meta-analyses, and systematic maps (for review definitions, see Moher et al. (2015)). Primary literature, opinions, corrections, and editorials were excluded.

- Exposure: Systematic reviews should focus on biological, environmental or medical aspects of the burdens of any of the 35 PFAS of emerging importance listed in Supplementary Table 2. Relevant reviews on persistent organic pollutants with a significant component dedicated to PFAS were also included.
- Outcome: Reviews should focus on the impact of PFAS on the health of people, animals or the environment, levels of contamination, detection strategies, and analysis of toxicity (all in biota/biota tissue or the environment). Methodological studies were excluded. Reviews on topics such as remediation/removal technologies of PFAS from wastewater/soil/environment, manufacturing technologies, policies, economic analyses or risk management were also excluded.
- Other criteria: Reviews must have a full-text version available for examination. Reviews can be from any year of publication and written in any language.

2.3. Piloting

We ran a pilot search in the Scopus database and a pilot data extraction during the development of the research protocol. The piloting stage assessed the comprehensiveness of the search strategy and the effectiveness of the data extraction process. As a first piloting step, fourteen systematic reviews were manually collected as benchmark bibliographic records from Google Scholar and used to validate the sensitivity of the pilot search string crafted for the Scopus database (see Table S3 from Vendl et al. (2022)). As the search string did not find all fourteen studies, it was improved and tested again. The final search string successfully retrieved all benchmark studies (see Table S1 from Vendl et al. (2022)). Among these benchmark records, twelve could be found in the Web of Science database, and our corresponding search string successfully retrieved all of them. In contrast, only five benchmark records were available in PubMed, which has a stronger focus on medical content, and our tailored search string, utilising MeSH Terms, captured all five pertinent reviews. Subsequently, a random sample of 100 studies from the Scopus search was retrieved to test and refine the screening and inclusion criteria using Rayyan QCRI (Ouzzani et al., 2016), a free web tool for knowledge synthesis. Two authors (CV and ML) independently screened these studies and tested data extraction tables through pilot data extraction to refine data gathering and coding procedures.

2.4. Literature searches

We followed the search strategy refined in the research protocol. Accordingly, we did not restrict our search based on publication date, language, or subject/discipline codes. One reviewer (LR) ran literature searches for eligible reviews on the 7th and 8th of March 2022 using three main databases (i.e., Scopus, Web of Science Core Collection, and PubMed) and nine secondary databases (i.e., Cochrane, Prospero, Epistemonikos, Australian Policy Observatory, PrePrints, Biorxiv, OSF, BASE, and OpenGrey). LR used the final search strings developed in the research protocol to conduct the literature search. The search parameters, strings, and the number of hits for each database are presented in detail in Supplementary Table 3. Potential duplicates were removed using custom text-processing code in R software (version 4.2.1) (R Core Team, 2022), and the remaining studies were uploaded to the Rayyan QCRI online software for title and abstract screening. To ensure that the systematic map remained current, LR conducted an update search on the 6th and 7th of February 2023 to identify relevant reviews published from the 1st of March to the 31st of December 2022. The search was conducted on the same databases as the primary search using the same search strategy but restricted to 2022. Reviews published between the 1st of January and the 28th of February 2022, which were already included in the map, were excluded during the screening at the full-text level. The results of the update search are provided in Supplementary Table 4. In addition to the primary and update searches, a supplementary search was conducted on Scopus on the 5th of February 2023 to retrieve all types of reviews, including both systematic and non-systematic reviews. This broader range of reviews was used to conduct a supplementary bibliometric analysis of the entire PFAS research field. The same criteria applied to our main searches were also applied to the supplementary search. A search string was customised to find all available types of reviews until the end of 2022. The respective search query string, the search records, and further search details are provided in Supplementary Table 5.

2.5. Screening of articles

The screening process followed well-established guidelines (Moher et al., 2009). During article screening, LR and ML independently screened the title and abstract of studies based on the eligibility criteria. The reviewers evaluated the inclusion criteria at the title and abstract screening level using a first decision tree (see Fig. 2 from Vendl et al. (2022)). The same reviewers independently performed the full-text screening following a second decision tree (see Fig. 3 from Vendl et al. (2022)). To ensure an unbiased screening process, reviewers did not evaluate any articles they authored. In cases where the article was written in a language other than English and known by any of the reviewers, it was translated. Any decisional conflicts that arose during the title and abstract screening and full-text screening were discussed and resolved by the reviewers. The percentage of conflicts between the two reviewers was 6.6% (102 conflicts out of 1542 bibliographic records) and 5.8% (13 conflicts out of 222 bibliographic records) for the title and abstract screening and full-text screening, respectively. The screening of all types of reviews for supplementary bibliometric analyses followed the same steps, except that the inclusion criteria did not limit the inclusion to systematic-like reviews only.

2.6. Data extraction, warehousing, and coding strategy

We used the free software Zotero (www.zotero.org, version 6.0.26) to store and reference all retrieved reviews during the literature search. Data extraction was performed by LR using four inter-connected Google Forms to extract the pre-determined items. A second reviewer (ML) double-checked the data extracted from a random sample of 15% (i.e., 16 studies). The disagreement ratio between the reviewers did not exceed 10%. Thus, only one reviewer (LR) extracted the data from the remaining reviews.

Extracted data were stored in four different tables, organised according to the type of data collected and connected through unique study IDs. The data tables include:

- "Main" - main data for the systematic map covering information on the publication and its scope.
- "Species" - scientific names of all species other than humans considered in the reviews.
- "PFAS_types" - types of PFAS considered in the reviews.
- "AMSTAR2" - questions of the AMSTAR2 quality assessment scheme applied to each systematic review.

Additionally, the table "PFAS_info" holds fixed information on the PFAS types, including their abbreviations, CAS numbers, and carbon chain lengths (derived from Kirk et al. (2018) and Pelch et al. (2019)). The data extraction tables were implemented as Google Forms and converted to Excel sheets and .csv files. The raw extracted data, the analysis code, and additional data are stored and publicly available in the GitHub repository (https://github.com/ThisIsLorenzo/PFAS_Systematic_Evidence_Map). The tables and their meta-data are explained in detail in the code book (Supplementary Table 6). Fixed data fields (e.g., checkboxes) that required more information were accompanied by a comment field allowing free text entry during data extraction. The comment fields were used to document the data extraction process. As stated in the protocol, we planned to contact the review's authors if the required information was not provided. However, there was no need to request any additional data. Finally, data for bibliometric analyses were downloaded directly from Scopus using the included articles' Digital Object Identifier (DOI) for each individual review in our SEM (Supplementary Table 13).

2.7. Critical appraisal

To assess the quality of the reviews, we conducted a critical appraisal of the included studies. We employed a modified version of the AMSTAR2 checklist. This checklist focuses on the review method, reporting transparency, and limitations, and consists of 16 questions, with each response categorised as “yes”, “partially”, or “no”. Subsequently, we categorised the responses into “high”, “medium”, or “low” methodological quality (for additional information, see Supplementary Table 7).

Additionally, we included a comment field for each question to gather relevant information, such as verbatim review text sentences or paragraphs, references to figures or tables reporting extracted data, and any pertinent information on the score reason. The information from critical appraisal was used in a narrative synthesis of reviews' quality for each AMSTAR2 question. Besides the AMSTAR2 checklist, we extracted data on conflict of interest, funding sources, and raw data and analysis code availability.

2.8. Data mapping & synthesis criteria

Our approach to reviewing and mapping the evidence encompasses a narrative and concise description of the results, complemented by extensive representation through tables and graphs. To ensure a rigorous and standardised methodology, we organised the research outputs based on the three-part division of research questions and objectives. One author (LR) turned the database into an interactive web application (accessible for free at the following link: https://hi-this-is-lorenzo.shinyapps.io/PFAS_SEM_Shiny_App/) using the "shiny" package (version 1.7.5.1) (Chang et al., 2023). All analyses were conducted in the R environment (version 4.2.1) (R Core Team, 2022). For data manipulation, we utilised the "*tidyverse*" collection of open-source packages (version 1.3.2) (Wickham et al., 2019), specifically the "*dplyr*" package (version 1.0.10) (Wickham et al., 2022a). We used the "*tidyr*" package (version 1.2.1) (Wickham et al., 2022b) for data cleaning and the "*ggplot2*" package (version 3.4.0) (Wickham et al., 2016) for visualisation. For bibliometric analysis, we employed the "*bibliometrix*" package (version 4.0.1) (Aria & Cuccurullo, 2017). The complete list of packages used in this SEM is provided in Supplementary Table 8.

2.9. Deviations and Additions to the Protocol

The research protocol was subject to twelve minor changes, which are detailed, justified, and qualitatively assessed in Supplementary Table 9. These modifications were necessary to ensure comprehensive and precise scrutiny of the available evidence related to the subject matter and to elucidate previously ambiguous aspects. Briefly, these twelve changes and additions are listed below:

- Inclusion of additional PFAS types: We expanded our inclusion criteria to encompass five additional types of PFAS, namely perfluorooctanesulfonamide (FOSA), N-ethyl perfluorooctanesulfonamide (NEtFOSA), N-methyl fluorooctane sulfonamide (NMeFOSA), bis(perfluorohexyl)phosphinic acid (6:6 PFPIA), and perfluorohexylperfluorooctylphosphinic acid (6:8 PFPIA). For details on chemical compounds refer to Supplementary Table 2.
- Bibliometric analysis focus: We shifted our planned bibliometric analysis on all review types to supplementary materials and performed the main bibliometric analysis exclusively on systematic-like reviews.
- Literature screening assignments: Changes were made in the team of reviewers responsible for the literature screening.
- Inclusion of indoor dust-related reviews: We added reviews related to indoor dust to the systematic evidence map under the subject of environmental exposure.
- Inclusion of food-related reviews: We added reviews related to food and food packaging to the systematic evidence map under the subject of human exposure.
- Categorization of plant reviews: Reviews focused on plants were categorised as environmental exposure.
- DOI extraction: We extracted and recorded the DOIs of the included reviews (see Supplementary Table 6).
- Scopus search string modification: The search string in Scopus was adjusted to retrieve bibliographic records for our bibliometric analysis (see Supplementary Table 5).
- Addition of "Systematic_approach" column: A new column named "Systematic_approach" was introduced in the "Main" data table to extract information regarding whether a review follows a systematic approach.
- Clarification of missing species names: If the scientific or common name of the species reviewed was missing, it was searched on Google and noted in the comment column in the

relative data table.

- Additional data columns: Two new columns, "Class_scientific_name" and "Broad_taxa," were incorporated into the "Species" data table to capture information about the class and broad taxa of species.
- Broad PFAS group inclusion: The broad PFAS groups PFCs, PFSA, and PFCA were incorporated into the "PFAS_types" data table.

3. Results and Discussion

3.7. Search and screening outcomes

Three primary databases, namely Scopus, Web of Science Core Collection, and PubMed were searched and yielded 1227, 937, and 40 bibliographic records, respectively. Including grey literature and additional databases further increased the number of studies identified for screening (i.e., an additional 290 bibliographic records), as presented in Supplementary Table 3. In total, 2494 bibliographic records were identified in our searches. The flow diagram below shows the screening process (Fig. 2).

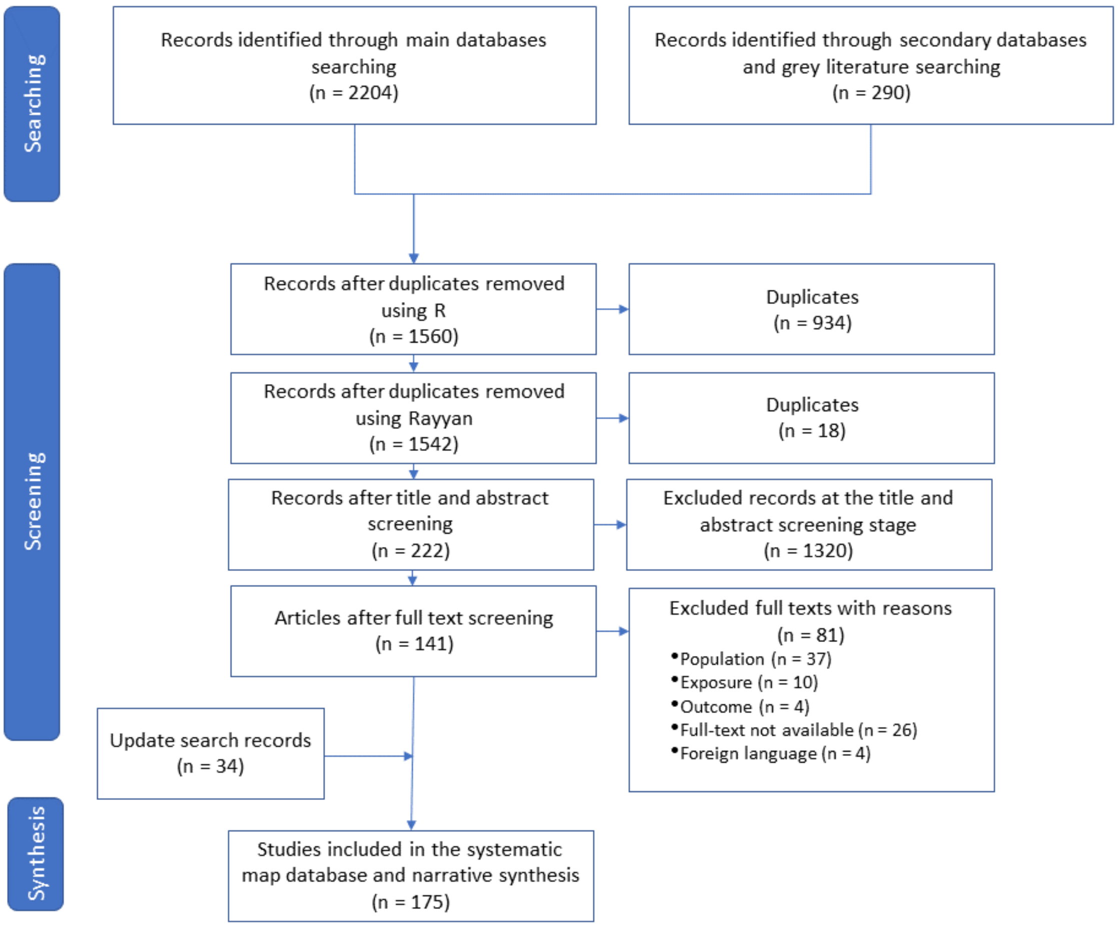

Fig. 2. ROSES flow diagram illustrating the process of study selection. Note: an additional flowchart regarding the search update conducted in February 2023 is available in Supplementary Figure 1.

At the end of the study selection process, 141 (approximately 9%) bibliographic records were retained. In addition, 34 eligible records were identified as a result of the update search (see Supplementary Figure 1), bringing the total number of systematic reviews included in our systematic evidence map to 175. The reasons for excluding individual records at the full-text stage were justified and recorded (see Supplementary Table 10). Individual records excluded at the full-text stage during the update search, together with a detailed list of included reviews in the map, can be found in supplementary materials (see Supplementary Tables 11, 12, and 13). The search for all review types (Supplementary Table 5) retrieved 2416 records, in which titles and abstracts were screened for inclusion by LR, ML, and CV. Of the 2416 records, 1886 were excluded. Of the 530 included records, 13 were not found in the Scopus database (Supplementary Table 14). Thus, a total of 517 records were included in the supplementary bibliometric analysis.

3.8. Mapping

Our systematic evidence map (SEM) revealed a steady annual rise in published reviews on PFAS exposures from 2016 (Fig. 3. See also Supplementary Figures 2 and Supplementary Figure 3). Likewise, Pelch et al. (2022) and Vendl et al. (2024) both observed a similar rise in publications over time in the primary literature concerning human health and wildlife exposure to PFAS in their respective systematic maps of primary literature. These publication trends might reflect a combination of a growing interest in the impacts of PFAS on the environment and a decreasing cost of chemical analyses. Recent reviews on PFAS exposure are more likely to include quantitative synthesis, as illustrated in Fig. 3a and Fig. 3b. In line with this trend, 24% of reviews published between 2013 and 2019 include quantitative analysis, compared to 36% of reviews published between 2020 and 2022. Meta-analyses are a powerful tool that can help establish a quantitative evidence base, often reconciling seemingly conflicting research outcomes (Gurevitch et al., 2018). From 2013, the systematic secondary literature increasingly included quantitative analyses to assess the impact of PFAS exposure (Fig. 3b). Approximately 40% of reviews published in 2022 included a quantitative data analysis. In the same year, reviews claiming themselves to be ‘systematic’ also started to emerge. However, it is noteworthy that the first review claimed to be systematic and focusing on a group of endocrine-disrupting chemicals, including PFAS, was published in 2011 (i.e., Caserta et al., 2011), as depicted in Fig. 3a.

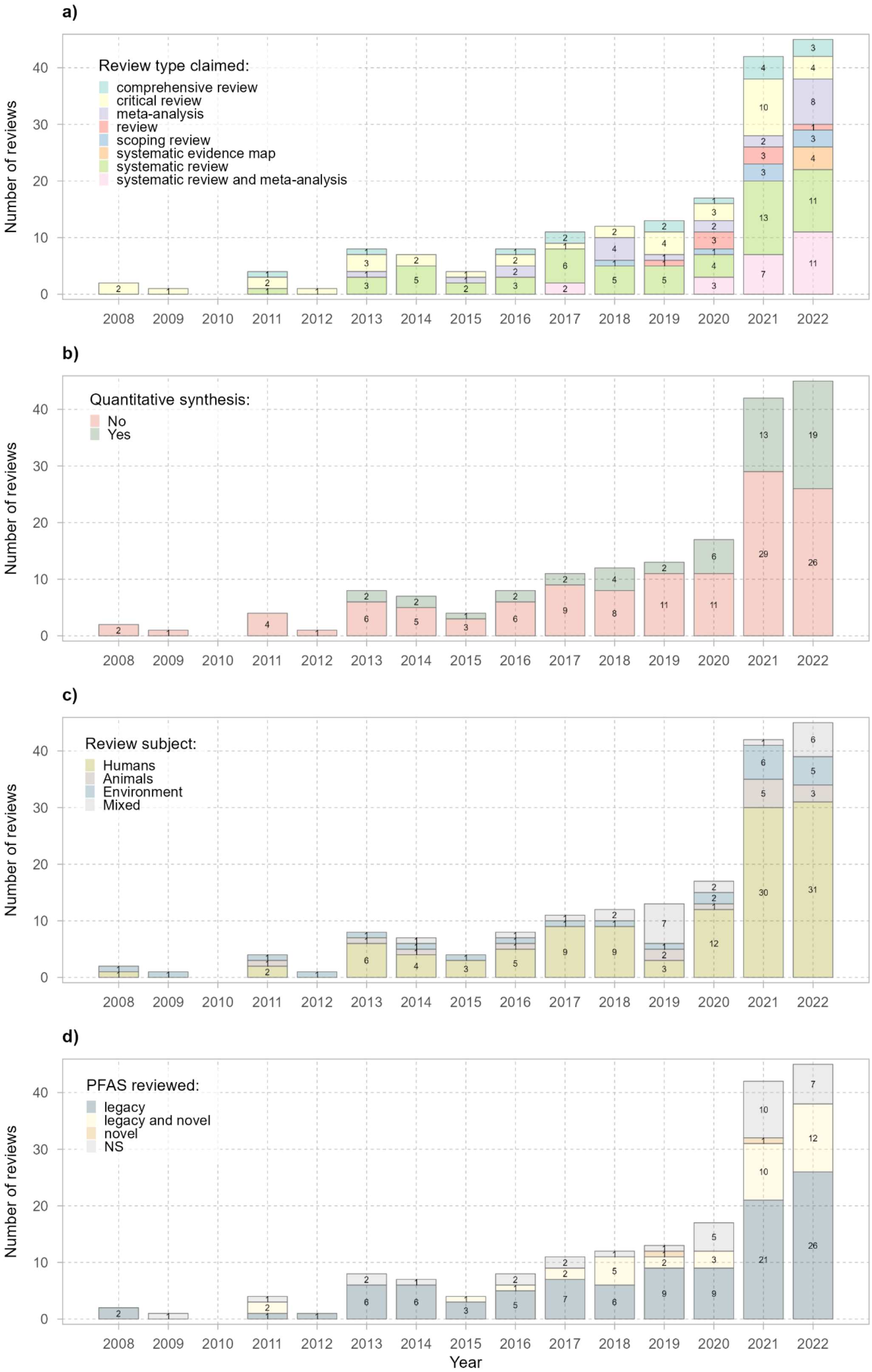

*Fig. 3. Bar charts showing publication time trends. **a)** The number of self-claimed review types over time (CoR = comprehensive review, CrR = critical review, MA = meta-analysis, ScR = scoping review, SEM = systematic evidence map, SR = systematic review, SR and MA = systematic review and meta-analysis), **b)** the distribution of review subjects over time, **c)***

the proportion of reviews that included a meta-analysis over time, ***d)*** *the proportion of reviews that focused on legacy or novel PFAS types over time (NS = not specified).*

A notable proportion (i.e., 61%) of the available systematic reviews is focused solely on human exposure, while reviews on environmental, animal, or a mix of these subjects are limited (Fig. 3c, Fig. 4c, and Supplementary Figure 4a). The increasing concern regarding the effects of these chemicals on human health has led to a substantial amount of primary literature being produced. Due to the diverse range of findings within this primary literature, reviews, and particularly meta-analyses, have endeavoured to gauge an overall effect by addressing this diversity. Following this pattern, we show that the most frequently used Medical Subject Headings and Qualifiers (MeSH) terms were "humans" and "toxicity," followed by "fluorocarbons" and "chemically induced" (Supplementary Figure 7). Furthermore, we categorised the outcomes of the reviews into six primary groups. The analysis revealed that the most frequently occurring outcomes were associated with general human health (38% of reviews), followed by those specifically concerning reproductive and developmental health (26% of reviews) (Supplementary Figure 4b).

The number of studies incorporated in a review is predominantly influenced by the research subject and the extent of corroborative evidence accessible. In this SEM, we did not notice a significant difference in the number of primary studies included in systematic reviews among different subjects (Supplementary Figure 8a). Moreover, we found that while most reviews on human health employ, and claim to employ, a systematic method (Fig. 4b and Fig. 4c), such approach is rare in reviews on the environment or animals, which similarly claim to be critical and comprehensive, but lack a systematic search and screening of the literature (Fig. 4a and Fig. 4d). By employing a systematic method, systematic reviews reduce bias, resulting in more dependable findings that can be used as a foundation for drawing reliable conclusions and making evidence-based decisions (Lasserson et al., 2022).

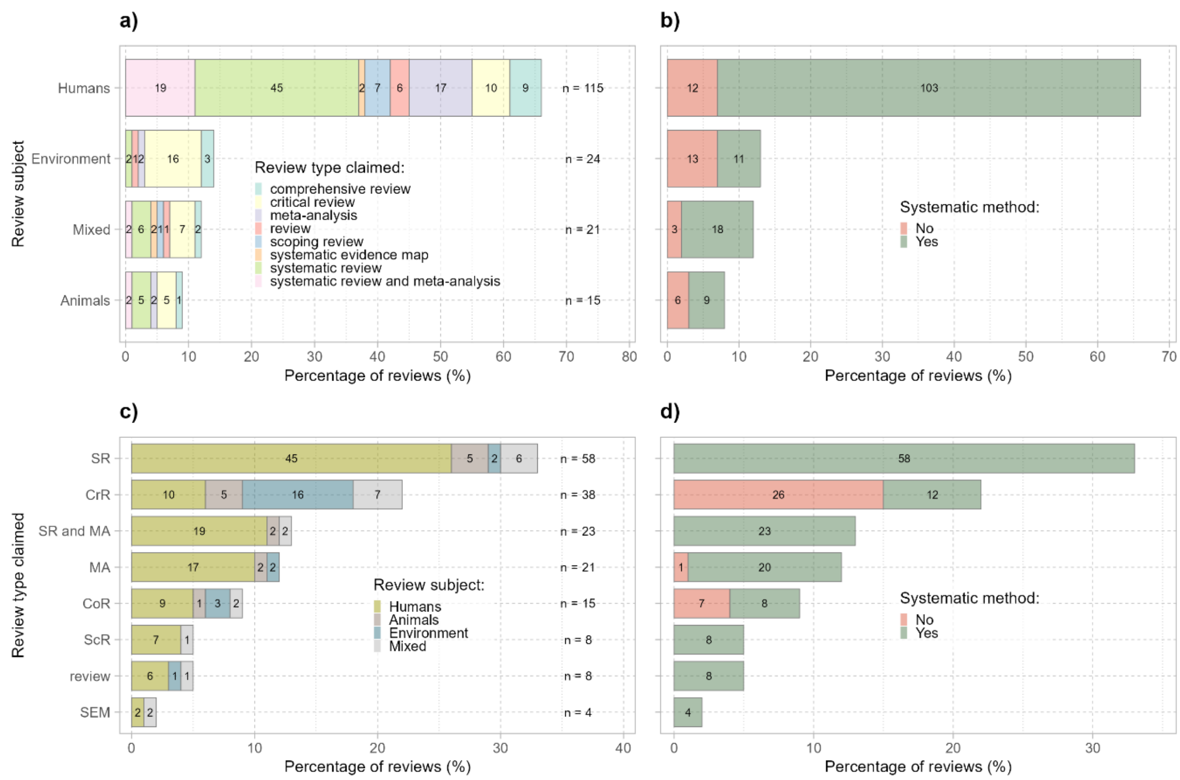

Fig. 4. Bar charts depicting the distributions of review subjects and self-claimed review types. ***a)*** *the distribution of reviews across various subjects and the proportion of each review type claimed for each subject,* ***b)*** *the percentage of reviews categorised by subject, further divided into those that utilised a systematic method and those that did not,* ***c)*** *the distribution of different self-claimed review types across subjects, along with the proportion of each subject reviewed by each type (SR = systematic review, CrR = critical review, SR and MA = systematic review and meta-analysis, MA = meta-analysis, CoR = comprehensive review, ScR = scoping review, SEM = systematic evidence review),* ***d)*** *the percentage of reviews categorised by type, further divided into those that utilised a systematic method and those that did not. The numerical values within the bars represent the review counts.*

An analysis of the reviewed compounds revealed that most of the reviews focused on PFAS specifically (i.e., 57%), rather than having a broader focus on POPs (Fig. 5a and Supplementary Figure 9a). This zoom-in on the fluorinated compounds by the systematic secondary research may be attributed to the increasing demand for specific reviews from institutions and stakeholders. Additionally, 70% of reviews cover the exposure to multiple PFAS rather than focusing on only one (Fig. 5a and Fig. 5b). However, the mere inclusion of various PFAS types in these reviews does not automatically imply a specific emphasis on the toxicity of PFAS mixtures. Instead, these reviews tend to adopt a broader perspective. Nonetheless, deepening our understanding of the toxicity associated with PFAS mixtures holds great significance in evaluating their risk, since synergistic effects influence the combined toxicity of PFAS mixtures (Ojo et al., 2020). In 2021, there has been an increase in the number of published reviews that covered both legacy and novel compounds (i.e., 25% of the total number of reviews in 2020, 35% in 2021, and 32% in 2022), as shown in Fig. 3d. However, reviews focused solely on novel compounds were only 2 out of 175 reviews included in this SEM. These two reviews were a systematic evidence map published in 2022 (Pelch et al., 2022), which included Nafion by-product 2 and hydrofluoroether-based compounds (Hydro-Eve), and a systematic review and meta-analysis on animals (Banyoi et al., 2022), which included perfluorohexylperfluorooctylphosphinic acid (6:8 PFPiA). The widely detected legacy compounds PFOA and PFOS were the most frequently reviewed (Supplementary Figure 6a), followed by perfluorohexane sulfonate (PFHxS), perfluorononanoic acid (PFNA), and perfluorodecanoic acid (PFDA) (Fig. 5c). The median and mean number of primary studies included in reviews on legacy compounds (median = 27, mean = 38) did not significantly differ from those encompassing both legacy and novel compounds (median = 39, mean = 62) (Supplementary Figure 6b). Despite a lower quantity of reviews focusing on novel compounds compared to those centred on legacy compounds, the number of primary studies forming the basis for these reviews is comparable.

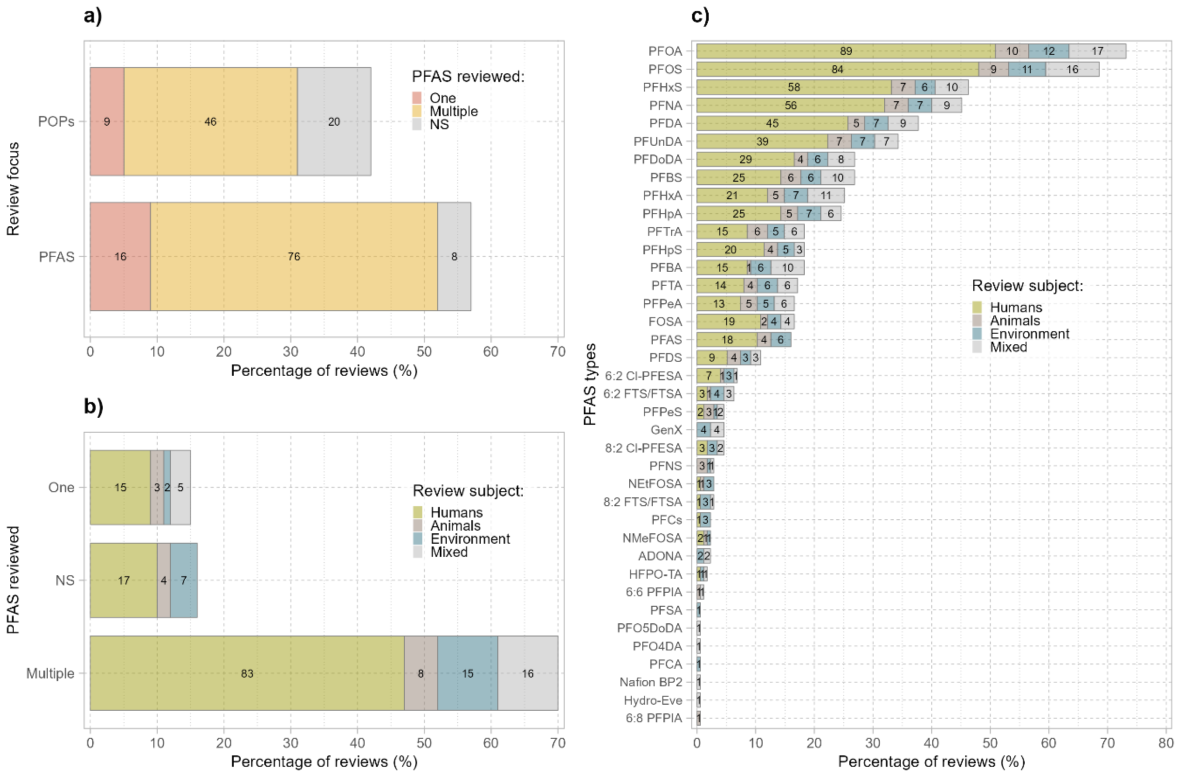

Fig. 5. Bar charts summarising the PFAS-related focus of the included reviews. ***A)*** *The percentage of reviews focused on PFAS or on POPs in general, along with the proportion of reviews that cover either one or multiple types of PFAS (NS = not specified),* ***b)*** *the distribution of reviews covering one or multiple PFAS compounds, with the proportion of each subject reviewed by each type,* ***c)*** *the different types of PFAS reviewed and the subjects that each type of PFAS was reviewed in. The numerical values within the bars represent the review counts.*

Moreover, our results did not show a particularly growing body of secondary research on the effects of PFAS exposure on animals (Fig. 3c), although five reviews were published in 2021. More than half (i.e., 56%) of reviews of animal studies were focused on laboratory animals (Supplementary Figure 10), such as rats and mice, which may not accurately represent the effects of PFAS exposure on wildlife species and its indirect effects on ecosystem functionality. Only one systematic review (i.e., Jha et al., 2021) collected evidence on human health risks associated with PFAS exposure through meat and milk consumption produced in crop-livestock systems. The lack of systematic reviews on this aspect of PFAS exposure is probably due to the limited number of primary studies addressing PFAS in livestock and game (Death et al., 2021). Around a third of reviews (i.e., 34%) covered wildlife species and 3 reviews (i.e., 9%) covered both laboratory and wildlife species (Supplementary Figure

10). The most reviewed classes were mammals, ray-finned fishes, and birds (Supplementary Figure 11a). The most commonly reviewed species were the two laboratory mammals *Rattus norvegicus* and *Mus musculus*, followed by the model animal *Danio rerio* (Zebrafish, Supplementary Figure 6b). Among reviews on PFAS exposure in wildlife, birds and fish species were overrepresented (Supplementary Figure 12a and Supplementary Figure 12b), suggesting a taxonomic bias. Finally, the limited systematic secondary literature on PFAS in the environment was not skewed towards any specific environmental compartment (Supplementary Figure 13). Half of these reviews covered a mixture of different compartments and around 40% of them covered freshwater or a mix of aquatic compartments.

3.9. Critical appraisal

Via the AMSTAR2 checklist, we identified areas of strength and weakness in the 175 systematic reviews examined. Overall, reviews scored well in terms of methodology (green colour in Fig. 6) when clearly explaining their selection of study designs for inclusion (Question 3), detailing the included studies (Question 8), and reporting potential sources of conflict of interest (COI) (Question 16). These results indicate that the systematic secondary research on PFAS exposure generally satisfies the recommendations of guidelines for systematic review in environmental science and management (Pullin & Stewart, 2006; Liberati et al., 2009). Of the reviews that included a COI statement, a small proportion (i.e., 8%) acknowledged the presence of conflict, while the majority (i.e., 92%) acknowledged the absence of conflict (Supplementary Figure 14a and Supplementary Figure 14b). However, the reviews were of a medium or low methodological quality (orange and red colours in Fig. 6) in the reporting of funding sources for studies included in the review (Question 10) and providing a list of excluded studies with justification (Question 7). Notably, 45% of reviews did not clearly delineate research questions and inclusion criteria (Question 1), and more than 80% did not explicitly state that the review methods were established *a priori* (Question 2). Such weaknesses are characteristic of traditional narrative syntheses (Campbell et al., 2019), which lack a planned systematic and transparent reviewing approach.

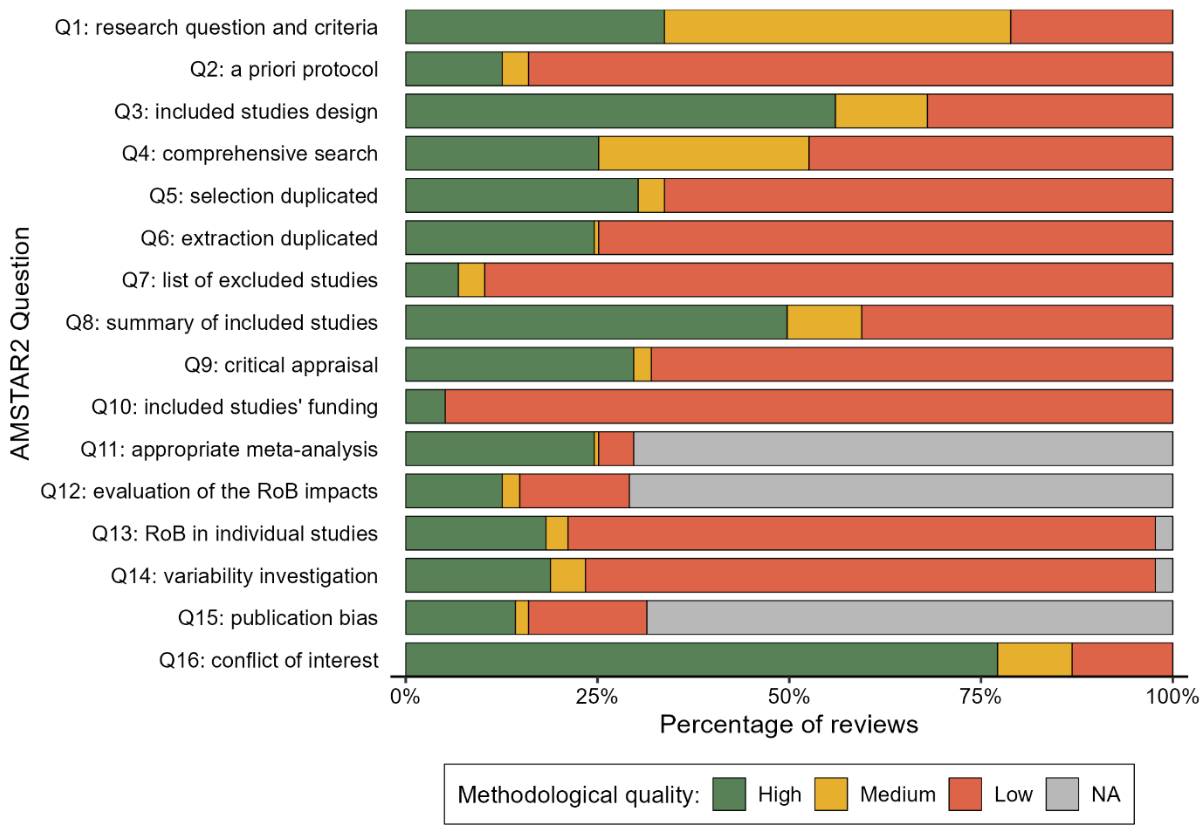

Fig. 6. Distribution of methodological quality scores for each of the 16 AMSTAR2 items across 175 systematic-like reviews on PFAS exposures. The bars are colour-coded as follows: Green: percentage of reviews that exhibit a high methodological quality for the corresponding AMSTAR2 item. Red: percentage of reviews demonstrating a low methodological quality for the corresponding AMSTAR2 item. Orange: percentage of reviews that exhibit a medium methodological quality for the corresponding AMSTAR2 item. Grey: item not applicable.

Furthermore, almost half of the reviews (i.e., 47%) did not provide enough information on the search strategy or did not conduct a comprehensive search of the literature (Question 4). Two-thirds of the reviews (i.e., 66%) had only one author involved in the study selection or did not provide information on how many reviewers participated in the selection process (Question 5). Similarly, 75% of reviews had only one author involved in the data extraction or did not declare how many reviewers participated in the process (Question 6). In 68% of reviews, the authors did not mention a risk of bias assessment for individual studies included in the review (Question 9), and 76% did not account for the risk of bias when discussing results (Question 13). We also found a general lack of discussion of dataset heterogeneity (74% of reviews) and assessing the potential impact of risk of bias on meta-analytic results (49% of reviews including quantitative analysis, Question 12) and investigating publication bias (Question 15). Overall, AMSTAR2 revealed methodological concerns or lack of transparency in specific aspects of review methods for more than half of the reviews (Fig. 6).

Subject-specific analysis revealed that the reviews with humans as the subject were generally of higher quality than those focused on animals or the environment (Supplementary Figure 15). A similar pattern can be observed for the quality of reviews with a systematic method of search and screening of the literature, with these reviews having a relevant higher average quality rating (Supplementary Figure 16). An analysis of time trends (Fig. 7) showed that even in recent reviews, more than half of them do not mention following any guidelines (Fig. 7a). Historically, guidelines for conducting systematic reviews in environmental and biological sciences were limited. Milestones like the Navigation Guide (Woodruff & Sutton, 2014) and the Office of Health Assessment and Translation (OHAT) handbook from the National Toxicology Program (NTP, 2019) have influenced standards in environmental health systematic reviews. A more recent notable guideline in environmental research is represented by COSTER (Whaley et al., 2020). In addition, authors can ensure quality reporting of systematic reviews by using available checklists, such as PRISMA (Page et al., 2021) and its ecology and evolution variant PRISMA-EcoEvo (O'Dea et al., 2021), and MOOSE (Brooke et al., 2021).

According to our results, recent reviews are more likely to include a COI statement (95% in 2022), since it became mandatory for most of the journals over the years, and a funding statement (98% in 2022) (Fig. 7b and Fig. 7d). These results are consistent with a systematic review by Darmon et al. (2018), where the authors found that COI and funding statement rates increased in the critical care literature over time. Notably, we found that 10% of reviews included in our map provided raw data (Supplementary Figure 14f) and only three reviews out of 175 made their analysis code available (Supplementary Figure 14g). This lack of transparency contributes to the reproducibility crisis, which is currently eroding the credibility of science. For example, Miyakawa (2020), as an Editor-in-Chief of

Molecular Brain, requested the raw data for 41 manuscripts and found out that 97% of the authors did not provide it. Wallach et al. (2018) surveyed a random sample of 149 biomedical articles published between 2015 and 2017 and discovered that only 18% of the sample discussed publicly available data and only 1% included a link to a study protocol. In this SEM, none of the included reviews provided a link to a study protocol published before conducting the review. However, study protocols are crucial for transparency, minimising bias, maintaining consistency, promoting collaboration, and documenting changes or deviations during the review process (Al Shakarchi, 2022). Protocols enhance the reliability of systematic reviews and contribute to the overall quality of evidence synthesis.

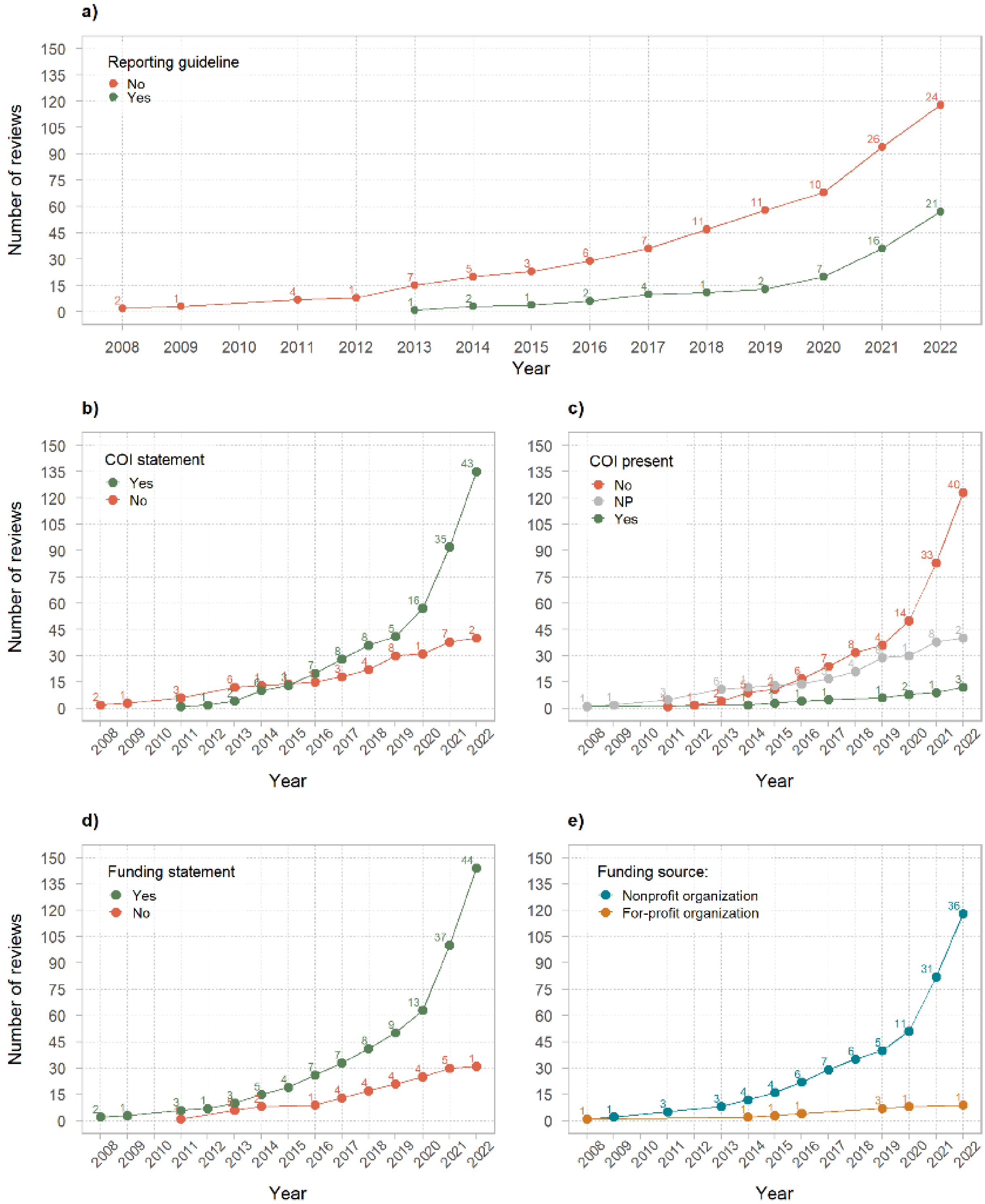

*Fig. 7. Cumulative time series plots. The lines show the cumulative trend in the number of reviews that: (**a**) adhere to reporting guidelines; (**b**) provide a conflict of interest statement, (**c**) acknowledge the presence of a conflict of interest (note: NP = statement not provided), (**d**) declare a funding statement; I are funded by a nonprofit or for-profit organisation. The numbers next to the data points represent the number of published reviews in each category in the respective year.*

Systematic reviews are efficient tools for synthesising evidence and informing health policy and decision-making (Cook et al., 1997). However, we have found several major shortcomings in the systematic secondary literature on PFAS exposure related to transparency, rigour, and quality control. The lack of transparency in data and code sharing, as well as in methodology, can impact the reproducibility of the results and the reliability of the research field. These findings are consistent with other assessments of systematic reviews in public health (Campbell et al., 2019) and highlight the need for improvement in the rigour and quality of the reviews on PFAS exposure. Taken together, this appraisal highlights the need for better implementation and reporting to ensure reproducibility, transparency, comprehensiveness, and reliability.

3.10. Bibliometric analysis

The leading countries producing reviews on PFAS exposure were the United States of America (USA) and China (Supplementary Figure 17). Spain and Italy are subsequent prominent contributors in this domain. All the top ten nations in this field are considered to have very high gross domestic product by the World Bank (The World Bank (n.d.)), the United Nations (United Nations (n.d.)), and the Organization for Economic Cooperation and Development (OECD) (OECD (n.d.)). There was a significant underrepresentation of countries from Africa, South-East Asia, Central America, and Eastern Europe (Supplementary Figure 20). This underrepresentation could stem from various factors, such as limited research funding and resources (Salager-Meyer, 2008), scarce opportunities for collaboration and training, language barriers, and a lack of visibility on the global research stage. It is plausible that these regions are short of opportunities and expertise in producing evidence syntheses (Man et al., 2004) or prioritising alternative research domains according to their specific needs.

Moreover, except for China, the ten most productive nations exhibit a moderate or high level of English proficiency, according to the world's largest ranking of countries and regions by English skills (EF, 2022), with English serving as an official or commonly used language for communication and education. This bias towards research originating from developed countries, particularly those with English as the predominant language, is likewise observed in other research disciplines (Moriguchi, 2022; Neimann Rasmussen & Montgomery, 2018; Song et al., 2010).

To address the existing research disparity, it is imperative to foster international collaborations, capacity-building initiatives, and knowledge-sharing endeavours (UNESCO, 2023). International cooperation holds the potential to generate reliable knowledge that is universally recognised and effectively tackles the challenges associated with the lack of diversity (UNESCO, 2023). We found that the two most productive countries – the USA and China – produced most of their publications solely authored by researchers from their own country (i.e., 78% of publications for the USA and 76% of publications for China; Supplementary Figure 17). This observation highlights the need to enhance international research partnerships, enrich the exchange of knowledge, and diversify perspectives in the field of PFAS exposure research.

An analysis of the country of affiliation of review authors uncovered the global network of collaborations. Fig. 8 illustrates the network of collaborations within countries and among countries in the research field. It is evident how several nations which did not have a significant network of collaborations within their own borders (Fig. 8a), instead exhibited a relatively robust network of inter-country collaborations (e.g., Sweden, Germany, Austria, Norway, Greece; Fig. 8b). These nations, despite playing a relatively secondary role in the production of systematic reviews, still contributed significantly to the global collaboration network. The possibilities of discovery on the impacts of PFAS exposure can be expanded through international collaboration, allowing researchers to achieve findings that surpass what a single team could accomplish independently. In addition, such collaboration enables researchers to nurture their existing relationships and expand their scientific network (Dusdal & Powell, 2021).

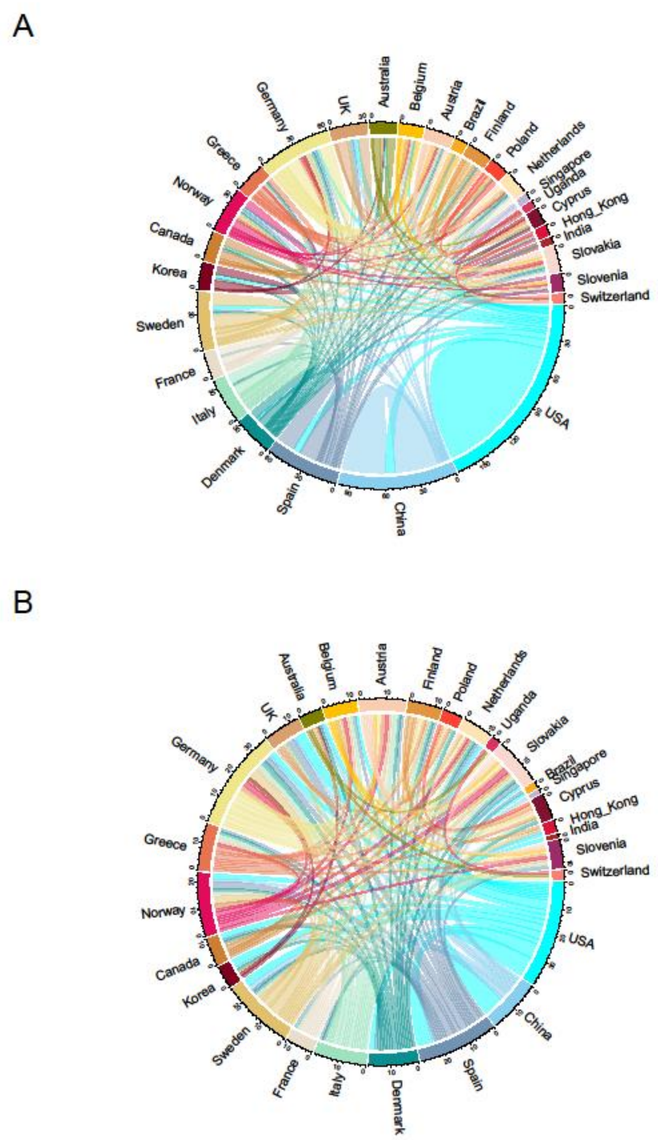

Fig. 8. Chord diagrams illustrating country collaborations. Values on the axis show the number of systematic-like reviews on PFAS exposure authored by researchers from the respective country. Arcs represent the number of reviews co-authored by reviewers from different countries. ***a)*** *the diagram shows the total number of collaborations per country (i.e., intra-country collaborations and collaborations between affiliated countries).* ***b)*** *the chord diagram shows the number of exclusive inter-country collaborations. Note: some of the less involved countries (i.e., countries with only one collaboration) were removed from the plots to enhance visual readability.*

Analysing the clustered network of collaborations (Supplementary Figure 21) revealed three main authorship collaboration groups led by the USA, Sweden, and Germany, respectively. Europe appears divided into two collaboration groups: Sweden's cluster is closer to the larger international cluster led by the USA and China, and Germany's cluster is closer to a smaller and isolated collective led by Australia. The USA, China, and Spain collaborated exclusively with nations with limited global visibility. This pattern suggests a partially fragmented scenario of international collaboration where some nations engage in single or double partnerships.

In terms of dominating and connected study topics, examining the co-occurrence of keywords (Supplementary Figure 22 and Supplementary Figure 28) identified two broad topic clusters: one associated with compound nomenclature and non-human subjects of review, and a second cluster comprising human-related terms. The keyword co-occurrence analysis in systematic reviews (Supplementary Figure 22) demonstrated that the term "meta-analysis" is more frequently associated with human-related terms than non-human subjects. This pattern aligns with our findings regarding the occurrence of meta-analyses among systematic reviews across different subject areas (Fig. 4b). The fact that the term "meta-analysis" is more frequently associated with human-related terms suggests that there is a growing and shared interest in quantifying the human health impacts of PFAS.

When it comes to influential publications, the most cited manuscript (Conder et al., 2008), averaging 51 citations per year, with a total of 821 citations, was published in 2008 and explored the bioaccumulation potential of perfluorinated acids (Supplementary Figure 18). The country that has received the most citations so far was the USA, with a total of 4317 citations, while Canada had the highest impact per publication, with an average article citation of 278. Regarding publication sources, Environmental Research emerges as the most influential journal in this research area, with 13 articles, followed by Science of The Total Environment and International Journal of Environmental Research and Public Health, with 11 and 10 articles, respectively.

The findings of the bibliometric analysis suggest that fostering international collaboration could advance our understanding of the impacts of PFAS exposure. The different collaboration clusters identified in the study may reflect countries' research priorities and interests. The additional bibliometric analysis on all types of reviews did not show substantially different results from the main bibliometric analysis. The larger sample size (i.e., 517 reviews) expanded our overview but still revealed the same most productive countries in producing reviews on the research topic (Supplementary Figure 23 and Supplementary Figure 26). The USA and China were the major actors in the global scenario, with a similar pattern of international collaborations (Supplementary Figure 27). Two narrative reviews, one of monitoring and toxicological findings on perfluoroalkyl acids (Lau et al., 2007) and another one on sources, fate and transport of perfluorocarboxylates (Prevedouros et al., 2006), lead as the most cited reviews in the PFAS exposure research topic (Supplementary Figure 25).

4. Limitations

Our systematic evidence map (SEM) has inherent limitations and presents several opportunities for improvement. Our literature search was conducted in English, which may potentially introduce a language bias by overlooking relevant literature in other languages (Amano et al., 2016; Amano et al., 2021). Furthermore, establishing research patterns and discipline categories in our evidence map was based on prior knowledge of the literature. However, alternative categorisations may yield slightly different results. Exploring alternative categorisations could offer valuable insights from different perspectives and enhance the coverage of the evidence map. Using multiple terms to refer to PFAS exposure in the literature made it challenging to comprehensively include all potentially relevant search terms, including terminology specific to human, environmental, or animal health. Future research can expand and refine the search strategy to encompass a broader range of terms, ensuring a more comprehensive identification of relevant studies. The critical appraisal employed in our work presents intrinsic limitations that are shared with its previous version (i.e., AMSTAR). These limitations are extensively discussed by Faggion (2015), including the difficulties in the objective interpretation of some items and the partial capture of the true methodological quality of systematic reviews. Our SEM focused on 35 commonly studied PFAS compounds. There are many other PFAS that have not been studied as extensively. However, as we showed in this map, the body of systematic secondary literature on PFAS exposure is steeply growing, especially for novel compounds. Furthermore, this SEM does not include any governmental or other agency reviews as they were not included in the protocol's eligibility criteria and are beyond the scope of this map. Finally, the quality of this tertiary research, intended as the completeness and correctness of the information it contains, is closely dependent on the quality of the secondary research sources on which it is based. By addressing these limitations and leveraging them as opportunities for improvement, future evidence maps can overcome current constraints and provide a more robust foundation for decision-making and further research in this field.

5. Gaps and Opportunities for Evidence Synthesis

The existing literature exhibited several notable gaps in the distribution of systematic reviews concerning PFAS exposure, opening opportunities for evidence synthesis. The prevailing focus of systematic reviews was on human exposure, while subjects related to animals and environmental compartments were notably underrepresented. In reviews focused on human subjects, there was a predominant emphasis on reproductive and developmental health outcomes, while a limited number of reviews addressed other aspects of human health outcomes or the occurrence and exposure of contaminants. Regarding animal-focused reviews, those examining experimental laboratory studies predominated over those investigating observational studies on wildlife. Furthermore, avian and actinopterygian species (ray-finned fishes) were disproportionately represented in wildlife reviews, whereas taxa such as reptiles, insects, crustaceans, and mammals, to a lesser extent, were underrepresented. In environmental reviews, freshwater environments received the most attention, whereas terrestrial, inland ecosystems were underexamined.

Regarding chemical compounds, a substantial body of literature exists on perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS); however, there remains considerable potential for further research focusing on emerging PFAS. While numerous reviews explored human exposure to PFOA and PFOS, most reviews addressing novel PFAS concentrate on animal and environmental subjects.

6. Conclusions: implications and future perspectives

This systematic evidence map (SEM) was developed to provide an overview of the systematic secondary evidence concerning the impacts of PFAS exposure on humans, animals, and the environment. The SEM's publicly available database facilitates access to the body of literature allowing the navigation, visualisation, and download of data. Here, we illustrate how this SEM and its online database meet the needs of diverse audiences, including scientists, regulators, and individuals.

Primarily, our SEM serves as a foundational tool for scientists across academia, government, and the nonprofit sector, providing a comprehensive resource for literature reviews. Our rigorous documentation eliminates the need for redundant search and screening processes, offering direct access to relevant systematic reviews. Researchers can access the database through the online platform and design inquiries into various aspects, including exposure of specific subjects to specific compounds.

This SEM is also designed to streamline the identification of quality reviews on specific PFAS exposure topics. With the increasing identification of PFAS-contaminated sites worldwide, residents, governments, and regulatory agencies seek high-quality information on various aspects of PFAS exposure. Within this SEM, we have grouped, categorised, and assessed the rigorousness of review methods and provided free access to this information. Additionally, the database facilitates the comparison of reviews' quality on specific aspects and steps of the review process.

Moreover, our SEM serves as a tool to spot data gaps. For instance, although a few systematic reviews have been conducted on animal exposure in controlled environments, systematic reviews on wildlife remain limited and characterised by taxonomic bias. The integration of our secondary literature map with available primary literature maps, such as Vendl et al. (2024) for PFAS in wildlife, provides a complete picture of the research field and its data gaps.

Our bibliometric results facilitate cross-disciplinary communication and collaboration between researchers from diverse fields, such as environmental science, toxicology, epidemiology, and public health. Different nations and research groups investigating PFAS exposure and impacts may possess distinct disciplinary priorities, whether focused on human health or ecosystem function assessment. By identifying research patterns, this SEM fosters interdisciplinary collaboration and recognises the national diversity of research groups. Diverse collaborations would promote a more integrated approach to the study of PFAS exposure and its impact on a broader scale.

Finally, our SEM contributes to developing best practices for reporting systematic reviews on PFAS exposure by highlighting areas where transparency and reliability can be enhanced. While the quantity of research expands our knowledge, the commitment to transparent methodologies, robust data analysis, and reproducibility solidifies the credibility and integrity of scientific advancements. By emphasising the importance of these principles, our study contributes to the ongoing improvement of research practices in the field of environmental pollution.

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Authorship contribution statement

We followed the CRediT (Contributor Roles Taxonomy) (CASRAI, 2020) and MeRIT (Method Reporting with Initials for Transparency) (Nakagawa et al., 2023) authorship guidelines. The corresponding author ensured that all authors agreed with their contributions described in the authorship statement.

Authorship statement

Conceptualisation: LR, CV, ML, SN

Data curation: LR

Formal analysis: LR, ML

Funding acquisition: LR, SN, GN, DH

Investigation: LR

Methodology: LR, CV, ML, SN

Project administration: LR

Software: LR, ML, SN

Supervision: ML, SN, MDT

Validation: ML

Visualisation: LR

Shiny App development: LR

Writing – Original Draft: LR

Writing – Review and Editing: all authors

Competing interests

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.

Raw data, analysis code and other materials

Raw data, analysis code, and additional materials are stored in the following GitHub repository: https://github.com/ThisIsLorenzo/PFAS_Systematic_Evidence_Map.

References

Ahrens, L., & Bundschuh, M. (2014). Fate and effects of poly-and perfluoroalkyl substances in the aquatic environment: A review. Environmental toxicology and chemistry, 33(9), 1921-1929.

Al Shakarchi, J. (2022). How to write a systematic review or meta-analysis protocol. Journal of Surgical Protocols and Research Methodologies, 2022(3), snac015.

Amano, T., González-Varo, J. P., & Sutherland, W. J. (2016). Languages are still a major barrier to global science. PLoS biology, 14(12), e2000933.

Amano, T., Berdejo-Espinola, V., Christie, A. P., Willott, K., Akasaka, M., Báldi, A., ... & Sutherland, W. J. (2021). Tapping into non-English-language science for the conservation of global biodiversity. PLoS Biology, 19(10), e3001296.

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of informetrics, 11(4), 959-975.

Bach, C. C., Bech, B. H., Brix, N., Nohr, E. A., Bonde, J. P. E., & Henriksen, T. B. (2015). Perfluoroalkyl and polyfluoroalkyl substances and human fetal growth: a systematic review. Critical reviews in toxicology, 45(1), 53-67.

Banyoi, S. M., Porseryd, T., Larsson, J., Grahn, M., & Dinnétz, P. (2022). The effects of exposure to environmentally relevant PFAS concentrations for aquatic organisms at different consumer trophic levels: Systematic review and meta-analyses. Environmental Pollution, 120422.

Boisvert, G., Sonne, C., Rigét, F. F., Dietz, R., & Letcher, R. J. (2019). Bioaccumulation and biomagnification of perfluoroalkyl acids and precursors in East Greenland polar bears and their ringed seal prey. Environmental pollution, 252, 1335-1343.

Bossi, R., Dam, M., & Rigét, F. F. (2015). Perfluorinated alkyl substances (PFAS) in terrestrial environments in Greenland and Faroe Islands. Chemosphere, 129, 164-169.

Brooke, B. S., Schwartz, T. A., & Pawlik, T. M. (2021). MOOSE reporting guidelines for meta-analyses of observational studies. JAMA surgery, 156(8), 787-788.

Campbell, M., Katikireddi, S. V., Sowden, A., & Thomson, H. (2019). Lack of transparency in reporting narrative synthesis of quantitative data: a methodological assessment of systematic reviews. Journal of clinical epidemiology, 105, 1-9.

Caserta, D., Mantovani, A., Marci, R., Fazi, A., Ciardo, F., La Rocca, C., ... & Moscarini, M. (2011). Environment and women's reproductive health. Human reproduction update, 17(3), 418-433.

CASRAI. (2020). CRediT: Contributor roles taxonomy. CASRAI. Retrieved from https://casrai.org/credit/ (accessed 11 February 2023).

Chang, W., Cheng, J., Allaire, J., Sievert, C., Schloerke, B., Xie, Y., Allen, J., McPherson, J., Dipert, A., & Borges, B. (2023). shiny: Web Application Framework for R. R package version 1.7.5.1. Retrieved from https://CRAN.R-project.org/package=shiny

Chappell, G. A., Thompson, C. M., Wolf, J. C., Cullen, J. M., Klaunig, J. E., & Haws, L. C. (2020). Assessment of the mode of action underlying the effects of GenX in mouse liver and implications for assessing human health risks. Toxicologic pathology, 48(3), 494-508.

Conder, J. M., Hoke, R. A., Wolf, W. D., Russell, M. H., & Buck, R. C. (2008). Are PFCAs bioaccumulative? A critical review and comparison with regulatory criteria and persistent lipophilic compounds. Environmental science & technology, 42(4), 995-1003.

Cook, D. J., Mulrow, C. D., & Haynes, R. B. (1997). Systematic reviews: synthesis of best evidence for clinical decisions. Annals of internal medicine, 126(5), 376-380.

Cordner, A., De La Rosa, V. Y., Schaider, L. A., Rudel, R. A., Richter, L., & Brown, P. (2019). Guideline levels for PFOA and PFOS in drinking water: the role of scientific uncertainty, risk assessment decisions, and social factors. Journal of exposure science & environmental epidemiology, 29(2), 157-171.

Darmon, M., Helms, J., De Jong, A., Hjortrup, P. B., Weiss, E., Granholm, A., ... & Azoulay, E. (2018). Time trends in the reporting of conflicts of interest, funding and affiliation with industry in intensive care research: a systematic review. Intensive care medicine, 44, 1669-1678.

Death, C., Bell, C., Champness, D., Milne, C., Reichman, S., & Hagen, T. (2021). Per-and polyfluoroalkyl substances (PFAS) in livestock and game species: A review. Science of The Total Environment, 774, 144795.

Dusdal, J., & Powell, J. J. (2021). Benefits, motivations, and challenges of international collaborative research: a sociology of science case study. Science and Public Policy, 48(2), 235-245.

ECHA. (2012). Candidate List of substances of very high concern for Authorisation. European Chemical Agency; ED/169/2012. Retrieved from https://echa.europa.eu/candidate-list-table (accessed 10 September 2023).

ECHA. (2013). Candidate List of substances of very high concern for Authorisation. European Chemical Agency; ED/69/2013. Retrieved from https://echa.europa.eu/candidate-list-table (accessed 10 September 2023).

ECHA. (2015). Candidate List of substances of very high concern for Authorisation. European Chemical Agency; ED/79/2015. Retrieved from https://echa.europa.eu/candidate-list-table (accessed 10 September 2023).

EF (2022) EF Education First EPI 2022 – EF English Proficiency Index: The world's largest ranking of countries and regions by English skills. Available at: https://www.ef.com/wwen/epi/ (accessed 19 May 2023).

Faggion, C. M. (2015). Critical appraisal of AMSTAR: challenges, limitations, and potential solutions from the perspective of an assessor. BMC Medical Research Methodology, 15(1), 1-5.

Forsthuber, M., Kaiser, A. M., Granitzer, S., Hassl, I., Hengstschläger, M., Stangl, H., & Gundacker, C. (2020). Albumin is the major carrier protein for PFOS, PFOA, PFHxS, PFNA and PFDA in human plasma. Environment international, 137, 105324.

Glüge, J., Scheringer, M., Cousins, I. T., DeWitt, J. C., Goldenman, G., Herzke, D., ... & Wang, Z. (2020). An overview of the uses of per-and polyfluoroalkyl substances (PFAS). Environmental Science: Processes & Impacts, 22(12), 2345-2373.

Gomis, M. I., Vestergren, R., Borg, D., & Cousins, I. T. (2018). Comparing the toxic potency in vivo of long-chain perfluoroalkyl acids and fluorinated alternatives. Environment international, 113, 1-9.

Grandjean, P., Heilmann, C., Weihe, P., Nielsen, F., Mogensen, U. B., Timmermann, A., & Budtz-Jørgensen, E. (2017). Estimated exposures to perfluorinated compounds in infancy predict attenuated vaccine antibody concentrations at age 5-years. Journal of immunotoxicology, 14(1), 188-195.

Guo, H., Wang, J., Yao, J., Sun, S., Sheng, N., Zhang, X., ... & Dai, J. (2019). Comparative hepatotoxicity of novel PFOA alternatives (perfluoropolyether carboxylic acids) on male mice. Environmental science & technology, 53(7), 3929-3937.

Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. Nature, 555(7695), 175-182.

Haddaway, N. R., Woodcock, P., Macura, B., & Collins, A. (2015). Making literature reviews more reliable through application of lessons from systematic reviews. Conservation Biology, 29(6), 1596-1605.

Haddaway, N. R., Macura, B., Whaley, P., & Pullin, A. S. (2018). ROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence, 7, 1-8.

Haukås, M., Berger, U., Hop, H., Gulliksen, B., & Gabrielsen, G. W. (2007). Bioaccumulation of per- and polyfluorinated alkyl substances (PFAS) in selected species from the Barents Sea food web. Environmental Pollution, 148(1), 360-371.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. (2017). Some chemicals used as solvents and in polymer manufacture.

ITRC Interstate Technology and Regulatory Council. (2022). Per- and Polyfluoroalkyl Substances (PFAS) - Technical and Regulatory Guidance. Retrieved from https://pfas-1.itrcweb.org/ (accessed 24 May 2022).

Jha, G., Kankarla, V., McLennon, E., Pal, S., Sihi, D., Dari, B., ... & Nocco, M. (2021). Per-and polyfluoroalkyl substances (PFAS) in integrated crop–livestock systems: environmental exposure and human health risks. International journal of environmental research and public health, 18(23), 12550.

Kirk, M., Smurthwaite, K., Braunig, J., Trevenar, S., D'Este, C., Lucas, R., ... & Armstrong, B. (2018). The PFAS health study: systematic literature review.

Lasserson, T.J., Thomas, J. and Higgins, J.P.T. (2022). Chapter 1: Starting a review. In: J.P.T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M.J. Page and V.A. Welch (eds.) Cochrane Handbook for Systematic Reviews of Interventions version 6.3 (updated February 2022). Cochrane. Available at: https://training.cochrane.org/handbook/current/chapter-01 [Accessed: 14/06/2023].

Lau, C., Anitole, K., Hodes, C., Lai, D., Pfahles-Hutchens, A., & Seed, J. (2007). Perfluoroalkyl acids: a review of monitoring and toxicological findings. Toxicological sciences, 99(2), 366-394.

Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P., ... & Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Annals of internal medicine, 151(4), W-65.

Man, J. P., Weinkauf, J. G., Tsang, M., & Sin, J. H. D. D. (2004). Why do some countries publish more than others? An international comparison of research funding, English proficiency and publication output in highly ranked general medical journals. European journal of epidemiology, 19, 811-817.

Miner, K. R., Clifford, H., Taruscio, T., Potocki, M., Solomon, G., Ritari, M., ... & Mayewski, P. A. (2021). Deposition of PFAS 'forever chemicals' on Mt. Everest. Science of the Total Environment, 759, 144421.

Miyakawa, T. (2020). No raw data, no science: another possible source of the reproducibility crisis. Molecular brain, 13(1), 1-6.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group*. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Annals of internal medicine, 151(4), 264-269.

Moher, D., Stewart, L., & Shekelle, P. (2015). All in the family: systematic reviews, rapid reviews, scoping reviews, realist reviews, and more. Systematic reviews, 4(1), 1-2.

Moriguchi, Y. (2022). Beyond bias to Western participants, authors, and editors in developmental science. Infant and Child Development, 31(1), e2256.

Nakagawa, S., Samarasinghe, G., Haddaway, N. R., Westgate, M. J., O'Dea, R. E., Noble, D. W., & Lagisz, M. (2019). Research weaving: visualizing the future of research synthesis. Trends in ecology & evolution, 34(3), 224-238.

Nakagawa, S., Ivimey-Cook, E. R., Grainger, M. J., O'Dea, R. E., Burke, S., Drobniak, S. M., ... & Lagisz, M. (2023). Method Reporting with Initials for Transparency (MeRIT) promotes more granularity and accountability for author contributions. nature communications, 14(1), 1788.

National Toxicology Program (NTP). (2019). Handbook for conducting a literature-based health assessment using OHAT approach for systematic review and evidence integration. U.S. Department of Health and Human Services, Office of Health Assessment and Translation (OHAT). Retrieved from https://ntp.niehs.nih.gov/sites/default/files/ntp/ohat/pubs/handbookmarch2019_508.pdf (accessed 24 February 2024).

Neimann Rasmussen, L., & Montgomery, P. (2018). The prevalence of and factors associated with inclusion of non-English language studies in Campbell systematic reviews: a survey and meta-epidemiological study. Systematic Reviews, 7(1), 1-12.

Obsekov, V., Kahn, L. G., & Trasande, L. (2023). Leveraging systematic Reviews to Explore disease burden and costs of per-and polyfluoroalkyl substance exposures in the United States. Exposure and Health, 15(2), 373-394.

O'Dea, R. E., Lagisz, M., Jennions, M. D., Koricheva, J., Noble, D. W., Parker, T. H., ... & Nakagawa, S. (2021). Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. Biological Reviews, 96(5), 1695-1722.

OECD. (2015a). Working Towards a Global Emission Inventory of PFASs: Focus on PFCAS—Status Quo and the Way Forward (OECD Environment, Health and Safety Publications Series on Risk Management No. 30). Paris, France. Retrieved from https://www.oecd.org/chemicalsafety/risk-management/Working%20Towards%20a%20Global%20Emission%20Inventory%20of%20PFASS.pdf (accessed 13 July 2023).

OECD. (2015b). Risk Reduction Approaches for PFASs - A Cross-Country Analysis. (OECD Environment, Health and Safety Publications Series on Risk Management No. 29). Paris, France. Retrieved from https://www.oecd.org/chemicalsafety/risk-management/Risk_Reduction_Approaches%20for%20PFASS.pdf (accessed 8 August 2023)

OECD. (n.d.). Gross domestic product (GDP). Retrieved from http://stats.oecd.org/Index.aspx?DataSetCode=SNA_TABLE1 (accessed 10 May 2023).

Ojo, A. F., Peng, C., & Ng, J. C. (2020). Combined effects and toxicological interactions of perfluoroalkyl and polyfluoroalkyl substances mixtures in human liver cells (HepG2). Environmental Pollution, 263, 114182.

Olsen, G. W., Mair, D. C., Lange, C. C., Harrington, L. M., Church, T. R., Goldberg, C. L., ... & Ley, C. A. (2017). Per-and polyfluoroalkyl substances (PFAS) in American Red Cross adult blood donors, 2000–2015. Environmental research, 157, 87-95.

Ouzzani, M., Hammady, H., Fedorowicz, Z., & Elmagarmid, A. (2016). Rayyan—a web and mobile app for systematic reviews. Systematic reviews, 5, 1-10.

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. International journal of surgery, 88, 105906.

Pelch, K. E., Reade, A., Kwiatkowski, C. F., Merced-Nieves, F. M., Cavalier, H., Schultz, K., ... & Varshavsky, J. (2022). The PFAS-Tox Database: A systematic evidence map of health studies on 29 per-and polyfluoroalkyl substances. Environment international, 167, 107408.

Pelch, K. E., Reade, A., Wolffe, T. A., & Kwiatkowski, C. F. (2019). PFAS health effects database: Protocol for a systematic evidence map. Environment international, 130, 104851.

Pinas, V., Van Dijk, C., & Weber, R. (2020). Inventory and action plan for PFOS and related substances in Suriname as basis for Stockholm Convention implementation. Emerging Contaminants, 6, 421-431.

Prevedouros, K., Cousins, I. T., Buck, R. C., & Korzeniowski, S. H. (2006). Sources, fate and transport of perfluorocarboxylates. Environmental science & technology, 40(1), 32-44.

Pullin, A. S., & Stewart, G. B. (2006). Guidelines for systematic review in conservation and environmental management. Conservation biology, 20(6), 1647-1656.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Routti, H., Krafft, B. A., Herzke, D., Eisert, R., & Oftedal, O. (2015). Perfluoroalkyl substances detected in the world's southernmost marine mammal, the Weddell seal (Leptonychotes weddellii). Environmental Pollution, 197, 62-67.

Salager-Meyer, F. (2008). Scientific publishing in developing countries: Challenges for the future. Journal of English for academic purposes, 7(2), 121-132.

Shea, B. J., Reeves, B. C., Wells, G., Thuku, M., Hamel, C., Moran, J., ... & Henry, D. A. (2017). AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. bmj, 358.

Shi, Y., Vestergren, R., Nost, T. H., Zhou, Z., & Cai, Y. (2018). Probing the differential tissue distribution and bioaccumulation behavior of per-and polyfluoroalkyl substances of varying chain-lengths, isomeric structures and functional groups in crucian carp. Environmental science & technology, 52(8), 4592-4600.

Shoeib, M., Harner, T., & Vlahos, P. (2006). Perfluorinated chemicals in the Arctic atmosphere. Environmental science & technology, 40(24), 7577-7583.

Smithwick, M., Mabury, S. A., Solomon, K. R., Sonne, C., Martin, J. W., Born, E. W., ... & Muir, D. C. (2005). Circumpolar study of perfluoroalkyl contaminants in polar bears (Ursus maritimus). Environmental science & technology, 39(15), 5517-5523.

Song, F., Parekh, S., Hooper, L., Loke, Y. K., Ryder, J., Sutton, A. J., ... & Harvey, I. (2010). Dissemination and publication of research findings: an updated review of related biases. Health technology assessment, 14(8), 1-220.

Taniyasu, S., Yamashita, N., Moon, H. B., Kwok, K. Y., Lam, P. K., Horii, Y., ... & Kannan, K. (2013). Does wet precipitation represent local and regional atmospheric transportation by perfluorinated alkyl substances?. Environment international, 55, 25-32.

The World Bank. (n.d.). GDP (current US$). Retrieved from https://https://data.worldbank.org/indicator/NY.GDP.MKTP.CD (accessed 10 May 2023).

UNESCO (2023) Scientific research cooperation: Why collaborate in science? Benefits and examples. Available at: https://www.unesco.org/en/scientific-research-cooperation-why-collaborate-science-benefits-and-examples (accessed 24 May 2023).

United Nations. (n.d.). Human Development Reports. Retrieved from http://hdr.undp.org/en/content/income-gini-coefficient (accessed 10 May 2023).

Usman, M., & Hanna, K. (2023). Europe: hold industry accountable for forever chemicals. Nature, 618(7965), 457-457.

Vélez, M. P., Arbuckle, T. E., & Fraser, W. D. (2015). Maternal exposure to perfluorinated chemicals and reduced fecundity: the MIREC study. Human reproduction, 30(3), 701-709.

Vendl, C., Taylor, M. D., Bräunig, J., Gibson, M. J., Hesselson, D., Neely, G. G., ... & Nakagawa, S. (2022). PFAS exposure of humans, animals and the environment: Protocol of an evidence review map and bibliometric analysis. Environment International, 158, 106973.

Vendl, C., Taylor, M. D., Bräunig, J., Ricolfi, L., Ahmed, R., Chin, M., ... & Nakagawa, S. (2024). Profiling research on PFAS in wildlife: Systematic evidence map and bibliometric analysis. Ecological Solutions and Evidence, 5(1), e12292.

Wallach, J. D., Boyack, K. W., & Ioannidis, J. P. (2018). Reproducible research practices, transparency, and open access data in the biomedical literature, 2015–2017. PLoS biology, 16(11), e2006930.

Wang, Z., DeWitt, J. C., Higgins, C. P., & Cousins, I. T. (2017). A never-ending story of per-and polyfluoroalkyl substances (PFASs)?.

Whaley, P., Aiassa, E., Beausoleil, C., Beronius, A., Bilotta, G., Boobis, A., ... & Halsall, C. (2020). Recommendations for the conduct of systematic reviews in toxicology and environmental health research (COSTER). Environment international, 143, 105926.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., ... & Yutani, H. (2019). Welcome to the Tidyverse. Journal of open source software, 4(43), 1686.

Wickham H, François R, Henry L, Müller K (2022a). _dplyr: A Grammar of Data Manipulation_. R package version 1.0.10, <https://CRAN.R-project.org/package=dplyr>.

Wickham H, Girlich M (2022b). _tidyr: Tidy Messy Data_. R package version 1.2.1, <https://CRAN.R-project.org/package=tidyr>.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D. A., François, R., ... & Yutani, H. (2019). Welcome to the Tidyverse. Journal of open source software, 4(43), 1686.

Wickham, H., Chang, W., & Wickham, M. H. (2016). Package 'ggplot2'. Create elegant data visualisations using the grammar of graphics. Version, 2(1), 1-189.

Wolffe, T. A., Whaley, P., Halsall, C., Rooney, A. A., & Walker, V. R. (2019). Systematic evidence maps as a novel tool to support evidence-based decision-making in chemicals policy and risk management. Environment international, 130, 104871.

Woodruff, T. J., & Sutton, P. (2014). The Navigation Guide systematic review methodology: a rigorous and transparent method for translating environmental health science into better health outcomes. Environmental health perspectives, 122(10), 1007-1014.

Yamashita, N., Kannan, K., Taniyasu, S., Horii, Y., Petrick, G., & Gamo, T. (2005). A global survey of perfluorinated acids in oceans. Marine pollution bulletin, 51(8-12), 658-668.