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Global research on elasmobranchs and pollution: A bibliometric and network analysis

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ABSTRACT

Background: Elasmobranchs are vital for maintaining marine ecosystem balance through trophic regulation and energy transfer but face increasing threats from anthropogenic pollution, including chemical contaminants that may bioaccumulate in exposed animals and pose both ecological and human health risks.
Objective: This study aims to map global institutional collaborations and publications concening global research on pollution in elasmobranchs through a bibliometric and network analysis. This mapping offers a comprehensive view of research trends, gaps, and key contributors, aiding in conservation efforts.
Methods: PRISMA guidelines were applied and a bibliometric and network analysis was performed, retrieving 71 peer-reviewed articles indexed in the Web of Science Core Collection and published between 2013 and 2022 which were then assessed.
Results: Publication trends varied, with a recent decline to early-period levels. Marine Pollution Bulletin is the leading journal in this field. Main keywords include Bioaccumulation, Carcharhinidae, Mercury, and Maternal offloading. The most frequent research areas are Environmental Sciences & Ecology and Marine & Freshwater Biology, with Toxicology as the central network node. Brazil and the USA lead in publication counts, but Brazil shows limited international collaboration. Brazilian institutions dominate the top five most productive organizations, led by the Oswaldo Cruz Foundation and the Pontifical Catholic University of Rio de Janeiro. The University of California ranks as the top North American institution and fifth overall. The Oswaldo Cruz Foundation, Pontifical Catholic University of Rio de Janeiro, University of California, and University of Miami are central nodes in institutional collaboration networks.
Conclusion: This study enhances understanding of global research on elasmobranchs and pollution by clarifying institutional collaboration networks and identifying the leading institutions and countries driving the field. Such mapping provides a strategic foundation to prioritize research directions, foster international cooperation, and align conservation actions with regions and taxa most at risk, thereby strengthening both scientific progress and evidence-based management of elasmobranchs.

1. Introduction

Elasmobranchs (sharks, rays and skates), play an important role in marine ecosystems as apex predators and mesopredators, regulating prey populations and maintaining ecological balance (Heupel et al., 2014; Frisch et al., 2016). Their influence extends through trophic cascades and top-down control mechanisms, shaping community structure and ecosystem dynamics (Navia et al., 2010). Studies have shown that population declines of these animals can lead to significant ecological imbalances, such as mesopredator release and altered prey distributions (Ferretti et al., 2010). Furthermore, their role as ecosystem connectors due to their broad distribution and their extensive diet range, facilitates energy transfer between marine environments, contributing to overall ecological resilience (Bornatowski et al., 2014; Shipley et al., 2023). For example, many coastal elasmobranchs feed in productive nearshore habitats such as seagrass beds or estuaries, where they consume

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crustaceans and small fish, and later migrate offshore, transferring this energy to pelagic food webs when they are preyed upon by larger predators (García-Rodríguez et al., 2021; Klinard et al., 2025).

Overfishing, whether through targeted catch or bycatch, remains the primary threat to this group, having caused alarming population declines to several elasmobranch species in recent decades (Dulvy et al., 2021). Currently, about 37 % of all described species are classified as at risk of extinction (IUCN, 2025). In addition to overfishing, other anthropogenic pressures, such as habitat degradation, pollution, and climate change, are interconnected and also contribute to global elasmobranch population declines (Dulvy et al., 2021). These threats are often considered secondary, primarily due to the difficulty in establishing direct links between them and mortality rates high enough to drive population declines or impair recruitment. Nevertheless, their potential impact should not be underestimated.

In particular, due to their long lifespans and high trophic levels, elasmobranchs are especially vulnerable to chemical pollutants (*i.e.,* metals, persistent organic pollutants (POPs), microplastics, contaminants of emerging concern) and have become important marine ecosystem health bioindicators (Tiktak et al., 2020; Alves et al., 2022). Studies on the effects of chemical pollution on elasmobranchs are steadily expanding in the last few years, revealing it as a growing concern for their health and conservation.

Despite growing awareness of the environmental threats these animals face, scientific research on their interactions with pollutants remains fragmented and unevenly distributed, with the first review in this sense carried out in 2019 for batoids only (Bezerra et al., 2019), the first concerning both sharks and rays, in 2020 (Tiktak et al., 2020) and the first to exclusively focus on filter feeders, in 2023 (Boldrocchi et al., 2023). Furthermore, a comprehensive bibliometric and network analysis of global research trends is lacking, which would allow the clarification of institutional collaboration networks and the identification of leading institutions and countries driving the field. This mapping of scientific efforts provides a strategic foundation for prioritizing research directions, fostering international cooperation, and aligning conservation actions with regions and taxa most at risk, thereby strengthening both scientific progress and evidence-based management of elasmobranchs.

In this context, the present study aimed to map institutional collaboration networks and identify the key institutions and countries driving research concerning global research on chemical pollution in elasmobranchs through a bibliometric and network analysis. The focus was on more established pollutants, such as metals and persistent organic pollutants, where research is more advanced and consolidated, rather than on other contaminants such as microplastics and contaminants of emerging concern, for which the scientific basis is still comparatively limited (Tiktak et al., 2020; Alves et al., 2022). Including additional categories, such as microplastics or CECs, would have broadened the scope to the point where an in-depth and meaningful assessment of trends and collaborations would not have been feasible. Nevertheless, when such emerging contaminants appeared under the broader established keywords, they were included in our analysis and discussion.

To achieve this, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were applied, along with a bibliometric and network analysis, to systematically assess peer-reviewed publications on the topic. The PRISMA framework ensures transparency, consistency, and methodological rigor throughout the literature review process (Page et al., 2021). Bibliometric analyses involve the quantitative evaluation of publications, citations, and related bibliographic data to identify patterns in research impact, productivity, and thematic trends. Complementarily, network analysis examines the relationships between entities, such as researchers, institutions, or keywords, represented as nodes connected by edges. This method is frequently used in academic contexts to uncover collaboration dynamics, information dissemination pathways, and influential actors within a scholarly domain (Comarú et al., 2021; Maciel Braga and Mota, 2021).

Our study provides a global overview of the research carried out in the last decade, identifying key researchers, organizations, their collaborative networks, and the research subjects of their collaborative efforts, thus offering valuable insights for future research and interinstitutional collaborations between researchers from organizations around the world aiming at elasmobranch conservation.

2. Methods

The PRISMA guidelines were applied to identify, screen, and select articles related to elasmobranchs and pollution, indexed in the Web of Science Core Collection and published between 2014 and 2023. This ten-year window was chosen to provide an overview of the most recent research trends in the field. The data/text mining software VantagePoint 11.0 was employed to treat the metadata of the retrieved articles and bibliometrics and network analysis techniques to perform the analysis and generate the results. The following search strategy (query) was used in the WoS advanced search mode to identify scientific publications on the study subject:

TI= ("pollution" or "pollutant*" or "contaminant*" or "metal" or "metals" or "metalloid*" or "persistent organic pollutant*" or "POP" or "polycyclic aromatic hydrocarbon*" or "PAH" or "polybrominated diphenyl ether*" or "PBDE" or "polychlorinated biphenyl*" or "PCB" or "phthalate*" or "pesticide*" or "chlorinated" or "brominated" or "organic" or "organics" or "inorganic" or "inorganics") AND TI= (("elasmobranch*" or "shark" or "sharks" or "stingray" or "stingrays" or "ray" or "rays" or "skate" or "skates") NOT ("X-ray*" or "y-ray*" or "gamma-ray*" or "ultraviolet-ray*" or "Infrared-ray*" or "alpha-ray*" or "beta-ray*" or "delta-ray*" or "cosmic-ray*" or "neutron-ray*" or "proton-ray*" or "terahertz-ray*" or "laser ray*")).

The timespan covered the last ten years (2014–01–01–2023–12–31), and only articles, review articles, and early access articles were included. For precision, only the field tag title (TI), which searches for the query's descriptors in the titles of the above-mentioned documents, was used. The search strategy uses descriptors collected in the Medical Subject Headings (MeSH) – a controlled vocabulary thesaurus that indexes PubMed publications (MeSH: ncbi.nlm.nih.gov/mesh/) – and free text words related to elasmobranchs and pollution. To prevent the collection of publications on other types of rays, we used the Boolean operator NOT to exclude terms such as X-ray or gamma-ray, which could have appeared due to the generic search term "ray". The search was carried out on April 09, 2024, and obtained 124 results.

The 124 records retrieved were imported in plain text format into VantagePoint software for processing and analysis. No duplicate entries were identified. A manual screening of all records was conducted by reviewing their titles and/or abstracts to determine eligibility. Articles addressing both elasmobranchs and pollution were included, while those outside the scope of the study were excluded. One author (RAH-D) conducted the initial screening and excluded 53 articles. A second author (FM) independently reviewed a random sample comprising 20 % of both included and excluded records and reported no discrepancies. The final dataset consisted of 71 records that met the inclusion criteria. A comprehensive list of included and excluded articles is provided in the Supplementary Material. The identification, screening, and selection process, conducted in accordance with PRISMA guidelines, is summarized in Fig. 1.

For each article, the following fields were evaluated: publication year, journal, title, abstract, author keywords (AKs), Research Area (RA, as classified by Web of Science), author affiliations (organizations), countries, citation counts, and cited references with associated Digital Object Identifiers (DOIs). Author keywords and organization names were cleaned and standardized using the VantagePoint list cleanup tool, supplemented by manual review. To extract information related to pollutants, the title, abstract, and AKs fields were merged, and a targeted search was conducted based on a predefined list of pollutants provided

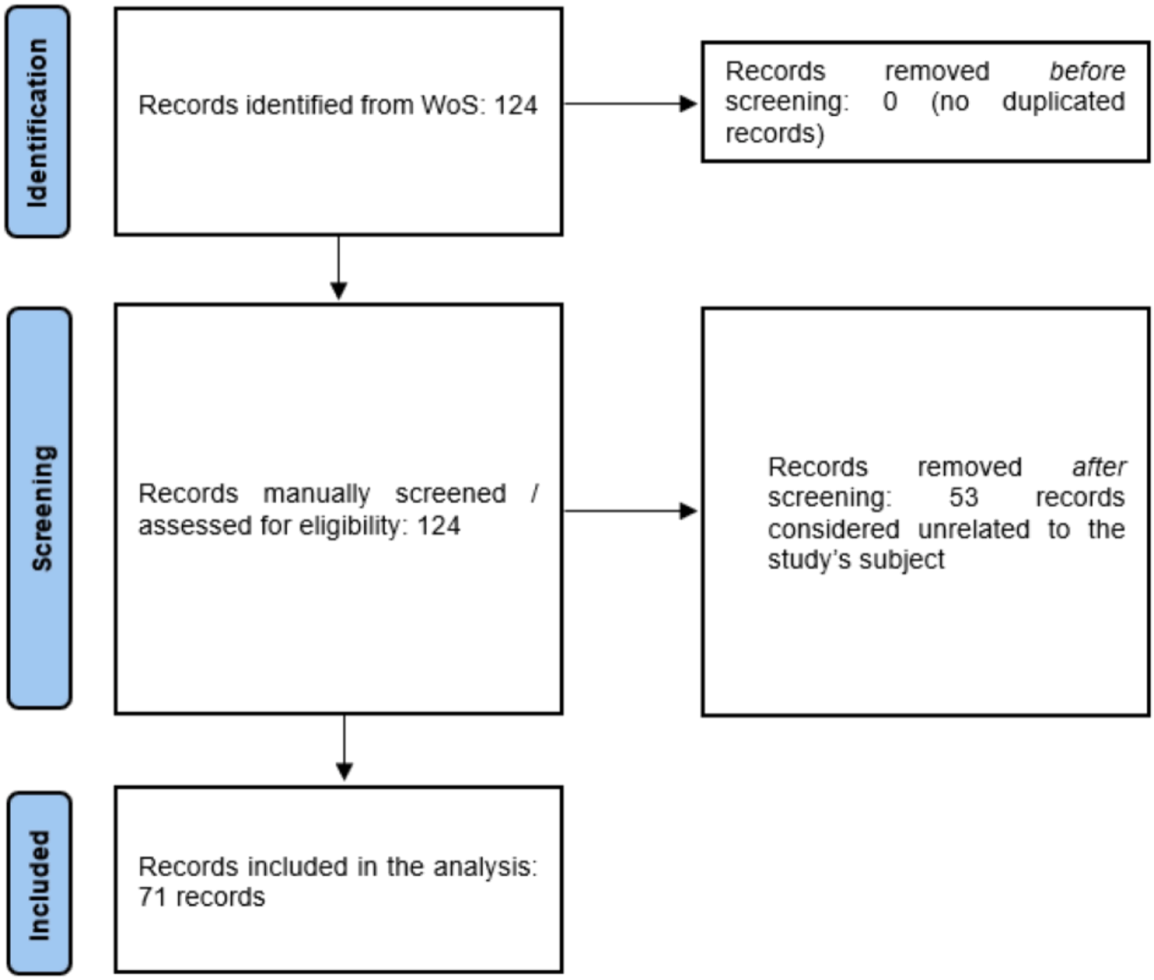

Fig. 1. Method flowchart following PRISMA guidelines assessing the subject of elasmobranchs and pollution.

in the Supplementary Material. The identified pollutants were grouped according to their names, and the VantagePoint tool's "create field from group names" function was used to generate a new field for subsequent analysis.

Co-occurrence matrices for author keywords (AKs), research areas (RAs), countries, organizations, and pollutants were generated using VantagePoint and subsequently imported into Gephi 0.10 for network visualization and analysis. Networks were constructed and analyzed using five centrality metrics: degree centrality (DC), weighted degree centrality (WDC), closeness centrality (CC), betweenness centrality (BC), and eigenvector centrality (EC). DC measures the number of direct connections a node has, while WDC incorporates the strength (weight) of those connections. CC assesses how close a node is to all other nodes by calculating the shortest paths within the network. BC quantifies how often a node appears on the shortest paths between other nodes, indicating its role as a bridge. EC evaluates both the number and the importance of a node's connections by considering the centrality of its neighboring nodes (Lopes et al., 2024; Scott et al., 2014). All networks were arranged using the Fruchterman–Reingold layout algorithm (Gephi documentation). Node size and color represent WDC values, while the thickness of the edges reflects the frequency of co-occurrence between nodes. Centrality measure results for all networks are available in the Supplementary Material. Graphs and figures were created using GraphPad Prism v.8, and were integrated with the network visuals generated in Gephi. Journal impact factors for 2022 were retrieved from Clarivate's Journal Citation Reports 2023 (http://jcr.clarivate.com/).

3. Study limitations

The trade-off between precision and coverage is a key consideration in any bibliometric or network analysis. In this study, we prioritized precision by restricting our search to article titles indexed in the Web of Science (WoS) database. This choice was based on the rationale that descriptors appearing in titles are more likely to directly reflect the article's core subject, thereby reducing the likelihood of retrieving irrelevant records. In contrast, using the WoS Topic (TS) field, encompassing titles, abstracts, author keywords, and Keywords Plus, would have broadened the search but also introduced greater potential for irrelevant results or "noise." By emphasizing precision, we enhanced the reliability of the dataset and streamlined the screening process, avoiding unnecessary efforts. However, this focus on precision may have limited the overall breadth of the literature captured, potentially reducing the exploratory scope of the study. Nonetheless, given the objective of this research, where accurate identification of relevant literature is critical, this approach is justified.

The exclusive use of a single database may also be seen as a limitation. However, this is a common practice in bibliometric and network analyses (Comarú et al., 2021; Lopes et al., 2024; Maciel Braga and Mota, 2021). Merging data from multiple databases requires substantial methodological effort due to differences in metadata structures, field availability, and coverage. WoS was chosen for its recognized strengths, including broad subject coverage, high-quality metadata, standardized Impact Factor indexing, and decades-long archival depth. While there are cases where combining databases is necessary, such as when analyzing time periods not fully covered by one source (Mota et al., 2022), WoS alone was deemed sufficient to meet the goals of this study.

Additionally, only peer-reviewed articles written in English were included, which introduces a language and publication bias that may exclude valuable contributions from non-English-speaking countries or gray literature sources. This limitation may disproportionately affect the visibility of research conducted in the Global South or published in regional journals not indexed by WoS. Consequently, while our approach improves consistency and ensures a certain level of quality control, it may still underrepresent the global scope of research on elasmobranchs and pollution, particularly in regions where English is not the primary scientific communication language.

4. Results

Overall, the annual number of publications fluctuated considerably throughout the study period, reaching a peak in 2022 and a low point in 2018. Although the number of articles increased by 275 % between 2020 and 2022, the final year of the analysis still recorded fewer publications than 2014, representing a 53.33 % decline compared to the peak year (Fig. 2a). *Marine Pollution Bulletin* (MAR POLLUT BULL) emerged as the leading journal publishing research on elasmobranchs and pollution, accounting for 38.03 % of all articles. It was followed by *Environmental Pollution* (ENVIRON POLLUT) and *Science of the Total Environment* (SCI TOTAL ENVIRON), each contributing with 9.86 % of the publications (Fig. 2b). All three journals are published by Elsevier's ScienceDirect platform. Among the journals with two or more articles published during the period, Impact Factors (as reported in 2022) ranged from 3.7 (*PLOS ONE*) to 11.4 (*Environmental Science & Technology*, ENVIRON SCI TECHNOL), with a median Impact Factor of 5.2.

Many of the most frequent keywords reflect the descriptors used in the search strategy. Nonetheless, several keywords appeared at relatively high frequencies, such as *bioaccumulation* (present in 8 articles; 11.27 % of total publications), *Carcharhinidae* (6; 8.45 %), *mercury* (6; 8.45 %), and *maternal offloading* (5; 7.04 %) (Fig. 3a). The keyword co-occurrence network (Fig. 3b) highlights *Sharks* as the most central node across all centrality metrics (Degree Centrality [DC]: 22.0; Weighted Degree Centrality [WDC]: 106.0; Eigenvector Centrality [EC]: 1.0; Closeness Centrality [CC]: 0.923077; and Betweenness Centrality [BC]: 0.22762). *Elasmobranchs* ranked second in DC (16.0), CC (0.75), and BC (0.092492), while *pollution* ranked second in WDC (60.0), and *PCBs* ranked second in EC (0.794168). The most frequent keyword co-occurrences were between *Sharks* and *Pollution* (co-cited six times), followed by *Sharks* and *PCBs* (5), and *Sharks* with *Metals*, *Mercury*, and *Trace elements* (each co-cited four times).

The most frequently assigned Research Area (RA) is *Environmental Sciences & Ecology*, which encompasses 53 of the articles indexed in WoS during the study period, equivalent to 74.65 % of all publications. *Marine & Freshwater Biology* ranks second, assigned to 46.48 % of the publications, while *Toxicology* ranks third, comprising 12.68 % of the total (Fig. 4a). Despite being third in frequency, *Toxicology* stands out as the most central node in the RA co-occurrence network based on all centrality metrics except for Weighted Degree Centrality (WDC), where it ranks third (WDC: 22.0). Specifically, it holds the highest values for Degree Centrality (DC: 6.0), Eigenvector Centrality (EC: 1.0), Closeness Centrality (CC: 0.65), and Betweenness Centrality (BC: 0.52381). *Endocrinology & Metabolism* ranks second in DC (5.0) and EC (0.797284) and shares second place in CC (0.5) with *Environmental Sciences & Ecology* and *Marine & Freshwater Biology*. It also shares second position in BC (0.209524) with *Food Science & Technology*. In contrast, *Environmental Sciences & Ecology* is the most central RA in terms of WDC (76.0), followed by *Marine & Freshwater Biology* (WDC: 66.0) (Fig. 4b).

Over the past decade, researchers from Brazil and the United States of America (USA) were the most prolific in publishing scientific articles on elasmobranchs and pollution, each contributing with 23.94 % of all publications. Both countries reached their peak output in 2021, though publication numbers dropped to less than half by 2023 (Fig. 5a). In the country collaboration network, the USA holds the highest values in Weighted Degree Centrality (WDC: 22.0) and Betweenness Centrality (BC: 0.194872), indicating a prominent role in international collaboration. Brazil ranks fourth in both Degree Centrality (DC: 4.0) and WDC (12.0), while it holds lower ranks in Eigenvector Centrality (EC: 0.560004; 9th), Closeness Centrality (CC: 0.428571; 8th), and BC (0.014615; 8th). Italy, the third most productive country with 11.27 % of publications, is the most central node in the network in terms of DC (9.0) and EC (1.0), and ranks second in WDC (20.0) and BC (0.171282). Notably, Taiwan, the Philippines, South Korea, and China all share the highest CC value (1.0), suggesting equal proximity to other nodes in the network. The most frequent international collaborations occurred between researchers from the USA and Brazil, and between France and Portugal, with three co-authored articles in each pair (Fig. 5b).

While the USA and Brazil were the most productive countries in terms of total article production, the country network analysis reveals that the USA leads in WDC and BC, indicating its dominant influence and high connectivity in terms of research collaborations. Brazil, ranked fourth in DC and WDC, and ninth in EC, as well as eighth in CC and BC, demonstrates a moderate level of collaboration and influence within the network, though it does not hold the same level of prominence in international research collaboration as the leading countries. Italy, on the other hand, emerges as the most central node in DC and EC, and the second most central in WDC and BC. This positions Italy as a key player in the network, with a high number of direct connections and strong integration into the broader collaboration dynamics.

Concerning USA and Brazil as the most frequent co-authors in the retrieved articles, one study investigated metal bioaccumulation and detoxification mechanisms in blue sharks (*Prionace glauca*), providing the first report on several metals in this species and establishing baseline elemental data that can aid in biomonitoring and conservation efforts in the western North Atlantic (Hauser-Davis et al., 2021). Another

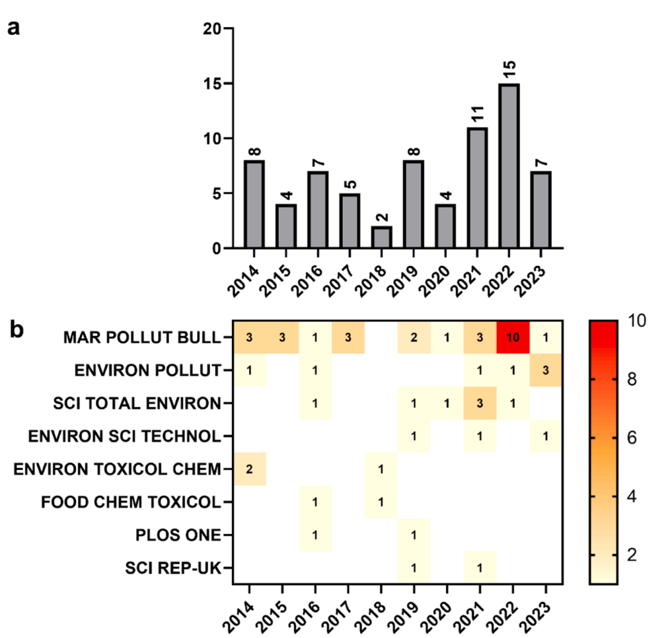

Fig. 2. Publication and Journals on the subject of elasmobranchs and pollution. (a) Annual publications; (b) Annual evolution of papers published by journals with two or more articles published during the study period. MAR POLLUT BULL – Marine Pollution Bulletin; ENVIRON POLLUT – Environmental Pollution; SCI TOTAL ENVIRON – Science of the Total Environment; ENVIRON SCI TECHNOL – Environmental Science and Technology; ENVIRON TOXICOL CHEM – Environmental Toxicology and Chemistry; FOOD CHEM TOXICOL – Food and Chemical Toxicology; SCI REP-UK – Scientific Reports – United Kingdom.

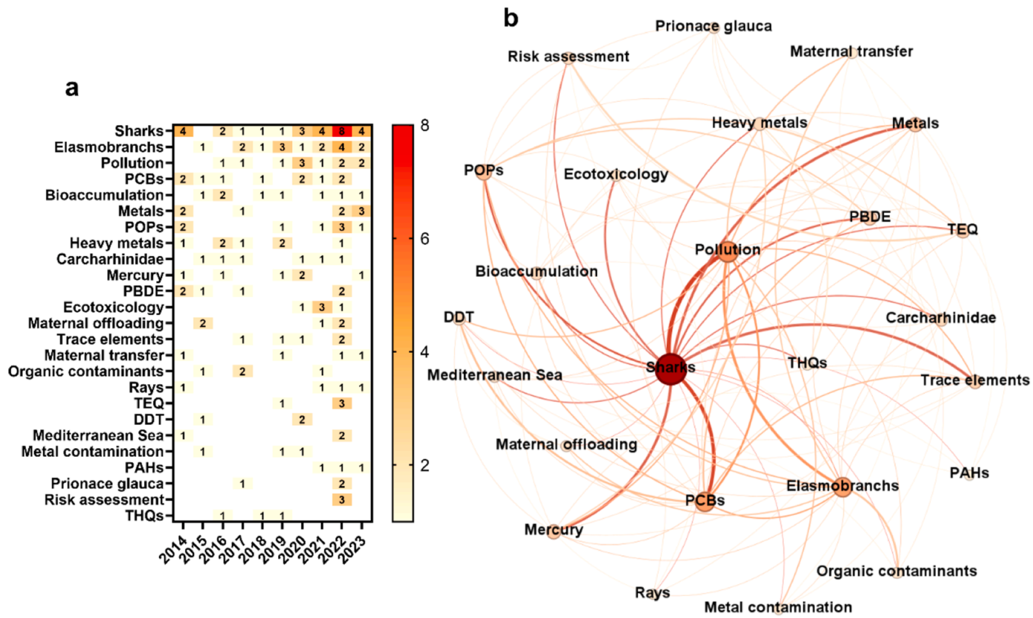

Fig. 3. Keywords. (a) Frequency of keywords over time. (b), Keyword network. Undirected network comprising 25 nodes and 114 edges. Nodes refer to keywords, and edges refer to the co-occurrence between keywords. A and B are keywords with a frequency of over three. Abbreviations: Polychlorinated biphenyls (PCBs), Persistent organic pollutants (POPs), Polybrominated Diphenyl Ethers (PBDE), Toxic equivalent (TEQ), Dichlorodiphenyltrichloroethane (DDT), and Polycyclic Aromatic Hydrocarbons (PAHs), Target hazard quotients (THQs).

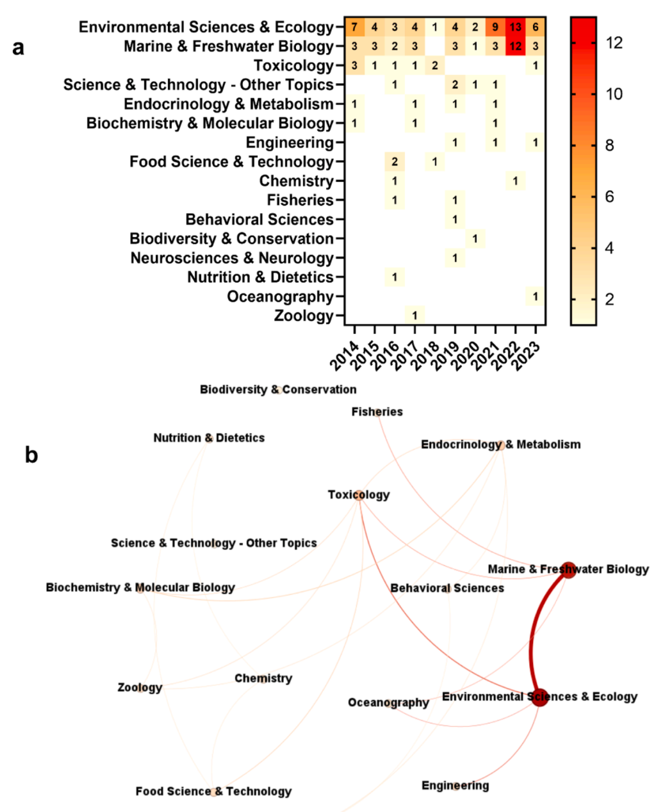

Fig. 4. Research Areas. (a) Frequency of RAs over time (all RAs: 16). (b) Network of RAs (all RAs). Undirected network comprising 16 nodes and 20 edges. Nodes refer to RAs, and edges refer to the co-occurrence between RAs.

significant study examined metal concentrations in various tissues of coastal sharks from Brazilian waters, finding correlations between metal exposure, serum biomarkers, and health indicators. These findings suggest potential physiological disturbances related to pollution (Wosnick et al., 2021). Additionally, research focused on the lesser numbfish (*Narcine brasiliensis*), a near-threatened ray species, explored subcellular metal partitioning and maternal transfer of contaminants, further expanding knowledge on metal detoxification mechanisms in marine species (Hauser-Davis et al., 2022).

Regarding the network of organizations, Fiocruz and PUC-Rio, as the main central nodes in DC, WDC, and EC, have the highest number of connections, the strongest influence, and are linked to other highly influential organizations, making them key players in the network. The six organizations that share the highest CC in the network, including UCLA and IQOG, play a crucial role in disseminating information, as they exhibit the shortest paths to all other nodes. Finally, leading in BC, the University of Miami is the most relevant organization in connecting different parts of the network, acting as a bridge for information flow between otherwise unconnected nodes.

The most frequent research collaborations were between Fiocruz and PUC-Rio, with eight co-authored papers, Fiocruz and UFRJ (5), UFRJ and PUC-Rio (5), and UFRJ and IMAM (5), all based in Rio de Janeiro, southeastern Brazil. The collaboration between Fiocruz and PUC-Rio is reflected in eight studies, including three featuring partnerships between Brazilian and North American authors. Some studies assess oxidative stress associated with metal accumulation, such as in nurse sharks (*Ginglymostoma cirratum*) (Wosnick et al., 2021), and investigate the impact of pollutants on elasmobranch physiology, including the maternal transfer of metals in *Narcine brasiliensis* (Lopes et al., 2019). This collaboration also extends to other contaminant classes, such as the systematic review on PAH contamination in elasmobranchs (Monteiro et al., 2023), further enhancing knowledge of pollution-induced physiological disruptions in marine species. These collaborations overlap with studies co-authored by Fiocruz and UFRJ, as well as almost all of the studies co-authored by UFRJ and IMAM, except for an investigation on organochlorine contaminants in the Rio skate (*Rioraja agassizii),* a vulnerable batoid species (Corrêa et al., 2022).

During the study period, a total of seventeen research organizations published at least three articles on the topic of elasmobranchs and pollution. Of these, 47.06 % are based in Brazil, while 23.53 % are from North America, highlighting the dominance of these two regions in

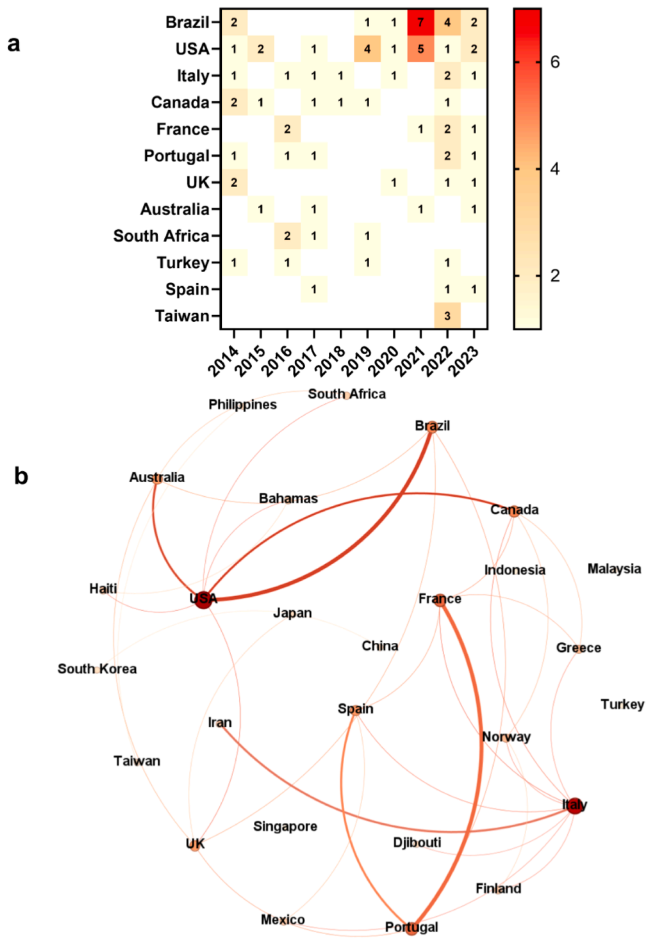

Fig. 5. Countries. (a) Country publications over time (countries with a frequency greater than or equal to three). (b) Country network (all countries: 27). Undirected network comprising 27 nodes and 35 edges. Nodes refer to countries, and edges refer to the co-occurrence between countries.

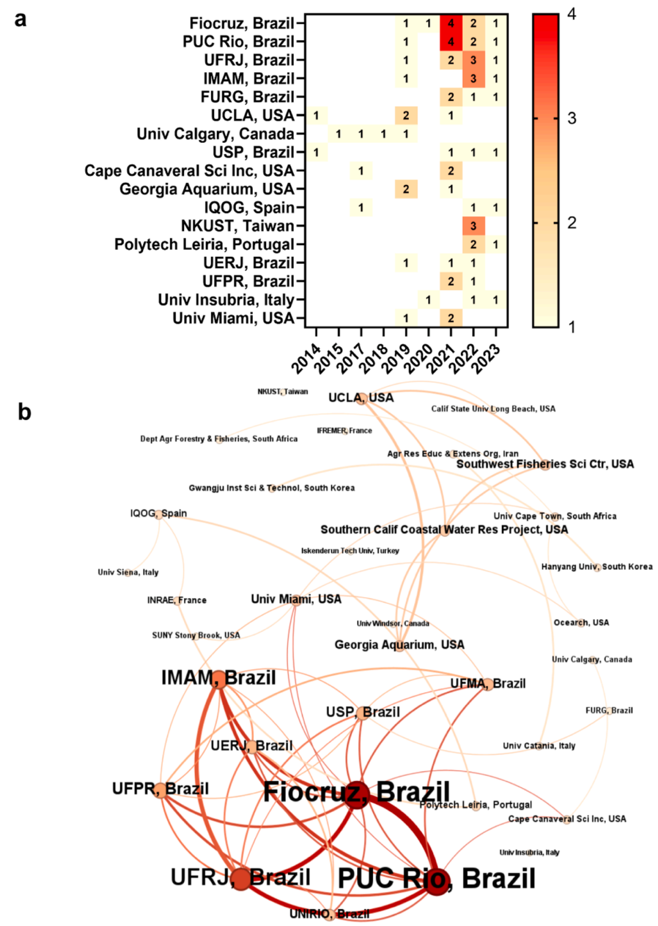

Fig. 6. Organizations. (a) Organization publications over time (organizations with a frequency greater than or equal to three). (b) Organization network (organizations with a frequency greater than or equal to two). Undirected network comprising 35 nodes and 55 edges. Nodes refer to organizations, and edges refer to the co-occurrence between organizations.

contributing to the literature. Brazilian institutions particularly stand out, occupying the top five spots in the ranking of the most prolific organizations. Leading the list is the Oswaldo Cruz Foundation (Fiocruz), which contributed 12.68 % of all publications. This is followed by the Pontifical Catholic University of Rio de Janeiro (PUC-Rio) with 11.27 %, and the Federal University of Rio de Janeiro (UFRJ) with 9.86 %. In terms of North American institutions, the University of California, Los Angeles (UCLA) is the most productive, publishing 5.63 % of all articles, and shares the fifth position with three other organizations (Fig. 6a).

The network analysis reveals that Fiocruz and PUC Rio are the most central organizations in terms of centrality metrics. These two institutions lead in Degree Centrality (DC: 10.0), Weighted Degree Centrality (WDC: 60.0), and Eigenvector Centrality (EC: 1.0), indicating their prominent roles within the network of research organizations. Interestingly, the highest Closeness Centrality (CC: 1.0) is shared by six organizations, including UCLA and others from diverse countries such as Spain, Iran, Italy, and South Korea. Furthermore, the University of Miami leads in Betweenness Centrality (BC: 0.090909), a metric that emphasizes the university's role as a bridge between different clusters in the network. Fiocruz and PUC Rio follow closely behind in BC, with scores of 0.04596, indicating their substantial influence in connecting different research communities. The collaboration patterns reveal frequent co-authorships between institutions, particularly between Fiocruz and PUC Rio, who co-authored eight papers together. Other noteworthy collaborations include Fiocruz and UFRJ, UFRJ and PUC Rio, and UFRJ and IMAM, all of which had five co-authored articles each (Fig. 6b).

As of the date of data collection, the dataset included 11 articles with 26 or more citations in the Web of Science (WoS). The top three most cited papers were: *Blue sharks (Prionace glauca) as bioindicators of pollution and health in the Atlantic Ocean: Contamination levels and biochemical stress responses* (DOI: 10.1016/j.scitotenv.2016.04.085) with 78 citations, which assessed blue sharks as pollution and health bioindicators in the Atlantic Ocean, focusing on contamination levels and biochemical stress responses to evaluate their suitability as a sentinel species for oceanic pollution; *Heavy metal concentrations in edible muscle of whitecheek shark, Carcharhinus dussumieri (Elasmobranchii, Chondrichthyes) from the Persian Gulf: A food safety issue* (DOI: 10.1016/j.fct.2016.09.002) with 75 citations, which investigated the bioaccumulation of heavy metals in the edible muscle of the whitecheek shark (*Carcharhinus dussumieri*), assessing potential health risks associated with seafood consumption and reinforcing the importance of monitoring pollutant transfer in marine food webs and *Are whale sharks exposed to persistent organic pollutants and plastic pollution in the Gulf of California (Mexico)? First ecotoxicological investigation using skin biopsies* (DOI: 10.1016/j.cbpc.2017.03.002) with 66 citations, which highlights toxicological risk assessments related to POPs and plastic pollution in whale sharks (*Rhincodon typus*), providing new insights into the role of large filter-feeding species as marine pollution bioindicators (Fossi et al., 2017). (Fig. 7a), all emphasizing key concerns in the field of elasmobranch ecotoxicology. Among the 2745 references with a DOI cited in the articles, 12 were cited 14 times or more. The three most frequently

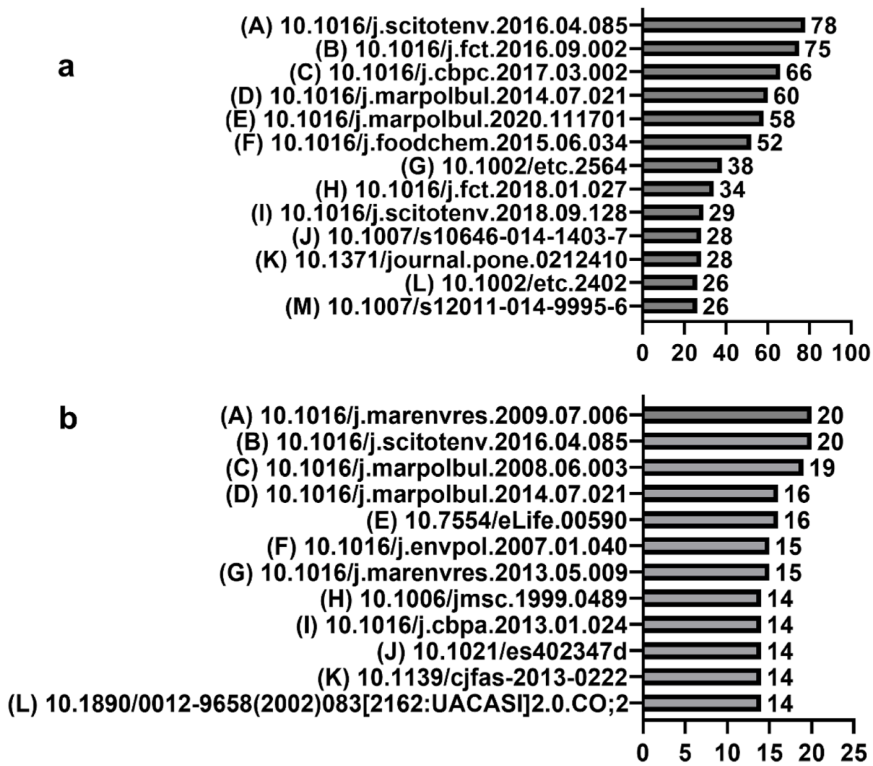

Fig. 7. Article citations in WoS, and author-cited references. (a) DOIs of articles comprising our dataset that were cited in WoS (with 26 or more citations). (b) DOIs of references cited in the articles comprising our dataset (references with 14 or more citations).

cited references were: *Mercury in 16 demersal sharks from southeast Australia: Biotic and abiotic sources of variation and consumer health implications* (DOI: 10.1016/j.marenvres.2009.07.006) with 20 citations, *Blue sharks (Prionace glauca) as bioindicators of pollution and health in the Atlantic Ocean* (DOI: 10.1016/j.scitotenv.2016.04.085) with 20 citations, and *Hg, Zn and Cu levels in the muscle and liver of tiger sharks (Galeocerdo cuvier) from the coast of Ishigaki Island, Japan: Relationship between metal concentrations and body length* (DOI: 10.1016/j.marpolbul.2008.06.003) with 19 citations (Fig. 7b).

The most frequently mentioned pollutants in the analyzed articles are iron (Fe), Polychlorinated biphenyls (PCBs), POPs, and mercury (Hg), which account for 33.80 %, 26.76 %, 19.72 %, and 15.45 % of all publications, respectively. The pollutants that were most often co-mentioned together include PCBs and POPs (8 mentions), PCBs and Dichlorodiphenyltrichloroethane (DDT) (8), Fe and POPs (6), lead (Pb) and cadmium (Cd) (6), Fe and PCBs (5), PCBs and OPCs (5), POPs and DDT (5), Hg and Cd (5), and Pb and Hg (5) (Fig. 8a). The co-occurrence network of pollutants (Fig. 8b) reveals that Fe is the most central node, based on all centrality metrics (DC: 19; WDC: 86.0; EC: 1.0; CC: 0.827586; BC: 0.216445). Cadmium and lead rank second in DC (17), while PCBs hold the second position in WDC (82.0). Cadmium is also second in EC (1.0) and CC (0.774194), and PBDE ranks second in BC (0.113468).

5. Discussion

The assessment of scientific publications on elasmobranchs and pollution over the last decade revealed several highlights, trends, and collaboration patterns in the field. Regarding publication venues, *Marine Pollution Bulletin* plays a prominent role, disseminating 38.03 % of the total articles. A total of 37.04 % of these articles were published in 2022, indicating a peak in scholarly attention in recent years. The journal is published monthly, and its articles on this subject were spread throughout the year, rather than being concentrated in any special issue dedicated to elasmobranchs and pollution (Marine Pollution Bulletin, 2025). This suggests a growing and ongoing interest in the field, with the journal consistently being a key platform for relevant research.

It is important to highlight that, despite the broader ecological relevance of ecotoxicological research for the stability and health of aquatic ecosystems, high-impact journals with a wider scope, such as those focused on environmental management or aquatic conservation, tend to publish comparatively fewer studies on this topic. This may reflect either a lack of interest from these journals in research with a specific focus on wildlife toxicology, or a tendency among submitted studies to underemphasize broader ecological and conservation implications in their conclusions. This trend is particularly concerning given that ecotoxicological data on elasmobranchs provide critical insights into the effects of pollution on aquatic life and the cascading ecological consequences. The current tendency to relegate such studies to niche journals risks limiting their visibility and impact, especially considering the wide range of stakeholders, from conservation practitioners to policymakers, who could benefit from scientific evidence to inform legal and management strategies addressing aquatic pollution.

The analysis of the most frequent keywords offers valuable insights into the research priorities within the field of elasmobranch pollution studies. The prominence of terms like 'sharks,' 'pollution,' and 'bioaccumulation' highlights a significant focus on contamination processes and their impacts on elasmobranch species, which have direct implications for population health and conservation management, especially when emphasizing critical contaminant pathways and life-stage vulnerabilities. Furthermore, the interconnection of keywords such as 'PCBs,' 'heavy metals,' and 'mercury' highlights the central role of chemical contaminants in this area of study. These pollutants are known to bioaccumulate in marine food webs, posing considerable risks to marine organisms (Alava et al., 2018; Harding et al., 2018; Mcintyre and Beauchamp, 2007). Recent studies have documented metal(loid) contamination even in remote regions, including tiger sharks in the Fernando de Noronha Archipelago (Rangel et al., 2025) and Greenland

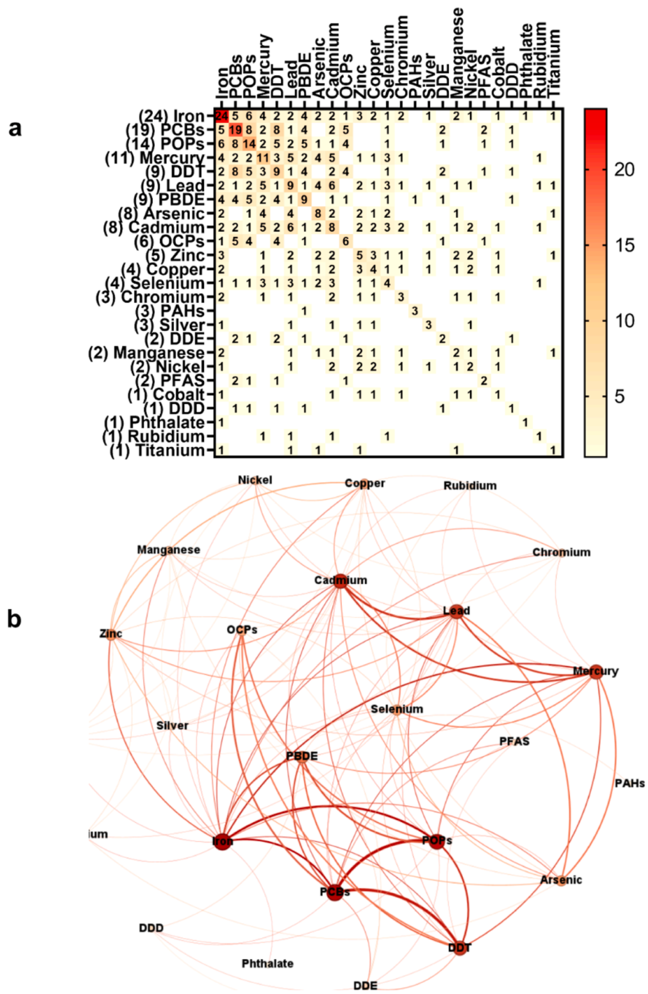

Fig. 8. Pollutants. (a) Ranking and cooccurrence of all mentioned pollutants. (b) Network of all pollutants. Undirected network comprising 25 nodes and 118 edges. Nodes refer to pollutants, and edges refer to the co-occurrence between pollutants.

sharks in the Arctic (Biton-Porsmoguer et al., 2024), which further highlights the widespread exposure of elasmobranchs to pollutants and raises concerns about their potential ecological and health implications.

The frequent co-occurrence of the words sharks, metals and POPs illustrates a focus on well-characterized contaminants, enabling comparisons across regions and supporting evidence-based management. In the present review, the term “sharks” was considered as it appeared in the titles of the selected publications, without further examination of the specific species included in each study. We acknowledge that some authors use “sharks” as a cumulative term to broadly describe elasmobranchs, which may encompass both sharks and rays, even if not explicitly stated in the title. While this choice may introduce a degree of ambiguity regarding the exact taxa assessed in the underlying studies, it ensured consistency and reproducibility in our search and selection process. Future reviews could benefit from a more detailed examination of study content to disentangle taxonomic scope; however, this was beyond the objectives of the present study. It is also important to note that rays and skates are still significantly understudied compared to sharks concerning pollution (Tiktak et al., 2020). Both, however, are highly vulnerable to pollutants due to their habitat preferences, as rays generally present more intimate contact with sediments throughout their life spans than their shark counterparts, potentially leading to higher exposure levels, as sediments are known pollutant sinks (Chiaia-Hernández et al., 2022; Corrêa et al., 2022). Thus, more efforts should be directed specifically towards this group concerning pollution assessments.

On a sidenote regarding keywords, it is important to note that one of the main keywords retrieved in this assessment, "heavy metals," is widely used in both scientific and non-expert literature to describe metals and metalloids associated with pollution, toxicity, and adverse effects on biota. However, this term has been considered incorrect and misleading by the International Union of Pure and Applied Chemistry (IUPAC) since at least 2003 (Duffus, 2002). The term is commonly applied to metals based on criteria like density, atomic weight, atomic number, and toxicity, often including elements with a density above 5 g/cm^3 , as well as metalloids such as arsenic (As) and nonmetals like selenium (Se). Despite this, the term is most frequently used to refer to metals and metalloids associated with contamination and potential toxicity or ecotoxicity, which is scientifically inaccurate. Toxicity depends on chemical form, bioavailability, and dose, not weight or density (Duffus, 2001). Since no single criterion can apply to all elements grouped under this term, it is inconsistent and imprecise. As a result, scientists now favor more precise classifications, such as "trace metals" for elements present in small quantities, "toxic metals" for those with hazardous properties, "essential metals" for biologically necessary elements, and "transition metals" based on their position in the periodic table. Additionally, metalloids like Se and As are now recognized as distinct from metals. Despite these efforts to move away from the term "heavy metals," its widespread use remains prevalent, as demonstrated by its prominence as one of the most significant keywords retrieved in this study.

The relatively high frequency of "maternal offloading" as a keyword suggests increasing attention to the role of pollutant transfer from mother to offspring in elasmobranch species (Lyons and Adams, 2015; Lyons and Lowe, 2013; Martins et al., 2021; Reistad et al., 2021; Weijs et al., 2015). These findings align with the keyword network analysis, which reveals that central themes such as ’sharks,’ ’pollution,’ and ’bioaccumulation’ continue to drive research in the field. Additionally, there is a clear connection between keywords related to contaminants, including ’PCBs,’ ’heavy metals,’ and ’mercury.’ However, maternal offloading in elasmobranchs remains an underexplored topic, with most research focusing on mercury due to its well-documented neurotoxicity and bioaccumulation. Some studies have also investigated the transfer of POPs such as PCBs and organochlorine pesticides. Yet, limited research has been conducted on the maternal transfer of technologically critical elements (TCEs) like titanium, rubidium, and rare earth elements (REEs), as well as per- and polyfluoroalkyl substances (PFAS), emerging pesticides, pharmaceuticals, and personal care products. A few studies have touched on pharmaceuticals and TCEs in highly threatened species, such as the Brazilian guitarfish (*Pseudobatos horkelii*) (Martins et al., 2020) and tiger sharks (*Galeocerdo cuvier*) (Wosnick et al., 2024), but none have specifically addressed the maternal transfer of these contaminants in elasmobranchs. The exception to this is two studies on the maternal transfer of titanium, both total and subcellular, in *Narcine brasiliensis* (Hauser-Davis et al., 2022).

The choice of keywords is a critical yet often overlooked aspect of scientific publishing, directly influencing the visibility of studies in systematic reviews, policy development, and extinction risk assessments. This oversight may partly explain why pollution is listed as a threat in only 6 % of the species assessed for extinction risk by the IUCN red list (Dulvy et al., 2021), despite mounting evidence that contaminant exposure can cause both lethal and sub-lethal effects that compromise recruitment and threaten population viability. This is especially concerning for elasmobranchs, a group of high conservation concern, whose ecological importance and biological characteristics make lethal exposure studies ethically unfeasible. In such cases, it becomes essential to consider alternative approaches for understanding contaminant impacts at the population or community level. One valuable strategy lies in recognizing that many physiological processes are evolutionarily conserved across vertebrates. This opens opportunities for cautiously inferring potential impacts in elasmobranchs based on findings from other taxa with shared traits, such as bony fishes (with similar osmo-ionic regulation and respiratory modes) and marine mammals (with comparable growth and reproductive strategies). While such inferences must be made conservatively, especially given that elasmobranchs sometimes exhibit unusual resilience to contaminant loads considered lethal in other taxa, they nonetheless offer an important path forward. Rather than disregarding available data, the scientific and conservation communities should work toward integrating this evidence into broader threat assessments to support more informed and effective protective measures.

The prominent role of the USA in elasmobranch ecotoxicology research is not surprising, given the high costs associated with contaminant analyses. However, marine pollution is a transboundary issue that disregards geographic and political borders, highlighting the urgent need for broader global participation in this research field. To expand ectoxicological studies on sharks and rays beyond traditional hubs, it is essential to ensure access to resources, analytical capacity, and professional training in other countries. International collaborations, when designed to include and empower local researchers, offer a promising pathway to achieve this expansion while avoiding the pitfalls of parachute science. Brazil stands out as a critical example: despite decades of systemic underfunding in science and technology, the country has made significant contributions to global knowledge in elasmobranch toxicology. This highlights the central role that Global South institutions, laboratories, and researchers can and must play in advancing this field.

Greater leadership from countries in the Global South is imperative, either through equitable partnerships or increased internal investment, especially considering that aquatic ecosystems in these regions are often among the most impacted by pollution (Wantzen et al., 2019; Dikobe et al., 2024). A promising model for fostering such collaboration lies in connecting elasmobranch researchers, who have access to animals and biological samples, with analytical laboratories, even those that may not traditionally work on this taxonomic group. A significant example is the 2024 study reporting the presence of cocaine and its metabolite benzoylecgonine in Brazilian sharpnose sharks (*Rhizoprionodon lalandii*) (de Farias Araujo et al., 2024). This unprecedented finding emerged from a unique partnership between shark researchers and Brazilian government analysts with the technical equipment required for such detections. This collaboration combined analytical capacity with ecological and conservation expertise, setting a precedent for future cross-disciplinary and cross-institutional efforts that can significantly advance the field of marine ecotoxicology.

The centrality of Toxicology as a research area, bridging Environmental Sciences & Ecology and Marine & Freshwater Biology, highlights its role in linking ecological monitoring with mechanistic understanding of pollutant effects. Similarly, the three most cited references in the dataset provide additional insights into metal accumulation, pollutant bioindicators, and their biological elasmobranch effects, indicating some of the main references guiding research in the field. The most cited reference (20 citations) was also the most cited overall in the field of elasmobranch ecotoxicology (Alves et al., 2016). This is somewhat expected, as it is a review on the subject compiling information from the scientific literature, although not in a systematic manner as conducted herein. Another study with 20 citations investigated total mercury (THg) and monomethylmercury (MMHg) concentrations in multiple deep-sea sharks and chimera species off southeast Australia, demonstrating that this metal primarily accumulates in muscle tissue and increases systematically with body size, from embryos to adults, reinforcing the idea of mercury bioaccumulation throughout marine food webs (Pethybridge et al., 2010). The third most cited article in the dataset (19 citations) examined mercury, zinc, and copper concentrations in tiger sharks from Japan, revealing that muscle mercury levels increase with body length, while hepatic mercury accumulation rises sharply after sexual maturity, suggesting physiological shifts in metal storage related to growth and dietary intake (Endo et al., 2008). Overall, these studies show growing concern over metal and organic pollutant bioaccumulation in elasmobranchs, their potential effects on marine ecosystem stability and elasmobranch health, and the risks associated with human consumption of contaminated sharks products.

Given the wide taxonomic diversity and broad distribution of elasmobranchs, contaminant exposure levels often reflect regional pollution rather than patterns generalizable to entire species. This highlights the need for coordinated efforts in elasmobranch toxicology to establish shared priorities and maximize the applicability of ecotoxicological data for conservation. Future studies should focus on contaminant assimilation and accumulation across groups defined by ecological traits (*e.g.,* benthic, pelagic, migratory), enabling a more integrative understanding of how anthropogenic pressures affect species through their interactions with the environment. Generating broader, comparative datasets will also help situate elasmobranch ecotoxicology within wider environmental and conservation frameworks, increasing its relevance and visibility.

Concerning the cited chemical contaminants, iron was the most frequently cited, likely due to its abundance in the environment and its role as both an essential and potentially toxic metal, depending on its concentration. Additionally, iron contamination is often associated with industrial activities, mining, and wastewater discharge, making it a key element assessed in environmental research. On the other hand, phthalates and PAHs were the least cited contaminants, possibly due to the cost and complexity of analytical techniques required for their detection. While metals can be analyzed using relatively accessible techniques such as atomic absorption spectroscopy (AAS) or inductively coupled plasma mass spectrometry (ICP-MS), phthalates and PAHs require more specialized and expensive methods, such as gas chromatography-mass spectrometry (GC-MS) or high-performance liquid chromatography (HPLC). These methods demand more sophisticated instrumentation, longer processing times, and often require extensive sample preparation, including sample cleanup and, in some cases, derivatization, which could contribute to the lower number of studies on these contaminants.

It is important to note that, concerning metals, subcellular metal partitioning assessments in elasmobranchs are still severely lacking. These analyses are a critical tool for assessing metal toxicity in aquatic organisms, as they provide insights into metal bioavailability across different cellular compartments, detoxification mechanisms, and the potential adverse effects of metals at the cellular level (Hauser-Davis et al., 2023). By distinguishing between metal fractions in cellular structures, subcellular metal partitioning helps clarify whether an organism is effectively sequestering metals to mitigate their toxicity or experiencing harmful effects from them. Furthermore, these assessments are crucial for understanding the trophic transfer of these contaminants, enhancing the ability to predict environmental and health risks linked to metal contamination. For elasmobranchs, the only studies published to date, to the best of our knowledge, are those focused on the lesser numbfish from southeastern Brazil (Hauser-Davis et al., 2022) and on blue sharks in the Western North Atlantic Ocean (Hauser-Davis et al., 2021). These studies offer valuable preliminary insights into the subcellular partitioning of metals, but much more research is needed to comprehensively evaluate how these processes work across diverse elasmobranch species and ecosystems.

The research focus on specific contaminants in elasmobranchs may be shaped by both historical concerns and evolving regulatory priorities. Metals, for instance, have long been recognized as significant environmental and public health hazards, which has led to decades of extensive research on their distribution, toxicity, and remediation. In addition, metal analyses are generally simpler, faster, and more cost-effective than that of POPs which often require complex extraction, cleanup, and sophisticated instrumentation. In contrast, organic contaminants such as phthalates, PFAS, and polycyclic aromatic hydrocarbons (PAHs) have only gained broader regulatory and scientific attention in more recent decades. A key turning point was the adoption of the Stockholm Convention on Persistent Organic Pollutants in 2001, which entered into force in 2004. This legally binding international treaty initially targeted 12 priority substances, often referred to as the "dirty dozen", including PCBs, dioxins, and several organochlorine pesticides such as DDT. Its primary objective was to eliminate or severely restrict the production, use, and release of these chemicals, thereby reducing their introduction into the environment (UN, 2001). Over time, the Convention has expanded its list to include additional compounds of emerging concern, such as specific per- and polyfluoroalkyl substances (PFAS) and brominated flame retardants, in recognition of their persistence, potential for bioaccumulation, and harmful effects on human and ecological health (UN, 2009).

Despite these international measures, some POPs remain in limited or ongoing use in certain countries, either due to exemptions, such as DDT for vector control in India and several African countries, among others (van den Berg, 2009) or lack of alternative substances. Moreover, many POPs are characterized by exceptionally long environmental half-lives, persisting for decades to centuries in soils, sediments, and aquatic systems (Guo et al., 2019). This longevity means that, even after production bans, legacy contamination continues to pose significant risks through bioaccumulation and biomagnification in food webs and long-range environmental transport in several areas worldwide, as demonstrated in several studies from different regions worldwide, such as in the North Atlantic, South Atlantic and the Mediterranean (Jürgens et al., 2016; Ferreira et al., 2019; Klinčić et al. 2020). The persistence of these substances, combined with historical widespread use, may account for their continued detection in marine species today. The more recent inclusion of certain contaminants as stated above in regulatory frameworks may also help explain their lower frequency in earlier ecotoxicological literature on elasmobranchs.

Lastly, of particular concern is the limited number of studies assessing the physiological effects, both lethal and sublethal, of contaminants in elasmobranchs. Similarly, indicators of systemic health remain underexplored, whether through non-lethal proxies such as body condition indices or traditional metrics such as the hepatosomatic and gonadosomatic indices, which require lethal sampling but could be obtained from specimens already deceased due to commercial fishing activities. It is paramount that future research integrates more health-related endpoints to better understand the biological impacts of contamination. A more holistic and multidisciplinary approach is needed, grounded in the One Health concept, which recognizes that anthropogenic impacts on the marine environment have consequences not only for ecosystem health but also for the animals that inhabit these systems and, ultimately, for human health, given the widespread consumption of elasmobranch species in many parts of the world. Only by broadening the scope of toxicological studies to include biological and ecological consequences will this research gain the visibility it merits, fostering greater scientific, regulatory, and public engagement with what is likely a more severe threat than currently acknowledged.

6. Conclusion

This study highlights a growing global interest in the effects of pollution on elasmobranchs, with research on this topic showing significant growth, particularly in the past decade. However, critical gaps remain in understanding how contaminants affect these species. Notably, there is a need for more research on the physiological effects of pollutants, including sublethal endpoints such as oxidative stress, immune responses, and reproduction, as these are directly relevant to population viability and can inform management thresholds. Greater attention to maternal offloading and early-life exposure is also needed, given their implications for recruitment and long-term population health. The standardization of broader health indicators, such as body condition and organ indices, is also crucial for assessing population-level risks and understanding the long-term effects of contamination, and would facilitate cross-study comparisons and strengthen their use in risk assessments. Incorporating ecological traits, including migratory behavior and habitat use, into exposure analyses can help identify species and habitats most vulnerable to contamination, guiding conservation priorities. While countries such as the USA and Brazil are leading on the subject, it is paramount to expand research efforts globally, particularly in the Global South, where aquatic ecosystems are often most impacted by pollution, which will improve the representativeness of global assessments and help managers target high-risk areas. Collaborative, cross-border partnerships, especially those that include local researchers, are key to overcoming barriers like limited access to high-cost analytical tools and expertise. Finally, interdisciplinary One Health approaches and collaborative networks that enable technology transfer will not only improve research capacity but also enhance the relevance of findings to fisheries management, pollution mitigation, and policy development.

CRediT authorship contribution statement

Fabio Mota: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Bernardo Cabral:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Natascha Wosnick:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Renato Matos Lopes:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Rachel Ann Hauser-Davis:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, 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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104519.

Data availability

Data will be made available on request.

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