Global research trends on bivalve biomarkers for heavy metal pollution: a bibliometric analysis

Izhamil Hidayah[1,2], *La Ode* Abdul Fajar Hasidu [1,4], *Neviaty* P. Zamani[1*], *Dietriech* G. Bengen[1], *Joko* Santoso[3], *Hedi* Indra Januar[2]

[1]Marine Science Departement, Faculty of Fisheries and Marine Science, IPB University, Bogor, Indonesia
[2]Research Center for Ecology, National Research and Innovation Agency, Bogor, Indonesia
[3]Aquatic Product Technology Department, Faculty of Fisheries and Marine Science, IPB University, Bogor, Indonesia
[4]Marine Science Study Program, University of Sembilanbelas November, Kolaka, Indonesia.

Abstract. This study presents a bibliometric analysis of global research trends on heavy metal biomarkers in bivalves published between 2000 and 2025. The analysis was conducted using data retrieved from the Scopus database, resulting in 311 initial records, of which 309 documents met the inclusion criteria after screening. Bibliometric mapping and descriptive analyses were performed using VOSviewer and Microsoft Excel to evaluate publication trends, country contributions, leading authors, and keyword co-occurrence networks. The results indicate a substantial increase in publications after 2010, with a peak in 2020 (22 articles). France (52 publications), China (44 publications), and Italy (29 publications) emerged as the leading contributors, while tropical countries accounted for only 25 studies (approximately 8%), with Indonesia contributing a single publication. Keyword analysis identified four major thematic clusters: environmental monitoring and bioaccumulation, pollutant-specific chemical analyses, biochemical and molecular responses, and additional coastal contaminants such as polycyclic aromatic hydrocarbons (PAHs). These findings confirm the central role of bivalves as effective bioindicators of heavy metal pollution and highlight a persistent research gap in tropical regions. This study provides a focused bibliometric synthesis that can support future international collaboration, capacity building in tropical countries, and the integration of advanced approaches in marine biomonitoring.

Keywords: Heavy metals, Biomarkers, Bivalves, Environmental monitoring, Bibliometric analysis

* Corresponding author: neviaty@apps.ipb.ac.id

1 Introduction

Owing to their persistence, bioaccumulation, and toxicity, heavy metal contaminants in marine ecosystems pose a critical global challenge. Cadmium, lead, mercury, and arsenic are released into aquatic environments through industrial processes, mining, agriculture, and urban runoff. These pollutants accumulate in sediments and marine organisms, biomagnify through the food web, and ultimately threaten human health via seafood consumption [1, 2]. Recent assessments suggest that approximately 40% of the world's seas are significantly affected by human activities, with coastal waters being the most severely affected [3].

Bivalves, including mussels, oysters, clams, and scallops, are widely used as bioindicators because of their sedentary lifestyle, filter feeding capacity, and ability to bioaccumulate contaminants [4, 5]. Their filtering activity enables them to concentrate pollutants at levels far exceeding ambient concentrations, making them highly sensitive to environmental change [6]. In addition to their ecological roles, bivalves are also of major economic significance. The global production of marine bivalves exceeded 15 million tons per year from 2010 to 2015, representing approximately 14% of total marine production. Nearly 90% of this production comes from aquaculture, primarily in Asia [7].

A wide range of biomarkers, including metallothionein induction, oxidative stress responses, enzymatic activity, and histopathological alterations, have been used to assess heavy metal exposure in bivalves [8, 9]. Recent advances in molecular biology and metabolomics have further expanded the toolkit for exploring species-specific biochemical responses and pollutant-induced physiological disruptions [10]. These approaches strengthen the potential of bivalves as ecological indicators and tools to ensure seafood safety.

Despite a growing number of studies on this topic worldwide, tropical regions remain underrepresented. Indonesia, for example, is home to some of the world's highest marine biodiversity but has contributed relatively few studies on heavy metal biomarkers in bivalves. This gap constrains the development of effective management strategies for ecosystems under the pressure of pollution, overfishing, habitat degradation, and climate change. Additionally, while bibliometric analyses have been conducted in broader fields, such as marine pollution and ecotoxicology, no systematic bibliometric synthesis has specifically addressed heavy metal biomarkers in bivalves.

This study aimed to address this issue by conducting a comprehensive bibliometric analysis of heavy metal biomarker research in bivalves published between 2000 and 2025. Specifically, the study will (i) characterize global publication trends; (ii) identify leading authors, institutions, and funding agencies; (iii) map thematic structures through keyword analysis; and (iv) highlight knowledge gaps in tropical regions. This study provides a novel insight base to strengthen international collaboration and guide future research in biomarker-based marine pollution monitoring.

2 Materials and methods

2.1 Data source and search strategy

Bibliometric data from May to June 2025 were retrieved from the Scopus database. The search was conducted using the following query string in the *TITLE-ABS-KEY* field: *(biomarkers OR biomarker) AND (heavy metal OR "heavy metals") AND (bivalve OR bivalvia)*. This search string was designed to capture publications that focused on the use of biomarkers to assess heavy metal contamination in bivalves.

2.2 Inclusion and exclusion criteria

The initial search identified 311 publications indexed in the Scopus database between 2000 and 2025. A multi-step screening process was subsequently applied to ensure the relevance and quality of the dataset. The inclusion criteria comprised peer-reviewed journal articles, review papers, and conference proceedings that explicitly addressed the application of biomarkers for assessing heavy metal contamination in bivalves. Conversely, non-research items such as editorials, short surveys, errata, and notes were excluded, along with studies focusing on non-bivalve taxa (e.g., bacteria, plankton, and fish) or pollutants other than heavy metals, including pesticides and plastics. Following the application of these criteria, a total of 309 documents were retained for the final bibliometric analysis.

2.3 Data processing and analysis

The final dataset was exported in CSV format and analyzed using a combination of bibliometric visualization and descriptive statistical tools. VOSviewer (version 1.6.19) was employed to construct and visualize bibliometric networks, including keyword co-occurrence, co-authorship relationships, and international collaboration patterns, owing to its strength in generating cluster-based maps commonly used in bibliometric studies. In parallel, Microsoft Excel 2021 was used to compute descriptive statistics, such as annual publication trends, distributions of document types, and citation patterns. This integrated approach enabled both quantitative analyses (e.g., publication counts and citation metrics) and qualitative assessments (e.g., thematic clustering and author collaboration networks) of the research landscape on heavy metal biomarkers in bivalves.

3 Results and discussion

3.1 Publication trends

The bibliometric analysis revealed fluctuating but generally increasing publication outputs on heavy metal biomarker research in bivalves between 2000 and 2025 (**Fig. 1**). A total of 309 articles were identified during this period, with a marked growth observed after 2010. The annual number of publications reached its highest point in 2020, with 22 articles, reflecting heightened global concern over marine pollution and increased recognition of biomarkers as essential tools for environmental monitoring. However, a sharp decline occurred in 2021 (n = 7), which may be attributed to the COVID-19 pandemic that redirected scientific efforts and funding priorities toward human health research [11].

Following this decline, research activity has gradually recovered, with 11–13 publications annually between 2022 and 2024, indicating renewed momentum in the field. By mid-2025, only three publications were indexed; however, this figure is expected to rise as database indexing is fully completed later in the year. Regression analysis of publication output over time showed a significant upward trend ($R^2 = 0.72$), suggesting that despite temporary fluctuations, the long-term trajectory of the field remains positive.

The overall increase in publication output can be attributed to several interrelated factors. Advances in molecular and omics-based techniques have enabled more sensitive and mechanistic insights into biomarker responses, thereby expanding the scope and depth of ecotoxicological research [10]. In parallel, policy-driven environmental monitoring initiatives, particularly in Europe and Asia, have increasingly incorporated biomarker-based approaches as part of regulatory frameworks for marine pollution assessment. Additionally, the rapid expansion of aquaculture and growing concerns over seafood safety have intensified

the demand for ecotoxicological evaluations using bioindicators, such as bivalves, to assess the impacts of heavy metal contamination in coastal ecosystems.

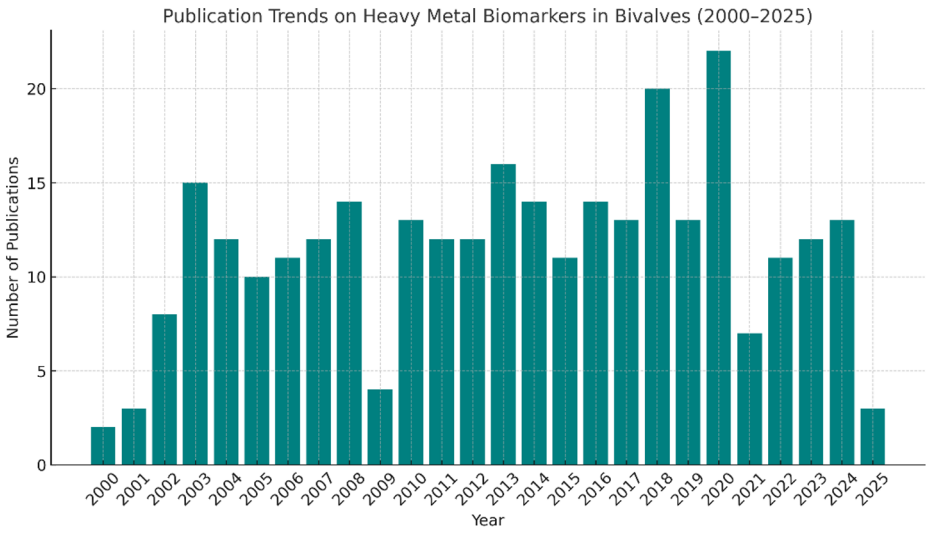

Fig. 1. Publication trends on heavy metal biomarker research in bivalves from 2000 to 2025. The figure shows the annual number of publications indexed in Scopus, illustrating the temporal evolution of research activity in this field and a general increase in output after 2010.

Despite global growth, research output from tropical countries has remained limited throughout the two-decade period. Of the 309 documents analyzed, less than 10% originated from tropical regions, with Indonesia contributing to only one study. This imbalance underscores a persistent knowledge gap in biodiversity-rich areas that are highly vulnerable to pollution yet underrepresented in global scientific discourse. Addressing this gap requires enhanced research capacity, targeted funding, and stronger international collaboration.

3.2 Institutional affiliations

The analysis of author affiliations highlights the strong contribution of leading international research institutions in the field of heavy metal biomarker studies in bivalves. The **Centre** National de la Recherche Scientifique (CNRS, France) emerged as the most productive institution, with 16 publications reflecting France's long-standing investments in marine ecotoxicology and environmental monitoring. Similarly, the Chinese Academy of Sciences (15 publications) and the Ministry of Education of China (12 publications) illustrated China's rapid expansion in marine pollution research, supported by large-scale national funding programs and government priorities in environmental sciences (**Fig. 2**).

Fig. 2 also shows other institutions with notable contributions, including the Ocean University of China (12 publications), Université de Bordeaux (11), and IFREMER (France, 9), all of which are recognized hubs for marine science and coastal pollution monitoring. Prominent European institutions, such as Universidade do Algarve (Portugal), CSIC–ICMAN (Spain), and La Rochelle Université (France), each contributed eight publications, emphasizing the collaborative strength of Southern and Western Europe. Outside Europe and Asia, contributions came from North America, particularly from the University of North Carolina at Charlotte (seven publications), which has produced influential studies linking heavy metal exposure to biomarker responses in marine organisms.

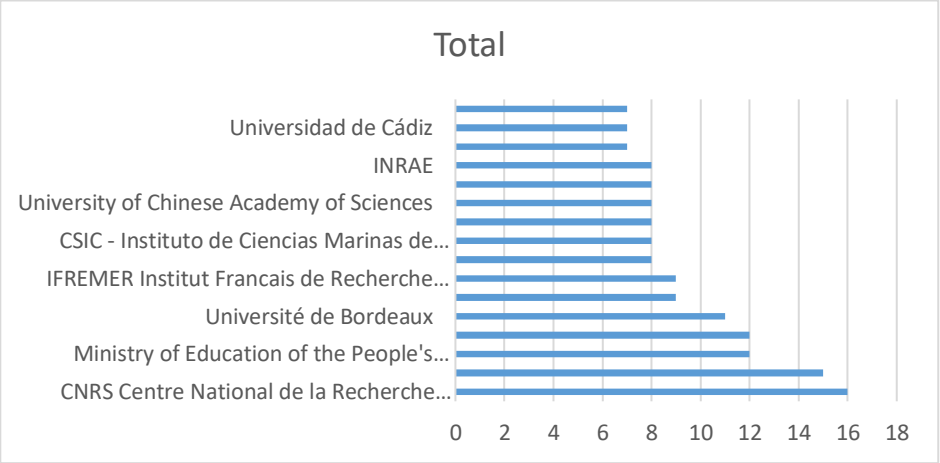

Fig. 2. Institutional affiliations contributing to heavy metal biomarker research in bivalves. The figure shows the distribution of publications among leading institutions, emphasizing the prominent contributions of European and East Asian research centers.

The dominance of French and Chinese institutions reflects not only strong research capacity, but also robust funding mechanisms and policy-driven monitoring frameworks. By contrast, institutions from tropical countries remain underrepresented, with most contributing only one or two publications over the past two decades. This limited institutional presence highlights the significant disparity in global research capacity. Strengthening collaboration between established institutions in Europe and Asia and biodiversity-rich but underrepresented nations such as Indonesia, the Philippines, and Kenya will be crucial for advancing biomarker applications in vulnerable tropical marine ecosystems.

3.3 Document types

The distribution of document types indicates that research on heavy metal biomarkers in bivalves was dominated by original research articles (n = 271; 87.7%) (**Fig. 3**). This prevalence reflects the empirical nature of the field, with most studies focusing on experimental investigations, field surveys, and laboratory analyses of the effects of pollutants on bivalves. The high proportion of primary research highlights strong evidence supporting biomarker applications in environmental monitoring.

This figure shows that review papers (n = 13; 4.2%) represent a smaller proportion, but play an important role in synthesizing knowledge, identifying gaps, and outlining future research directions. The presence of review articles suggests that the field has reached a level of maturity where scholars increasingly consolidate findings to guide subsequent investigations. However, the relatively low number also indicates that more systematic reviews and meta-analyses are needed to integrate the diverse findings across regions and species.

Conference proceedings (n = 10; 3.2%) contributed to the dissemination of the preliminary results, methodological innovations, and emerging research topics. While these publications are valuable for academic exchange, their limited number may reflect the challenges in sustaining research dissemination from tropical and developing countries, where conference participation is often constrained by funding.

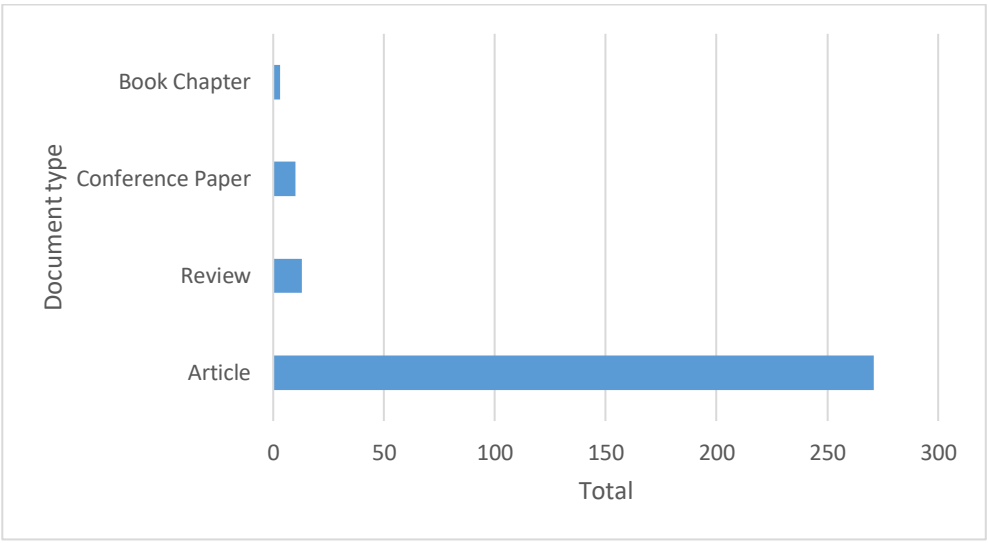

Fig. 3. Distribution of document types in heavy metal biomarker research on bivalves. The figure shows the relative contribution of different publication types, with original research articles representing the dominant form of scientific output.

Book chapters (n = 3, 1.0%) were identified in the dataset, offering broader theoretical perspectives and integrative discussions on marine pollution and biomarker science. Although few in number, these publications have provided conceptual frameworks that support the advancement of biomarker applications beyond empirical case studies.

Overall, the predominance of original research articles demonstrates the field's empirical strength. However, the relatively small number of reviews and book chapters highlights the opportunity for scholars, particularly from underrepresented regions, to contribute by conducting syntheses and meta-analyses. Such efforts would help bridge fragmented studies and provide global perspectives necessary for policy formulation and transboundary environmental management.

3.4 Country contributions

At the national level, research on heavy metal biomarkers in bivalves is heavily concentrated in developed nations. France (52 publications) leads the global output, largely driven by strong institutional hubs, such as CNRS and IFREMER, which have long-standing expertise in marine pollution monitoring. China (44 publications) ranks second, reflecting its rapid growth in marine ecotoxicology supported by substantial government investment in environmental research. Italy (29) and the United States (27) also demonstrated significant contributions, consistent with their strong traditions in marine biology and environmental toxicology (**Fig. 4**).

Among the emerging contributors, Tunisia (24 publications) stands out in North Africa, where heavy metal contamination is a pressing concern due to industrial activities and coastal urbanization. Southern European nations, such as Spain (22) and Portugal (17), also contribute notably, reflecting regional collaboration networks and shared research infrastructures. Outside Europe and Asia, Canada (15) and India (11) are active contributors, while Brazil (10) and the United Kingdom (10) demonstrate engagement from South America and Western Europe, respectively. Smaller but consistent contributions were also recorded from Australia and Russia (nine each), as well as from Algeria and Greece (seven each).

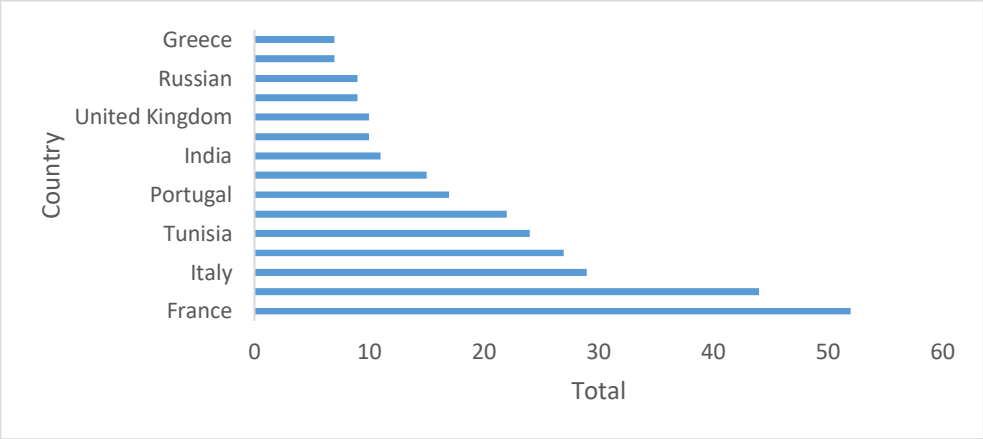

Fig. 4. Country-level contributions to heavy metal biomarker research in bivalves. The figure shows the distribution of publications by country, emphasizing the dominance of developed nations and the limited contributions from tropical regions.

Despite these global efforts, the overall contribution of tropical regions remains marginal. Of the 309 documents analyzed, fewer than 10% originated from tropical countries. Nations with exceptionally high marine biodiversity, such as Indonesia, the Philippines, Malaysia, and Kenya, have produced only one or two publications each over the past two decades. This disparity underscores a critical gap between regions that face the highest risks of heavy metal contamination and those that produce most of their scientific knowledge.

Several factors have contributed to this imbalance in research output across regions. Developed nations generally benefit from more advanced research infrastructure and greater funding availability, allowing sustained investment in marine ecotoxicology and biomarker-based studies. Furthermore, policy-driven environmental monitoring frameworks in Europe and East Asia often mandate routine pollutant assessments, which actively stimulate scientific research and publication. In contrast, many tropical countries remain poorly integrated into international collaboration networks, limiting their access to shared expertise, funding mechanisms, and large-scale research partnerships.

Addressing this inequality requires targeted funding schemes, capacity building, and stronger North–South collaboration. Enhancing the contributions of tropical countries is essential to ensure that global knowledge of biomarkers reflects the conditions of biodiversity hotspots that are most vulnerable to anthropogenic pressures.

3.5 Funding agencies

The analysis of funding sources underscores the pivotal role of national and international agencies in advancing research on heavy metal biomarkers in bivalves (**Fig. 5**). The National Natural Science Foundation of China (NSFC) emerged as the largest contributor, supporting 16 publications and highlighting China's strong governmental commitment to marine environmental sciences. In Europe, the Fundação para a Ciência e a Tecnologia (FCT, Portugal, 10 publications) and the European Regional Development Fund (ERDF, 7 publications) played central roles in fostering regional collaboration and prioritizing marine biodiversity and pollution control.

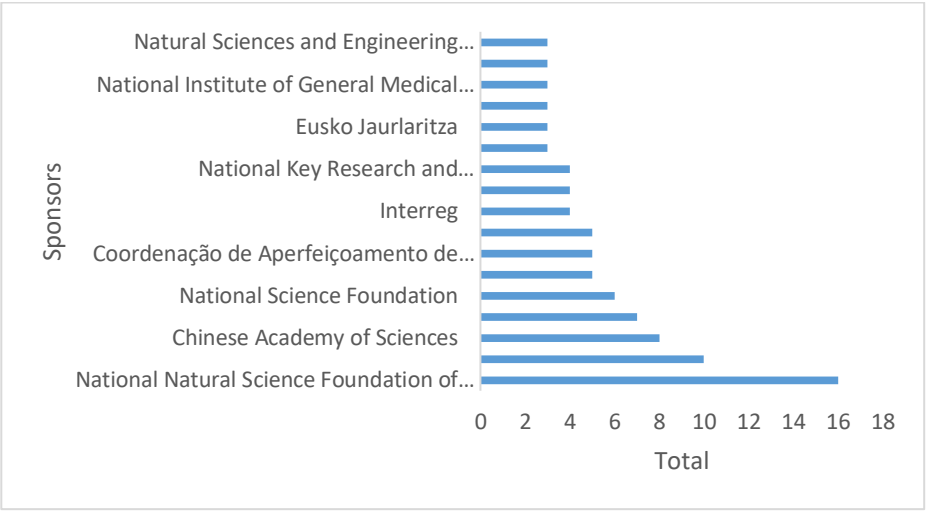

Fig. 5. Funding agencies supporting heavy metal biomarker research in bivalves. The figure shows the distribution of major funding sources, emphasizing the prominent contribution of agencies from China and Europe.

Additional major funding sources include the Chinese Academy of Sciences (CAS, eight publications) and the United States National Science Foundation (NSF, six publications), both of which reflect the importance of national-level agencies in sustaining ecotoxicological research. Brazil's CNPq and CAPES supported five publications in South America, signifying the country's growing involvement in marine biomonitoring. Contributions from international organizations, such as the European Commission (five publications) and Interreg (four publications), further emphasize the significance of cross-border funding in supporting marine environmental research.

Other contributors included the National Institute of Environmental Health Sciences (NIEHS, USA), National Key Research and Development Program of China, and Mexico's CONACYT, each supporting four publications. Several smaller agencies, including regional governments (e.g., Eusko Jaurlaritza, Spain), ministries of higher education in North Africa and the Middle East, and the National Institute of General Medical Sciences (NIGMS, USA), also provided important but less frequent support.

The dominance of Chinese and European funding agencies illustrates the concentration of financial investments in regions with well-developed research infrastructure and regulatory frameworks. Meanwhile, the absence of consistent funding mechanisms in tropical countries remains a significant barrier to expanding biomarker research in biodiversity hotspots, such as Southeast Asia and East Africa. This funding disparity reinforces global research imbalances; regions most vulnerable to pollution are the least represented in terms of financial support and scientific output.

Expanding funding opportunitiesthrough regional collaboration platforms, joint grants, and capacity-building initiativeswill be essential to empower tropical countries to contribute more substantially to global biomarker research. International agencies and donor organizations can play a strategic role in bridging this gap, ensuring that tropical ecosystems receive the scientific attention necessary to support sustainable management and conservation.

3.6 Leading authors

The author-level analysis identified several highly productive and influential scholars, whose work has shaped the field of heavy metal biomarker research in bivalves (**Table 1**). **Table 1** shows that some authors have a higher number of publications and citations than others. Mohamed Banni and Julián Blasco emerged as leading contributors, each with eight publications and citation counts of 410 and 423, respectively. Their work, particularly in North Africa and Southern Europe, has significantly advanced the understanding of biomarker applications for assessing marine pollution. Blasco's sustained impact is further reflected in his h-index of 53, which indicates a broad influence across ecotoxicology and biomarker science. Other prominent figures include Maria João Bebianno (seven publications, 548 citations, h-index 59), whose extensive research in Portugal has provided foundational insights into biomarker responses and ecotoxicological risk assessments. Jean Claude Amiard (seven publications, 458 citations, h-index 49) has also contributed to theoretical and empirical advancements in marine biomonitoring.

Table 1. Leading authors in heavy metal biomarker research on bivalves. The table summarizes the most productive authors and their bibliometric indicators, reflecting their scientific impact in this research area.

Author	Document	Citation	Total Document	Total Citation	h-index
Banni, Mohamed	8	410	144	5702	46
Blasco, Julián	8	423	249	9244	53
Bebianno, Maria João	7	548	219	11422	59
Churlaud, Carine	7	125	51	1674	25
Geffard, Alain	7	363	140	3478	33
Amiard, Jean Claude	7	458	148	72222	49
Boussetta, Hamadi	6	327	55	2325	34
Breitwieser, Marine Paomia	6	113	14	207	8
Huet, Valérie	6	123	33	822	17
Meng, Fanping	6	191	97	1653	22

Mid-level contributors such as Carine Churlaud and Alain Geffard (7 publications each, with 125 and 363 citations, respectively) represent a younger generation of researchers who maintain strong engagement in marine ecotoxicology. Meanwhile, Hamadi Boussetta (6 publications, 327 citations) and Fanping Meng (6 publications, 191 citations) have expanded biomarker research in Tunisia and China, respectively—regions increasingly recognized for their contributions. Notably, Marine Paomia Breitwieser (6 publications, 113 citations) and Valérie Huet (6 publications, 123 citations) illustrate growing female leadership in the field, particularly within European research consortia.

Overall, bibliometric evidence demonstrates that the field is shaped by a relatively small group of highly cited authors, predominantly based in Europe. Collectively, these individuals have built a strong empirical and theoretical foundation for biomarker applications, reinforcing the role of bivalves as sentinel organisms in marine pollution monitoring. However, the lack of influential authors in tropical countries has highlighted a critical gap. Encouraging the development of early career researchers and fostering international mentorship programs could help to diversify the geographic distribution of intellectual leadership in this field.

3.7 Keyword co-occurrence analysis

Fig. 6 presents the keyword co-occurrence map generated using VOSviewer, providing an overview of the thematic structures that define research on heavy metal biomarkers in bivalves. The analysis identified four main clusters, each representing a distinct yet interconnected research theme. The red cluster corresponds to environmental monitoring and bioaccumulation and forms the core of the field, with central keywords such as environmental monitoring, pollution, toxicity, bivalves, metallothionein, and bioaccumulation. These terms emphasize the fundamental role of bivalves as sentinel organisms for assessing heavy metal contamination and ecosystem health, while the frequent occurrence of metallothionein highlights its widespread application as a biomarker of metal exposure.

The green cluster represents pollutant-specific chemical analyses and includes keywords such as cadmium, zinc, chromium, biochemistry, and risk assessment. Studies within this cluster primarily focus on quantifying individual heavy metals in bivalve tissues and linking their concentrations to ecological or toxicological risks, with the dominance of Cd and Zn reflecting their common occurrence in industrial effluents and coastal pollution sources. The blue cluster is characterized by molecular and cellular response keywords, including oxidative stress, metabolism, gene expression, proteins, and antioxidants. This cluster illustrates the increasing emphasis on mechanistic approaches that employ molecular and biochemical biomarkers to elucidate the physiological effects of heavy metal exposure, reflecting the integration of omics-based methodologies such as transcriptomics, proteomics, and metabolomics into biomarker research [4,10]. Finally, the yellow cluster represents broader ecological and organic pollutant contexts, linking heavy metals with co-occurring contaminants such as polycyclic aromatic hydrocarbons (PAHs), sediments, coastal waters, and environmental pollutants. This pattern suggests a growing recognition of multiple-stressor interactions in coastal ecosystems, which is essential for developing more realistic ecological risk assessments**.**

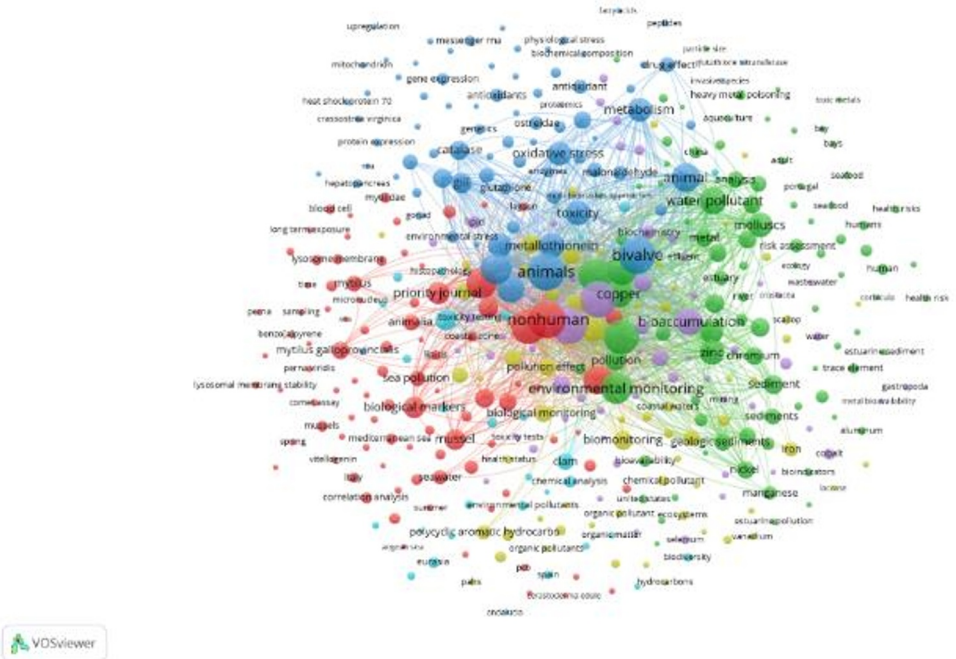

Fig. 6. Keyword co-occurrence network in heavy metal biomarker research on bivalves. The figure shows the main thematic clusters derived from keyword co-occurrence analysis, highlighting dominant research themes in the field.

Overall, the keyword network highlighted the maturity and evolving directions of the field. Central terms, such as pollution, toxicity, and bivalves, reflect the well-established foundations of biomarker-based monitoring. Simultaneously, the relatively sparse occurrence of terms related to emerging contaminants, such as microplastics, pharmaceuticals, and nanoparticles, indicates underexplored areas that represent promising opportunities for future research.

Bridging the gap between ecological monitoring and molecular approaches while expanding to include emerging pollutants will be critical for strengthening the role of bivalve biomarkers in global environmental management.

3.8 Tropical region analysis

Of the 309 publications analyzed, only 25 (approximately 8%) specifically addressed heavy metal biomarkers in bivalves within tropical regions, as shown in **Fig. 7**. This proportion highlights the significant underrepresentation of tropical ecosystems in the global literature despite their exceptionally high biodiversity and vulnerability to anthropogenic pressures.

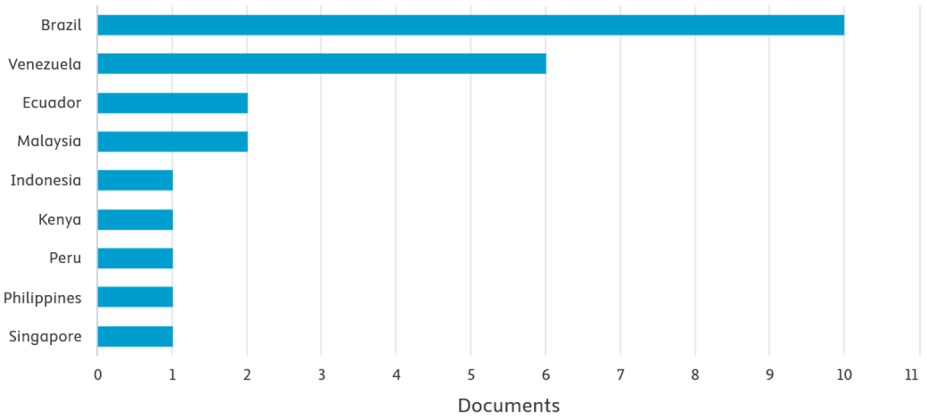

Fig. 7. Publications on heavy metal biomarker research in bivalves by country. The figure shows the distribution of publications by country, emphasizing the low contribution from tropical regions.

At the country level, Brazil led with 10 publications, followed by Venezuela with six. Both countries have focused on the impacts of industrial discharge, mining activities, and coastal urbanization on local bivalve populations. Ecuador and Malaysia contributed two publications each, whereas Indonesia, Kenya, Peru, the Philippines, and Singapore produced only one publication each across the entire 25-year period. This distribution underscores the limited research capacity in Southeast Asia and Africa, regions that are simultaneously biodiversity hotspots and are highly exposed to pollution.

The temporal trend showed a slow start, with fewer than one publication annually from 2000 to 2010. Research activity gradually increased after 2012, with a more consistent upward trajectory from 2016 onwards. A peak was recorded in 2020 and 2022 (three publications each year), suggesting growing but modest engagement of tropical countries in the global research landscape (**Fig. 8**).

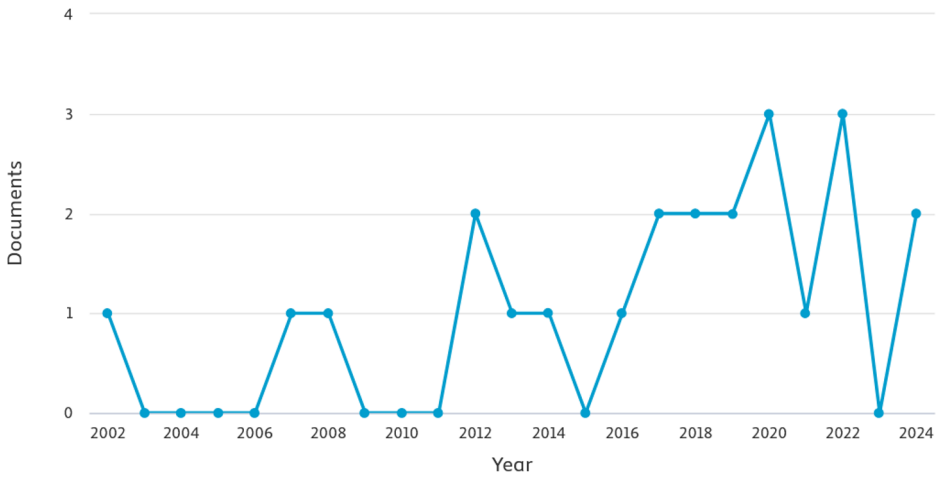

Fig. 8. Annual publications on heavy metal biomarker research in bivalves from tropical regions. The figure shows year-by-year publication output, highlighting a gradual increase over time.

Keyword network analysis is a critical component of this study because it provides an empirical foundation for understanding how research on heavy metal biomarkers in tropical regions is structured and where major knowledge gaps persist (**Fig. 9**). By revealing three dominant clusters, heavy metal contamination and biomonitoring, biomarker applications and biological responses, and metabolic changes with human health implications, the analysis clarifies the thematic landscape that has guided tropical ecotoxicology research to date.

Keyword network analysis of tropical studies revealed three major thematic clusters that characterize the current research focus in these regions. The first cluster is associated with heavy metal contamination and biomonitoring, emphasizing lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) as dominant pollutants commonly assessed in tropical coastal environments. The second cluster highlights biomarker applications and biological responses, with particular emphasis on the role of bivalves in metal bioaccumulation and the evaluation of organism health. The third cluster relates to metabolic changes and human health risks, linking aquatic pollution to broader ecotoxicological processes and potential public health implications.

Central hubs, such as heavy metals, biomarkers, pollution, and bivalves, confirm their reliance on these organisms as sentinel species. However, the relative absence of keywords associated with emerging contaminants (e.g., pharmaceuticals, microplastics, and nanomaterials) indicates research domains that remain largely underexplored in tropical contexts.

The findings reveal three critical implications for research on heavy metal biomarkers in tropical regions. First, significant scientific gaps persist, resulting in limited understanding of pollution dynamics in ecosystems that are among the most diverse and environmentally vulnerable. Second, a clear capacity gap, characterized by limited laboratory infrastructure, research funding, and international collaboration, continues to constrain scientific output from tropical countries. Third, a policy gap remains evident, as the scarcity of tropical-focused biomarker studies reduces the availability of robust scientific evidence to support environmental management and seafood safety decision-making.

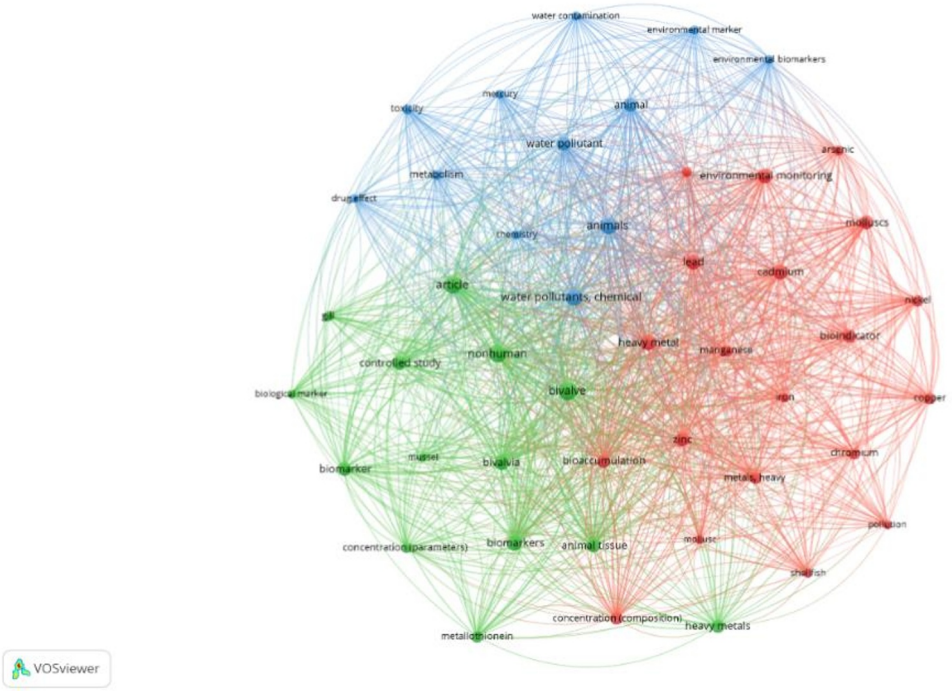

Fig. 9. Keyword network of heavy metal biomarker studies in tropical regions. This figure presents the keyword co-occurrence network derived from studies conducted in tropical regions, illustrating the main thematic clusters and research focus areas. The network highlights dominant themes related to heavy metal contamination, biomarker applications, and biological responses, while indicating limited coverage of emerging research topics.

Addressing these challenges requires targeted and coordinated strategies. Strengthening international collaborations between well-established institutions in Europe and Asia and research centers in tropical regions is essential to facilitate knowledge exchange and capacity building. In addition, expanding regional and international funding schemes would support ecotoxicological research in biodiversity hotspots. Furthermore, sustained training and mentoring of early career researchers from tropical countries are crucial for developing a new generation of contributors to this field. By addressing these scientific, capacity, and policy gaps, tropical nations, particularly Indonesia, can assume a more prominent role in advancing global research on heavy metal biomarkers in bivalves and contribute more effectively to the sustainable management of marine ecosystems.

4 Conclusion

This bibliometric analysis provides a systematic synthesis of global research on heavy metal biomarkers in bivalves conducted between 2000 and 2025 and yields several key insights into the development of this field. The results demonstrate a steady growth in research output, particularly after 2010, with publications peaking in 2020, reflecting increasing global concern over marine pollution and the expanding role of biomarkers in environmental monitoring. Research activity is strongly geographically concentrated, with France, China, and Italy emerging as the dominant contributors due to robust institutional capacity and sustained funding mechanisms, while tropical countries remain severely underrepresented. Keyword mapping reveals substantial thematic diversity, with four major clusters

encompassing environmental monitoring, pollutant-specific analyses, molecular and biochemical responses, and co-occurring contaminants; however, emerging pollutants such as microplastics and pharmaceuticals remain largely unexplored. The intellectual landscape of the field is shaped by a relatively small group of highly cited authors and institutions, predominantly based in Europe, underscoring the need for broader participation from underrepresented regions. Notably, only 8% of the analyzed studies were conducted in tropical ecosystems, with Indonesia contributing just a single publication, despite its status as a global marine biodiversity hotspot.

Overall, this study confirms the pivotal role of bivalves as bioindicators of heavy metal pollution while emphasizing the urgent need to expand biomarker research in tropical ecosystems. Future progress will depend on strengthening international collaborations, enhancing local research capacity, and integrating advanced technologies into biomonitoring. Such initiatives are essential for developing evidence-based strategies to safeguard marine biodiversity, ensure seafood safety, and support sustainable coastal management in the face of increasing anthropogenic pressure.

References

1. H.A. El-Serehy, H.A. Aboulela, F. Al-Misned, M. Kaiser, K.A.S. Al-Rasheid, H.E. El-Din, Turk. Heavy metals contamination of a Mediterranean coastal ecosystem, Eastern Nile Delta, Egypt. J. Fish. Aquat. Sci., **12**, 747–753 (2012). https://doi.org/10.4194/1303-2712-v12_4_03
2. P.K. Krishnakumar, M.A. Qurban, G. Sasikumar, in Trace elements - human health and environment (IntechOpen, London, 2018). https://doi.org/10.5772/intechopen.76938
3. B.S. Halpern, S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. d'Agrosa, R. Watson, A global map of human impact on marine ecosystems. Science. **319**, 948–952 (2008). https://doi.org/10.1126/science.1149345
4. H. Wu, W. Wang, Tissue-spesific toxicological effects of cadimum in green mussels (*Perna viridis*): nuclear magnetic resonance-based metabolomics study. Environ. Toxicol. Chem. **30**, 806–812 (2011). https://doi.org/10.1002/etc.446
5. M. Breitwieser, A. Viricel, M. Graber, L. Murillo, V. Becquet, C. Churlaud, H. Thomas, Short-term and long-term biological effects of chronic chemical contamination on natural populations of a marine bivalve. PLoS One. **11**, e0150184 (2016). https://doi.org/10.1371/journal.pone.0150184
6. A. Sarkar, D. Ray, A.N. Shrivastava, S. Sarker, Molecular biomarkers: their significance and application in marine pollution monitoring. Ecotoxicology. **15**, 333–340 (2006). https://doi.org/10.1007/s10646-006-0069-1
7. J.W.M. Wijsman, K. Troost, J. Fang, A. Roncarati, Global production of marine bivalves. Trends and challenges, in A.C. Smaal, J.G. Ferreira, J. Grant, J.K. Petersen, Ø. Strand (eds.), Goods and services of marine bivalves, Springer, pp. 7–26 (2018). https://doi.org/10.1007/978-3-319-96776-9_2
8. P.T.Y. Leung, T.J. Park, Y. Wang, C.M. Che, K.M.Y. Leung, Isoform-spesific responses of metallothioneins in a marine pollution biomonitor, the green-lipped mussel *Perna viridis*, toward different stress stimulations. Proteomics. **14**, 1796–1807 (2014). https://doi.org/10.1002/pmic.201300439
9. M.G. Lionetto, R. Caricato, M.E. Giordano, Pollution biomarkers in the framework of marine biodiversity conservation: state of art and perspectives. Water. **13**, 1847 (2021). https://doi.org/10.3390/w13131847

10. B. Duarte, E. Feijão, R.C. Carvalho, I.A. Duarte, A.P. Marques, M. Maia, J. Hertzog, A.R. Matos, M.T. Cabrita, I. Cacador, A. Figueiredo, M.S. Silva, C. Cordeiro, V.F. Fonseca, Untargeted metabolomics reveals antidepressant effects in a marine photosynthetic organism: the diatom *Phaeodactylum tricornutun* as a case study. Biology. **11**, 1770 (2022). https://doi.org/10.3390/biology11121770
11. J. Gao, Y. Yin, K.R. Myers, K.R. Lakhani, D. Wang, Potentially long-lasting effects of the pandemic scientist. Nat. Commun. **12**, 6188 (2021). https://doi.org/10.1038/s41467-021-26428-z