

Bioindicator Trends in Studying Environmental Pollution: A Systematic Review

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Abstract

Scientists, government agencies, and the public are keenly interested in evaluating ecosystem health. As a result, there has been an increase in research investigating the efficacy of various bioindicators as markers of environmental pollutants. This article presents a review of bioindicators from 2013-2023 indexed by Scopus. The overall aim is to examine temporal trends in publications regarding bioindicators, contaminants of concern, species used as bioindicators, and potential future research. By entering the terms "bioindicators, environmental pollution, and environmental literature" into the search menu of the Scopus database, we obtained a total of 136 articles. After applying our criteria, we narrowed down our research to only 31 articles. We used the PRISMA framework for inclusion and exclusion purposes. Our SLR results showed that the most studied environmental pollution was air and freshwater pollution. The dominant keywords used in this study were bioindicators, animals, environmental monitoring and biomonitoring. The most studied country for bioindicators of environmental pollution is Italy. The most studied pollution is heavy metal and chemical pollution. The most used bioindicator organisms are invertebrates and plants, while the least used are algae or diatoms. Future research on potential bioindicators includes the application of diatoms in water quality assessment, the relationship between bioindicator monitoring and its impact on communities, interspecies comparisons to identify the most effective indicators, and studies on the level of understanding and skills of communities in the use of bioindicator organisms. Overall, this review serves as a comprehensive reference for the development of research and application of bioindicators in environmental monitoring.

Keywords: Bioindicators; Trends; Environmental Pollution; Systematic Review

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INTRODUCTION

Environmental pollution is a serious global challenge (Liu et al., 2019; Yadav et al., 2021), posing increasing threats to ecosystem balance and public health through the accumulation of pollutants such as heavy metals, microplastics, and persistent organic compounds (Zhu et al., 2023; Chen et al., 2024). The WHO estimates that more than two million premature deaths per year are caused by pollution (WHO, 2021). Furthermore, globally pollution-related deaths account for 23% of all deaths each year (Ngwenya et al., 2024). Industrial development and urban expansion have significantly increased pollutant levels originating from sources such as wastewater discharge, vehicular emissions, and agricultural runoff (Strokal et al., 2021; Thompson

and Darwish, 2019). Traditional monitoring methods that rely on physicochemical analysis are accurate but do not always reflect the biological impact of pollutants (Kumari & Khare, 2018). Given these challenges, there is a growing need for more holistic and innovative monitoring strategies, such as bioindicators (Parmar, 2016).

Pollution monitoring mechanisms are essential to effective environmental management and remediation. Although physicochemical methods are widely used, they present several limitations, including high operational costs, the requirement for sophisticated infrastructure, and restricted ability to capture biological impacts or long-term ecological changes (Hamzah, 2014; Madheshiya et al., 2022; Dong et al., 2022). In contrast, bioindicators offer multiple advantages: they are cost-effective, can detect sublethal and cumulative effects, and reflect ecosystem-level responses. For instance, diatoms and lichens have demonstrated utility in signaling early signs of water and air pollution early warnings that conventional methods often miss (Ghannem et al., 2018; Chowdhury et al., 2023). Consequently, there has been increasing advocacy for integrating biological monitoring tools to complement and enhance traditional techniques (Asif et al., 2018).

To fully leverage these advantages, it is necessary to clearly define what constitutes a bioindicator and how these organism functions across varying pollution contexts. Bioindicators are organisms or biological responses that provide information about environmental health and pollutant presence (Chowdhury et al., 2023). They act as natural sensors, responding to environmental changes in observable and quantifiable ways (Ghannem et al., 2018). Bioindicators are highly diverse, ranging from enzyme activity in microbes, metal accumulation in plant tissues, to behavioral alterations in animals (Caro, 2016; Dubey et al., 2022; Rajamanickam et al., 2021). However, despite their growing use, there remains limited synthesis regarding which types of environmental contaminants are commonly targeted and how specific bioindicators are selected and applied across different studies. This gap calls for a comprehensive evaluation of both the pollutant types addressed and the biological agents involved.

In response to this need, recent years have witnessed a surge in bioindicator research that embraces molecular and omics-based innovations (Vallaeyes et al., 2017). Advanced genomic, proteomic, and metabolomic tools have been increasingly employed to unravel bioindicator response mechanisms at the cellular and molecular levels. Improved high-capacity screening methods have facilitated the discovery of new pollution bioindicators and biomarkers (Shen et al., 2016; De Sousa et al., 2018; Katar et al., 2023). Additionally, there is an increasing trend to use bioindicators in urban ecological assessment, reflecting the expansion of the scope of environmental monitoring (Zukal et al., 2015; Jakop et al., 2024; Yorkina et al., 2016). This development marks a paradigm shift towards more sensitive bioindicator based assessments. Accordingly, this systematic review aims to (1) identify publication trends related to the use of bioindicators over the past decade, (2) examine the types of contaminants assessed through bioindicators, and (3) explore emerging patterns in the selection and application of bioindicators in environmental pollution studies.

Numerous systematic literature reviews have been conducted. However, research tends to focus on individual pollutants or specific organisms; few reviews provide a broad synthesis of bioindicators across different pollutant types and environmental contexts. According to a search on Google Scholar, only three

publications were found that systematically reviewed bioindicators in the context of environmental contamination. These studies discuss the concept of bioindicators as natural indicators of pollution (Parmar et al., 2016), provide a historical review from 1970 to 2005 (Burger, 2006), and explore the development and use of bioindicators in ecological assessment (Burger, 2006). However, no recent review has comprehensively examined how bioindicators have been utilized in pollution-related research over the last ten years. This reinforces the relevance of conducting a review that aligns with the three research questions: (1) trends in publication, (2) targeted pollutants, and (3) bioindicator usage patterns. This review is crucial for researchers aiming to use bioindicators as central elements in environmental assessment and offers insights for directing future funding, research, and policy attention, especially toward underrepresented species and pollutant types, thus reinforcing the global relevance and applicability of bioindicator, based monitoring.

METHOD

A Systematic Literature Review (SLR) is a structured and rigorous method used to identify, evaluate, and synthesize all relevant literature to address a specific research question (Snyder, 2019; Xiao & Watson, 2019). This study adopts the SLR approach following the five-step framework proposed by Denyer and Tranfield (2009), as illustrated in Figure 1. This framework has been widely applied in previous SLR-based studies. Furthermore, the design and execution of this review adhere to the key methodological principles highlighted by Han et al. (2020), ensuring transparency, replicability, and analytical rigor.

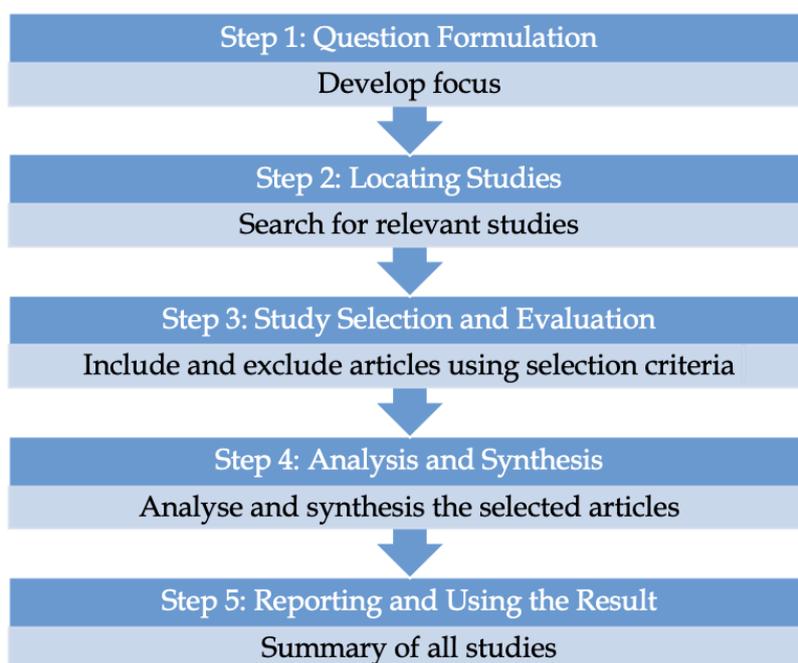


Figure 1. The SLR process consists of five steps, as modified from Denyer and Tranfield's (2009) framework by Han et al. (2020)

Step 1: Question Formulation

The first step is to determine the scope of the research. The following questions are proposed and attempted to be answered by this research (from 2013 to 2023). The selected research focus is as follows: RQ1: What is the trend of publication of

bioindicators to determine environmental pollution over the last ten years? RQ2: Which contaminants are most commonly identified using bioindicators?; RQ3: What are the trends in bioindicators used to determine environmental pollution?

Step 2: Locating Studies

The second phase of the systematic literature review is to identify, select, evaluate, and catalog the main contributions related to the review question. The objective of this study is to utilize bioindicators to assess environmental contamination. Articles were obtained by conducting a search using a Scopus account. Scopus was chosen due to its broad multidisciplinary coverage and strong reputation for indexing high-quality scientific articles (Gusenbauer & Haddaway, 2020). The search was limited to articles published between 2013 and 2023. The keywords used were “bioindicators,” “environmental literature,” and “environmental pollution.” The data obtained were saved in CSV and RIS formats and then stored in Mendeley Reference Manager. The VOS-viewer software was then used for visual display. This database was chosen due to its accessibility in academic institutions and its use in previous similar research. The literature articles generated from the keyword search were analyzed to conduct a backward search. Additional sources from specific study references were analyzed to continue the investigation. No additional research was found during this process.

Step 3: Study Selection and Evaluation

At this stage, a structured selection process was carried out to ensure that the studies included in the review were relevant, high-quality, and aligned with the research objectives. The inclusion criteria consisted of four main points: (1) the article must be indexed in Scopus and published between 2013 and 2023; (2) it must address topics related to bioindicators and environmental pollution; (3) it must be written in English; and (4) it must contain the specified keywords. To ensure transparency, this process was divided into four filtering phases, as illustrated in Figure 2. In the first phase, a total of 136 records retrieved through keyword searches were screened based on titles and abstracts. Articles that did not explicitly mention bioindicators, environmental monitoring, or pollution-related themes were excluded. In the second phase, articles were filtered by Scopus subject categories. Only those under environmental science, agricultural and biological sciences, biochemistry, genetics, and molecular biology were retained, resulting in 120 eligible articles. The third phase involved excluding 44 non-English articles—such as those written in Spanish, Chinese, Hungarian, and Polish—resulting in 76 remaining studies. In the fourth phase, a full-text assessment was conducted to determine the degree of alignment with the review’s thematic focus. This step evaluated whether each article (i) explicitly discussed the application of bioindicators in assessing environmental pollution and (ii) contributed either empirically or conceptually to the field. Articles that failed to meet these conditions were removed. Ultimately, 31 articles were selected for synthesis and further analysis.

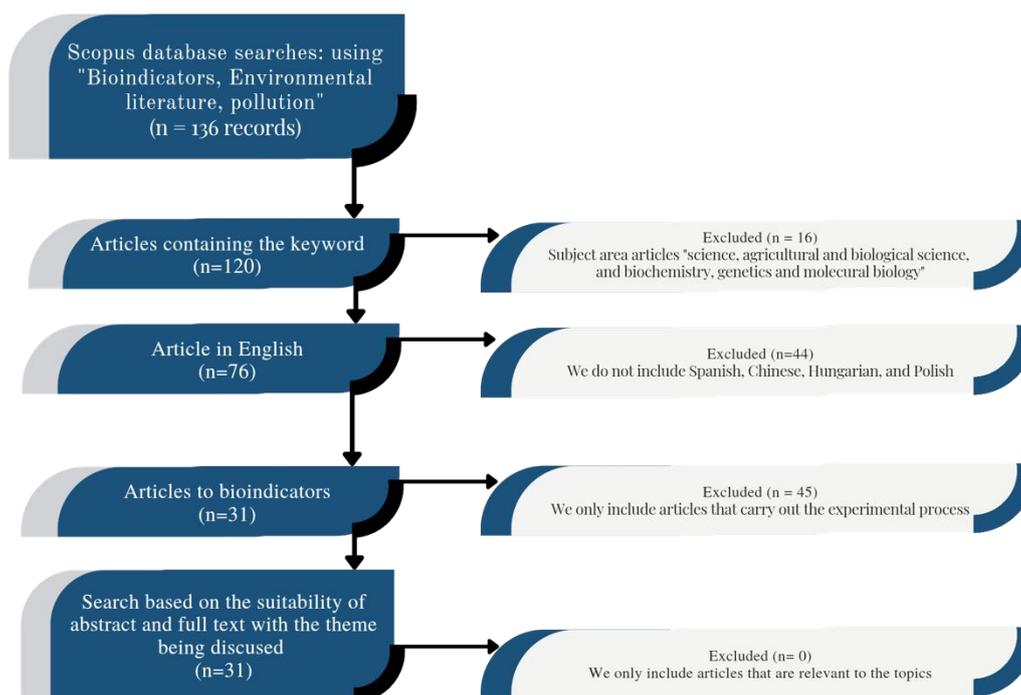


Figure 2. Review process for study selection

Step 4: Analysis and Synthesis

In this phase, the selected articles were thoroughly examined to identify key patterns, themes, and trends related to the use of bioindicators for environmental pollution monitoring. The analysis focused on publication trends, targeted contaminants, and the types of bioindicators employed. Articles were categorized according to their research focus and were synthesized based on thematic similarities. The synthesized data were tabulated and visualized using descriptive statistics and thematic mapping to enhance interpretation and clarity. This approach facilitated the identification of both knowledge gaps and emerging trends in the field.

Step 5: Reporting and Using the Result

As shown in Figure 1, the final step involved reporting and summarizing the synthesized findings to answer the research questions. The results were compiled into a structured narrative that discusses the overall trends in bioindicator research over the past decade. The findings highlight prevalent contaminants monitored using bioindicators, and commonly used organisms. This comprehensive summary provides valuable insights for researchers and practitioners in environmental science and policy, paving the way for future research directions and improved applications of bioindicators.

Ethical Considerations

This review relies solely on secondary data from publicly available sources and does not involve any human or animal subjects. We note that no original data were gathered for this work. All information was obtained from peer-reviewed articles, databases, and other publicly accessible literature. Stating this promotes transparency in our methods and adheres to sound research practices.

RESULTS AND DISCUSSION

Bioindicators Publication Trend For 1 Decade

Publication trends (presentation of published articles) in the last ten years (2013-2023) are presented in Figure 3. Trends in Bioindicator Research on Pollution (2013-2023) Figure 3 shows the distribution of publications related to different types of environmental pollution using bioindicators from 2013 to 2023. Air pollution occupies the highest position with a proportion of 38%, followed by freshwater pollution at 27% of the total publications. The dominance of the topic of air pollution reflects its urgency as a global issue, especially due to its direct impact on human health, such as respiratory disorders and cardiovascular diseases (Knippertz et al., 2015; Kinney, 2018). In addition, the high use of sensitive bioindicator organisms such as lichens and aquatic plants that are easy to observe is driving the growth of studies on this theme (Godzik et al., 2020; Michel et al., 2024; Varela et al., 2023). This trend is also in line with the increasing global awareness of the role of air pollution in climate change and public health (Orru et al., 2017; Nakazato et al., 2018; Lam et al., 2022). Meanwhile, the large number of publications addressing bioindicators in the context of freshwater pollution is inseparable from their proximity to people's lives and their vital role as the main source of water for domestic, agricultural and industrial purposes (Vasistha et al., 2021; Bawra & Pawar, 2023). The proximity of these ecosystems to human activities makes them more vulnerable to pollution, prompting the need for continuous water quality monitoring (Nguyen et al., 2023; Zhu et al., 2023).

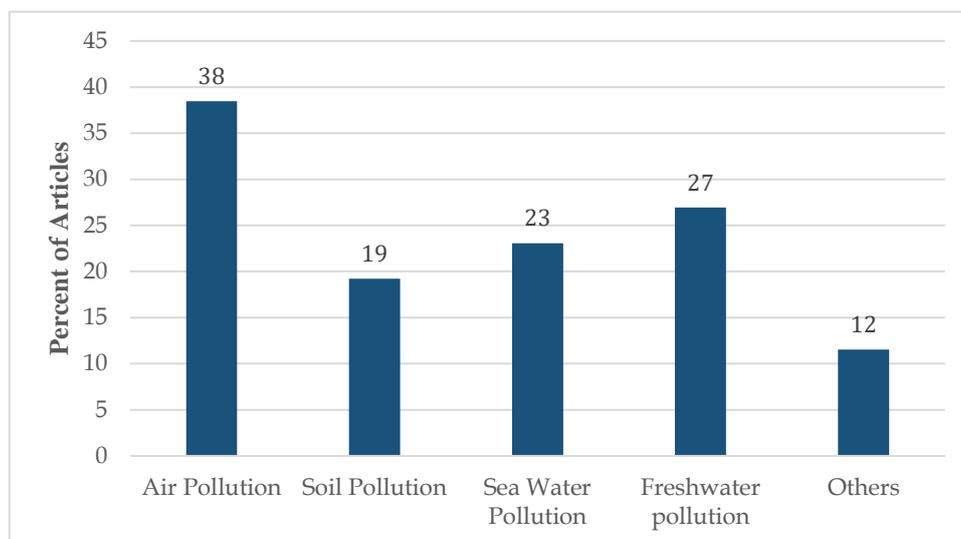


Figure 3. Research Trends in Bioindicators of Pollution (2013-2023)

On the other hand, marine (23%) and soil (19%) pollution. The lower number of publications on marine and soil pollution is likely due to the complexity and longer time involved in developing effective bioindicators in these media. This finding is in line with Pillet et al. (2021), who stated that the development of bioindicators in marine and soil environments still faces various technical and methodological obstacles. Bioindicator development in the ocean has a major challenge, namely heterogeneity and high physico-chemical dynamics, which complicate the consistency of bioindicator responses (Areco et al., 2021; Lyons et al., 2010). As for soil media, matrix complexity and high spatial variation make it more difficult to evaluate contaminants and their impacts (Ghannem et al., 2024; Kim et al., 2024).

represents about 8.2% of the total 193 countries in the world. Italy ranked highest with the most number of publications (7 articles). Italy's dominance in this field can be attributed to its long tradition in scientific research, particularly in the fields of environmental and biomedical sciences. Historical institutions such as the Istituto Superiore di Sanità (ISS), under the leadership of prominent scientists such as Domenico Marotta, have become major research centers and helped shape the academic culture in Italy (Cozzoli et al., 2011; Lusito, 2021). This scientific heritage supports the emergence of an active research community in the field of bioindicators. Moreover, the strong integration of Italian research institutions into international collaboration networks fosters knowledge exchange across countries, increasing scientific productivity and visibility (Di Bernardino et al., 2022; Brandi & Carbara, 2004). Furthermore, government support through strategic programs such as the National Research Program and the creation of technology districts has strengthened national research capacity (Zorzoliu, 2012; Richiedei & Pezzagno, 2022). The use of bioindicators is also increasingly encouraged in environmental policy-making and legislation programs (Kienzl et al., 2003), making Italy one of the centers of bioindicator research development.

Table 1. Nationality and continent of authors regarding the use of bioindicators in environmental pollution

Country	Continent	n
Italia	Europe	7
United State	North America	4
Poland	Europe	3
Spain	Europe	2
Croatia	Europe	2
Mexico	North America	2
India	Asia	2
Egypt	North Africa	1
Kosovo	Europe	1
United Kingdom	Europe	1
Germany	Europe	1
Brazil	South America	1
Argentina	South America	1
New Caledonia	Oceania	1
Curacao	South America	1
Turkiye	Europe	1

Contaminant Trends in Bioindicator Use

Table 2 shows that heavy metals and chemical contaminants have been the dominant focus in bioindicator research over the past decade, each appearing in 12 articles. This pattern reflects the substantial impact of these two pollutant groups on the environment and human health. These findings align with work by Cuschieri et al. (2023) and Panghal et al. (2024), which report that bioindicators are used to detect both the presence and biological effects of heavy metals and hazardous chemicals; these substances can accumulate in organism tissues and lead to physiological disruptions or ecosystem damage. Moreover, heavy metals in particular cannot be

biologically degraded and can transfer through the food chain up to humans (Ebrahimi et al., 2020; Parida & Patel, 2023). Such accumulation may result in organ damage, metabolic disturbances, oxidative stress, and DNA damage (Mitra et al., 2022). The high frequency of studies using bioindicators to detect heavy metal pollutants and chemical contaminants is also driven by increasing industrial activity, mining, urbanization, and the use of pesticides and other harmful chemicals in community environments (Huang et al., 2018; Akansha et al., 2024). Researchers are concerned about the long-term implications for public health and ecosystem quality.

Table 2. Contaminant Group

Contaminant Group	Number	References
Heavy metal	12	(Borghesi et al., 2017; Silici et al., 2016; Govers et al., 2014; Skibniewska & Skibniewski, 2023; Hédouin, L et al., 2016; Squadrone et al., 2019; Comess et al., 2021; Breidenbach et al., 2023; Brasso et al., 2020; Skorbiłowicz et al., 2018; Khalil et al., 2017; Gago-Tinoco)
Chemical contaminant	12	(Pizzolotto et al., 2018; Tripathi & Nema, 2023; Guerranti et al., 2017; Raghu, 2015; DeMille et al., 2023; Caro-Borrero et al., 2021; Arias et al., 2022; Bęś et al., 2019; de Souza et al., 2023; Salmaso et al., 2019; Venkatachalapathy et al., 2015; Valon et al., 2023)
Microplastic	3	(Valente et al., 2022; Savage, et al., 2022; Celis-Hernández et al., 2021)
General Pollutant	2	(Mifsud, 2014; Bzzi et al., 2023)
Radioactive Radiation	2	(Babić et al., 2020; Herceg et al., 2016)

Contaminant Trends in Bioindicator Use

Invertebrates are the most widely used bioindicator type in environmental pollution monitoring studies, as reflected in the 15 articles that used them (Table 3). Some examples of invertebrates used as bioindicators in the analyzed studies include odonates (Bazzi et al., 2023), the bumblebee *Bombus terrestris* (Breidenbach et al., 2023), and marine sponges (Celis-Hernández et al., 2021). The widespread use of invertebrates is driven by their high sensitivity to pollutants, flexibility of application across a wide range of systems, both terrestrial and aquatic, and the availability of diverse methodological approaches to assess ecosystem condition (Dvoretzky & Dvoretzky, 2023; Andújar et al., 2018). Furthermore, invertebrates are easy to collect and have short life cycles, making them suitable for periodic environmental monitoring and detecting short-term changes (Bonada et al., 2006; Borges et al., 2021). In addition, these organisms are also favored for their ease of sampling and ability to

generate representative data on ecosystem health status (Parikh et al., 2021; Sumudumali et al., 2021).

Table 3. Type of Bioindicator

Type of Bioindicator	Number	References
Invertebrata	15	Pizzolotto et al., 2018; Silici et al., 2016; Guerranti et al., 2107; Babić et al., 2020; Govers et al., 2014; Bazzi et al., 2023; Hédouin et al., 2016; Caro-Borrero et al., 2021; Arias et al., 2022; de Souza et al., 2023; Breidenbach et al., 2023; Savage et al., 2022; Skorbiłowicz et al., 2018; Celis-Hernández et al., 2021; Gago-Tinoco et al., 2014)
Plants	11	Tripathi et al., 2023; Babić et al., 2020; Guerranti et al., 2107; DeMille et al., 2013; Caro-Borrero et al., 2021; Beş et al., 2019; Comess et al., 2021; de Souza et al., 2023; Herceg et al., 2016; Salmaso et al., 2019; Venkatachalapathy et al., 2015
Vertebrata	5	de Souza et al., 2023; Valente et al., 2022; Valon et al., 2013; Khalil et al., 2017; Mifsud, 2017
Mamalia	5	Raghu, 2015; Borghesi et al., 2017; Skibniewska et al., 2023; Squadrone et al., 2019; Brasso et al., 2020
Alga/Diatom	2	Salmaso et al., 2019; Venkatachalapathy et al., 2015

In second place, plants were used as bioindicators in 11 articles. Some of the species used include *Ficus benghalensis* L. (Tripathi et al., 2023), the moss *Hypnum cupressiforme* (Babić et al., 2020), and *Festuca arundinacea* (DeMille et al., 2023). The high utilization of plants as bioindicators is due to their sedentary ecological characteristics and ability to photosynthesize. This is in line with previous findings showing that plants, being sedentary, are able to reflect local environmental conditions consistently over time (Sevik et al., 2020; Cen, 2015). In addition, their intensive interaction with the environment through photosynthesis, which involves the absorption of carbon dioxide and the release of oxygen, makes plants a natural indicator of air quality (Sharkey, 2020; de Souza, 2016). Furthermore, plants are also widely utilized in phytoremediation and biomonitoring studies of pollutants in air and soil (Kalendar et al., 2024;).

Meanwhile, algae or diatoms are the least used organisms. This is due to the high need for taxonomic expertise. This is in accordance with previous research that shows taxonomic expertise is needed to identify diatom species, which requires the use of high-resolution microscopy and a deep understanding of silica morphology (Schultzet al., 2024; Wilks & Armand, 2017). Diatoms have very wide morphological variation, and errors in identification can result in inaccurate ecological

interpretations (Venkataramanan et al., 2024). In addition, analysis of diatom data requires specialized statistical approaches, such as biotic indices (e.g. Trophic Diatom Index, Specific Pollution Sensitivity Index), as well as digital microscopy-based image processing or deep learning, which most environmental researchers have not yet mastered (Kim & Lee, 2025; Dalu & Froneman, 2016). Another challenge is the geographical variation in the application of biotic indices. Indices developed in one region are not always directly applicable to other regions without modification. For example, indices designed in Europe are not necessarily applicable in regions such as South Africa or the French West Indies, requiring local adaptation or the development of new, contextualized indices (Xue et al., 2023; Henry et al., 2024).

Future Potential

The review identified three important aspects that need to be the main focus in the future development of bioindicator research: (1) the limited research on diatoms as water quality indicators, (2) the need to link bioindicator monitoring results with real implications for society, and (3) the importance of comparative studies between bioindicator species. Firstly, although diatoms have been shown to be very effective as bioindicators of water quality, research using them is still very limited, especially in developing countries and tropical regions. This is due to several technical constraints, such as the need for in-depth taxonomic expertise, high-resolution microscopy and complex data processing (Wilks & Armand, 2017; Schultz et al., 2024). Diatoms have the ability to record rapid and detailed changes in water quality, making them a potential biological indicator. Local capacity building, integration of technologies such as digital imagery and machine learning, and cross-institutional collaboration are strategic steps to expand the use of diatoms in sustainable water quality monitoring (Kim & Lee, 2025). Second, while bioindicator research has focused on measuring environmental quality, little research has examined the social and health impacts on communities living near monitored ecosystems. Information obtained from bioindicators can be used to detect potential risks to human health, food safety and the sustainability of local livelihoods, such as agriculture and fisheries (Wright, 2018). For example, the accumulation of heavy metals in aquatic organisms can signal danger to fishing communities that consume catches from these waters. Therefore, bioindicator research results should be translated into responsive environmental policies and participatory community education programs, so that the knowledge generated has a direct impact on environmental protection and social welfare.

Third, bioindicator studies have so far been dominated by a single approach, namely the use of one species for one type of contaminant, without comparing effectiveness between species. In fact, each organism has different tolerance and sensitivity to various pollutants (Hamza et al., 2014). Comparative studies between species are essential to identify the most accurate, efficient, and relevant species in local and cross-regional contexts (Dalu & Froneman, 2016). As pointed out by Tokatli (2022), a multi-species approach within a single monitoring site can increase data reliability and enrich ecological interpretation. Fourth, the increased use of bioindicators in environmental quality monitoring has not been matched by research on public understanding and awareness of bioindicator organisms. Most studies still focus on technical aspects carried out by researchers, while public involvement and

understanding of the use of bioindicator organisms such as diatoms, aquatic insects, and macroinvertebrates remains very limited (Fernández et al., 2021). However, these organisms serve as early indicators of ecological disturbances that can directly impact community life (Parmar et al., 2016). Studies exploring public perception, understanding, and involvement in environmental monitoring processes have the potential to open up opportunities for collaboration between scientists, educators, and local communities. This collaboration will not only improve data quality but also foster collective awareness of the importance of preserving ecosystems and public health (Bertuol-Garcia et al., 2018; Kaufman & Curl, 2019). By increasing public awareness of the role of bioindicators, not only can the quality of monitoring data be improved, but a sense of collective responsibility for maintaining environmental quality can also be fostered.

CONCLUSION

This SLR produced interesting results. First, it was found that the most researched environmental pollution was air and freshwater pollution. Second, the keywords that were widely used by the authors were bioindicators, animals, environmental monitoring, and biomonitoring. Third, the country with the most research on bioindicators in environmental pollution is Italy. Fourth, the most studied pollution is heavy metal and chemical pollution. Fifth, invertebrates and plants are the most widely used bioindicators, while the least is algae or diatoms. In the future, bioindicator research has potential in four areas: first, the use of diatoms as bioindicators of water quality; second, linking bioindicator monitoring results to their impact on communities; third, conducting interspecies comparisons to identify the most effective indicators; and fourth, studying the level of community understanding and skills in recognizing and utilizing bioindicator organisms. This review encourages researchers and policymakers to adopt a more diverse, comparative, and community-oriented approach to environmental bioindication.

RECOMMENDATION

This research is limited to this systematic literature review because it only uses limited keywords from one Scopus-indexed journal. Expanding the sample of higher quality journals, such as DOAJ, SINTA, ERIC, Scopus, and Web of Science, is recommended to conduct further research. It can also be used to compare the results of various Systematic Literature Review analyses of bioindicators.

Author Contributions

Conceptualization, MINF; writing—preparation of original drafts, SM, SZ, and I; writing—reviewing and editing. All authors have read and provided feedback on the published version of the manuscript.

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Conflict of interests

The authors declare no conflict of interest.

REFERENCES

- Akansha, K., Jain, M., Sharma, B. M., & Bharat, G. K. (2024). Global environmental occurrence of heavy metals. In *Endocrine-Disrupting Chemicals* (pp. 237-247). Elsevier.
- Andújar, C., Arribas, P., Gray, C., Bruce, C., Woodward, G., Yu, D. W., & Vogler, A. P. (2018). Metabarcoding of freshwater invertebrates to detect the effects of a pesticide spill. *Molecular Ecology*, 27(1), 146-166.
- Areco, M. M., Salomone, V. N., & dos Santos Afonso, M. (2021). Ulva lactuca: A bioindicator for anthropogenic contamination and its environmental remediation capacity. *Marine Environmental Research*, 171, 105468.
- Arias, M. J., Vaschetto, P. A., Marchese, M., Regaldo, L., & Gagneten, A. M. (2022). Benthic Macroinvertebrates and Zooplankton Communities as Ecological Indicators in Urban Wetlands of Argentina. *Sustainability*, 14(7), 4045.
- Asif, N., Malik, M., & Chaudhry, F. N. (2018). A review of on environmental pollution bioindicators. *Pollution*, 4(1), 111-118.
- Babić, D., Skoko, B., Franić, Z., Senčar, J., Šoštarić, M., Petroci, L., ... & Marović, G. (2020). Baseline radioecological data for the soil and selected bioindicator organisms in the temperate forest of Plitvice Lakes National Park, Croatia. *Environmental Science and Pollution Research*, 27, 21040-21056.
- Bawra, B., & Pawar, M. (2023). Changes in Freshwater Systems Management and Governance: A Case Study From Mandla Madhya Pradesh. In *Perspectives on Global Biodiversity Scenarios and Environmental Services in the 21st Century* (pp. 1-21). IGI Global.
- Bazzi, G., Galimberti, A., Foglini, C., Bani, L., Bazzi, L., Bonvicini, P., ... & Assandri, G. (2023). Odonate diversity of a highly urbanised region: An annotated checklist of the damselflies and dragonflies (Insecta, Odonata) of Lario and Brianza (Lombardy, N Italy). *Biodiversity Data Journal*, 11.
- Bertuol-Garcia, D., Morsello, C., N. El-Hani, C., & Pardini, R. (2018). A conceptual framework for understanding the perspectives on the causes of the science-practice gap in ecology and conservation. *Biological Reviews*, 93(2), 1032-1055.
- Beś, A., Warmański, K., & Adomas, B. (2019). Long-term responses of Scots pine (*Pinus sylvestris* L.) and European beech (*Fagus sylvatica* L.) to the contamination of light soils with diesel oil. *Environmental Science and Pollution Research*, 26, 10587-10608.
- Borghesi, F., Dinelli, E., Migani, F., Bechet, A., Rendón-Martos, M., Amat, J. A., ... & Gillingham, M. A. (2017). Assessing environmental pollution in birds: a new methodological approach for interpreting bioaccumulation of trace elements in feather shafts using geochemical sediment data. *Methods in Ecology and Evolution*, 8(1), 96-108.
- Brandi, M. C., & Carbara, L. (2004). Foreign Researchers in Italy: Push and Pull Factors. *Studi Emigrazione*, (156).
- Brasso, R., Rittenhouse, K. A., & Winder, V. L. (2020). Do songbirds in wetlands show higher mercury bioaccumulation relative to conspecifics in non-wetland habitats?. *Ecotoxicology*, 29(8), 1183-1194.

- Breidenbach, L. R., Benner, L., Roß-Nickoll, M., Linnemann, V., & Schäffer, A. (2023). Monitoring metal patterns from urban and agrarian sites using the bumblebee *Bombus terrestris* as a bioindicator. *Environmental Science and Pollution Research*, 1-14.
- Burger, J. (2006). Bioindicators: a review of their use in the environmental literature 1970–2005. *Environmental Bioindicators*, 1(2), 136-144.
- Caro-Borrero, A., Carmona-Jiménez, J., Rivera-Ramírez, K., & Bieber, K. (2021). The effects of urbanization on aquatic ecosystems in peri-urban protected areas of Mexico City: The contradictory discourse of conservation amid expansion of informal settlements. *Land Use Policy*, 102, 105226.
- Caro, T. (2016). Behavior and conservation, conservation and behavior. *Current opinion in behavioral sciences*, 12, 97-102.
- Celis-Hernández, O., Ávila, E., Ward, R. D., Rodríguez-Santiago, M. A., & Aguirre-Téllez, J. A. (2021). Microplastic distribution in urban vs pristine mangroves: Using marine sponges as bioindicators of environmental pollution. *Environmental Pollution*, 284, 117391.
- Cen, S. (2015). Biological monitoring of air pollutants and its influence on human beings. *The open biomedical engineering journal*, 9, 219.
- Chandel, P., Mahajan, D., Thakur, K., Kumar, R., Kumar, S., Brar, B., ... & Sharma, A. K. (2023). A review on plankton as a bioindicator: A promising tool for monitoring water quality. *World Water Policy*.
- Chowdhury, S., Dubey, V. K., Choudhury, S., Das, A., Jeengar, D., Sujatha, B., ... & Kumar, V. (2023). Insects as bioindicator: A hidden gem for environmental monitoring. *Frontiers in Environmental Science*, 11, 273.
- Comess, S., Donovan, G., Gatzolis, D., & Deziel, N. C. (2021). Exposure to atmospheric metals using moss bioindicators and neonatal health outcomes in Portland, Oregon. *Environmental Pollution*, 284, 117343.
- Cozzoli, D., & Capocci, M. (2011). Making biomedicine in twentieth-century Italy: Domenico Marotta (1886–1974) and the Italian Higher Institute of Health. *The British journal for the history of science*, 44(4), 549-574.
- Cuschieri, A., Azzopardi, J. I., & Blundell, R. (2023). Effect of non-essential heavy metals on human health. In *Heavy metals in the environment: management strategies for global pollution* (pp. 117-133). American Chemical Society.
- Dalu, T., & Froneman, P. W. (2016). Diatom-based water quality monitoring in southern Africa: challenges and future prospects. *Water SA*, 42(4), 551-559.
- De Sousa, C. S., Hassan, S. S., Pinto, A. C., Silva, W. M., De Almeida, S. S., Soares, S. D. C., ... & Azevedo, V. (2018). Microbial omics: applications in biotechnology. In *Omics technologies and bio-engineering* (pp. 3-20). Academic Press.
- de Souza, C. P., Guedes, T. D. A., & Fontanetti, C. S. (2016). Evaluation of herbicides action on plant bioindicators by genetic biomarkers: a review. *Environmental monitoring and assessment*, 188, 1-12.
- DeMille, K. F., Emsbo-Mattingly, S. D., Krieger, G., Howard, M., Webster, K. B., & DaCosta, M. (2023). Novel gas exposure system for the controlled exposure of plants to gaseous hydrogen fluoride. *Environmental Monitoring and Assessment*, 195(6), 752.
- Denyer, D., & Tranfield, D. (2009). Producing a systematic review.

- Di Bernardino, A., Iannarelli, A. M., Diémoz, H., Casadio, S., Cacciani, M., & Siani, A. M. (2022). Analysis of two-decade meteorological and air quality trends in Rome (Italy). *Theoretical and Applied Climatology*, 149(1), 291-307.
- Dong, L., Zhang, L., Peng, Z., Guo, J., Zhang, X., Zhou, L., ... & Huang, Y. (2022). Monitoring and ecological risk assessment of contaminants in freshwater bodies by bioindicators in China: a proposed framework. *Environmental Science and Pollution Research*, 29(54), 82098-82109.
- Dubey, D., Kumar, S., & Dutta, V. (2022). Algae and macrophytes as bioindicators of freshwater ecosystem. In *Environmental Studies and Climate Change* (pp. 441-467). CRC Press.
- Dvoretzky, A. G., & Dvoretzky, V. G. (2023). Shellfish as biosensors in online monitoring of aquatic ecosystems: A review of Russian studies. *Fishes*, 8(2), 102.
- Ebrahimi, M., Khalili, N., Razi, S., Keshavarz-Fathi, M., Khalili, N., & Rezaei, N. (2020). Effects of lead and cadmium on the immune system and cancer progression. *Journal of Environmental Health Science and Engineering*, 18, 335-343.
- Fernández-Llamazares, Á., López-Baucells, A., Velazco, P. M., Gyawali, A., Rocha, R., Terraube, J., & Cabeza, M. (2021). The importance of Indigenous Territories for conserving bat diversity across the Amazon biome. *Perspectives in ecology and conservation*, 19(1), 10-20.
- Gago-Tinoco, A., González-Domínguez, R., García-Barrera, T., Blasco-Moreno, J., Bebianno, M. J., & Gómez-Ariza, J. L. (2014). Metabolic signatures associated with environmental pollution by metals in Doñana National Park using *P. clarkii* as bioindicator. *Environmental Science and Pollution Research*, 21, 13315-13323.
- Ghannem, S., Bacha, O., Fkiri, S., Kanzari, S., Aydi, A., & Touaylia, S. (2024). Soil and Sediment Organisms as Bioindicators of Pollution. *Ecologies*, 5(4), 679-696.
- Ghannem, S., Touaylia, S., & Boumaiza, M. (2018). Beetles (Insecta: Coleoptera) as bioindicators of the assessment of environmental pollution. *Human and Ecological Risk Assessment: An International Journal*, 24(2), 456-464.
- Godzik, B. (2020). Use of bioindication methods in national, regional and local monitoring in Poland—Changes in the air pollution level over several decades. *Atmosphere*, 11(2), 143.
- Govers, L. L., Lamers, L. P., Bouma, T. J., Eygensteyn, J., de Brouwer, J. H., Hendriks, A. J., ... & van Katwijk, M. M. (2014). Seagrasses as indicators for coastal trace metal pollution: a global meta-analysis serving as a benchmark, and a Caribbean case study. *Environmental Pollution*, 195, 210-217.
- Guerranti, C., Perra, G., Alessi, E., Baroni, D., Caserta, D., Caserta, D., ... & Focardi, S. E. (2017). Biomonitoring of chemicals in biota of two wetland protected areas exposed to different levels of environmental impact: results of the “PREVIENI” project. *Environmental monitoring and assessment*, 189, 1-14.
- Gusenbauer, M., & Haddaway, N. R. (2020). Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. *Research synthesis methods*, 11(2), 181-217.
- Hamza-Chaffai, A. (2014). Usefulness of bioindicators and biomarkers in pollution biomonitoring. *International Journal of Biotechnology for Wellness Industries*, 3(1), 19.

- Han, Y., Chong, W. K., & Li, D. (2020). A systematic literature review of the capabilities and performance metrics of supply chain resilience. *International Journal of Production Research*, 58(15), 4541-4566.
- Hédouin, L., Metian, M., Teyssié, J. L., Oberhänsli, F., Ferrier-Pagès, C., & Warnau, M. (2016). Bioaccumulation of ⁶³Ni in the scleractinian coral *Stylophora pistillata* and isolated Symbiodinium using radiotracer techniques. *Chemosphere*, 156, 420-427.
- Heinry, L., Guéguen, J., Boutry, S., Delmas, F., Lefrançois, E., Eulin-Garrigue, A., ... & Tison-Rosebery, J. (2024). Assessment of river ecological status in the French West Indies based on diatom flora. *Environmental Monitoring and Assessment*, 196(9), 860.
- Herceg Romanić, S., Kljaković-Gašpić, Z., Bituh, T., Žužul, S., Dvorščak, M., Fingler, S., ... & Stipičević, S. (2016). The impact of multiple anthropogenic contaminants on the terrestrial environment of the Plitvice Lakes National Park, Croatia. *Environmental monitoring and assessment*, 188, 1-16.
- Huang, Y., Chen, Q., Deng, M., Japenga, J., Li, T., Yang, X., & He, Z. (2018). Heavy metal pollution and health risk assessment of agricultural soils in a typical peri-urban area in southeast China. *Journal of environmental management*, 207, 159-168.
- Jacob, D. E., Nelson, I. U., Izah, S. C., Ukpong, E., Akpan, U. U., & Ogwu, M. C. (2024). Bioindicators in recreational planning and development: Balancing nature and human activities. In *Biomonitoring of pollutants in the global south* (pp. 835-878). Singapore: Springer Nature Singapore.
- Jan, K., & Wani, J. M. (2024). Bioindicators of Environmental Pollution With Emphasis to Wetlands of Kashmir. In *Sensors for Environmental Monitoring, Identification, and Assessment* (pp. 269-283). IGI Global.
- Kalendar, R., Levei, E., Cadar, O., & Senila, M. (2024). Trends and challenges in plant biomonitoring, bioremediation and biomining. *Frontiers in plant science*, 15, 1486752.
- Katara, P., Tyagi, S., & Gupta, M. K. (2023). Integrative Omics: Trends and Scope for Agriculture. In *Genomics of Plant-Pathogen Interaction and the Stress Response* (pp. 1-16). CRC Press.
- Kaufman, J. D., & Curl, C. L. (2019). Environmental health sciences in a translational research framework: more than benches and bedsides. *Environmental Health Perspectives*, 127(4), 045001.
- Khalil, M. T., Gad, N. S., Ahmed, N. A., & Mostafa, S. S. E. D. (2017). Antioxidant defense system alternations in fish as a bio-indicator of environmental pollution. *Egyptian Journal of Aquatic Biology and Fisheries*, 21(3), 11-28.
- Kienzl, K., Riss, A., Vogel, W., Hackl, J., & Götz, B. (2003). Bioindicators and biomonitors for policy, legislation and administration. In *Trace Metals and other Contaminants in the Environment* (Vol. 6, pp. 85-122). Elsevier.
- Kim, M. S., Chae, E., Min, H. G., & Kim, J. G. (2024). Applicability of *Brassica juncea* as a bioindicator for As contamination in soil near the abandoned mine area. *Journal of Environmental Management*, 358, 120805.
- Kim, S. M., & Lee, J. H. (2025). Selecting indicator-diatom taxa and its application for simplifying trophic diatom index for biological water quality assessment. *Journal of Ecology and Environment*, 49.

- Kinney, P. L. (2018). Interactions of climate change, air pollution, and human health. *Current environmental health reports*, 5, 179-186.
- Knippertz, P., Evans, M. J., Field, P. R., Fink, A. H., Liousse, C., & Marsham, J. H. (2015). The possible role of local air pollution in climate change in West Africa. *Nature Climate Change*, 5(9), 815-822.
- Kumari, K., & Khare, A. (2018). Integration of Biomarker approach in pollution monitoring programme of aquatic ecosystem. *Biosynthetic Technology and Environmental Challenges*, 331-354.
- Lam, D. C. L., Nakanishi, Y., & Fukuchi, Y. (2022). Future challenges and their impact on respiratory health and lung cancer. *Lung Diseases and Cancer (ERS Monograph)*. Sheffield, European Respiratory Society, 48-58.
- Li, Y., Chen, B., Yang, S., Jiao, Z., Zhang, M., Yang, Y., & Gao, Y. (2025). Advances in environmental pollutant detection techniques: Enhancing public health monitoring and risk assessment. *Environment International*, 109365.
- Liu, L., Bilal, M., Duan, X., & Iqbal, H. M. (2019). Mitigation of environmental pollution by genetically engineered bacteria – current challenges and future perspectives. *Science of The Total Environment*, 667, 444-454.
- Lusito, F. (2021). Science Outside Academies: An Italian Case of “Scientific Mediation” – From Joule’s Seminal Experience to Lucio Lombardo Radice’s Contemporary Attempt. *Foundations of Science*, 26(3), 757-790.
- Lyons, B. P., Thain, J. E., Stentiford, G. D., Hylland, K., Davies, I. M., & Vethaak, A. D. (2010). Using biological effects tools to define good environmental status under the European Union Marine Strategy Framework Directive. *Marine Pollution Bulletin*, 60(10), 1647-1651.
- Madheshiya, P., Gupta, G. S., Sahoo, A., & Tiwari, S. (2022). Biomonitoring tools and bioprogramming: An overview. *New paradigms in environmental biomonitoring using plants*, 341-366.
- Michel, L., Renaudin, M., Darnajoux, R., Blasi, C., Vacherand, G., Le Monier, P., ... & Bellenger, J. P. (2024). Evaluating the effect of moss functional traits and sampling on elemental concentrations in *Pleurozium schreberi* and *Ptilium crista-castrensis* in Eastern Canada (Québec) black spruce forest. *Science of The Total Environment*, 907, 167900.
- Mifsud, D. A. (2014). A status assessment and review of the herpetofauna within the Saginaw Bay of Lake Huron. *Journal of Great Lakes Research*, 40, 183-191.
- Mitra, S., Chakraborty, A. J., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., ... & Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *Journal of King Saud University-Science*, 34(3), 101865.
- Møller, A. P., & Mousseau, T. A. (2015). Strong effects of ionizing radiation from Chernobyl on mutation rates. *Scientific reports*, 5(1), 8363.
- Nakazato, R. K., Esposito, M. P., Cardoso-Gustavson, P., Bulbovas, P., Pedroso, A. N. V., de Assis, P. I. L. S., & Domingos, M. (2018). Efficiency of biomonitoring methods applying tropical bioindicator plants for assessing the phytotoxicity of the air pollutants in SE, Brazil. *Environmental Science and Pollution Research*, 25, 19323-19337.
- Nguyen, H. H., Venohr, M., Gericke, A., Sundermann, A., Welti, E. A., & Haase, P. (2023). Dynamics in impervious urban and non-urban areas and their effects on

- run-off, nutrient emissions, and macroinvertebrate communities. *Landscape and Urban Planning*, 231, 104639.
- Ngwenya, S., Mashau, N. S., Mudau, A. G., Mhlongo, S. E., & Traoré, A. N. (2024). Community Perceptions on Health Risks Associated With Toxic Chemical Pollutants in Kwekwe City, Zimbabwe: A Qualitative Study. *Environmental Health Insights*, 18, 11786302241260487.
- Orru, H., Ebi, K. L., & Forsberg, B. (2017). The interplay of climate change and air pollution on health. *Current environmental health reports*, 4, 504-513.
- Panghal, A., Thakur, A., Deore, M. S., Goyal, M., Singh, C., & Kumar, J. (2024). Multimetal exposure: Challenges in diagnostics, prevention, and treatment. *Journal of Biochemical and Molecular Toxicology*, 38(6), e23745.
- Parida, L., & Patel, T. N. (2023). Systemic impact of heavy metals and their role in cancer development: a review. *Environmental Monitoring and Assessment*, 195(6), 766.
- Parikh, G., Rawtani, D., & Khatri, N. (2021). Insects as an indicator for environmental pollution. *Environmental Claims Journal*, 33(2), 161-181.
- Parmar, T. K., Rawtani, D., & Agrawal, Y. K. (2016). Bioindicators: the natural indicator of environmental pollution. *Frontiers in life science*, 9(2), 110-118.
- Pillet, M., Marengo, M., Gobert, S., Lejeune, P., Leduc, M., Fullgrabe, L., ... & Thomas, H. (2021). Environmental Quality of Coastal Areas in the Mediterranean Sea and Potential Risks to Human Health. *Marine Environmental Quality: Healthy Coastal Waters*, 103-143.
- Pizzolotto, R., Mazzei, A., Bonacci, T., Scalercio, S., Iannotta, N., & Brandmayr, P. (2018). Ground beetles in Mediterranean olive agroecosystems: Their significance and functional role as bioindicators (Coleoptera, Carabidae). *PloS one*, 13(3), e0194551.
- Raghu, V. (2015). Study of dung, urine, and milk of selected grazing animals as bioindicators in environmental geoscience—a case study from Mangampeta barite mining area, Kadapa District, Andhra Pradesh, India. *Environmental monitoring and assessment*, 187, 1-10.
- Rajamanickam, K., Balakrishnan, J., Thangaswamy, S., & Muthusamy, G. (2021). Microbial Enzymes and Their Mechanisms in the Bioremediation of Pollutants. In *Recent Advancements in Bioremediation of Metal Contaminants* (pp. 36-53). IGI Global.
- Richiedei, A., & Pezzagno, M. (2022). Territorializing and monitoring of sustainable development goals in Italy: An overview. *Sustainability*, 14(5), 3056.
- Salmaso, F., Quadroni, S., Compare, S., Gentili, G., & Crosa, G. (2019). Benthic diatoms as bioindicators of environmental alterations in different watercourses of northern Italy. *Environmental monitoring and assessment*, 191, 1-17.
- Sangwan, S., Kumar, M., Lamba, R., Singh, S., Kumari, A., & Wati, L. Bioindicators: Natural Biotic Sensors of Environmental Pollution and Ecological Disturbance. In *Environmental Nexus Approach* (pp. 311-337). CRC Press.
- Savage, G., Porter, A., & Simpson, S. D. (2022). Uptake of microplastics by the snakelocks anemone (*Anemonia viridis*) is commonplace across environmental conditions. *Science of The Total Environment*, 836, 155144.
- Schultz, K., Dreßler, M., Jacques, O., Frank, M., Springer, A., & Hübener, T. (2024). Morphological and taxonomic implications of the formation of colonies in

- Cyclostephanos and Stephanodiscus (Bacillariophyta). *European Journal of Phycology*, 59(1), 71-81.
- Sevik, H., Cetin, M., Ucun Ozel, H., Ozel, H. B., Mossi, M. M. M., & Zeren Cetin, I. (2020). Determination of Pb and Mg accumulation in some of the landscape plants in shrub forms. *Environmental Science and Pollution Research*, 27, 2423-2431.
- Sharkey, T. D. (2020). Emerging research in plant photosynthesis. *Emerging topics in life sciences*, 4(2), 137-150.
- Shen, W., Zhu, N., Cui, J., Wang, H., Dang, Z., Wu, P., ... & Shi, C. (2016). Ecotoxicity monitoring and bioindicator screening of oil-contaminated soil during bioremediation. *Ecotoxicology and Environmental Safety*, 124, 120-128.
- Silici, S., Uluozlu, O. D., Tuzen, M., & Soylak, M. (2016). Honeybees and honey as monitors for heavy metal contamination near thermal power plants in Mugla, Turkey. *Toxicology and industrial health*, 32(3), 507-516.
- Skibniewska, E. M., & Skibniewski, M. (2023). The Total Mercury Concentration in Organs of Eurasian Magpies (*Pica pica*) and Common Woodpigeons (*Columba palumbus*) from the Warsaw Municipal Area. *Animals*, 13(4), 575.
- Skorbiłowicz, E., Skorbiłowicz, M., & Cieśluk, I. (2018). Bees as bioindicators of environmental pollution with metals in an urban area. *Journal of Ecological Engineering*, 19(3), 229-234.
- Squadrone, S., Brizio, P., Favaro, L., Todino, G., Florio, D., Da Rugna, C., & Abete, M. C. (2019). Humboldt penguins' feathers as bioindicators of metal exposure. *Science of the Total Environment*, 650, 1734-1739.
- Strokal, M., Bai, Z., Franssen, W., Hofstra, N., Koelmans, A. A., Ludwig, F., ... & Kroeze, C. (2021). Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. *npj Urban sustainability*, 1(1), 24.
- Sumudumali, R. G. I., & Jayawardana, J. M. C. K. (2021). A review of biological monitoring of aquatic ecosystems approaches: with special reference to macroinvertebrates and pesticide pollution. *Environmental management*, 67(2), 263-276.
- Thompson, L. A., & Darwish, W. S. (2019). Environmental chemical contaminants in food: review of a global problem. *Journal of toxicology*, 2019.
- Tokatli, C. (2022). Comparisons of diatoms and fishes as toxic metal bioindicator: A case study of an A-class wetland in northwest Turkey under effect of an intensive paddy cultivation stress. *Environmental Science and Pollution Research*, 29(58), 87231-87244.
- Tripathi, D. P., & Nema, A. K. (2023). Seasonal variation of biochemical parameters and air pollution tolerance index (APTI) of selected plant species in Delhi city, and detailed meta-analysis from Indian metropolitan cities. *Atmospheric Environment*, 119862.
- Valente, T., Pelamatti, T., Avio, C. G., Camedda, A., Costantini, M. L., de Lucia, G. A., ... & Matiddi, M. (2022). One is not enough: Monitoring microplastic ingestion by fish needs a multispecies approach. *Marine Pollution Bulletin*, 184, 114133.
- Vallaëys, T., Klink, S. P., Fleouter, E., Le Moing, B., Lignot, J. H., & Smith, A. J. (2017). Bioindicators of marine contaminations at the frontier of environmental monitoring and environmental genomics. *pharmaceuticals*, 57, 58.

- Valon, M., Valbona, A., Fahri, G., Qenan, M., Dhurat, K., & Fatmir, C. (2013). Evaluating Environmental Pollution by Applying Oxidative Stress Biomarkers as Bioindicators of Water Pollution in Fish. *Polish Journal of Environmental Studies*, 22(5).
- Varela, Z., Boquete, M. T., Fernández, J. A., Martínez-Abaigar, J., Núñez-Olivera, E., & Aboal, J. R. (2023). Mythbusters: unravelling the pollutant uptake processes in mosses for air quality biomonitoring. *Ecological Indicators*, 148, 110095.
- Vasistha, P., & Ganguly, R. (2021). Water quality and designated best use (DBU) determination of Bhim Taal Lake of Panchkula, Haryana. In *Water Security and Sustainability: Proceedings of Down To Earth 2019* (pp. 43-50). Springer Singapore.
- Venkatachalapathy, R., & Karthikeyan, P. (2015). Diatom indices and water quality index of the Cauvery River, India: implications on the suitability of bioindicators for environmental impact assessment. *Environmental Management of River Basin Ecosystems*, 707-727.
- Venkataramanan, A., Kloster, M., Burfeid-Castellanos, A., Dani, M., Mayombo, N. A., Vidakovic, D., ... & Beszteri, B. (2024). "UDE DIATOMS in the Wild 2024": a new image dataset of freshwater diatoms for training deep learning models. *GigaScience*, 13, giae087.
- Wilks, J. V., & Armand, L. K. (2017). Diversity and taxonomic identification of *Shionodiscus* spp. in the Australian sector of the Subantarctic Zone. *Diatom Research*, 32(3), 295-307.
- World Health Organization. (2021). *WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. <https://www.who.int/publications/i/item/9789240034228>.
- Wright, L. P., Zhang, L., Cheng, I., Aherne, J., & Wentworth, G. R. (2018). Impacts and effects indicators of atmospheric deposition of major pollutants to various ecosystems-A review. *Aerosol and Air Quality Research*, 18(8), 1953-1992.
- Xue, H., Wang, L., Zhang, L., Wang, Y., Meng, F., & Xu, M. (2023). Exploration of Applicability of Diatom Indices to Evaluate Water Ecosystem Quality in Tangwang River in Northeast China. *Water*, 15(20), 3695.
- Yadav, P., Singh, J., Srivastava, D. K., & Mishra, V. (2021). Environmental pollution and sustainability. In *Environmental sustainability and economy* (pp. 111-120). Elsevier.
- Yorkina, N. V. (2016). Impact of technogenic pollution of urban environment on vitality indicators of urban biota (Mollusk fauna, soil mesofauna, epiphytic lichens). *Moscow University Biological Sciences Bulletin*, 71, 177-183.
- Zhu, L., Husny, Z. J. B. M., Samsudin, N. A., Xu, H., & Han, C. (2023). Deep learning method for minimizing water pollution and air pollution in urban environment. *Urban Climate*, 49, 101486.
- Zorzoliu, R. (2012). Regional and sustainable development in Italy (as a member of EU). *Procedia-Social and Behavioral Sciences*, 58, 514-522.
- Zukal, J., Pikula, J., & Bandouchova, H. (2015). Bats as bioindicators of heavy metal pollution: history and prospect. *Mammalian Biology*, 80, 220-227.