Fronteiras: Journal of Social, Technological and Environmental Science
http://periodicos.unievangelica.edu.br/fronteiras/
ISSN 2238-8869

Article

Evaluation of the Main Potentially Toxic Elements and Bioindicator Organisms

Débora Tavares Sarabia[1], Maria do Socorro Mascarenhas [2], Margareth Batistote [3]

[1] Doctoral student in Programa of Pós Graduação in Recursos Naturais at the Universidade Estadual of Mato Grosso do Sul (UEMS). ORCID: 0000-0002-5329-7691. E-mail: dbrsarabia@gmail.com

[2] Doctor in Recursos Naturais at the Programa of Pós Graduação in Recursos Naturais of Universidade Estadual of Mato Grosso do Sul (UEMS). ORCID: 0000-0002-5343-4502. E-mail: maria_mascarenhas@outlook.com

[3] Senior Teacher in Programa of Pós Graduação in Recursos Naturais at the Universidade Estadual of Mato Grosso do Sul (UEMS). ORCID: 0000-0001-9865-2362. E-mail: margarethbatistote@gmail.com

ABSTRACT
Environmental quality is a recurring concern in the area of public health, as the presence of contaminants can cause changes in the environment and affect human life. Therefore, this study aimed to carry out a bibliographical survey of an exploratory/descriptive nature, through the Science Direct platform, carrying out a screening in order to highlight the main, potentially toxic compounds (EPTs) and bioindicator organisms used in cytotoxicity and genotoxicity analyses. , developed through a review using the following keywords "Potentially Toxic Elements, Toxicity, Genotoxicity, Water Bodies, Aquatic Ecosystem" with a time frame between 2013 and 2023. Some inclusion and exclusion criteria were applied for the selection of articles. Based on the panorama of publications analyzed, around 82% are restricted access and only 18% are open access and there was also a gradual and significant increase in the number of articles published, in the period from 2013 to 2023. During the screening, they were identified several toxic compounds, including heavy metals; medicines; anticorrosives; particulate materials; dyes and microplastics. When evaluating the diversity of organisms used as bioindicators, it is possible to observe the use of fish 36.6%, followed by 8.4% of mussels and only 7% of microorganisms, followed by plants and humans 5.6% respectively. The results of this study highlight the wide diversity of bioindicators and the worrying presence of Potentially Toxic Elements (PTEs) in the environment, which highlights the importance of studies aimed at these compounds. The main organisms used as bioindicators were fish, mussels and microorganisms, plants and human beings. The use of living organisms as bioindicators has potential for environmental management and monitoring due to their versatility in detecting Potentially Toxic Elements, proving to be a valuable green tool to be used in toxicological studies.
Keywords: living organisms, emerging compounds, environment.

RESUMO
A qualidade ambiental é uma preocupação recorrente na área da saúde pública, visto que a presença de contaminantes podem desencadear alterações no meio ambiente e afetar a vida humana. Portanto, este estudo teve como objetivo realizar um levantamento bibliográfico de natureza exploratória/descritiva, através da plataforma Science Direct, realizando uma triagem a fim de evidenciar os principais, elementos potencialmente tóxicos (EPTs) e os organismos bioindicadores utilizados em análises de citotoxicidade e genotoxicidade, desenvolvida por meio de uma revisão utilizando as seguintes palavras-chave "Potentially Toxic Elements, Toxicity, Genotoxicity, Water Bodies, Aquatic Ecosystem" com um recorte temporal entre 2013 à 2023. Foram aplicados alguns critérios de inclusão e exclusão para a seleção dos artigos. Com base no panorama de publicações analisadas, cerca de 82% são de acesso restrito e apenas 18% são de acesso aberto e ainda houve um aumento gradativo e expressivo no número de artigos publicados, no período de 2013 a 2023. Durante a triagem foram identificados diversos compostos tóxicos, dentre eles temos os metais pesados; os medicamentos; os anticorrosivos; os materiais particulados; corantes e os microplásticos. Na avaliação da diversidade de organismos utilizados como bioindicadores, pode observar, a utilização dos peixes 36.6%, seguido de 8,4% do mexilhão e apenas 7% de microrganismos, seguido das plantas e do ser humano 5.6% respectivamente. Os resultados deste estudo destacam a ampla diversidade de bioindicadores e a presença preocupante de Elementos Potencialmente Tóxicos (EPTs) no meio ambiente o que ressalta a importância de estudos direcionados a estes compostos. Os principais organismos utilizados como bioindicadores, foram os peixes, os mexilhões e microrganismos, as plantas e seres humanos. O Uso de organismos vivos como bioindicadores, apresentam

Submissão: 06/07/2024 | Aceite: 16/09/2024 | Publicação: 14/11/2024

v.13, n.4, 2024 • p. 279-295. • DOI http://dx.doi.org/10.21664/2238-8869.2024v13i4p.279-295

potencial para o gerenciamento e monitoramento ambiental em virtude da sua versatilidade na detecção dos Elementos Potencialmente Tóxicos, mostrando ser uma valiosa ferramenta verde a ser empregada em estudos toxicológicos.
Palavras-chave: organismos vivos, compostos emergentes, meio ambiente.

Introduction

The preservation of environmental quality is an essential concern in the field of public health, given that the presence of contaminants has the potential to trigger significant changes in the environment and directly affect human life. Such as potentially toxic elements (PTEs), which are substances of different origins that can be present in the most diverse concentrations, in the air, water or soil (Martins-Gomes et al. 2022; Shahi Khalaf Ansar et al. 2023). This wide distribution highlights the complexity of carrying out systematic monitoring in relation to the toxicity of these compounds in nature and their respective damage to organisms.

The origin of these contaminants may be associated with human activities, some of which are highly polluting that result in the formation of compounds such as surfactants and emulsifiers, mainly arising from agricultural practices (Saravanan et al. 2021; Badmus et al. 2021). As well as organic waste from agro-industrial, petrochemical and agrochemical sectors, represent a substantial threat to both human health and environment when disposed of inappropriately (Chen et al. 2019; Jaskuła & Sojka 2022; Caballero-Gallardo et al. 2020; Nabgan et al. 2022; Rani et al. 2023). In this context, it is essential to highlight the presence of PTEs in water represents a significant threat, requiring the implementation of effective detection and monitoring strategies (Zhang et al. 2020).

It is a fact that contamination of water resources threatens the balance of aquatic ecosystems, because these chemicals have the ability to cause harm to living organisms (Sun et al. 2019; Moghanm et al. 2020). In this way, the detection and monitoring of these elements in water makes it possible to preserve the environment and promote the population's quality of life. For this purpose, different organisms are used, that according to Li et al. (2022), may present changes in their physiology, morphology and others, due to the accumulation of these substances.

Thus, the use of test organisms or bioindicators has highlighted as a promising approach, as it allows the assessment of the presence and impact that these contaminants can cause on ecosystems. Bioindicators are living organisms that have the ability to respond to environmental changes resulting from the presence of pollutants. (Yuan et al. 2022; Zhang et al. 2022; Sagova-Mareckova et al. 2021). There are numerous bioindicator organisms, such as fish, rats, brine shrimp, daphnia magna and plants. (Zeyad et al. 2019; Roda et al. 2019; Da Silva et al. 2020; Saha et al. 2024; Ribeiro et al. 2021;).

Other promising organisms are microorganisms, which are present in all ecosystems and are major degraders of organic and inorganic compounds. Furthermore, microbial abundance and diversity vary according to their habitat. Microorganisms can be classified as resistant or sensitive to selective pressures in the presence of PTEs (Carlson et al. 2019). Studies report that the metabolism of microorganisms is sensitive to environmental changes, and response mechanisms are fundamental (Lew & Glinska-Lewczuk, 2018; Semedo & Song, 2019). Microorganisms are strongly associated with the degradation of contaminants, and their use in the diagnosis of PTEs is simple, effective and low cost (Tang et al. 2019).

Other examples are yeasts, which have been widely used in microbiological research and offer significant advantages for their use as a bioindicator (Daskalova et al. 2021), as it provides an assessment of the toxicity of compounds and their effects at the cellular level (Wołejko et al. 2022). The use of this microorganism has the advantage of low cost, reduced analysis time, high cell multiplication capacity, and adaptability to adverse conditions, that can allow a rapid response to environmental stimuli (Sarabia et al. 2021; Chowdhury et al. 2023). According to Nielsen (2019), *S. cerevisiae* has a high genetic correlation with eukaryotic organisms, including humans, which makes it an important tool for this type of assessment. In addition to being able to measure the genotoxic and mutagenic effects of EPTs (Islam et al. 2020; Brtnicky et al. 2021).

The advantage of cultivating and manipulating this microorganism makes it possible to conduct experiments under controlled conditions without risks. These characteristics make studies feasible, as the response mechanisms to different compounds and their concentrations are easy to identify and quantify (Echeverri-Jaramillo et al. 2022; Tavares et al. 2022). Furthermore, they can provide important information and provide a better understanding of responses to contaminants in different ecosystems.

In this context, studies focused on the use of bioindicators to evaluate Potentially Toxic Elements have been applied in several ecosystems, and can predict the management of toxic compounds, contributing to environmental monitoring and management. Therefore, this study aims to carry out a survey of the main potentially toxic elements (PTEs), in the period from 2013 to 2023, as well as highlight the main bioindicator organisms used.

Material and methods

Location of study development

The study as well as the tests were carried out at the Laboratory of Biotechnology, Biochemistry and Biotransformation of the Centro de Estudos em Recursos Naturais - CERNA of the Universidade Estadual de Mato Grosso do Sul - UEMS/Dourados-MS.

Exploratory research

The research was carried out through a bibliographical review of an exploratory/descriptive nature, using published databases. The search was conducted on the Science Direct platform, using keywords in English such as (Potentially Toxic Elements, Toxicity, Genotoxicity, Water Bodies, Aquatic Ecosystem). Inclusion and exclusion criteria were applied to select articles, such as:

a) Year of publication between 2013 and 2023;
b) Research Articles;
c) Reporting the presence of PTEs;
d) Open access articles.

The selection of articles was based on relevance within the topic of this research. The data were then grouped and compiled qualitatively and later tabulated quantitatively with Excel 2019 software.

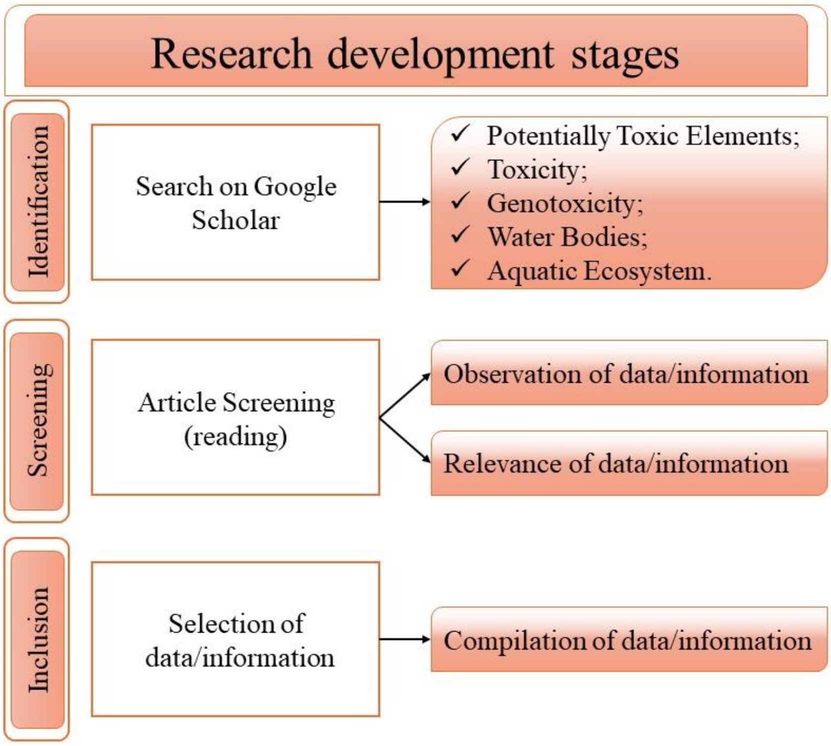

Figure 1. Flowchart of research development stages according to the PRISMA model (2020). Source: authors.

Results and Discussion

Based on the analysis of the panorama of publications related to Potentially Toxic Elements, it was observed that in the period from 2013 to 2023 there was a gradual and significant increase in the number of published articles, that were mostly composed of research articles (Figure 2A). It was also possible to verify that in the last 3 years of the sample analysis period there was a significant increase in publications, especially in 2022 when compared to 2021, that there were approximately twice as many publications related to Potentially Toxic Elements, it can be observed that the opposite occurred in 2023, where the number of review articles was greater than in 2022. Furthermore, among the data collected between 2013 and 2023, approximately 82% are restricted access and only 18% are open access (Figure 2B).

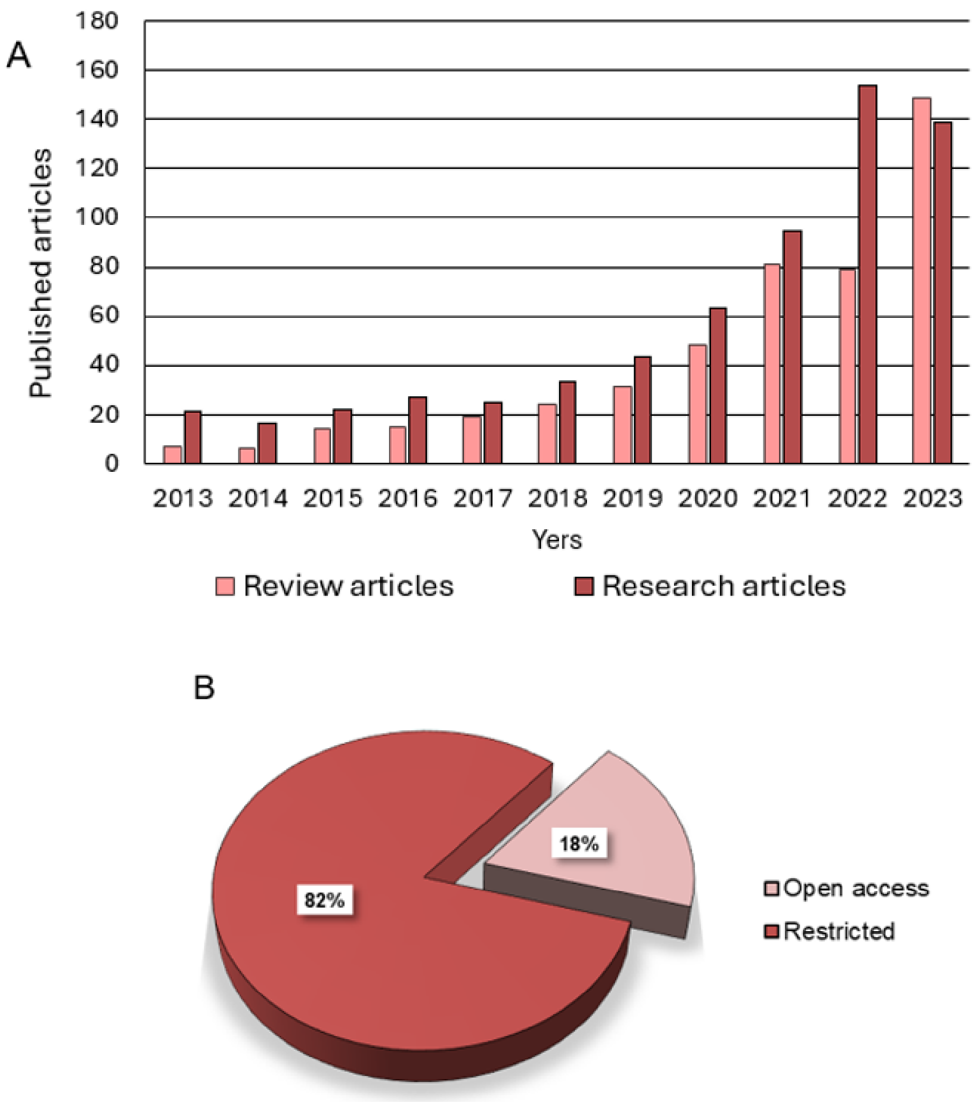

Figure 2. Overview of publications related to Potentially Toxic Elements in water bodies from 2013 to 2023 (A) and evaluation of publications of open and restricted access articles related to Potentially Toxic Elements in water bodies in the last ten years (B). Source: authors.

Notably, the increase in the number of research publications was in the year 2022, which may be related to the health emergency conditions faced worldwide, as according to Marques (2022), there were around 500 thousand studies related to COVID-19, among the years of 2020 and 2021, in other words, during this period the research focus was more on studies related to the pandemic in the health area, showing a certain stabilization in 2022, possibly due to social distancing. Furthermore, according to Conceição et al. (2023), Kuroda et al. (2021) e De Andrade et al. (2024) during the COVID-19 pandemic there was an exponential increase in the consumption of chemical products (disinfectants) and pharmaceuticals (azithromycin, ciprofloxacin, caffeine, ibuprofen, losartan and triclosan).

Another example is electronic waste, which has increased exponentially, contributing to the accumulation of PTEs in the world, given that this waste contains heavy metals such as copper (Cu), nickel (Ni), lead (Pb) and chromium (Cr). In 2019, China generated 10.1 million metric tons (Mt) of electronic waste, and this number is expected to increase to 27.2 Mt by 2030 and 51.6 Mt by 2050 (Zeng et al. 2020; Forti et al. 2020). Furthermore, according to Rajput et al. (2021) and Rajesh et al. (2022), in India, the electronic waste generated annually is 10% and its increase is directly related to population growth, that is, as the population increases, the amount of waste generated also increases. Another example is Brazil, which is one of the main generators of electronic waste and only 3.6% is recycled (Dias et al. 2022; D' Almeida et al. 2022). Toxic waste is persistent and generally has a high degree of toxicity, which represents a constant threat to the environment and humanity.

The research about Potentially Toxic Elements presents in the environment, carried out through the screening of open access research articles, identified several toxic compounds. Among them are heavy metals (mercury, methylmercury, arsenic, cadmium), medications (sulfamethoxazole), anticorrosives (zinc orthophosphate, sodium orthophosphate and sodium silicate), particulate materials (iron ore), dyes (benzidine, monoacetylbenzidine, diacetylbenzidine, *α*-naphthylamine, *β*-naphtylamine) and microplastics (polyethylene, acrylates, polyamide, polyethylene terephthalate, polypropylene, polystyrene, polyurethane, polyvinyl chloride, polycarbonate, polymethyl methacrylate), as shown in Table 1.

Table 1. Survey of the main Potentially Toxic Elements (PTEs).

Potentially Toxic Elements	Efeitos	Referências
Mercury (THg), methylmercury (MeHg) and arsenic (As)	Micronucleus and the two nuclear alterations (i.e. nuclear buds and binucleated) were identified in fish erythrocytes. Both species, statistically significant differences in genotoxic variables were observed compared to the control group.	Cruz-Esquivel et al. 2023
Mercury	Insectivores had the highest concentration of mercury in the liver and spleen and the highest number of micronuclei.	Calao-Ramos et al. 2021
Sulfamethoxazole (antibiotic)	Histopathological analysis of gills and liver revealed various alterations including pycnotic nuclei, bile stagnation, vacuolization in the liver, and partial and complete fusion of lamella and blood congestion in gills.	Iftikhar et al. 2022
Zinc orthophosphate, sodium orthophosphate, sodium silicate (Corrosion inhibitors)	In contrast, sodium silicate dosage at 10 mg/L resulted in decreased bacterial growth and antibiotic resistance selection compared to the other corrosion inhibitor additions. Source water collected from the drinking water treatment plant intake pipe resulted in less significant changes in antibiotic resistant bacteria (ARB) and antibiotic-resistance genes (ARGs) abundance due to corrosion inhibitor addition compared to source water collected from the pier at the recreational beach.	Kimbell et al. 2023

Particulate matter (PM) PM2.5, PM10, and PM20 Iron Ore	Evidence indicates that the PMs main composition is hematite and quartz, and the PM10 values sampled were higher than those reported by the local government agency. Scanning Electron Microscopy analysis showed the presence of Fe, Si, Mg, Al, Zi, Ca, and emerging metallic contaminants, such as Ba and Ti, in environmental samples.	Morozesk et al. 2021
Benzidine, mono-acetyl benzidine, diacetyl benzidine, α,β-naphthylamine	Remarkable variations in the concentrations of the two aromatic amines were found in the muscle tissue of *Saragus saragus* and *Siganus rivulatus*. The data suggest that in early pregnancy failure there is an increase in markers of oxidative stress and a probable decrease in maternal antioxidant defenses.	Saad et al. 2016
Microplastics and cadmium (Cd)	The abundance of soil microplastics in the winter was significantly correlated with Cd, indicating that microplastics and heavy metals present a risk of coexposure to soil organisms. The response of in situ earthworms to microplastic–Cd pollution revealed that microplastics can be used as a vector to transfer heavy metals in the soil environment and may accumulate in the bodies of soil organisms. Multiomics techniques demonstrated bacterial community structure dysbiosis and metabolic changes of in situ earthworms under microplastic heavy metal-contaminated soils. The abundance of microplastics in earthworm casts and intestines was higher than that in the soil samples.	Jiang et al. 2022

Source: Prepared by the authors based on the research carried out.

According to Córdoba-Tovar et al. (2022) and Økelsrud and Lydersen (2016), we can consider mercury (Hg), methylmercury (MeHg) and arsenic (As) as toxic pollutants, as they can present extreme toxicity even in low concentrations and when they reach the aquatic system, whether through natural or anthropogenic sources (mining or agricultural activities), they can cause adverse effects and trigger problems for both human health and the environment.

Furthermore, studies such as those by Dos Santos et al. (2020) and Kortei et al. (2020) identified the presence of these metals in both fish and water, and in some fish the concentrations were above the limit permitted for human consumption. Moreover, genotoxic changes were observed in fish, which is alarming, given that the persistence of these compounds in the environment increases their toxic potential, especially when it occurs across trophic levels, a process known as biomagnification. In relation to particulate matter, these have caused great concern related to climate change, due to atmospheric pollution and damage to the population, pas they can cause various health disorders such as allergies, lung infections, high blood pressure and premature deaths (Park et al. 2020; Morozesk et al. 2021; Prunicki et al. 2021).

In addition, there are microplastics, which are plastic particles with a diameter of <5 mm, it can have a low density which floats or be of high density which accumulates (Sarkar et al. 2021). The Mediterranean Sea is one of the areas most impacted by microplastics, with the highest concentrations of floating plastic particles worldwide (Eriksen et al. 2014; Oz et al. 2019). Microplastics can have several entry routes into environmental compartments, such as agriculture, mining, highways and the urban environment, besides being a major environmental problem, it can lead to the development of physiological abnormalities in fish and the contamination of water resources, soil and air (Corradini et al. 2021; Raza et al. 2023).

However, the significant increase in the use of medications during the COVID-19 Pandemic and the lack of adequate effluent treatment may result in these compounds ending up in water bodies or even the soil (Barros & Silva 2023). Furthermore, Iftikhar et al. (2022) found changes in the analyses of the gills and liver of *Cyprinus carpio* and observed that even at extremely low concentrations, antibiotics bioaccumulate and can cause oxidative stress, and long-term exposure can lead to the production of reactive oxygen species, the final pathway for toxicity. Studies carried out by Kumari et al. (2017), Zheng et al. (2019) and Chen et al. (2018), observed effects of PTEs on organisms, where they caused a decrease in reproductive capacity, reduced embryonic viability, teratogenesis, reduced enzymatic processes, oxidative stress, endocrine dysregulation, damage to deoxyribonucleic acid-DNA and cell death.

The biological organisms used as bioindicators have important characteristics such as sensitivity, survival capacity, tolerance to adverse environmental conditions, are versatile in real-time response mechanisms, have high reproducibility and are economically viable. In the evaluation of the diversity of organisms used as bioindicators, in relation to the publications analyzed, it can be observed that fish are the most used with a percentage of 36.6%, mussels 8.4%, microorganisms 7%, followed by plants and humans 5.6% respectively (Figure 3).

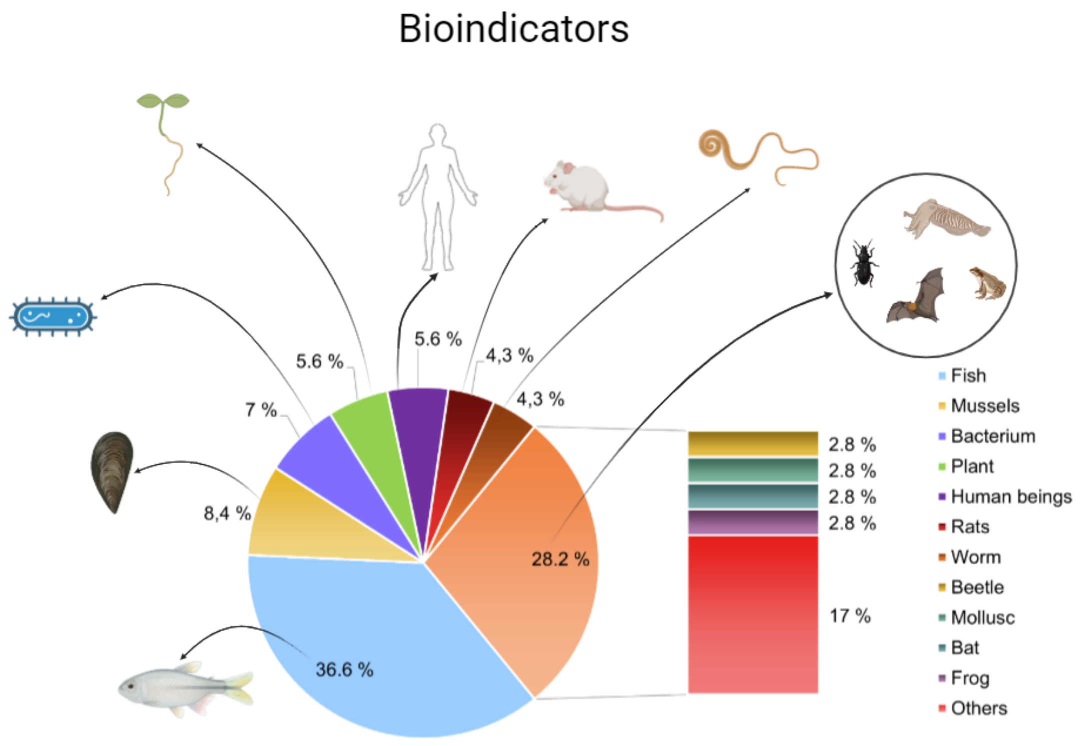

Figure 3. Assessment of the percentage of use of bioindicators used in open research articles. Source: authors.

Environmental pollution has been one of the main problems in global ecosystems. The presence of these pollutants must be detected and remediated, this being an important role of biological indicators, such as plants, animals and/or microorganisms. These indicators are often used to detect changes in an ecosystem, and can indicate positive and negative changes in relation to the environment and have the potential to be a valuable tool (Zaghloul et al. 2020).

Fish are widely used as bioindicators of water quality, their life cycle generally occurs in an aquatic environment and they have a great ability to accumulate metals in their muscles (Javed & Usmani, 2019; Vieira et al. 2020). Studies have evaluated the potential of fish as bioindicators of pollution by metals and polycyclic aromatic hydrocarbons. The data showed that, in the presence of chemical compounds, fish can trigger responses of genotoxic effects in different tissues, the formation of micronuclei, DNA fragmentation and bioaccumulation (Juma et al. 2018; Ali et al. 2020).

Molluscs, which generally live at the bottom of the water, have restricted mobility and are an important indicator in ecological assessments, as the accumulation of metals in these organisms often reflects the concentrations found in the water and sediment (Hayes et al. 2015; Moreira et al. 2020). Studies focused on crustaceans common on Brazilian beaches, such as *Atlantorchestoidea brasiliensis*, *Excirolana braziliensis*, *Emerita brasiliensis* e *Ocypode quadrata*, stand out as species sensitive to anthropogenic impact and, therefore, can be used as bioindicators for environmental monitoring (Cardoso et al. 2016; Schlacher et al. 2016).

These factors awaken our vision regarding the importance of using bioindicators to monitor the quality of the ecosystem. Another bioindicator widely used in toxicological studies are plants, as over time they have played an important role in assessing ecological risks related to radioactive and chemical contamination of soils, water, solid waste, industrial and agricultural pollutants (Antoniadis et al. 2017; Tarish et al. 2024).

Thus, although there is a great microbial diversity with varied structure and form, with comprehensive mechanisms of rapid and efficient responses, they are still little used. Microorganisms are highly sensitive and can be used as biological indicators, being able to demonstrate pollution conditions in the environment. Their use is a promising green technological tool in the remediation of organic and inorganic pollutants in environments (Gourmelon et al. 2016; Jiang et al. 2019; Vaid et al. 2022; Yang et al. 2023).

However, the diversity in the use of bioindicators reaffirms the sensitivity of biological matrices to a given contaminant, as well as the mechanisms of action triggered by them, which can result in morphological, physiological and biochemical changes (Iftikhar et al. 2022). According to Zhang et al. (2016) and Feng et al. (2018), microorganisms are more sensitive to stress caused by contaminants than animals and plants. Therefore, the yeast *Saccharomyces cerevisiae* has shown great potential as a bioindicator, proving to be a useful tool, easy to handle, with high survival capacity, low cost, rapid growth, and able to survive adverse conditions, which allows for a rapid return due to stimuli triggered in the environment (Sarabia et al. 2021; Tavares et al. 2022).

Furthermore, yeast has a high degree of genetic homology with eukaryotic organisms, including humans (Nielsen, 2019; Hori et al. 2023), which makes them important in the evaluation of genotoxicity and mutagenicity to PTEs, which may be present in water bodies, soil and air (Islam et al. 2020; Brtnicky et al. 2021). However, the use of microorganisms as bioindicators has stood out, but there are few studies on these organisms. This is possibly due in part to the lack of applied research around the world using microorganisms, despite their importance and presence in all ecosystems.

Conclusion

According to a study survey, in the last decade the number of research articles related to Potentially Toxic Elements was preponderant. In the data panorama for the years 2013 to 2023, around 82% are restricted access and only 18% are open access, which highlights the obstacles in accessing scientific research.

Among the Potentially Toxic Elements, several chemical compounds that are harmful to the environment and the health of animals and humans were found, such as: medicines, heavy metals, anticorrosives, dyes, microplastics. The diversity of these toxic compounds and their associated effects on the environment highlight the need for environmental policies, that can minimize their emission into the environment, aiming at sustainability.

Among the main organisms used as bioindicators, fish, mussels and microorganisms stand out, as they presented a significant percentage of use in environmental analyses, as well as plants and human beings. The use of living organisms as bioindicators has potential for environmental management and monitoring due to their versatility n detecting potentially toxic elements, proving to be a valuable green tool to be used in toxicological studies.

Acknowledgment

The Universidade Estadual de Mato Grosso Do Sul (UEMS); Programa de pós-Graduação em Recursos Naturais (PGRN); Fundação de Apoio ao Desenvolvimento do Ensino, Ciência e Tecnologia do Estado de Mato Grosso do Sul (FUNDECT); Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Código 001.

References

Ali, D, Almarzoug, MH, Al Ali, H, Samdani, MS, Hussain, SA, Alarifi, S. 2020. Fish as bio indicators to determine the effects of pollution in river by using the micronucleus and alkaline single cell gel electrophoresis assay. Journal of King Saud University-Science, 32(6):2880-2885.

Antoniadis, V, Shaheen, SM, Boersch, J, Frohne, T, Du Laing, G, Rinklebe, J 2017. Bioavailability and risk assessment of potentially toxic elements in garden edible vegetables and soils around a highly contaminated former mining area in Germany. Journal of environmental management, 186:192-200.

Badmus, SO, Amusa, HK, Oyehan, TA, Saleh, TA 2021. Environmental risks and toxicity of surfactants: Overview of analysis, assessment, and remediation techniques. Environmental Science and Pollution Research, 28:62085–62104.

Barros, JC, Silva, SN 2023. Perfil de utilização de psicofármacos durante a pandemia de COVID-19 em Minas Gerais, Brasil. Revista Brasileira de Epidemiologia, 26:e230059.

Brtnicky, M, Datta, R, Holatko, J, Bielska, L, Gusiatin, ZM, Kucerik, J, Hammerschmiedt, T, Danish, S, Radziemska, M, Mravcova, L, Fahad, S, Kintl, A, Sudoma, M, Ahmed, N, Pecina, V 2021. A critical review of the possible adverse effects of biochar in the soil environment. Science of the Total Environment, 796:148756.

Caballero-Gallardo, K, Alcala-Orozco, M, Barraza-Quiroz, D, De la Rosa, J, Olivero-Verbel, J 2020. Environmental risks associated with trace elements in sediments from Cartagena Bay, an industrialized site at the Caribbean. Chemosphere, 242:125173.

Calao-Ramos, C, Gaviria-Angulo, D, Marrugo-Negrete, J, Calderón-Rangel, A, Guzmán-Terán, C, Martínez-Bravo, C, Mattar, S 2021. Bats are an excellent sentinel model for the detection of genotoxic agents. Study in a Colombian Caribbean region. Acta Tropica, 224:106141.

Cardoso, RS, Barboza, CA, Skinner, VB, Cabrini, TM 2016. Crustaceans as ecological indicators of metropolitan sandy beaches health. Ecological Indicators, 62:154-162.

Carlson, HK, Price, MN, Callaghan, M, Aaring, A, Chakraborty, R, Liu, H, Kuehl JV, Arkin, AP, Deutschbauer, AM 2019. The selective pressures on the microbial community in a metal-contaminated aquifer. The ISME Journal, 13(4):937-949.

Córdoba-Tovar, L, Marrugo-Negrete, J, Barón, PR, Díez, S 2022. Drivers of biomagnification of Hg, As and Se in aquatic food webs: A review. Environmental Research, 204:112226.

Chen, H, Wang, P, Du, Z, Wang, G, Gao, S 2018. Oxidative stress, cell cycle arrest, DNA damage and apoptosis in adult zebrafish (Danio rerio) induced by tris (1, 3-dichloro-2-propyl) phosphate. Aquatic Toxicology, 194:37-45.

Chen, R, Chen, H, Song, L, Yao, Z, Meng, F, Teng, Y 2019. Characterization and source apportionment of heavy metals in the sediments of Lake Tai (China) and its surrounding soils. Science of the Total Environment, 694:133819.

Chowdhury, S, Dubey, VK, Choudhury, S, Das, A, Jeengar, D, Sujatha, B, Kumar, A, Kumar, N, Semwal, A, Kumar, V 2023. Insects as bioindicator: A hidden gem for environmental monitoring. Frontiers in Environmental Science, 11:273.

Conceição, KC, Villamar-Ayala, CA, Plaza-Garrido, A, Toledo-Neira, C 2023. Seasonal behavior of pharmaceuticals and personal care products within Chilean rural WWTPs under COVID-19 pandemic conditions. Journal of Environmental Chemical Engineering, 11(5):110984.

Corradini, F, Casado, F, Leiva, V, Huerta-Lwanga, E, Geissen, V 2021. Microplastics occurrence and frequency in soils under different land uses on a regional scale. Science of the Total Environment, 752:141917.

Cruz-Esquivel, Á, Díez, S, Marrugo-Negrete, JL 2023. Genotoxicity effects in freshwater fish species associated with gold mining activities in tropical aquatic ecosystems. Ecotoxicology and Environmental Safety, 253:114670.

Da Silva, EP, Benvindo-Souza, M, Cotrim, CFC, Motta, AGC, Lucena, MM, Antoniosi Filho, NR, Pereira, J, Formiga, KTM, Silva, DM 2020. Genotoxic effect of heavy metals on Astyanax lacustris in an urban stream. Heliyon, 6(9).

D'Almeida, FS, de Carvalho, RB, dos Santos, FS, de Souza, RFM 2022. On the hibernating electronic waste in Rio de Janeiro higher education community: An assessment of population behavior analysis and economic potential. Sustainability, 13(16):9181.

Daskalova, AV, Tomova, AA, Kujumdzieva, AV, Velkova, LG, Dolashka, PA, Petrova, VY 2021. Menadione and hydrogen peroxide trigger specific alterations in RNA polymerases profiles in quiescent *Saccharomyces cerevisiae* cells. Biotechnology & Biotechnological Equipment, 35(1):1190-1199.

De Andrade, HN, De Oliveira, JF, Siniscalchi, LAB, Da Costa, JD, Fia, R 2024. Global insight into the occurrence, treatment technologies and ecological risk of emerging contaminants in sanitary sewers: Effects of the SARS-CoV-2 coronavirus pandemic. Science of The Total Environment, 921:171075.

Dias, P, Palomero, J, Cenci, MP, Scarazzato, T, Bernardes, AM 2022. Electronic waste in Brazil: Generation, collection, recycling and the covid pandemic. Cleaner Waste Systems, 3:100022.

Dos Santos, SL, Viana, LF, Merey, FM, do Amaral Crispim, B, Solorzano, JC, Barufatti, A, Cardoso, CAL, Lima-Junior, SE 2020. Evaluation of the water quality in a conservation unit in Central-West Brazil: Metals concentrations and genotoxicity in situ. Chemosphere, 251:126365.

Echeverri-Jaramillo, G, Jaramillo-Colorado, B, Junca, H, Consuegra-Mayor, C 2022. Towards the development of microbial ecotoxicology testing using chlorpyrifos contaminated sediments and marine yeast isolates as a model. Microorganisms, 10(10):1-15.

Eriksen, M, Lebreton, LC, Carson, HS, Thiel, M, Moore, CJ, Borerro, JC, Galgani, F, Ryan, PG, Reisser, J 2014. Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PloS one, 9(12), e111913.

Feng, G, Xie, T, Wang, X, Bai, J, Tang, L, Zhao, H, Wei, W, Wang, M, Zhao, Y 2018. Metagenomic analysis of microbial community and function involved in Cd-contaminated soil. BMC Microbiology, 18:1-13.

Forti, V, Balde, CP, Kuehr, R, Bel, G 2020. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, 120.

Gourmelon, V, Maggia, L, Powell, JR, Gigante, S, Hortal, S, Gueunier, C, Letellier, K, Carriconde, F 2016. Environmental and geographical factors structure soil microbial diversity in New Caledonian ultramafic substrates: a metagenomic approach. Plos one,11(12):e0167405.

Hayes, KA, Burks, RL, Castro-Vazquez, A, Darby, PC, Heras, H, Martín, PR, Qiu, JW, Thiengo, SC, Vega, IA, Wada, T, Yusa, Y, Burela, S, Cadierno, MP, Cueto, JA, Dellagnola, FA, Dreon,MS, Frassa, MV, Giraud-Billoud, M, Godoy, MS, Ituarte, S, Koch, E, Matsukura, K, Pasquevich, MY, Rodriguez, C, Saveanu, L, Seuffert, ME, Strong, EE, Sun, J, Tamburi, NE, Tiecher, MJ, Turner, RL, Valentine-Darby, PL, Cowie, RH 2015. Insights from an integrated view of the biology of apple snails (*Caenogastropoda: Ampullariidae*). Malacologia, 58(1–2):245-302.

Hori, Y, Engel, C, Kobayashi, T 2023. Regulation of ribosomal RNA gene copy number, transcription and nucleolus organization in eukaryotes. Nature Reviews Molecular Cell Biology, 24(6):414-429.

Iftikhar, N, Zafar, R, Hashmi, I 2022. Multi-biomarkers approach to determine the toxicological impacts of sulfamethoxazole antibiotic on freshwater fish Cyprinus carpio. Ecotoxicology and Environmental Safety, 233:113331.

Islam, N, Dihingia, A, Khare, P, Saikia, BK 2020. Atmospheric particulate matters in an Indian urban area: Health implications from potentially hazardous elements, cytotoxicity, and genotoxicity studies. Journal of Hazardous Materials, 384: 121472.

Jaskuła, J, Sojka, M 2022. Assessment of spatial distribution of sediment contamination with heavy metals in the two biggest rivers in Poland. Catena, 211: 105959.

Javed, M, Usmani, N 2019. An overview of the adverse effects of heavy metal contamination on fish health. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 89:389-403.

Jiang, B, Adebayo, A. Jia, J, Xing, Y, Deng, S, Guo, L, Liang, Y, Zhang, D 2019. Impacts of heavy metals and soil properties at a Nigerian e-waste site on soil microbial community. Journal of hazardous materials, 362:187-195.

Jiang, X, Jiang, X, Yang, Y, Wang, Q, Liu, N, Li, M 2022. Seasonal variations and feedback from microplastics and cadmium on soil organisms in agricultural fields. Environment International, 161:107096.

Juma, RR, Salum, NS, Tairova, Z, Strand, J, Bakari, SS, Sheikh, MA 2018. Potential of Periophthalmus sobrinus and Siganus sutor as bioindicator fish species for PAH pollution in tropical waters. Regional Studies in Marine Science, 18, 170-176.

Kimbell, L K, LaMartina, EL, Kohls, S, Wang, Y, Newton, RJ, McNamara, PJ 2023. Impact of corrosion inhibitors on antibiotic resistance, metal resistance, and microbial communities in drinking water. Msphere, 8(5):e00307-23.

Kortei, NK, Heymann, ME, Essuman, EK, Kpodo, FM, Akonor, PT, Lokpo, SY, Boady NO, Ayim-Aconor, M, Tettey, C 2020. Health risk assessment and levels of toxic metals in fishes (*Oreochromis noliticus and Clarias anguillaris*) from Ankobrah and Pra basins: Impact of illegal mining activities on food safety. Toxicology Reports, 7:360-369.

Kumari, B, Kumar, V, Sinha, AK, Ahsan, J, Ghosh, AK, Wang, H, DeBoeck, G 2017. Toxicology of arsenic in fish and aquatic systems. Environmental Chemistry Letters, 15:43-64.

Kuroda, K, Li, C, Dhangar, K, Kumar, M 2021. Predicted occurrence, ecotoxicological risk and environmentally acquired resistance of antiviral drugs associated with COVID-19 in environmental waters. Science of the Total Environment, 776:145740.

Lew, S, Glińska-Lewczuk, K 2018. Environmental controls on the abundance of methanotrophs and methanogens in peat bog lakes. Science of the total environment, 645:1201-1211.

Li, X, Zhao, B, Luo, L, Zhou, Y, Lai, D, Luan, T 2022. In vitro immunotoxicity detection for environmental pollutants: Current techniques and future perspectives. TrAC Trends in Analytical Chemistry, 158:116901.

Marques, F 2022. Produção científica sobre Covid-19 afeta o equilíbrio da geração de conhecimento. Disponível em: https://revistapesquisa.fapesp .br/producao-cientifica-sobre-covid-19-afeta-o-equilibrio-da-geracao-de-conhecimento/. Acesso em: 11 de março de 2024.

Martins-Gomes, C, Silva, TL, Andreani, T, Silva, AM 2022. Glyphosate vs. glyphosate-based herbicides exposure: A review on their toxicity. Journal of Xenobiotics, 12(1):21-40.

Moghanm, FS, El-Banna, A, El-Esawi, MA, Abdel-Daim, MM, Mosa, A, Abdelaal, KA 2020. Genotoxic and anatomical deteriorations associated with potentially toxic elements accumulation in water hyacinth grown in drainage water resources. Sustainability, 12(5):2147.

Moreira, LB, Sasaki, ST, Taniguchi, S, Peres, TF, Figueira, RCL, Bícego, MC, Martins, RV, Costa-Lotufo, LV, Abessa, DMS 2020. Biomarkers responses of the clam *Anomalocardia flexuosa* in sediment toxicity bioassays using dredged materials from a semi-arid coastal system. Heliyon, 6(5):1-11.

Morozesk, M, Da Costa Souza, I, Fernandes, MN, Soares, DCF 2021. Airborne particulate matter in an iron mining city: Characterization, cell uptake and cytotoxicity effects of nanoparticles from PM2.5, PM10 and PM20 on human lung cells. Environmental Advances, 6:100125.

Nabgan, W, Jalil, AA, Nabgan, B, Ikram, M, Ali, MW, Lakshminarayana, P 2022. A state of the art overview of carbon-based composites applications for detecting and eliminating pharmaceuticals containing wastewater. Chemosphere, 288: 132535.

Nielsen, J 2019. Yeast systems biology: Model organism and cell factory. Biotechnology Journal, 14(9):1800421.

Økelsrud, A, Lydersen, E, Fjeld, E 2016. Biomagnification of mercury and selenium in two lakes in southern Norway. Science of the Total Environment, 566: 596-607.

Öz, N, Kadizade, G, Yurtsever, M 2019. Investigation of heavy metal adsorption on microplastics. Applied Ecology and Environmental Research, 17(4):7301-7310.

Park, S, Allen, RJ, Lim, C-H 2020. A likely increase in fine particulate matter and premature mortality under future climate change. Air Quality, Atmosphere & Health, 13:143-151.

Prunicki, M, Cauwenberghs, N, Lee, J, Zhou, X, Movassagh, H, Noth, E, Lurmann, F, Hammond, SK, Balmes, JR, Desai, M, WU, JC, Nadeau, KC 2021. Air pollution exposure is linked with methylation of immunoregulatory genes, altered immune cell profiles, and increased blood pressure in children. Scientific reports, 11(1):4067.

Rajesh, R, Kanakadhurga, D, Prabaharan, N 2022. Electronic waste: A critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environmental Challenges, *7*:100507.

Rajput, R, Rinki, Nigam, NA 2021. An overview of E-waste, its management practices and legislations in present Indian context. Journal of Applied and Natural Science, 13(1):34-41.

Rani, GM, Sonu, Pathania, D, Abhimanyu, Umapathi, R, Rustagi, S, Huh, YS, Gupta, VK, Kaushik, A, Chaudhary, V 2023. Agro-waste to sustainable energy: A green strategy of converting agricultural waste to nano-enabled energy applications. Science of The Total Environment, 875:162667.

Raza, T, Rasool, B, Asrar, M, Manzoor, M, Javed, Z, Jabeen, F, Younis, T 2023. Exploration of polyacrylamide microplastics and evaluation of their toxicity on multiple parameters of *Oreochromis niloticus*. Saudi Journal of Biological Sciences, 30(2):103518.

Ribeiro, OMR, Pinto, MQP, Ribeiro, C, Tiritan, ME, Carrola, JSC 2021. A dáfnia como sensor da ecotoxicidade. Revista de Ciência Elementar, 9(02):044.

Roda, E, Bottone, MG, Biggiogera, M, Milanesi, G, Coccini, T 2019. Pulmonary and hepatic effects after low dose exposure to nanosilver: Early and long-lasting histological and ultrastructural alterations in rat. Toxicology reports, 6:1047-1060.

Saad, AA, El-Sikaily, AM, El-Badawi, ES, El-Sawaf, GA, Shaheen, NE, Omar, M M, Zakaria, MA 2016. Relation between some environmental pollutants and recurrent spontaneous abortion. Arabian Journal of Chemistry, 9:S787-S794.

Sagova-Mareckova, M, Boenigk, J, Bouchez, A, Cermakova, K, Chonova, T, Cordier, T, Eisendle, U, Elersek, T, Fazi, S, Fleituch, T, Frühe, L, Gajdosova, M, Graupner, N, Haegerbaeumer, A, Kelly, A-M, Kopecky, J, Leese, F, Nõges, P, Orlic, S, Panksep, K, Pawlowski, J, Petrusek, A, Piggott, JJ, Rusch, JC, Salis, R, Schenk, J, Simek, K, Stovicek, A, Strand, DA, Vasquez, MI, Vralstad, T, Zlatkovic, S, Zupancic, M, Stoeck, T, Stoeck, T 2021. Expanding ecological assessment by integrating microorganisms into routine freshwater biomonitoring. Water Research, 191:116767.

Saha, G; Chandrasekaran, N 2024. A combined toxicological impact on Artemia salina caused by the presence of dust particles, microplastics from cosmetics, and paracetamol. Environmental Pollution, 348:123822.

Sarabia, DT, Mueller, LP, Santos, Mascarenhas do SM, Batistote, M 2021. Physiological response to the action of the agrotoxic 2,4-Dichlorophenoxiacetic acid in Saccharomyces cerevisiae. Research, Society and Development, 11:e408101119912.

Saravanan, A, Karishma, S, Kumar, PS, Varjani, S, Yaashikaa, PR, Jeevanantham, S, Ramamurthy, R, Reshma, B 2021. Simultaneous removal of Cu (II) and reactive green 6 dye from wastewater using immobilized mixed fungal biomass and its recovery. Chemosphere, 271:129519.

Sarkar, DJ, Sarkar, SD, Das, BK, Sahoo, BK, Das, A, Nag, SK, Manna, RK, Behera, BK, Samanta, S 2021. Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system. Water research, 192:116853.

Schlacher, TA, Lucrezi, S, Connolly, RM, Peterson, CH, Gilby, BL, Maslo, B, Olds, AD, Walker, SJ, Leon, JX, Huijbers, CM, Weston, MA, Turra, A, Hyndes, GA, Holt, RA, Schoeman, DS 2016. Human threats to sandy beaches: A meta-analysis of ghost crabs illustrates global anthropogenic impacts. Estuarine, Coastal and Shelf Science, 169:56-73.

Semedo, M, Song, B 2019. From genes to nitrogen removal: determining the impacts of poultry industry wastewater on tidal creek denitrification. Environmental Science & Technology, 54(1):146-157.

Shahi Khalaf Ansar, B, Kavusi, E, Dehghanian, Z, Pandey, J, Asgari Lajayer, B, Price, GW, Astatkie, T 2023. Removal of organic and inorganic contaminants from the air, soil, and water by algae. Environmental Science and Pollution Research, 30(55):116538-116566.

Sun, Y, Yu, IKM, Tsang, DCW, Cao, X, Lin, D, Wang, L, Graham, NJD, Alessi, DS, Komárek, M, Ok, YS, Feng, Y, Li, XD 2019. Multifunctional iron-biochar composites for the removal of potentially toxic elements, inherent cations, and hetero-chloride from hydraulic fracturing wastewater. Environment International, 124:521-532.

Tavares, DS, Mueller, LP, Santos, Mascarenhas DSM, Batistote, M 2022. The toxological profile of the agrotoxic acid 2,4 Dichlophenoxyacetic in Fleischmann® yeast. Fronteira: Journal of Social, Technological and Environmental Science, 11:141-149.

Tang, J, Zhang, J, Ren, L, Zhou, Y, Gao, J, Luo, L, Yang, Y, Peng, Q, Huang, H, Chen, A 2019. Diagnosis of soil contamination using microbiological indices: A review on heavy metal pollution. Journal of Environmental Management, 242:121-130.

Tarish, M, Ali, RT, Shan, M, Amjad, Z, Rui, Q, Akher, SA,Al Mutery, A 2024. Plant Tissues as Biomonitoring Tools for Environmental Contaminants. International Journal of Plant Biology, 15(2):375-396.

Vaid, N, Sudan, J, Dave, S, Mangla, H, Pathak, H 2022. Insight into microbes and plants ability for bioremediation of heavy metals. Current Microbiology, 79(5):141.

Vieira, TC, Rodrigues, APDC, Amaral, PM, de Oliveira, DF, Gonçalves, RA, e Silva, CR, Vasques, RO, Malm, O, Silva-Filho, EV, Godoy, JM de O, Machado, W, Filippo, A, Bidone, ED 2020. Evaluation of the bioaccumulation kinetics of toxic metals in fish (*A. brasiliensis*) and its application on monitoring of coastal ecosystems. Marine pollution bulletin, 151:110830.

Wołejko, E, Wydro, U, Odziejewicz, JI, Koronkiewicz, A, Jabłońska-Trypuć, A 2022. Biomonitoring of soil contaminated with herbicides. Water, 14:1534.

Yang, X, You, M, Liu, S, Sarkar, B, Liu, Z, Yan, X 2023. Microbial responses towards biochar application in potentially toxic element (PTE) contaminated soil: a critical review on effects and potential mechanisms. Biochar, 5(1):57.

Yao, K, Lv, X, Zheng, G, Chen, Z, Jiang, Y, Zhu, X, Wang, Z, Cai, Z 2018. Effects of carbon quantum dots on aquatic environments: comparison of toxicity to organisms at different trophic levels. Environmental science & technology, 52(24):14445-14451.

Yuan, Q, Wang, P, Wang, X, Hu, B, Liu, S, Ma, J 2022. Abundant microbial communities act as more sensitive bio-indicators for ecological evaluation of copper mine contamination than rare taxa in river sediments. Environmental Pollution, 305:119310.

Zaghloul, A, Saber, M, Gadow, S, Awad, F 2020. Biological indicators for pollution detection in terrestrial and aquatic ecosystems. Bulletin of the National Research Centre, 44(1):1-11.

Zeng, X, Ali, SH, Tian, J, Li, J 2020. Mapping anthropogenic mineral generation in China and its implications for a circular economy. Nature communications, 11(1):1544.

Zeyad, MT, Kumar, M, Malik, A 2019. Mutagenicity, genotoxicity and oxidative stress induced by pesticide industry wastewater using bacterial and plant bioassays. Biotechnology Reports, 24:e00389.

Zhang, A, Li, X, Xing, J, Xu, G 2020. Adsorption of potentially toxic elements in water by modified biochar: A review. Journal of Environmental Chemical Engineering, 8:104196.

Zhang, M, Sun, Q, Chen, P, Wei, X, Wang, B 2022. How microorganisms tell the truth of potentially toxic elements pollution in environment. Journal of Hazardous Materials, 431:128456.

Zhang, L, Yang, Y, Lin, Y, Chen, H 2022. Human health, environmental quality and governance quality: Novel findings and implications from human health perspective. Frontiers in Public Health, 10:890741.

Zhang, W, Chen, L, Zhang, R, Lin, K 2016. High throughput sequencing analysis of the joint effects of BDE209-Pb on soil bacterial community structure. Journal of Hazardous Materials, 301:1-7.

Zheng, NA, Wang, S, Dong, WU, Hua, X, Li, Y, Song, X, Chu, Q, Hou, S, Li, Y 2019. The toxicological effects of mercury exposure in marine fish. Bulletin of Environmental Contamination and Toxicology, 102:714-720.