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Bibliometric analysis on carcinogenic and non-carcinogenic risk assessment of heavy metals from cereal products

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Abstract

Heavy metal contamination of food is a critical global health issue due to its toxic, bioaccumulative, and often carcinogenic effects. This study presents a comprehensive bibliometric analysis of research published between 2000 and 2024 on health risk assessments associated with heavy metal exposure through the consumption of cereal products. Data were extracted from the Web of Science database and analyzed using VOSviewer software to visualize trends in terms of authors, institutional and international collaboration, and areas of thematic interest. The findings reveal a growing scientific interest in this field, with a peak in publication volume in 2020. China emerged as the main contributor, accounting for almost half of all publications, followed by Iran, Spain, and Brazil. The Chinese Academy of Sciences and Shahid Beheshti University of Medical Sciences were among the most active institutions. Journals such as Environmental Science and Pollution Research and Science of the Total Environment were identified as key publication platforms. The collaborative analysis highlights China and the USA as major centres of international collaboration, with peripheral but active contributions from countries such as England, Bangladesh, and Malaysia. Most studies focused on exposure pathways and assessed both carcinogenic and non-carcinogenic health risks, frequently reporting values above safe thresholds. These findings highlight the urgent need for national long-term monitoring programmes and the development of country-specific strategies to reduce exposure to heavy metals in food, thereby enhancing public health protection and regulatory compliance.

Keywords

Bibliometrics, cereals, risk assessment, potentially toxic elements, VOSviewer, Web of Science

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Introduction

Cereals have been a fundamental part of the human diet since prehistoric times, especially in developing countries, due to their wide availability, long shelf life, and nutritional value [1]. Rich in minerals (Fe, Mg, Zn, Cu, P, K), B-group vitamins, and phytochemicals, cereals contribute to a balanced diet and help prevent various health issues [2, 3].

Because whole meal products contain a high amount of indigestible fiber, they are characterized by a lower caloric content [3]. Due to their chemical composition, a daily consumption of 4–6 portions of cereal-derived products is recommended for a well-balanced and healthy diet [2]. Cereals can contribute towards reducing food insecurity because they can be used as a foundation for various food products [4].

Despite their nutritional benefits, food crops such as rice, soybeans, wheat, and corn—as well as their derived products—may contain harmful substances like pesticides, mycotoxins, and potentially toxic metals that pose risks to human and animal health [3, 5]. The presence of these contaminants in cereals, especially of arsenic in rice crops, is a global concern impacting especially the health of billions of rice consumers [1].

Food crops and agricultural products are the main source of human exposure to potentially toxic metals, especially in contaminated areas; thus, their monitoring is very important to ensure the quality of food products [1, 2, 6]. Soil, water, and air contamination, but also industry, transportation, agricultural treatments, harvesting process, storage, and/or sale are the main sources of crop pollution [2, 3].

The excessive use of contaminated wastewater or agrochemicals can accelerate the contamination of soil with toxic elements, which negatively affects food security, due to their absorption by vegetables and plants [5]. The application of fertilizers, pesticides, and herbicides is considered the major source of contamination of soils and crops with metals [7]. Plants can absorb toxic metals by direct foliar uptake processes during plant growth [1] and their bioaccumulation in the edible parts of the plants and vegetables [1, 5].

The levels of toxic metals from crops are influenced by many factors, like the pH and type of the soil, the soil composition, metal permissibility and selectivity, the content of metals in the soil, plant characteristics (type, specie, or genotype), the absorption ability of the plant, organic matter content, nutrient balance or cation exchange capacity [1, 5]. The accumulation of potentially toxic elements in the food chain and prolonged consumption of contaminated food products can affect the health of consumers [5], with food contamination with toxic metals being a public health concern [6].

Consumption of food products contaminated with heavy metals accounts for up to 90% of human exposure to these toxic elements, making dietary intake the primary route of exposure [5]. For this reason, the Food and Agriculture Organization (FAO), World Health Organization (WHO), European Commission (EC), and other regulatory bodies in the world imposed the allowable limits or maximum permitted concentrations of potentially toxic elements in different food products [1].

Toxic metals are classified by their carcinogenic potential according to international guidelines. Group 1 includes substances that are carcinogenic to humans, such as aluminum, inorganic arsenic and its compounds, cadmium and its compounds, chromium (VI) compounds, and nickel and its compounds. Group 2A comprises substances that are probably carcinogenic to humans, such as inorganic lead compounds. Group 2B consists of substances that are possibly carcinogenic to humans, including vanadium pentoxide, molybdenum trioxide, elemental lead, cobalt, methylmercury, and metallic nickel and its alloys. Group 3 includes substances that are not classifiable as to their carcinogenicity in humans, such as chromium (III) compounds, metallic chromium, copper, mercury and its inorganic compounds, selenium and its compounds, and organic arsenic compounds. Group 4 contains substances that are probably not carcinogenic to humans, such as manganese, silver, and zinc [8, 9]. The degree of toxicity associated with toxic metals depends on several factors, such as the way of exposure, the impact on intracellular balance, the deterioration of biological macromolecules through oxidative processes [5], as well as the level of absorption, concentration, and persistence of the toxic substance in the affected site [7].

It is therefore essential to understand the health risk levels, sources, and control measures related to heavy metal contamination in different parts of the world. Such knowledge can aid in developing effective strategies to mitigate the associated risks.

This article aims to apply a bibliometric analysis to map global trends in research on carcinogenic and non-carcinogenic risk assessments associated with toxic metal contamination in cereals and cereal products, from 2000 to 2024. The objective is to provide a comprehensive overview of the current state of global risk assessment studies and to help researchers identify potential future research directions.

Bibliometric analysis is a widely used method for identifying research trends and key issues by analyzing published literature, focusing on metrics like keyword frequency, publication volume, and institutional or geographic sources [10]. However, these conventional methods may not fully reflect the development trends within a specific research domain. In recent years, advanced techniques such as social network analysis and the use of impact factors (IFs) have been integrated into bibliometric studies. Despite this progress, relatively few studies have applied bibliometric analysis to assess health risks related to heavy metal exposure [11].

This study employs a bibliometric analysis based on data retrieved from the Web of Science (WOS) database to explore publication trends, research hotspots, and collaboration patterns, with the aim of identifying the scientific progress and knowledge gaps related to heavy metal contamination in cereals and cereal products.

Unlike previous studies that focused primarily on laboratory results and health risks caused by heavy metal contamination, this bibliometric analysis takes a different approach, analyzing how research is structured—who works with whom, which institutions collaborate, and what main topics are explored—helping to highlight future trends and directions in the field.

Data collection methodology

For bibliometric analysis, only English-language data from the WOS database—such as author, affiliation, keywords, abstracts, and citation details—was used. While publication and citation counts are commonly used to measure impact, they have limitations. To better assess influence, this study used the IF and h-index, which reflect both quantity and quality of publications. Specifically, IF 2023 and h-index 2024 were applied to evaluate the research impact of journals and countries.

The type of collaboration was identified based on the addresses of the authors. Articles where all authors were affiliated with institutions within the same country were categorized as "single country" publications, while articles with authors from multiple countries were grouped as "international collaboration". Similarly, articles where all authors were affiliated with the same institution were classified as "single institute publication", while articles with authors from different institutions were categorized as "inter-institutional collaborative publication" [12].

The research was conducted in April 2025 using the following keywords: "health risk assessment", "heavy metals", "cereal products", and "2000–2024" (the publication interval). Keywords used encompassed paper titles, abstracts, and keywords. A total of 49 articles met the selection criteria and were selected for the analysis.

The study used VOSviewer software (version 1.6.20) [13], a free mapping program, to conduct bibliometric analysis of the research. The software was used to analyze and classify the relationships between keywords, authors, countries, and organizations. Given that bibliometric analysis studies are distinct from conventional research, special attention was paid to identifying relevant keywords and assumptions [14].

Results of data collection

The trend of the global publication on “health risk assessment of heavy metals from cereal products”

The issue of heavy metals and their impact on human health has gained worldwide attention, with the reduction of associated risks being a significant concern for both researchers and policymakers [11].

A total of 49 articles related to the topic of “health risk assessment of heavy metals from cereal products” were extracted from the WOS database for this study, covering the period between 2000 and 2024. Table 1 provides an overview of the bibliographic statistics of these studies.

Table 1. Results of data collection [15]

Description	Results
Documents	49
Period	2000–2024
Sources (journals, books)	34
Authors	272
Organizations	118
Co-authors per document	5.55
All keywords	380
Countries	26
Total citations	2,231
Average citation per document	45.53
Document type	
Article	40
Review	9

The publication trend is illustrated in Figure 1, which shows that the year 2020 had the highest number of publications. This indicates a growing scientific awareness of the health risks linked to heavy metal contamination in cereals and cereal products. However, the number of publications declined during the 2021–2024 period compared to 2020. A possible explanation for this trend could be the impact of the COVID-19 pandemic, as in the following years (2021–2024), research funding, access to laboratories, and field activities were restricted, which could have slowed down experimental work and delayed the publication process. Also, many academic institutions and research centers experienced budget cuts, which led to a reduction in active projects and publications.

The top three years in terms of publication counts were 2020 (n = 9, 18.37%), followed by 2021 (n = 7, 14.29%), and 2022 (n = 6, 12.24%). The majority of publications were in the form of original articles, accounting for 81.63% (n = 40) of the total, followed by review articles at 18.37% (n = 9).

Environmental Science emerged as the top WOS category with the highest number of articles, making up 42.86% (21 publications) of the total. Other categories, such as Food Science Technology, Toxicology, Chemistry Applied, Engineering Environmental, and more, also contributed to the publication count. These findings indicate a significant focus on environmental concerns, food security, toxicology, and public health in the published articles [11].

Distribution of institutions

VOSviewer software was used to analyze the distribution of institutions that contributed to publications in this field. A total of 118 institutions were identified. Among them, the Chinese Academy of Sciences and Shahid Beheshti University of Medical Sciences had the highest number of publications (4), followed by Kermanshah University of Medical Sciences (3 publications).

This VOSviewer visualization illustrates the co-authorship relationships among major research organizations. The map displays institutions as nodes, with node size representing the number of

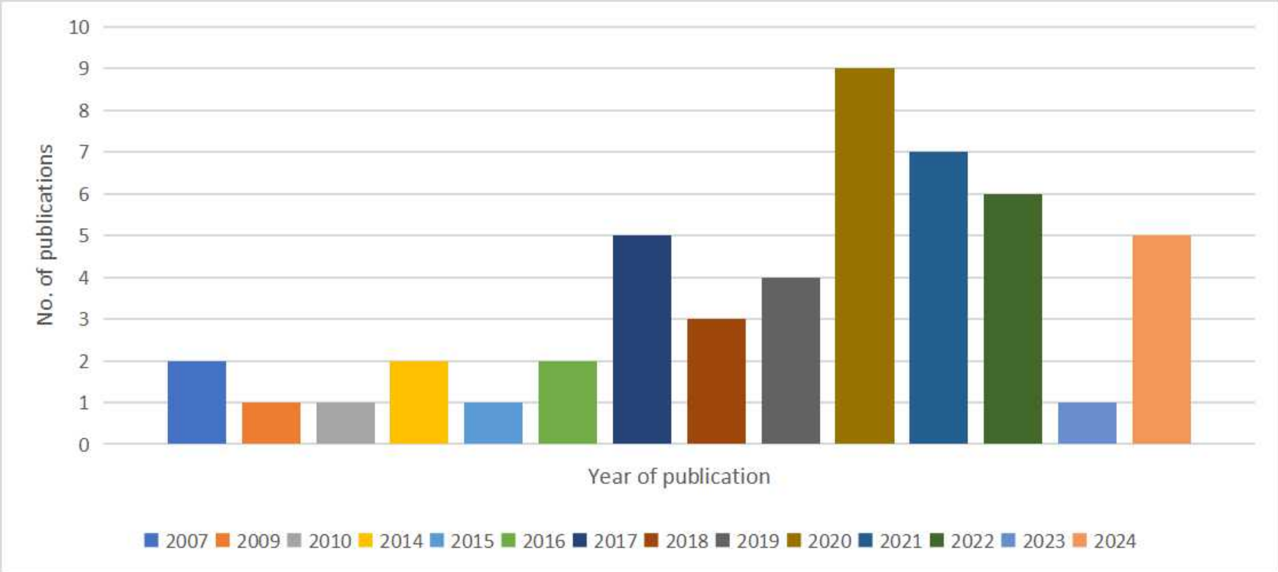

Figure 1. Number of publications in the period 2000–2024 on "health risk assessment of heavy metals from cereal products", no articles were published in the missing year

publications or co-authorship strength. Links between nodes indicate collaborative relationships based on shared publications, and link thickness reflects the intensity of that collaboration.

The Chinese Academy of Sciences (Figure 2, central node, blue cluster) acts as the primary hub, showing the highest number of co-author publications (*n* = 35) and strong collaborative ties with both, Cairo University (red cluster, right, link strength 12) and Shanghai Academy of Agricultural Sciences (green cluster, left, link strength 8). The color-coded clusters suggest regional or institutional research groupings, with each cluster representing a network of closely collaborating institutions.

Figure 2. The network visualization of organizations

The Chinese Academy of Sciences is the most central and influential institution, reflecting its global leadership in research output and collaboration. The node around Shanghai Academy of Agricultural Sciences and Cairo University indicates geographical collaboration and possible thematic alignments (e.g., agriculture, food security, environmental sciences). Also, the multiple connections between the Chinese Academy of Sciences and Cairo University indicate a strategic research partnership.

The visualization highlights transnational cooperation, especially between Chinese and Egyptian institutions, emphasizing the global nature of research into environmental and agricultural issues, such as heavy metal contamination.

These clusters indicate regional specialization or coordinated research efforts on topics such as agricultural contamination, food safety, and environmental monitoring. The visible links between Chinese and Egyptian institutions highlight a growing cross-continental interest in food contamination issues, potentially focusing on shared agricultural trade, food security, or exposure risk assessment in developing countries. Targeted funding and joint programs can be used to strengthen the frontiers of emerging research related to sustainable agriculture, food safety, and environmental toxicology.

Of the 49 articles reviewed, many were authored by researchers affiliated with a single institution (single institution publication). The most representative are the articles published by Ghanati et al. [16], 2019 from Shahid Beheshti University of Medical Sciences; Huang et al. [17], 2007 from the Geological Survey of Jiangsu Province; Page and Feller [18], 2015 from the Institute of Plant Sciences at the University of Bern; Zang et al. [19], 2017 from Lanzhou University; Biswas et al. [20], 2019 from Jadavpur University; Tang et al. [21], 2014 from Zhejiang University; Wei and Cen [22], 2020 from China University of Geosciences; Cao et al. [23], 2017 from the Chinese Academy of Agricultural Sciences and the China National Rice Research Institute; Babaahmadifooladi et al. [24], 2020 from Ghent University; Xiao et al. [25], 2020 from the China National Center for Food Safety Risk Assessment; Malissiova et al. [26], 2022 from the University of Thessaly, and Bielecka et al. [27], 2022 from the Medical University of Bialystok.

Notable examples of inter-institutional collaboration include the studies by Pirsaheb et al. [28], 2016, conducted by Kermanshah University of Medical Sciences and Tehran University of Medical Sciences; Tinggi and Schoendorfer [29], 2018, representing Queensland Health: Forensic and Scientific Services and The University of Queensland Medical School; Koch et al. [30], 2022, affiliated with the Medical University of Lublin and the Polish Academy of Sciences; Roman-Ochoa et al. [31], 2021 from Purdue University and the National University of San Agustín; Gonzalez et al. [32], 2020, involving Universitat Rovira i Virgili, the Barcelona Public Health Agency, and the Catalan Food Safety Agency.

Analysis of journals and research areas

A total of 49 articles on the health risk assessment of heavy metals from cereal products were published across 34 journals. Table 2 provides information on the top 10 most popular journals in this field, including their h-index and IF.

Table 2. List of the top 10 journals, number of publications, and citations on research associated with the health risk assessment of heavy metals from cereal products

No.	Name of the journal	Publications	Citations	Citation means	h-index 2024[1]	IF_{2023}[2]
1	Environmental Science and Pollution Research	4	63	15.75	212	0.99
2	Chemosphere	3	497	165.67	329	-
3	Food Additives and Contaminants Part B: Surveillance	3	109	36.33	46	8.1
4	Food and Chemical Toxicology	3	27	9.0	215	2.5
5	Science of the Total Environment	2	482	241	399	3.9
6	Nutrients	2	48	24	243	8.2
7	Food Control	2	33	16.5	174	4.8
8	Environmental Geochemistry and Health	2	32	16	99	5.6
9	Food Additives and Contaminants Part A: Chemistry analysis control	2	32	16	71	2.3
10	Food Science and Nutrition	2	24	12	74	2.3

[1] h-index (Hirsch index), the h-index of journals was taken from Scimago Journal & Country Rank [33]. [2] The IF (impact factor) was obtained from the official website of the journals

Environmental Science and Pollution Research had the most articles (*n* = 4), with a h-index 2024 of 212, followed by Chemosphere (3 articles) with a h-index 2024 of 329, Food Additives and Contaminants Part B: Surveillance (3 articles) with a h-index 2024 of 46, and Food and Chemical Toxicology (3 publications) with a h-index 2024 of 215. Science of the Total Environment had the highest citation means (*n* = 241), followed in descending order by Chemosphere (*n* = 165.67). The articles published in Food and Chemical Toxicology had the lowest citation mean (*n* = 9). The VOSviewer software revealed that journal citations were grouped into 6 clusters with 17 links and a total link strength of 18 (Figure 3).

This map reveals how scientific journals are interconnected in the research landscape. Journals positioned closer together are more frequently co-cited, indicating shared research interests or overlapping subject matter. Central journals like Food Additives & Contaminants or Environmental Science and Pollution Research serve as key sources for interdisciplinary research, linking food safety, environmental science, and public health. The obtained clusters are represented as follows:

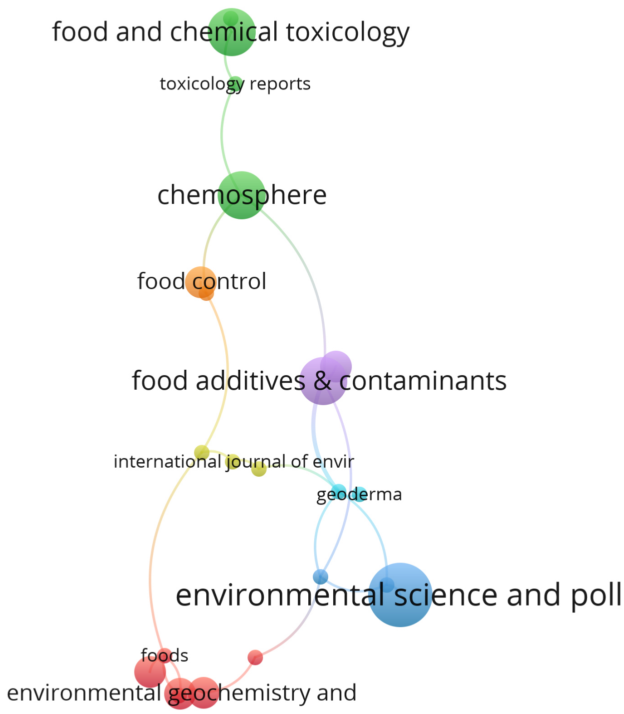

Figure 3. The network visualization of the most cited journals

- Blue cluster represented by journals like Environmental Science and Pollution Research, International Journal of Environmental Analytical Chemistry, Toxins reviews, with a focus on environmental pollution, food science, and sustainability issues.
- Red cluster represented by Science of the Total Environment, Environmental Geochemistry and Health, Nutrients, Foods, with focus on environmental contamination, human health, and nutrition.
- Green cluster represented by Food and Chemical Toxicology, Chemosphere, and Toxicology reports, with a focus on food toxicology, safety control, and chemical exposure.
- Purple node represented by Food Additives & Contaminants, connecting food safety, toxicology, and environmental issues.
- Yellow cluster represented by Journal of Cleaner Production, Journal of Trace Elements in Medicine and Biology, and International Journal of Environmental Research and Public Health, with a focus on sustainability, trace element analysis, and health implications.

The source co-occurrence analysis highlights a multidisciplinary research structure, with journals clustered around environmental science, toxicology, food safety, and public health, revealing integrated efforts to address heavy metal contamination in cereals and identifying key research frontiers at the intersection of environmental exposure and food quality control.

Analysis of publications

The top 9 citation documents from 2000 to 2024 are presented in Figure 4. The rank 1 with 463 citations is the article with authors Zheng N, Wang Q, Zhang X, Zheng D, Zhang Z, Zhang S from China with the article entitled "Population health risk due to dietary intake of heavy metals in the industrial area of Huludao city, China" [34]. In this study, the non-carcinogenic health risks associated with Hg, Pb, Cd, Zn, and Cu in cereals, sea products, and vegetables consumed by adults and children in the industrial area of Huludao, China, were estimated. This region has been heavily contaminated with toxic metals due to heavy metal smelting [35–37]. The target hazard quotient (THQ) and hazard index (HI) were calculated to evaluate the non-carcinogenic health risks from individual and combined heavy metals due to dietary intake.

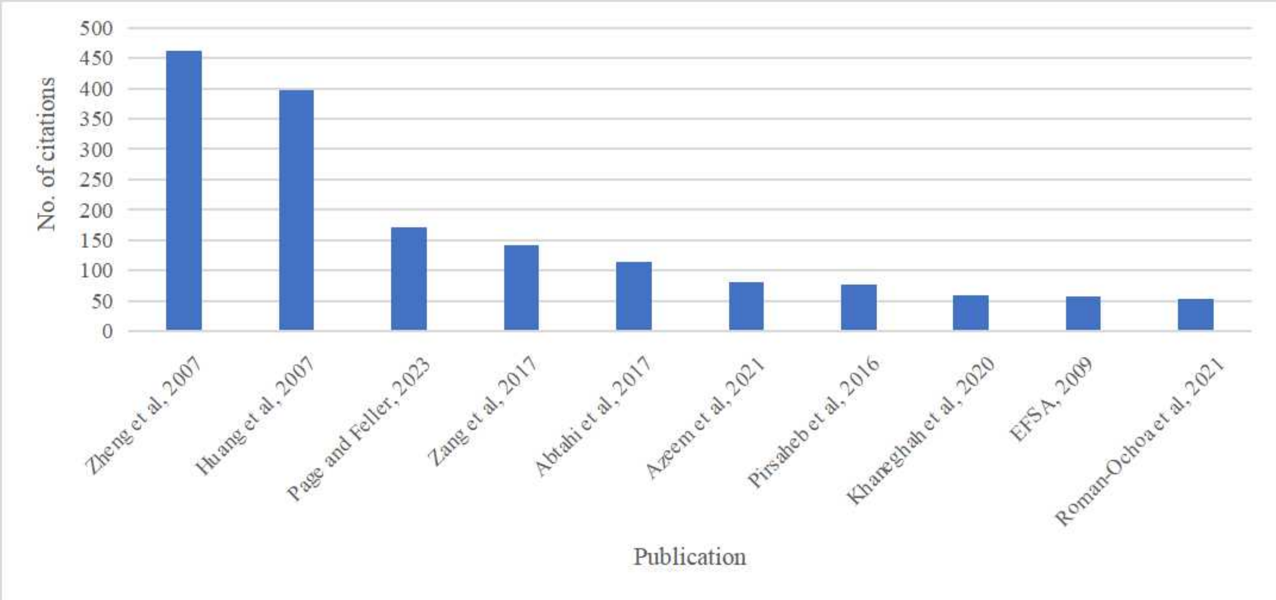

Figure 4. Top 10 cited publications in the field of health risk assessment of heavy metals from cereal products

THQ represents the ratio between the estimated exposure to a hazardous element and the reference dose at which no adverse health effects are anticipated [38]. The HI offers an overall evaluation of the cumulative risk posed by multiple heavy metals, for different exposure pathways, by accounting for the combined impact of their individual THQs [39].

The THQs for individual heavy metals from consuming individual foodstuffs in the industrial area of Huludao were all less than one, indicating a relatively low health risk associated with the intake of a single heavy metal through consumption of only one kind of foodstuff (e.g., vegetables). However, consuming the entire foodstuff could lead to potential health risks for both children and adults, as the HIs for heavy metals due to dietary intake were higher than one. The relative contributions of Hg, Pb, Cd, Zn, and Cu to the HIs were 1.7%, 11.7%, 24.0%, 23.4%, and 39.6% for adults, and 1.5%, 11.7%, 21.8%, 26.1%, and 38.8% for children. The results demonstrated that cereals, sea products, and vegetables were the main sources of heavy metal intake from foodstuffs for both adults and children [34].

The article of Huang SS, Liao Ql, Hua M, Wu XM, Bi KS, Yan CY, Chen B, Zhang XY, from China, with 397 citations, is ranked second and is entitled "Survey of heavy metal pollution and assessment of agricultural soil in Yangzhong district, Jiangsu Province, China" [17]. The concentration of Hg, Cd, Pb, Zn, Cu, As, Ni, and Cr in soil, cereal, and vegetable samples from the Yangzhong district in China was investigated in this article. The results indicated that the topsoil samples had higher concentrations of Hg, Cd, Cu, Pb, Zn, and as compared to the subsoil. Cd and Hg were found to have high levels in most agricultural soils, while Cr and Ni concentrations showed little spatial variation. Areas of urban development had high concentrations of Cu, Pb, and Zn, while high concentrations were primarily recorded at the two ends of the sampled alluvion. Cd, Hg, and total organic carbon (TOC) increased gradually to maximum values in the upper parts of soil profiles, while Cr and Ni occurred in low concentrations within sampled profiles. As, Pb, Cu, and Zn showed patterns of slight enrichment within the surface layer. The concentrations of Cd and Hg have increased since 1990 due to the long-term use of agrochemicals, while Cr and Ni contents remained steady over this period. Atmospheric deposition of material sourced from urban anthropogenic activity caused slight increases in the measured As, Cu, Pb, and Zn contents over time. The low concentrations of heavy metals in vegetables and cereals were due to the subalkaline nature of the soil, which limited their mobility. While the heavy metal concentrations measured did not pose a serious health risk, they affected the quality of agricultural products [16]. Heavy metals such as Cd, Pb, and As, even at concentrations below toxic thresholds, can disrupt essential physiological functions in plants, impair nutrient absorption, reduce yields, and negatively influence sensory attributes like taste, color, and texture. These adverse effects may compromise the quality of agricultural products, decreasing their market value and consumer acceptance [40].

These 2 publications were followed in descending order by Page and Feller [18], 2023; Zang et al. [19], 2017; Abtahi et al. [41], 2017; Azeem et al. [42], 2021; Pirsaheb et al. [28], 2016; Khaneghah et al. [43], 2020; EFSA [44], 2009; and Roman-Ochoa et al. [31], 2021.

Analysis of authors

From 2000 to 2024, none of the articles were authored by a single author; all of them involved two or more authors. Figure 5 displays the co-authorship collaborations between these authors. Khaneghah, Amin Mousavi from Poland and Fakhri, Yadolah from Iran were the most productive authors. Each of these authors contributed three articles to the period between 2000 and 2024.

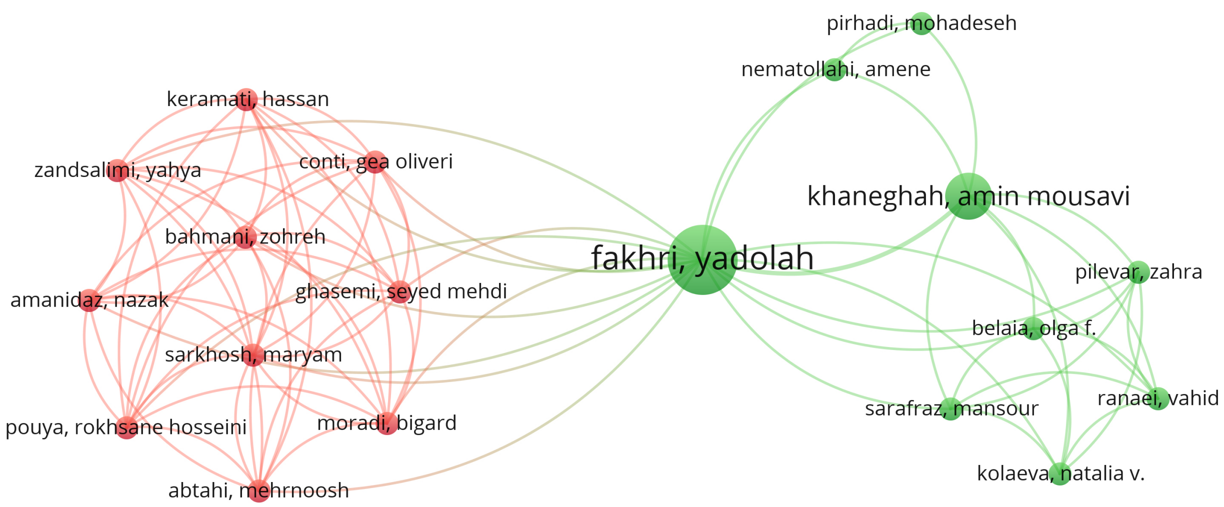

Figure 5. Co-authorship network visualization between the most connected authors

This VOSviewer visualization illustrates the co-authorship relationships among individual researchers based on their collaborative publications. Each node represents an author, and the size of the node reflects the number of publications or total link strength. The connecting lines indicate co-authorship ties, with thicker lines representing stronger collaborative relationships.

The network is divided into two main clusters: the green cluster, centered around Fakhri, Yadolah, shows extensive collaboration with authors such as Khaneghah, Amin Mousavi; Pilevar, Zahra; and Ranaei, Vahid, suggesting a cohesive research group likely focused on food safety and toxicology.

The second cluster (red), centered around authors like Bahmani, Zohreh; Ghasemi, Seyed Mehdi; and Sarkhosh, Maryam, indicates a second core group with strong intra-group collaboration, possibly focusing on environmental chemistry or analytical methods.

Fakhri, Yadolah acts as a key bridging author between the two clusters, linking otherwise separate collaborative groups. This bridging role highlights his influence in promoting interdisciplinary research and expanding the network's scientific impact.

The co-authorship analysis revealed two distinct research clusters, led by regional teams with strong internal collaboration. Fakhri, Yadolah emerged as a central figure bridging these clusters, underscoring his essential role in fostering interdisciplinary and international collaboration. Despite strong intra-cluster ties, limited connectivity between clusters suggests potential for improved interdisciplinary integration, particularly at the intersection of environmental monitoring and food toxicology research.

Figure 6 shows the author citation network, which revealed a total of 7 clusters with a total link strength of 994. Cluster 1 comprises 27 authors, with Khaneghah, Amin Mousavi, having the highest total link strength (61), followed by Fakhri, Yadolah (total link strength is 43); Nematollahi, Amene; Pirhadi, Mohadeseh (total link strength is 39); and Hosseini, Hedayat (total link strength is 32). Cluster 2 consists of 25 authors, being represented by Abdel-Rahman, Gomaa N.; Abu-Sree, YH.; El-Hassanin, Adel S.; Saleh, Essam M.; and Samak, Magdy R., with a total link strength of 19. Cluster 3, which includes 23 authors, is represented by Durand, Antonio E.; Hamaker, Bruce R.; Roman-Ochoa, Yony; Tejada, Teresa R.; and Yucra, Harry R., with a total link strength of 21. Cluster 4 comprises 21 authors, with Wang, Qichao; Zhang, Shaoqing; Zhang, Xiuwu; Zhang, Zhongsheng; Zheng, Dongmei; and Zheng, NA., having a total link strength of 19. Cluster 5 consists of 20 authors, with Duta, Denisa E.; Mocanu, Andreea L.; Musta-tea, Gabriel; Stroe, Corina A.; and Ungureanu, Elena L., having a total link strength of 17. Cluster 6 comprises 17 authors, with Atafar, Zahra; Fattahi, Nazir; Khamotian, Razieh; Pirsaheb, Meghdad; and Sharafi, Kiomars, having a total link strength of 24. Lastly, cluster 7 comprises 11 authors represented by Cen, Kuang and Wet, Junxiao, with a total link strength of 34.

Figure 6. Network visualization of authors' citations

The attribute total link strength denotes the cumulative strength of the co-authorship connections between a particular researcher and other researchers [45].

This visualization presents a citation network generated using VOSviewer, where each node represents an author, and the links indicate citation relationships between them. The size of each node reflects the citation impact of the author—larger nodes correspond to authors who are more frequently cited.

The map shows several distinct clusters, each marked by different colors, indicating authors who tend to cite or be cited together: Fakhri, Yadolah appears at the center of the network, indicating a pivotal role with a high number of citations from multiple clusters, suggesting broad influence across the field.

Authors like Wang, Qiang, Dai, Fen, and Bielecka, Joanna are part of a citation pathway that connects to Fakhri, Yadolah, indicating academic influence or methodological relevance. On the right side, Abdallah, Mohamed F. and Abdel-Rahman, Gomaa N. form a secondary citation chain, possibly representing a regional or thematic research group.

The central author, Fakhri, Yadolah, with the highest number of publications, acts as a bridge between author clusters (left and right groups). The left cluster (Bielecka, Joanna; Pan, Liubo; and others) is smaller but connected, indicating collaboration in a subfield or on specific projects with Fakhri, Yadolah. The right cluster (Abdallah, Mohamed F.; Abdel-Rahman, Gomaa N.) indicates strong co-authorship, with multiple connections to Fakhri, Yadolah.

We can observe a limited interconnectivity among peripheral authors, indicating a high potential for encouraging cross-group collaborations to enhance network resilience and diversity.

The linear structure of the network highlights a progression of citation influence from foundational or widely acknowledged authors toward more recent or regionally connected scholars. The diversity of clusters suggests interdisciplinary interest and citation across different domains related to food safety, environmental science, and toxicology.

Analysis of keywords

The analysis tools for software detected distinct keywords and variable numbers of keywords during different time periods, indicating the prevalence and emphasis of diverse topics, research trends, and hotspots in the field of study [46]. The occurrence of focused keywords was determined by the number of publications, exceeding a data threshold of 49 documents with 380 keywords, encompassing both author keywords and keyword plus.

Analyzing all of the keywords, it was found that the term “heavy-metal/metals” was the most commonly used (41 occurrences, accounting for 10.79% of all keywords). This was followed by “exposure/dietary exposure” (25, 6.58%), “cadmium” (20, 5.26%), “trace-elements” (14, 3.68%), “food”, “vegetable”, and “lead” (11, 2.89% each keyword). This indicates that the core research focus of the dataset is on the assessment of health risks associated with heavy metal contamination in food.

The co-occurrence network of all keywords is shown in Figure 7, where the keywords are divided into 19 clusters.

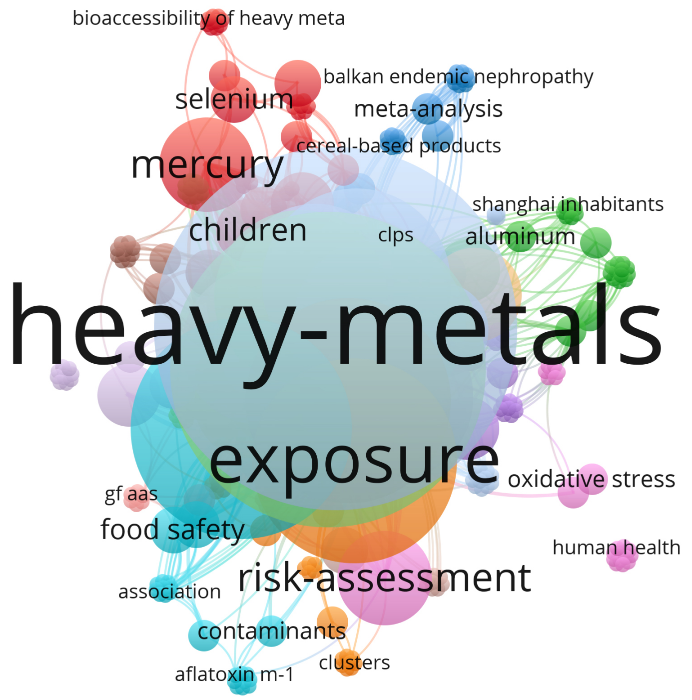

Figure 7. Keyword analysis—co-occurrence network of all keywords

The most representative clusters are:

- The red cluster focuses on trace metals, mercury, pollution, and children, suggesting studies on the toxicological effects of metal exposure, particularly in vulnerable populations.
- The green cluster includes terms like arsenic speciation, pesticides, and Bangladesh, pointing toward regional contamination studies and environmental toxicology.
- The blue cluster highlights meta-analysis, aflatoxins, and cadmium contamination, representing methodological reviews and research on specific contaminants.
- The purple and orange clusters are linked to risk assessment, cereals, fruits, and samples, indicating a focus on dietary exposure pathways and food safety assessments.

Overall, this keyword co-occurrence map provides a comprehensive overview of the key topics and research trends within the field of food contamination and toxicological risk assessment, helping to identify dominant themes as well as potential gaps for future research.

Notably, the commonly used keywords mostly refer to metals and their exposure routes, but there is a limited association with disease or other risk characterizations. The current focus on heavy metal health risk research has been on identifying exposure pathways and determining whether the risk levels surpass the threshold, as determined by quantitative risk indices [11].

Country collaboration analysis

The study performed a bibliometric analysis to determine the number of articles published by different countries based on author affiliation. The findings revealed a significant increase in the number of articles published from China in recent years. Although China started relatively late in 2007 with articles published by Huang et al. [17], 2007 and Zheng et al. [34], 2007, it has become the most productive country, publishing 20 articles on health risk assessment of heavy metals from cereal products between 2014–2024, accounting for almost half of the total publications on this topic. The highest number of documents published by China was in 2020 (5 publications), followed by 2017 (4 publications) and 2024 (3 publications) (Table 3).

Table 3. Top 6 productive countries on research associated with health risk assessment of heavy metals from cereal products, based on authors' affiliation

No.	Country	Publications	Citations	Citation per document	h-index 2024[1] of countries
1	China	20	1,308	65.40	1,455
2	Iran	6	272	45.33	541
3	Brazil	4	98	24.50	844
4	Spain	4	59	14.75	1,303
5	USA	3	161	53.67	3,213
6	Poland	3	89	29.67	792

[1] The h-index of journals was taken from Scimago Journal & Country Rank [32].

The increase in publications in developing countries could be attributed to growing awareness of environmental conservation and public health concerns, as well as the exacerbation of pollution issues due to rapid industrial expansion in recent decades. However, due to advanced technologies and production relocation to other nations, heavy metal pollution is less severe in developed countries compared to developing ones [11].

In recent years, international collaboration in research on the health risks of heavy metals has significantly increased [11]. Several published articles involved co-authors from two or three different countries.

Among the articles co-authored by researchers from two countries, several notable examples are representative. The article "Heavy metals (As, Cr, Pb, Cd and Ni) concentrations in rice (*Oryza sativa*) from Iran and associated risk assessment: a systematic review" was authored by researchers from Iran and Italy [41]. Another example, "Potentially toxic elements (PTEs) in cereal-based foods: A systematic review and meta-analysis", involved collaboration between Brazil and Iran [43]. Additional publications include: "Heavy metal contamination and health risk assessment in grains and grain-based processed food in Arequipa region of Peru" (USA and Peru) [31], "Risk profiling of exposures to multiclass contaminants through cereals and cereal-based products consumption: A case study for the inhabitants in Shanghai, China" (China and USA) [47], "Pb exposure from plant foods in Iran: a review" (Iran and Brazil) [48], and "Co-contamination and interactions of multiple mycotoxins and heavy metals in rice, maize, soybeans, and wheat flour marketed in Shanghai City" (Belgium and China) [49].

In the category of articles co-authored by researchers from three different countries, the most representative examples are: "Quantification of Heavy Metals and Pesticide Residues in Widely Consumed Nigerian Food Crops Using Atomic Absorption Spectroscopy (AAS) and Gas Chromatography (GC)" (Italy, Poland, and Nigeria) [50]; "Lead (Pb) Contamination in Agricultural Products and Human Health Risk Assessment in Bangladesh" (Australia, Bangladesh, and China) [51]; and "Toxicity assessment of heavy metals translocation in maize grown in the Ganges delta floodplain soils around the Payra power plant in Bangladesh" (Bangladesh, Malaysia, and Saudi Arabia) [52].

The countries that have been most active in international cooperation are China and Iran, followed by the USA, Italy, and Brazil. The growing international cooperation in this field may be due to the increasing awareness of the environmental and public health risks posed by heavy metals, as well as the need for joint efforts to combat these problems.

[Figure 8](#) depicts the distribution of countries based on their collaborative relationships and the strength of those relationships. The VOSviewer software identified four clusters of international cooperation. Cluster 1 (red color) consists of Australia, Bangladesh, Malaysia, and Saudi Arabia. Cluster 2 (green color) includes Egypt, Germany, and South Korea. Cluster 3 (blue color) includes Belgium, England, and Peoples R China, while Cluster 4 (yellow color) is composed of Peru and the USA.

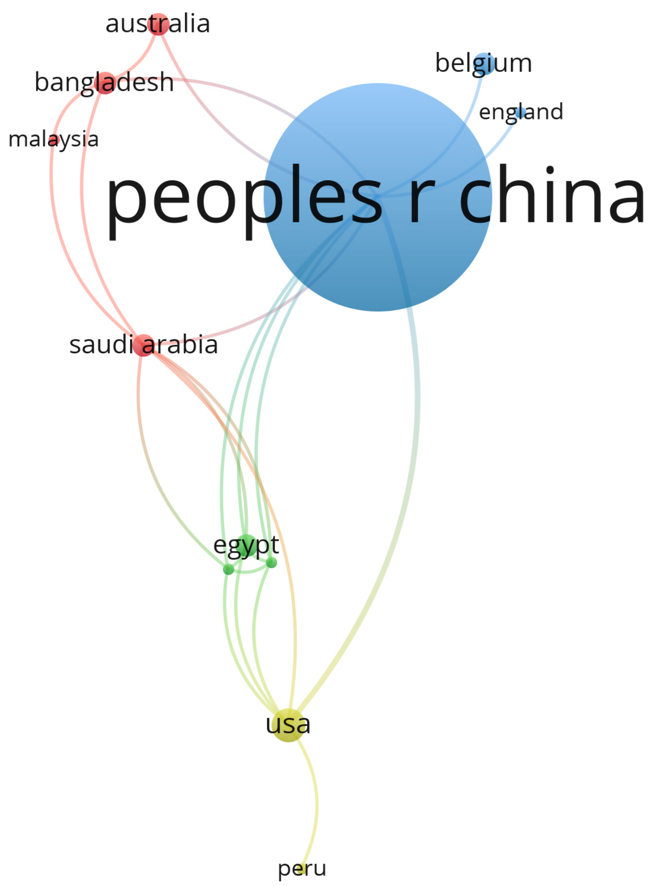

Figure 8. The network visualization of international cooperation

This visualization represents the collaborative relationships among countries based on co-authored publications within the analyzed dataset.

China ("Peoples R China") stands out as the central node, indicating that it has the highest number of publications and serves as a major hub in international collaboration. China has strong collaborative ties with: USA, Saudi Arabia, and Egypt, as evidenced by thicker connecting lines, with European countries like England, Belgium, and Germany, but also with Asia-Pacific partners including Malaysia, Bangladesh, and Australia. The USA forms another key hub, linking to Germany, Egypt, and Peru, suggesting its widespread involvement in international research.

The obtained clusters reveal regional cooperation patterns. The red cluster shows strong collaboration among Saudi Arabia, Malaysia, Bangladesh, and Australia. The strong cooperation between Egypt, Germany, and the USA is represented by the green cluster. European countries like England and Belgium are connected mainly through ties with China.

This co-authorship network suggests that China is the dominant contributor and collaborates extensively with both Western and Asian countries. The presence of multiple clusters indicates regional collaboration trends, while the strong centrality of certain countries (especially China and the USA) emphasizes their leadership roles in international scientific research.

The VOSviewer analysis provided a comprehensive mapping of research trends and collaborative networks in the field of heavy metal contamination, highlighting the growing scientific attention paid to this topic. However, the analysis also revealed a fragmented research landscape, with limited integration of mitigation strategies in the context of heavy metal exposure in the agri-food chain.

To address these challenges, it is essential to move from descriptive studies to the development and application of effective mitigation processes, such as phytoremediation, biochar amendments, and the implementation of precision agriculture practices, to reduce the accumulation of heavy metals in soils and crops [53].

Integrating these mitigation strategies into ongoing and future research can increase the practical relevance of heavy metal studies and contribute to the development of sustainable approaches to reduce the health risks associated with heavy metal exposure through food consumption.

Management of heavy metal pollution

The presence of heavy metals in farmland soils is becoming increasingly concerning due to their accumulation and difficult-to-degrade characteristics. The long-term use of fertilizers and metal-containing pesticides can lead to harmful levels of toxic metal accumulation. In addition, emissions from industry, traffic, and households also contribute significantly to pollution with these contaminants. Given the high toxicity of heavy metals, their accumulation in farmland can lead to the contamination of agricultural soil. As a result, toxic metals can be taken up by crops and accumulate in the food chain, posing a severe potential threat to both human health and the environment. Food crops grown in soil that is contaminated with toxic metals have the potential to accumulate these contaminants, which can have negative effects on the quality and safety of the food [54].

Consuming vegetables contaminated with heavy metals can have severe health implications for humans, including gastrointestinal cancer, weakened immune systems, mental growth retardation, and malnutrition. These heavy metals can accumulate in bones or fatty tissues through dietary intake, causing a depletion of essential nutrients and weakened immune defenses. Intrauterine growth retardation is also a concern for certain heavy metals, such as Al, Cd, Mn, and Pb [55]. One way to prevent the adverse effects of heavy metals on human health is to live in a clean environment and consume uncontaminated products.

For this purpose, the concept of the “right to environment” is considered to be a collective or solidarity right. Leib [56] (2011) divided substantive environmental rights into six sub-rights: the rights of nature, the right to a clean environment, the rights to natural resources, the right to water, the right to food, and indigenous land rights. The right to a clean environment is associated with preventing pathogens, toxins, and pollutants from entering the soil, which can pose high risks to ecosystems and human health. Considerable progress has been made by humanity in environmental issues, and today, the idea of a human right to a healthy environment is widely recognized in international law and supported by a large number of countries [57, 58]. Environmental legislation, court decisions, or the ratification of international agreements reflect the right to a healthy environment in the constitutions of 177 of the 193 UN member nations. The right to a suitable environment is a statutory right in most national constitutions [57, 58].

Although there is no specific policy on soil protection in the European Union (EU), a number of EU legal instruments exist for preventing soil contamination. The EC believes that soil protection can best be achieved by integrating it into other policies, such as those related to environmental, agricultural, regional development, transport, and research policies. Soil monitoring and the development of new actions based on monitoring results are also considered crucial by the EC [58, 59].

In regards to preventing soil contamination, the council of Europe in 2003 [60] suggests several methods, including: implementing strict controls over above-ground or below-ground installations, storage areas, and dumps; conducting ongoing monitoring of sites and surrounding areas; promptly and adequately addressing any incidents that occur; conducting an environmental audit prior to any change in site ownership and reporting such changes to public authorities [58].

Furthermore, the council of Europe in 2003 [60] provides a set of recommendations for the restoration of contaminated soils, which include: a) the implementation of systems to identify potential damage to soil resources and take appropriate action; b) regulations for spatial and town planning that include measures to ensure the subsequent use of previously polluted sites is appropriate and based on risk assessments; c) the identification of technical and financial responsibility for restoring contaminated soil based on the "polluter-pays principle"; d) the selection of restoration techniques that use physical, chemical, and biological processes. However, in some cases, it may be preferable to leave polluted sites undisturbed to avoid reactivating certain contaminants that have already been immobilized [58].

Mitigation processes

Ensuring food safety is a top priority worldwide, and it is jeopardized by human activities that release heavy metals into the environment, including wastewater irrigation, sludge application, and industrial discharges. Thus, remediating heavy metal pollution in soil is crucial to prevent its transfer into the soil-crop system. The pathways of heavy metal translocation from soil to crops are well-established, and efforts to remediate contaminated soil should focus on decreasing metal concentrations to minimize their subsequent transfer into crops [55].

There was a significant focus on the occurrence and development processes of contaminated soil, remediation techniques, and their applications. Specifically, research on the remediation of contaminated agricultural soil emerged as a current and important scientific issue and frontier field [46]. The remediation of heavy metals in soil is crucial for food safety and can be achieved through various methods that are environmentally friendly, rapid, and cost-effective. These approaches can be physical, biological, ecological, or chemical [55].

Remediation technologies can be classified into two types. The first classification is based on the location of the remediation treatment project, which can be either in situ or ex situ. In situ remediation techniques include bioremediation, immobilization, and stabilization, while ex situ remediation techniques include immobilization and stabilization, incineration, thermal desorption, and bioremediation. Among these technologies, bioremediation is currently the most commonly used innovative technology. However, many of these technologies have limitations in their scope of application and can potentially be expensive. Therefore, in addition to developing new remediation technologies, methods that can accurately evaluate the remediation target value are essential. Evaluating the bioavailability of heavy metals in soils is currently a popular topic in this field [46, 61].

Bioremediation, phytoremediation, electrokinetic remediation, and soil washing are some of the most widely used technologies for soil treatment. Bioremediation, which employs animals and microbes to remove, break down, and transform soil contaminants, is considered an economical and eco-friendly process compared to other methods like chemical and physical techniques. Similarly, phytoremediation is also a cost-efficient and environmentally friendly approach. However, bioremediation and phytoremediation have the drawbacks of low efficiency and a long implementation time. Consequently, researchers have started to explore the potential of combining various soil remediation technologies since 2011. This trend is evidenced by the significant research connections between different soil remediation technologies. For instance, bioremediation has been combined with electrokinetic remediation and phytoremediation [62].

The concept of phytoremediation was presented as a "green technology", but there were several practical limitations to its implementation. Instead of serving as a permanent solution for removing pollutants from the soil, the literature suggested that plant stabilization might be a way to reduce the bioavailability of polluting elements in situ. One commonly used technique of phytoremediation is phytostabilization, which involves the physical stabilization of a contaminated site through the use of vegetation cover. This method relies on the use of metallic-tolerant plants to reduce the bioavailability of heavy metals in the soil and immobilize them belowground to prevent them from entering the food chain [46, 63].

In addition to conventional physical and chemical treatment technologies, such as soil replacement, washing, heat treatment, solidification, and vitrification, studies were conducted to investigate changes in the form, availability, and effects of metals [46].

Nanotechnology is a promising area for the remediation of metallic contaminants. The H-G concept, which combines human health risk assessment with geospatial technologies, can help identify problematic soil sites and develop effective remediation measures. Land use policies and shifts should also be considered to locate agricultural fields away from sources of heavy metal contamination. The production of organic food without chemical applications is a multifaceted strategy that is gaining popularity worldwide, but it may not be feasible everywhere due to its high cost [55].

Gaps and recommendations

A key gap identified in this study is the limited number of publications addressing contamination and human exposure to toxic metals through the consumption of food products, resulting in an incomplete understanding of the associated health risks. Additionally, the analysis revealed a significant lack of collaboration among countries, authors, and research organizations, which restricts the development of comprehensive and comparative studies on this topic.

To address these gaps, it is essential to encourage the development of systematic review papers that can synthesize current trends and exposure pathways, providing a clearer picture of the global situation. Researchers should actively seek funding opportunities and participate in international collaboration initiatives to facilitate the exchange of data and methodologies. Organizing conferences, workshops, and webinar series dedicated to toxic metal contamination and exposure can enhance knowledge sharing within the scientific community. Furthermore, proposing special issues in targeted journals and using joint publications can foster interdisciplinary and multinational studies, allowing for a more robust and holistic assessment of toxic metal contamination and its implications for public health [64].

The VOSviewer co-occurrence analysis of keywords revealed several core research topics within the dataset, with “heavy metals,” “food”, “health risk,” “toxicity,” and “consumption” forming the central nodes of the network. These keywords, due to their high frequency and strong centrality, indicate that risk assessment of heavy metals in food systems remains a central research focus in this field.

Research hotspots identified include the assessment of toxic elements such as mercury and cadmium in food, their health impacts, and the evaluation of exposure through diet. Clusters related to “oxidative stress”, “trace elements”, and “risk assessment” point to an active interest in studying the mechanistic pathways of heavy metal toxicity and their biomarker responses in humans, which are currently areas of intensified research.

The main future trends and directions in the field of risk assessment of toxic metals from cereal products include: (1) the integration of advanced analytical methods for heavy metal detection in complex food matrices, aligning with the increasing demand for precise exposure assessments; (2) the exploration of regional variations in heavy metal contamination and its correlation with dietary patterns, particularly in developing countries, which represents a growing interdisciplinary research area; (3) studies linking chronic low-level exposure to heavy metals with non-communicable diseases through pathways such as oxidative stress and gut microbiome disruption, reflecting the shift from acute toxicity studies to chronic health impact evaluations.

Additional emerging areas for development in the coming year include the analysis of co-contamination by microplastics and heavy metals, the investigation of climate change effects on heavy metal mobilization within agricultural systems, and the application of AI (artificial intelligence) and machine learning for predictive risk assessment modeling.

Considering the widespread presence of heavy metals across various environmental compartments, a promising research hotspot is the application of AI for managing heavy metal pollution within the agri-food chain. AI and machine learning tools can facilitate the integration and analysis of large, complex datasets derived from soil, water, crop, and food contamination monitoring, enabling predictive modeling of heavy metal accumulation and mobility. These technologies can support the development of early warning systems, guide targeted interventions to mitigate contamination, and optimize monitoring strategies, thereby enhancing food safety and environmental sustainability. Moreover, AI-driven decision support systems can assist policymakers and stakeholders in designing effective risk management frameworks for heavy metal pollution in agriculture, aligning with the goals of precision agriculture and sustainable food systems [64].

Conclusions

In order to obtain a comprehensive understanding of research trends and contributions in the field of health risk assessment of heavy metals in cereal products, this study employed bibliometric analysis methods. A total of 49 articles published globally between 2000 and 2024 were examined, focusing on variables such as international and institutional collaboration, keyword usage, author productivity, and citation frequency. The findings revealed a notable growth in publication output, rising from just 2 articles in 2007 to 49 by 2024, underscoring the increasing awareness and concern regarding heavy metal contamination and its potential health risks. Most of the research was published in the journals Environmental Science and Pollution Research and Science of the Total Environment, with the most frequently cited studies authored by Zheng et al. [34] (2007) and Huang et al. [17] (2007).

China emerged as the leading contributor, accounting for nearly half of all publications, followed by Iran, Spain, and Brazil. China appears as the dominant hub, shown by the largest node and the most numerous and strongest connections. This indicates that China has the highest volume of research output and is highly collaborative internationally. The USA also plays a central role, with strong collaboration links particularly with Germany, Egypt, and China, reflecting a broad international research network. Countries like England, Belgium, Bangladesh, Malaysia, and Peru have fewer but still notable connections, often linking through major hubs like China or the USA, suggesting they are more peripheral yet active collaborators.

A large proportion of the studies focused on exposure pathways and the evaluation of carcinogenic and non-carcinogenic health risks at local or regional scales. The results suggest a pressing need for countries to undertake long-term investigations into the health impacts of heavy metal contamination in food, and to develop tailored preventive strategies aligned with their specific national contexts.

Given that many of the reviewed studies reported health risk levels exceeding regulatory thresholds, the establishment of ongoing national monitoring programs is strongly recommended. These programs would help manage and mitigate the presence of heavy metals in food products, thereby safeguarding public health.

Abbreviations

AI: artificial intelligence

EC: European Commission

EU: European Union

HI: hazard index

IFs: impact factors

THQ: target hazard quotient

WOS: Web of Science

Declarations

Author contributions

GM and LB: Conceptualization, Validation, Writing—review & editing, Supervision. ALM and CAS: Investigation, Writing—original draft, Writing—review & editing. ELU: Investigation, Writing—original draft, Writing—review & editing, Supervision. All authors read and approved the submitted version.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

Not applicable.

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