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Heavy Metals in Paddies of Perak, Malaysia: A Health Risk Assessment of Pre- and Post-Pandemic Periods and Global Bibliometric Review

Wan Hee Cheng[1,2]*, Yan Ji Teoh[1,2], Walton Wider[3], Kumar Krishnan[1,2], Chee Kong Yap[4], Leilei Jiang[5,6], Yixiao Cao[7], Rong Zou[8], Hao Wu[3], Kok Song Lai[9], Lina Gozali[10] and Wei Huang[1]

[1]Faculty of Health and Life Sciences, INTI International University, Nilai, Negeri Sembilan, Malaysia
[2]Center for Health, Well-being, and Environmental Sustainability, INTI International University, Nilai, Negeri Sembilan, Malaysia
[3]Faculty of Business and Communications, INTI International University, Nilai, Malaysia
[4]Department of Biology, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Serdang, Selangor, Malaysia
[5]International Cooperation and Exchange Office, Nanjing Normal University of Special Education, Nanjing 210038, China
[6]Faculty of Education and Liberal Arts, INTI International University, Nilai, Malaysia
[7]Massey Institute, Nanjing University of Finance & Economics, Nanjing, China
[8]School of Foreign Languages, Jiangsu Open University, Nanjing, Jiangsu, China
[9]Health Sciences Division, Abu Dhabi Women's College, Higher Colleges of Technology, 41012 Abu Dhabi, United Arab Emirates
[10]Department of Industrial Engineering, Tarumanagara University, Jakarta, Indonesia

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ABSTRACT

Paddy is susceptible to toxic heavy metals due to elevated levels of fertilizer use and biogeochemical processes occurring during redox events in paddy soil. Therefore, concentrations of Cu, As, Cd, Pb, Li, and Mn in paddy plants and sediments from three rice-producing sites in Perak, Malaysia, were quantified, and non-carcinogenic health risks (i.e. ADD, HQ and HI) were assessed. These elements tended to concentrate in the roots, indicating a high degree of retention from the soil. Comparison with a pre-pandemic study showed a relative decline in the concentrations of Cu, As, Pb, and Cd in the roots, stems, and grains of rice since the onset of the COVID-19 pandemic. Notably, all rice grains from both Kerian locations and Hilir Perak contained concentrations of Cu, As, Pb, and Cd within the FAO/WHO guidelines for safe consumption, and this study indicated no non-carcinogenic health risk from consumption for either adults or children (HQ < 1; HI < 1). Additionally, a mapping of the literature in this field from 1970 to the present, contained within the Web of Science (n=603), through both co-citation and co-word analyses, illustrated the intellectual structure of the field and identified emerging research trajectories. Generally, there has been a consistent focus on soil-to-rice transfer, dietary exposure to contaminants and the spatial risk governance. However, there is an increasing focus on remediation of contaminated land and reducing the bioavailability of contaminants in soil.

* Corresponding author
E-mail: wanhee.cheng@newinti.edu.my (Cheng Wan Hee)

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1 Introduction

Rice, scientifically known as *Oryza sativa* L., is among the world's most important cereal crops and is consumed by more than half of the global population, particularly in Asia, where it is a major source of calories, carbohydrates, and essential nutrients (FAO, 2021). Rice production is not only vital to global food security but also provides an important economic base for many developing nations, where smallholder rice production contributes to income generation and poverty alleviation (Seck *et al*., 2012). Although efforts to increase rice production support economic prosperity and food security worldwide, several issues threaten the sustainability of continued production. These threats are primarily attributed to anthropogenic activities, particularly contamination by potentially toxic elements (PTEs) such as heavy metals, which can significantly affect ecosystems and human health (Rodriguez *et al*., 2007; Rinklebe *et al*., 2016; Akram *et al*., 2025). Heavy-metal and metalloid contamination of agricultural soils can adversely affect crop growth and development and may ultimately influence agricultural productivity and food safety (Mondal et al., 2025).

Natural sources of heavy metal contamination originate from weathering processes of the earth's crust, whereas human-induced sources are created via industrial emissions, mining, application of synthetic chemical fertilizers and pesticides (Zakaria *et al*., 2021; Xiao *et al*., 2019; Teng *et al*., 2021). Heavy metals such as Cd, As, and Pb have been well documented in many studies on their toxicity potential and ability to accumulate in rice (Mao *et al*., 2019; Rahman *et al*., 2012). Heavy metals are taken up from the soil through plant roots and are translocated to the aerial parts and ultimately to the grains (Williams *et al*., 2007; Tang *et al*., 2019). Previous studies reported that Cd and As have high mobility and bioavailability in flooded paddy field soils and they are associated with significant accumulation in rice grain causing long-term health risks to consumers (Xiao *et al*., 2019; Du *et al*., 2018). Prolonged consumption of rice contaminated with these metals can cause health problems, such as cancer, cardiovascular illness, and neurodegenerative diseases (IARC, 2012; Satarug *et al*., 2010). Prolonged consumption of rice contaminated with heavy metals can cause health problems. Assessment of heavy-metal exposure should therefore consider not only the total concentration of metals in rice but also their bioavailable or bioaccessible fractions, as these provide a more realistic indication of potential human exposure (Dhevagi et al., 2021). Despite extensive studies on the bioaccumulation of heavy metals in soils and paddy fields prior to the COVID-19 pandemic, a comparison of pre- and post-pandemic data is not well studied. Therefore, the current study focuses on the heavy metal accumulation in soils and paddies in selected sites of Perak, one of the major rice-producing states that had often been overlooked in the northern part of Peninsular Malaysia. To further assess the possible health risks, bibliometric analysis was applied to present a structured bibliometric assessment of global research on heavy metal contamination in rice and its related health risks.

Despite the suitability of bibliometric approaches, comprehensive bibliometric assessments of heavy metal contamination in rice remain limited. Most existing studies emphasize empirical measurement and risk evaluation, while overlooking systematic analysis of how the field itself has developed, how research clusters are interconnected, and where conceptual or methodological gaps persist. Addressing this limitation is essential for advancing cumulative knowledge, guiding future empirical research, and supporting evidence-based policymaking in food safety and environmental governance.

To address this gap, the present study applies a structured bibliometric approach to examine how research on heavy metal contamination in rice has evolved, how research clusters are interconnected, and where conceptual and methodological gaps persist. This assessment is intended to guide future empirical research and support evidence-based policies in food safety and environmental governance.

Therefore, a structured bibliometric study was undertaken to evaluate all global research on heavy metal contamination in rice. Using data from the Web of Science Core Collection, co-citation and co-word analyses were integrated to map the intellectual structure, identify primary and emerging research themes, and highlight areas requiring further scholarly attention. Through this field-level synthesis, the study clarifies how research on rice contamination has evolved and provides strategic insights to inform future research, remediation efforts, and policy development.

The aims of this study are to (1) assess the distribution of metals in the different parts of paddy plants (roots, stems, and grains) and in sediments collected from the selected sampling sites; (2) compare metal accumulation in paddy plants and the health risks of rice consumption between the pre- and post-pandemic periods; (3) identify the intellectual structure of research on heavy metal contamination in rice through co-citation analysis; and (4) detect emerging themes and future research pathways using co-word analysis.

2 Material and Methods

2.1 Sample Collection

Paddy field samples were collected in October 2023 from rice-producing sites in Perak. Paddy grains, stems, roots, and the surrounding sediments were collected from three locations: Kerian 1 (4°03'48.4"N 101°03'51.0"E), Kerian 2 (25°00'57.1"N 100°34'52.2"E) and Hilir Perak (4°03'44.4"N 101°03'53.9"E). For trace metal analysis, all samples were collected from specific sites using a wooden scoop while the collectors wore rubber gloves, and the samples were stored in clean, labelled plastic bags. Samples were collected randomly from each site in triplicate replications and returned to the laboratory for further preparation and analysis.

2.2 Sample Treatment and Metal Determination

All the paddy samples, including grains, stems, and roots, were brought to the laboratory and separated manually. The samples were separated using labelled aluminium foil and dried at 60 °C in an oven to a constant dry weight. The samples were sent to ALS Technichem (M) Sdn. Bhd. for heavy metal concentration determination using an AGILENT 7700 series inductively coupled plasma mass spectrometer (ICP-MS) for As, Cd, Cu, Li, Mn, and Pb. The detection limits were 1 mg/kg for As, Cd, Cu, Mn, and Pb and 5 mg/kg for Li.

2.2.1 Statistical Analysis

Mean values were calculated from the metal concentration data, while differences among samples from different sites were assessed using analysis of variance (ANOVA) in MS Excel (version 2013, Microsoft, Redmond, WA, USA).

2.3 Trace Metals Data Treatment

2.3.1 Enrichment Factor (EF) and Translocation Factor (TF)

The food chain pathway (soil–plant–human) is known as one of the vital pathways for human exposure to soil contamination. The transfer of soil-to-plant is among the significant processes of human exposure to toxic elements via the food chain. The equations used to calculate the enrichment factor and translocation factor followed those reported by Lorestani *et al*. (2011) and Singh *et al*. (2011), respectively., factors are. The value of EF indicates the mechanism of heavy metals absorption from soil to paddy grain, whereas the value of TF examines the transport or transfer of the heavy metals from soil to other parts of the paddy plant (root, stem, grain).

2.3.2 Human Risk Assessment

The Human Risk Assessment (HRA) values, including the hazard quotient (HQ) and hazard index (HI), were calculated using the USEPA 2012 equation (U.S. EPA, 2012; Hang *et al*., 2009). The standard rice Ingestion Rates (IR) used for adults and children were 600 g/day and 198.4 g/day, respectively (Praveena and Omar, 2017). An HI value of <1 denotes possible chronic risks while HI value > 1 denotes possible noncancerous risks.

2.4 Bibliometric Approach

Bibliometric methods provide a quantitative approach to assess the scientific literature by mapping the output of publications, citation patterns, and collaborative networks across disciplines (Wider *et al*., 2024). A series of consistent metrics and indicators of networks give researchers insight into how knowledge evolves, where and how scholarly influence is distributed, and how research focus shifts through time. Bibliometric tools provide insight into the dynamics of research across various stages of the scientific process, allowing researchers to view how their discipline has developed. In addition, bibliometric tools aid researchers in visualizing the connection between theoretical concepts and their respective structures, thus enhancing their research inquiries (Zou *et al*., 2025).

Co-citation analysis is based on the premise that articles cited together share overlapping concepts; therefore, this method can be used to analyze the intellectual structure of a field and the relationships among publications (Jiang *et al*., 2025). In contrast, co-word analysis examines associations formed by the repeated use of terms or phrases to identify conceptual clusters and developmental pathways within a research topic, providing additional insight into how a field has developed and continues to evolve (Wider *et al*., 2024). Together, these methods establish a cohesive framework for understanding the historical development, current focus, and emerging trends in research on heavy metal contamination in rice.

2.5 Data Screening and Data Collection

This review explores the Web of Science (WoS) Core Collection to analyze global publications on heavy metal contamination in rice from 1977 through December 2024 (thereby excluding the 2025 records since they do not have significant citation data). WoS was used for this systematic literature review since it facilitates the inclusion of rigorously indexed high-quality academic sources by providing a uniform, internationally recognized database of peer-reviewed scholarly publications (Wider *et al*., 2024; Zou *et al*., 2025). English language publications were included to standardize language of records, eliminate cross-language, bracket indexing issues and to allow a basis for comparison of the words used to extract keywords, text citation contents, and thematically indexed clusters.

The query was applied to the TOPIC field and incorporated expressions such as (“heavy metal*” NEAR/3 rice), (“trace metal*” NEAR/3 rice), and (“risk assessment” NEAR/5 “heavy metal*” NEAR/5 paddy). The wildcard symbol (*) was included to capture spelling variations and word stems, thereby increasing retrieval sensitivity (Jiang *et al*., 2025). To establish uniformity in our research methodology, the dataset only included articles published in peer-reviewed journals; therefore, we excluded articles that were published as reviews, books or conference proceedings. Journal articles were prioritized for their standardized formats, empirical rigor, and comparability across publication years. After applying all criteria, 603 articles published between 1970 and 2024 were retained, providing a robust dataset for mapping the intellectual and thematic development of research on heavy metal contamination in rice.

3 Results & Discussion

The current study provides a comparative analysis of metal concentrations in paddy collected from Kerian and Hilir Perak during the pre- and post-pandemic periods. The post-pandemic mean concentrations of all heavy metals in the different paddy parts and sediments were determined from the current research sampling (Table 1), whereas the comparative pre-pandemic data were obtained from a previous study by Sibuar *et al*. (2022), which examined heavy metal accumulation at approximately the same locations.

3.1 Heavy metals in different paddy plant parts and sediments in Hilir Perak and Kerian

Based on Table 1, the mean values for Cu ranged from 0.0042 – 0.0220, 0.0025 – 0.0035, 0.0026 – 0.0030, 0.0026 – 0.0030, and 0.0043 – 0.0295 for roots, stem, grain, and sediments, respectively. The concentration of Cu (0.0295 ± 0.0009) in sediments from Hilir Perak was found to be higher than all samples from sites ($P<0.05$). The mean values of As ranged from 0.0003 – 0.0006, 0.0003 – 0.0004, 0.00005 – 0.0002, 0.0047 – 0.0095 for roots, stem, grain, and sediment, respectively. The concentration of As (0.0095 ± 0.0015) in sediments collected from Hilir Perak was the highest among all samples from all sites ($P < 0.05$).

The mean values of Cd ranged from 0.0002 – 0.0004, 0.0001 – 0.0002, 0.00004 – 0.00009, 0.00007 – 0.0002 for roots, stem, grain, and sediment, respectively. The concentration of Cd (0.0004 ± 0.00008) in roots collected from Hilir Perak showed the highest accumulation compared to other paddy parts and sediments ($P<0.05$). On the other hand, Pb mean values ranged from 0.0132– 0.0318, 0.0003 – 0.0025, 0.00006 – 0.0002, 0.0248– 0.0295 for roots, stem, grain, and sediment, respectively. The concentration of Pb (0.0318 ± 0.0150) in roots collected from Hilir Perak showed the highest accumulation compared with other paddy parts and sediments of all sites ($P<0.05$).

For Li, the mean values ranged from 0.0041–0.0064, “Below Detection Limit” (BDL) 0.0002, and BDL 0.0070–0.0156 for roots, stem, grain, and sediment. The concentration of Li (0.0156 ± 0.0015) in sediments from Hilir Perak was the highest among all samples from all sites ($P < 0.05$). The mean values of Mn ranged from 0.0846– 0.1755, 0.1783– 0.3950, 0.0285– 0.3030, and 0.0182– 0.0843 for roots, stem, grain, and sediment, respectively. Surprisingly, The Mn concentration in the stem from Kerian (0.3950 ± 0.0414) had the highest accumulation as compared to other paddy

parts and sediments (P<0.05).

Generally, Cu, As, Cd, and Pb accumulated at very high concentration in roots of the paddy plant (Figure 1). It is reported that paddy rice which is the staple food for a significant proportion of the populations around the world (especially in Southeast Asia) is highly efficient in the accumulation of heavy metals in soil. Studies of accumulation of heavy metals in paddy rice in southwestern China found that Cr, Cd, Pb, Cu and Zn were mainly accumulated in the order of root > stems > leaves (Zhang *et al*., 2020). While in Malaysia, it is reported As, Cd and Pb are higher in roots in Alor Setar (Liu *et al*., 2007; Zakaria *et al*., 2021). The bioaccumulation and translocation factors of heavy metals in paddy plants show that the roots are the main sites of heavy metals retention (especially As and Cd) due to chelation and adsorption (Du *et al*., 2018). However, a recent study in Hanzhong, Shaanxi, China, reported that As and Cd, associated with high mobility, were detected at higher concentration in rice grains, raising concerns for local residents (Xiao *et al*., 2019). The trend in which the roots act as the most important sites of heavy metals accumulation, together with their important contribution to the decrease of heavy metals translocating to the grains and other parts of the plants (reducing potential exposures to humans through eaten and tested rice) is apparent (Du *et al*., 2018; Xu *et al*., 2018; Xiao *et al*., 2019; Zhang *et al*., 2020; Sibuar *et al*., 2022; Aziz *et al*., 2023).

Satpathy *et al*. (2014) reported high levels of Mn in the shoots or stems of paddy. This is in line with our findings where the mean value of Mn was highest (0.751±0.544) in the stems compared to other parts of paddy and sediments. In Malaysia, this metal tends to occur more in the aerial parts of paddy compared to other heavy metals. For instance, in a study done in Kota Marudu, Sabah, it was found that Mn was the most prevalent metal in the rice husks, leaves and shoots (Yap *et al*., 2009). The elevated occurrence of this element in the aerial parts of the plant may be due to soil composition, plant physiology, and environmental characteristics, leading to its bioavailability and subsequent uptake by plants. This is particularly relevant in rice paddy fields, where soil conditions may promote Mn reduction and subsequent toxicity (Lidon, 2002). On top of that, the overexpression of specific transporters like OsNRAMP5 in rice can influence the uptake and translocation of Mn. While overexpression of OsNRAMP5 increases Mn uptake into the roots, it has a relatively small effect on Mn accumulation in the shoots, suggesting a complex regulatory mechanism that controls Mn distribution within the plant (Chang *et al*., 2020). Previous research in Malaysian paddy fields has reported the occurrence of heavy metals in agricultural soils and rice, highlighting potential concerns associated with their accumulation and consumption. Variations in metal concentrations among different paddy-growing regions further emphasize the need for continued monitoring of heavy-metal contamination and associated dietary risks in Malaysia (Yin et al., 2023).

3.2 Enrichment Factor (EF)

Enrichment factor (EF) was calculated to evaluate the transfer of the studied heavy metals (Cu, As, Cd, Pb, Li, and Mn) from soils to grains, and the results are displayed in Figure 1. The enrichment factor of the heavy metals was in decreasing order of Mn > Cd > Cu > As > Pb > Li. Despite the low level of heavy metals in paddy grains as shown in Table 1, there were a few heavy metals in which the EF values of several heavy metals were greater than 1 based on the average reading, mainly Cd and Mn. According to Figure 1, samples with EF more than 1 are from Kerian 1 and Kerian 2 paddy fields. Kerian 2 exhibited the highest EF for Mn (9.8697) and Cd (1.3636), followed by samples from Kerian 1 for Mn (8.3928) and Cd (1.3043).

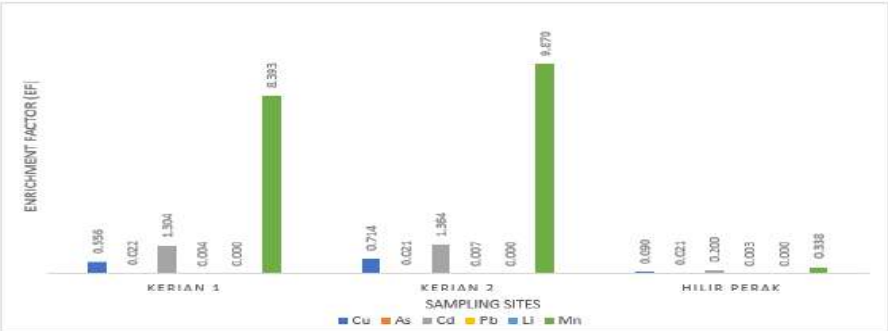

Figure 1 Enrichment factor from the soil to paddy grain from three sampled locations (Kerian, Kerian 2 and Hilir Perak).

Table 1 Heavy metals concentration in paddy plants and sediments collected from Kerian and Hilir Perak.

Collected Materials	Location	Heavy Metals Concentration (mg/kg)					
		Copper (Cu)	Arsenic (As)	Cadmium (Cd)	Lead (Pb)	Lithium (Li)	Manganese (Mn)
Roots	Kerian 1	0.0059±0.0002	0.0003±0.00004	0.0002±0.00004	0.0226±0.0029	0.0041±0.0003	0.0846±0.0276
	Kerian 2	0.0042±0.0007	0.0006±0.0002	0.0002±0.00008	0.0132±0.0019	0.0042±0.0005	0.1261±0.0445
	Hilir Perak	0.0220±0.0011	0.0006±0.0001	0.0004±0.00008	0.0318±0.0150	0.0064±0.0001	0.1755±0.0401
Stem	Kerian 1	0.0025±0.0001	0.0003±0.0001	0.0002±0.00004	0.0012±0.0007	0.0001±0.00002	0.3950±0.0414
	Kerian 2	0.0035±0.0006	0.0004±0.0002	0.0002±0.00006	0.0025±0.0008	0.0002±0.0002	0.2103±0.0742
	Hilir Perak	0.0028±0.0002	0.0004±0.0001	0.0001±0.00003	0.0003±0.000006	BDL	0.1783±0.0546
Grain	Kerian 1	0.0029±0.0001	0.0001±0.00001	0.0001±0.00001	0.0001±0.00003	BDL	0.1530±0.0175
	Kerian 2	0.0030±0.0003	0.00005±0.0001	0.0001±0.00001	0.0002±0.00003	BDL	0.3030±0.0476
	Hilir Perak	0.0026±0.0003	0.0002±0.00005	0.00004±0.00002	0.0001±0.0000	BDL	0.0285±0.0019
Sediments	Kerian 1	0.0054±0.0003	0.0059±0.0005	0.0001±0.00004	0.0248±0.0050	0.0070±0.0004	0.0182±0.0040
	Kerian 2	0.0043±0.0008	0.0047±0.0006	0.0001±0.00004	0.0284±0.0012	0.0098±0.0005	0.0307±0.0011
	Hilir Perak	0.0295±0.0009	0.0095±0.0015	0.0002±0.00001	0.0295±0.0009	0.0156±0.0015	0.0843±0.0115

An enrichment factor (EF) of more than 1 means that the plant not only absorbs heavy metal from the soil but also effectively accumulates it to higher concentrations in the plant than the surrounding soil (Sibuar *et al*., 2022). Compared to other cereal crops, rice accumulates more Cd and is the major dietary source of Cd for rice-eating populations (Grant *et al*., 2008; Arao *et al*., 2010). Cadmium is one of the most mobile and bioavailable elements occurring naturally in soils. Cadmium is not essential for plant growth or biological functions but is readily taken up by the roots of agricultural crops and transported to the crops' grains (Grant *et al*., 2008; McLaughlin *et al*., 1999).

An elevated EF value for heavy metals in paddy soils is a serious problem from the agricultural and environmental point of view owing to the specified paddy conditions favourable to these metals. Paddy soils undergo alternating flooding and drainage conditions, resulting in redox fluctuations that can influence the solubility and availability of Cd and Mn. Under flooded soil conditions, solubility and mobility of Mn increases compared to Cd whose availability depends on soil pH, organic matter and competing ions (Rinklebe *et al*., 2016). Such conditions are enhanced by the use of phosphate fertilizers, application of contaminated irrigation water, and industrial effluents leading to elevated EF in paddy soils (Hu *et al*., 2016; Zhao *et al*., 2015; Honma *et al*., 2016; Liu *et al*., 2011).

It has been reported that the enrichment of Cd and Mn in paddy soils is a global concern, with prominent contamination in China, Bangladesh and Southeast Asia. For example, paddy soils in China are largely contaminated with Cd (with high EF values arising from industrial pollution and intensive cultivation) (Hu *et al*., 2016; Zhao *et al*., 2015). In Bangladesh, paddy soils irrigated with contaminated groundwater accumulated much more Cd and Mn, leading to elevated concentrations in rice grains causing health risks (Rahman *et al*., 2012).

The findings of this study revealed higher concentrations of Cd and Mn in rice grains sampled from Kerian and Kerian 2, indicating that contamination of agricultural soils with these heavy metals could pose a potential risk to human health through the consumption of contaminated rice grains.

3.3 Translocation factor (TF)

The translocation factor (TF) is used to determine the accumulation and mobility of heavy metals in plants. The TF greater than 1 indicates the availability of heavy metals together with their mobility in the plants (Khan *et al*., 2008). In this study, three TFs were calculated: soil-to-root TF (TFsoil), root-to-stem TF (TFroot), and stem-to-grain TF (TFstem) as displayed in Figures 2, 3, and 4. In Figure 2, some of the TF for heavy metals are greater than 1, with the highest values were observed for Mn, ranging between 6.05 – 30.02, and followed by Pb, ranging between 1.10 – 4.19. In Figure 3, the highest TFroot values were observed for Mn (1.02 – 4.66), followed by As (0.67 – 1.00) and Cd (0.25 – 1.00). For TF stems, only two heavy metals showed values greater than 1, which were Mn (1.44) from Kerian 2 and Cu (1.20) from Kerian 1. These results corresponded with the quantification results in Table 1 whereby paddy roots accumulated the highest amount of Mn.

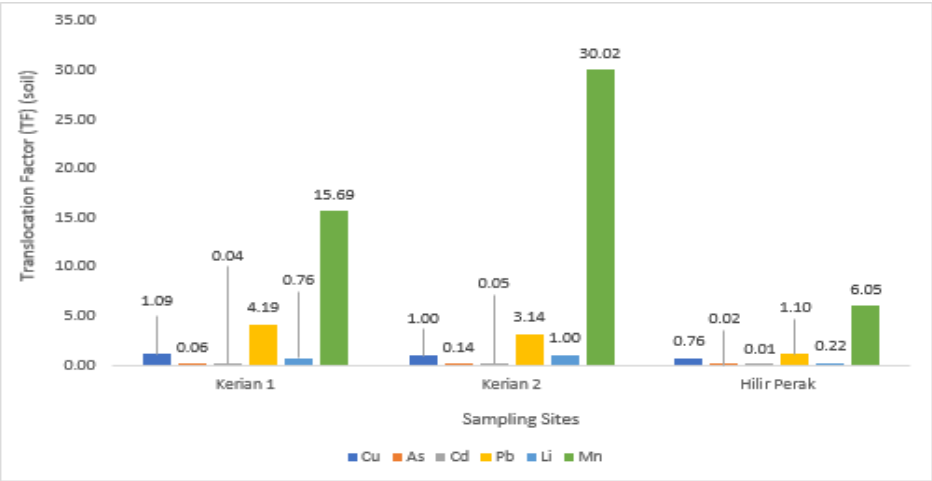

Figure 2 Translocation factor from soil to roots.

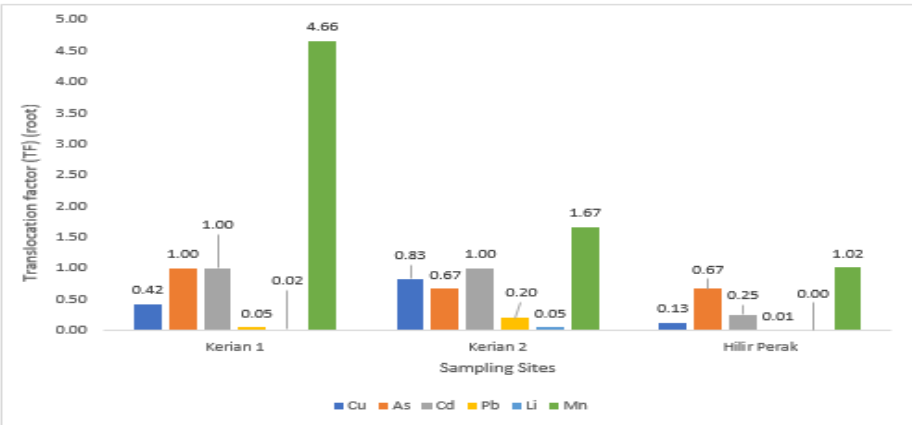

Figure 3 Translocation factor from roots to stem.

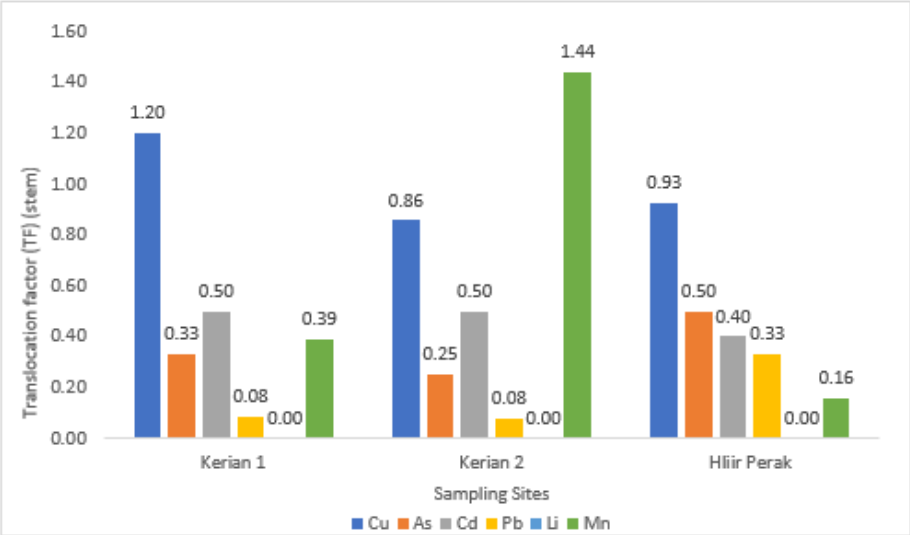

Figure 4 Translocation factor from stem to grain.

3.4 Comparison of Pre and Post Pandemic Period

In this study, the samples that were collected from Kerian and Hilir Perak were compared to the earlier findings from Sibuar *et al*. (2022) as a representation of the pre- and post-pandemic period (Table 2). In this comparison, only selected heavy metals such as As, Cd, Cu, and Pb have been compared, as these are the heavy metals that were analysed in both studies. Since multiple sites were sampled for both Sibuar and this study, the comparisons were made based on the calculated average of all sampling sites for both studies.

In general, a major reduction was observed in heavy metal accumulation from pre- to post-pandemic period in most of the collected sediments and paddy parts. According to Table 2, we observed a major reduction in all paddy parts from both locations, with an average reduction of As (99.8%), Pb (94.6%), Cu (92.8%), and Cd (88.1%) in decreasing order. However, sediments collected from Hilir Perak show an increase in heavy metals accumulation with As (111.3%), Cu (69.1%), and Pb (12.1%), except for Cd with a reduced record of 81.7%. Interestingly, the accumulation of heavy metals (Pb) in sediments from the Kerian region shows a slight increase of 1.2%, while the rest shows a reduction pattern, As (-35.6%), Cd (-93.1%), and Cu (-72.2%).

The COVID-19 pandemic appears to have influenced global environmental quality as it relates to reduced industrial operations, transportation, and agricultural activities. The progressive decrease in the concentration of heavy metals (As, Pb, Cu, and Cd) in the tissues of paddy plants from both Kerian and Hilir Perak is consistent with what has been found globally during and following COVID-19

The marked decline in anthropogenic activities, including industrial operations and transportation, was associated with lockdown measures during the pandemic, leading to reduced emissions and release of heavy metals into the environment (Akhtar *et al*., 2022; Ohadoma *et al*., 2020). For instance, Akhtar *et al*. (2022) reported that, due to restrictions on human activities around the Kerian River mouth, most heavy metal concentrations in water and soil were below or within permissible limits during the pandemic. A study in Nigeria also found that heavy metal risks in crops and soils decreased during the COVID-19 pandemic, with a notable proportion of samples showing non-detectable levels of Cd, Pb, and Ni (Ohadoma *et al*., 2020).

While paddy plant tissues indicated an overall reduction in heavy metal accumulation, the sediment samples showed a more complex pattern of accumulation in Hilir Perak and Kerian. Elevated concentrations of As, Cu, and Pb in samples from Hilir Perak indicate an active local source or post-lockdown resumption of activities which may have contributed to renewed contamination. This spatial variability is consistent with findings from other regions, where heavy metal pollution in paddy fields was found to be non-homogeneous and influenced by specific local sources such as agricultural practices, transportation, and industrial emissions (Xiao *et al*., 2019; Kang *et al*., 2020).

The contrasting pre- and post-pandemic data suggest that changes in heavy metal contamination of paddy tissues may be associated with the interruption of anthropogenic activities. However, regional variability and isolated increases in sediment contamination indicate the need for continuous monitoring and targeted pollution-remediation strategies to ensure safe rice production in the future.

3.5 Human Health Risk Assessment (HRA)

3.5.1 Average daily dose (ADD) and Noncarcinogenic risk during Pre and Post pandemic period

This study compares the average daily dose (ADD) values of selected heavy metals (As, Cd, Cu, and Pb) from Kerian and Sg. Manik (Hilir Perak) with earlier findings from Sibuar *et al*. (2022), representing pre- and post-pandemic periods. The ADD values are presented in Table 3, while the corresponding hazard quotient (HQ) and hazard index (HI) values are presented in Table 4. Only these metals were included, as they were the ones analysed in both studies. In general, we observed the ADD reduction in Kerian for both adults and children as follows: As (both -99.9%), Cd (-85.2%; -84.7%), Cu (-94.3%; -94.1%), and Pb (both -95.6%). In Hilir Perak, the reductions were As (both -99.8%), Cd (-91.7%; -91.6%), Cu (-94.0%; -95.5%), and Pb (both -97.4%).

The HQ values also showed substantial reductions in the post-pandemic period. According to Table 4, the HQ reduction in Kerian for adults and children was as follows: As (-99.8%; -99.9%), Cd (-85.3%; -84.4%), Cu (-94.4%; -94.5%), and Pb (-95.7%; -95.9%). Similar reductions were observed in Hilir Perak: As (both -99.7%), Cd (-92.2%; -91.5%), Cu (-94.3%; -91.1%), and Pb (both -96.3%). The lower HQ and overall HI values indicate reduced

noncarcinogenic risk from rice ingestion and are consistent with the substantial reduction in ADD.

The decline in heavy metal concentrations and ADD post-pandemic may result from a fall in industrial, agricultural and transportation activities during the pandemic, leading to reduced emissions and deposition of heavy metals in agricultural soils (Aravinthasamy *et al*., 2021; Selvam *et al*., 2022). Reported studies showed that the contaminant ratios of water and soil in India and China had dropped by 20% during lockdown periods, with a corresponding decline in the noncarcinogenic risk indices for children and adults (Aravinthasamy *et al*., 2021; Selvam *et al*., 2022). Although some HI values were >1, it was evident that the risk was lower as compared to pre-pandemic level (Aravinthasamy *et al*., 2021; Selvam *et al*., 2022).

The drastic decrease in ADD and non-carcinogenic risk in the post-pandemic period indicates a short-lived improvement in environmental quality and food safety especially in paddy growing regions. This is especially important for children who have generally low body weight and higher exposure levels relative to body mass (Zulkafflee *et al*., 2019; Aravinthasamy *et al*., 2021). Lower ADDs also indicate a decrease in risk of chronic health effects, including damage to the kidneys, neurological damage, and developmental delay.

Despite the observed improvements, some studies indicate that noncarcinogenic risks from heavy metals in rice may still exceed safe thresholds in certain areas, especially where historical contamination or ongoing anthropogenic activities persist (Zulkafflee *et al*., 2019; Sibuar *et al*., 2022; Zulkafflee *et al*., 2021). For example, even after reductions, HI values for certain metals were still > 1 in some populations or specific locations (Zulkafflee *et al*., 2021; Aravinthasamy *et al*., 2021). This highlights the need for continuous monitoring and implementation of pollution control measures to sustain the gains achieved during the pandemic and to protect public health in the long term.

Table 2 Heavy metals concentration in collected samples from Kerian and Hilir Perak (Pre and Post Pandemic Period).

		As			Cd			Cu			Pb		
		*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)
Kerian	Sediment	0.00830 ±0.003	0.00534 ±0.0010	-35.6	0.00276 ±0.0011	0.00008±0.0001	-93.1	0.01747 ±0.0007	0.00484 ±0.0012	-72.3	0.03733 ±0.0136	0.02665±0.0061	+1.2
	root	0.40666 ±0.141	0.00045 ±0.0003	-99.9	0.00150 ±0.0004	0.00020±0.0001	-86.6	0.06133 ±0.0083	0.00505 ±0.0013	-91.6	0.30333 ±0.0950	0.01790±0.0064	-98.0
	stem	0.08733 ±0.011	0.00040 ±0.0002	-99.5	0.00153 ±0.0006	0.00020±0.0001	-86.6	0.10900 ±0.1394	0.00300 ±0.0008	-97.2	0.01570 ±0.0176	0.00190±0.0013	-87.8
	grain	0.07400 ±0.008	0.00010 ±0.0001	-99.8	0.00077 ±0.0004	0.00010±0.00003	-86.6	0.05087 ±0.0535	0.00300 ±0.0004	-94.1	0.00343 ±0.0015	0.00020±0.0001	-94.1
Hilir Perak	Sediment	0.00453 ±0.0004	0.00958 ±0.0026	+111.3	0.00109 ±0.0002	0.00020±0.00002	-81.7	0.01747 ±0.0187	0.02953 ±0.0016	+69.0	0.02633 ±0.0037	0.02953±0.0016	+12.1
	root	1.36667 ±0.1154	0.00060 ±0.0001	-99.9	0.00163 ±0.0004	0.00040±0.0001	-75.5	0.11667 ±0.0057	0.02200 ±0.0019	-81.1	0.35000 ±0.0100	0.03190±0.0259	-90.8
	stem	0.17000 ±0.0519	0.00040 ±0.0002	-99.7	0.00373 ±0.0010	0.00010±0.0001	-97.3	0.11000 ±0.0245	0.00280 ±0.0004	-97.4	0.02800 ±0.0065	0.00026±0.00001	-99.4
	grain	0.35300 ±0.0070	0.00020 ±0.0001	-99.9	0.00080 ±0.0002	0.00004±0.00003	-95.0	0.05833 ±0.0092	0.00260 ±0.0006	-95.5	0.00390 ±0.0016	0.00010±0.00000	-97.4

Note: * Represents pre-pandemic period data were extracted from study done by Sibuar *et al*. (2022).
- Represents reduction in percentage.
+Represents increment in percentage.

Table 3 Average daily dose (Pre and Post Pandemic Period).

		As			Cd			Cu			Pb		
		Pre	Post	Reduction (%)	Pre	Post	Reduction (%)	Pre	Post	Reduction (%)	Pre	Post	Reduction (%)
Kerian	Adult	0.00070	0.0000010	-99.9	0.00001	0.0000011	-85.2	0.00050	0.0000287	-94.3	0.00003	0.0000014	-95.6
	Children	0.00075	0.0000010	-99.9	0.00001	0.0000012	-84.7	0.00051	0.0000305	-94.1	0.00003	0.0000015	-95.6
Hilir Perak	Adult	0.00089	0.0000016	-99.8	0.00001	0.0000006	-91.7	0.00042	0.0000255	-94.0	0.00004	0.0000010	-97.4
	Children	0.00096	0.0000017	-99.8	0.00001	0.0000007	-91.6	0.00060	0.000027	-95.5	0.00004	0.0000010	-97.4

Note: * Represents pre-pandemic period data were extracted from study done by Sibuar *et al*. (2022).
- Represents reduction in percentage.

Table 4 HQ and HI (Pre and Post Pandemic Period).

		HQ												HI		
		As			Cd			Cu			Pb					
		*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)	*Pre	Post	Difference from pre-pandemic (%)
Kerian	Adult	2.3444	0.0032	-99.8	0.0075	0.0011	-85.3	0.0125	0.0007	-94.4	0.0094	0.0004	-95.7	2.3739	0.0054	-99.8
	Children	2.5000	0.0034	-99.9	0.0077	0.0012	-84.4	0.0128	0.0007	-94.5	0.0099	0.0004	-95.9	2.5304	0.0057	-99.8
Hilir Perak	Adult	2.9777	0.0053	-99.7	0.0077	0.0006	-92.2	0.0105	0.0006	-94.3	0.0106	0.0003	-97.2	3.0067	0.0068	-99.8
	Children	2.4222	0.0056	-99.7	0.0083	0.0007	-91.5	0.0079	0.0007	-91.1	0.0082	0.0003	-96.3	2.4465	0.0073	-99.7

Note: * Represents pre-pandemic period data were extracted from study done by Sibuar *et al*. (2022).
- Represents reduction in percentage.

3.6 Publication Trends and Descriptive Analysis

The WoS search identified 603 peer-reviewed journal articles on heavy metal contamination in rice, which together received 26,020 citations (excluding self-citations), of which 24,533 were non-self-citations. The dataset produced an H-index of 84 and an average of 43.15 citations per article, indicating strong scholarly visibility and substantial academic impact. Because this study restricted the dataset to publications indexed through December 2024, the publication trend is reported only through that year. The earliest record appeared in 1977, but research activity remained minimal for several decades. Noticeable growth began after 2010, followed by a rapid acceleration from 2017 onward. The number of publications exceeded 50 in 2019 and reached their highest level from 2021–2023, reflecting heightened global attention to food safety and environmental contamination. Citation counts displayed a similar upward pattern, with a pronounced surge after 2018 and annual citations exceeded 3,000 after 2022 The number of publications exceeded 50 in 2019 and reached their highest level from 2021 – 2023, indicated an increase in worldwide interest in food safety and environmental pollution. Citations counts showed a prominent increase, especially after 2018, and annual citations exceeded 3,000 after 2022. Figure 5 presents the annual distribution of publications and citations from 1977 to 2024.

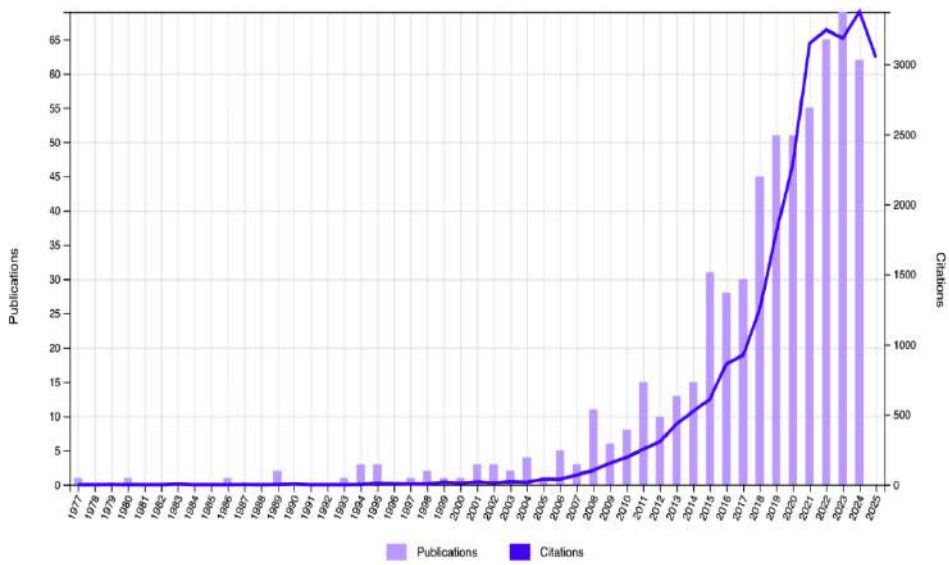

Figure 5 Annual number of publications and citations from 2015 to December 2024.

3.6.1 Co-citation Analysis

The co-citation analysis applied a citation threshold of 14, resulting in 58 referenced works included in the network. Figure 6 presents the resulting co-citation structure. Table 5 highlights the 10 most influential publications based on total link strength. Zhuang *et al*. (2009) ranked first, with 44 citations and a total link strength of 220. Hang *et al*. (2009) followed closely with 36 citations and a link strength of 219. Fu *et al*. (2008) ranked third, supported by 48 citations and a link strength of 216, forming the core of the field's intellectual foundation.

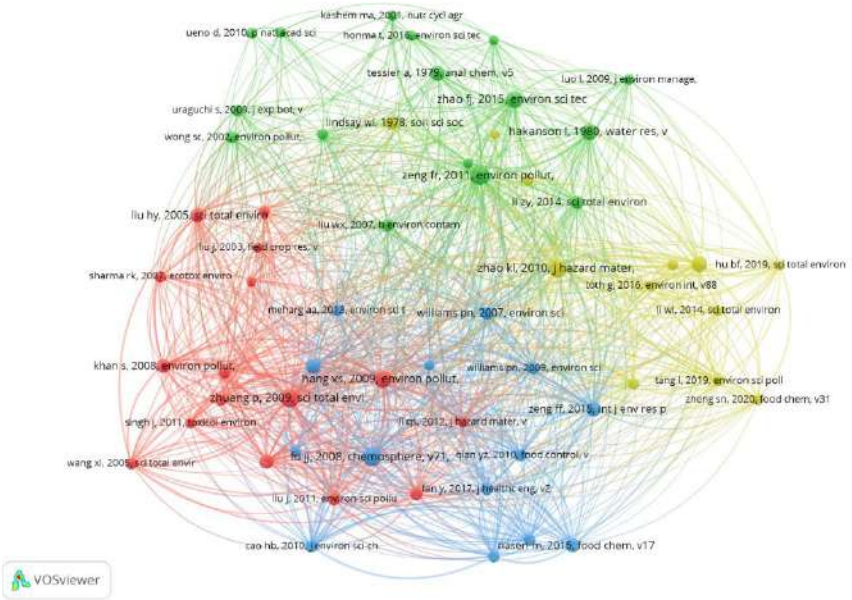

Figure 6 VOSviewer visualization of the co-citation network.

Table 5 Top ten documents based on total link strength.

No.	Documents	Citation	Total link strength
1	Zhuang, P., McBride, M. B., Xia, H., Li, N., & Li, Z. (2009). Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China. *Science of the Total Environment, 407*(5), 1551–1561.	44	220
2	Hang, X., Wang, H., Zhou, J., Ma, C., Du, C. & Chen, X. (2009). Risk assessment of potentially toxic element pollution in soils and rice (*Oryza sativa*) in a typical area of the Yangtze River Delta, *Environmental Pollution, 157(8-9)*, 2542–2549.	36	219
3	Fu, J. J., Zhou, Q., Liu, J., Liu, W., Wang, T., Zhang, Q., & Jiang, G. (2008). High levels of heavy metals in rice (*Oryza sativa* L.) from a typical e-waste recycling area in southeast China and its potential risk to human health. *Chemosphere, 71*, 1269–1275.	48	216
4	Zhao, K. L., Liu, X., Xu, J., & Selim, H. M. (2010). Heavy metal contaminations in a soil–rice system: Identification of spatial dependence in relation to soil properties of paddy fields. *Journal of Hazardous Materials, 181*(1-3), 778–787.	46	194
5	Zeng, F., Ali, S., Zhang, H., Ouyang, Y., Qiu, B., Wu, F., & Zhang, G. (2011). The influence of pH and organic matter content in paddy soil on heavy metal availability and their uptake by rice plants. *Environmental Pollution, 159*(1), 84–91.	46	192
6	Zeng, F., Wei, W., Li, M., Huang, R., Yang, F., & Duan, Y. (2015). Heavy metal contamination in rice-producing soils of Hunan Province, China and potential health risks. *International Journal of Environmental Research and Public Health, 12*(12), 15584–15593.	30	153
7	Cheng, F., Zhao, N., Xu, H., Li, Y., Zhang, W., Zhu, Z., & Chen, M. (2006). Cadmium and lead contamination in japonica rice grains and its variation among the different locations in southeast China. *Science of the Total Environment, 359*(1-3), 156–166.	26	136
8	Zheng, N., Wang, Q., Zhang, X., Zheng, D., Zhang, Z., & Zhang, S. (2007). Population health risk due to dietary intake of heavy metals in the industrial area of Huludao City, China. *Science of the Total Environment, 387*(1-3), 96–104.	19	135
9	Mao, C., Song, Y., Chen, L., Ji, J., Li, J., Yuan, X., Yang, Z., Ayoko, G. A., Frost, R. L., & Theiss, F. (2019). Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. *CATENA, 175*, 339–348.	31	129
10	Williams, P. N., Villada, A., Deacon, C., Raab, A., Figuerola, J., Green, A. J., Feldmann, J., & Meharg, A. A. (2007). Greatly enhanced arsenic shoot assimilation in rice leads to elevated grain levels compared to wheat and barley. *Environmental Science & Technology, 41*(19), 6854–6859.	24	129

The co-citation network analysis identified four major clusters, each reflecting a distinct intellectual direction within the field. These clusters link publications that are conceptually similar, and whose citation patterns closely converge. Within our visual representation, services with the same colour are closely related, showing the existence of cohesive clusters in the research proceedings. The next subsection describes the thematic nature of these clusters, and a description of the cluster itself.

- **Cluster 1 (red)** developed the theme of **"Human Exposure Pathways"**, encompassing 16 publications. This cluster investigates how heavy metal contamination of soils and rice-based food systems provide quantitative risks to human health. Early studies found acute contamination status in the vicinity of mining and smelting areas, with metals migrating to food crops (rice, vegetables, fish) (Zhuang *et al*., 2009; Zheng *et al*., 2007; Liu *et al*., 2005). Research comparing industrialised and wastewater irrigated regions further showed dietary intake as the main route for exposure and publishing on the accumulation of cadmium, lead and arsenic in edible crops and health risk linked to consumption (Hang *et al*., 2009; Khan *et al*., 2008; Sharma *et al*., 2007; Yu *et al*., 2006; Chaudhary & Sharma, 2024). Studies gradually extended into urban environments and the irrigation of crops with sewage, focusing on food-chain transfer and amplification of risk through the soil–plant form factor link (Chary *et al*., 2008; Wang *et al*., 2005). Further research revealed the modes of toxic effects and microbial alteration of nutrient cycling and metal mobility (Singh *et al*., 2011; Järup, 2003). Foundational discussions around food safety raised warning signs that have broader implications for public health (McLaughlin *et al*., 1999; Liu *et al*., 2003). Research using combined exposure models and estimates of potential carcinogenicity show a development towards capacity for health risk evaluation (Li *et al*., 2012; Cheng *et al*., 2006).

- **Cluster 2 (green)** centres on the theme of **"Soil Pollution Dynamics"** and draws on 16 publications. This cluster explores the geochemical, ecological and physiological processes that control heavy metal transport behaviour in rice-tilled land. Foundational work devised geochemical indicators and extraction procedures to identify metal fractions and potential mobility (Hakanson, 1980; Tessier *et al*., 1979). Accumulation analyses revealed major inputs from mines, fertilizer application, industry, and atmospheric conveyance, revealing hotspots and permanent soil contamination (Li *et al*., 2014; Liu *et al*., 2007; Wong *et al*., 2002; Luo *et al*., 2009). More detailed investigations connected soil characteristics, including pH, redox potential, nutrient content, and organic matter, to metal bioavailability, demonstrating how soil environments influence crop uptake potential (Zhou *et al*., 2015; Chen *et al*., 2015; Kashem & Singh, 2001). Physiological studies on rice examine the detection, insertion, and detoxification of metals and the cellular and molecular mechanisms surrounding arsenic and cadmium uptake in rice (Uraguchi *et al*., 2009; Sasaki *et al*., 2012; Ueno *et al*., 2010). Wider assessments of toxicity in plants elaborate on soil-plant interaction and ecology stress responses (Nagajyoti *et al*., 2010; Li *et al*., 2017).

- **Cluster 3 (blue)** presents the theme of **"Dietary Exposure Profiling"**, comprising 14 publications. This cluster examines heavy metal accumulation in rice grains and in complementary food sources that characterize dietary exposure risks. Research in both e-waste impacted areas and river basins in conjunction with agricultural tasks showed As, Cd, and Pb elevated in rice and vegetables, linking to serious potential health effects (Zeng *et al*., 2015; Satpathy *et al*., 2014). Studies have compared information on the cultivation conditions (e.g. aerobic vs flooded systems) facilitating speciation or metals in rice and their accumulation in grains (Williams *et al*., 2007). Other studies evaluate an understanding of multiple exposure through rice, vegetables and drinking water (Rahman *et al*., 2012).

- **Cluster 4 (yellow)** advances the theme of **"Spatial Risk Governance"**, encompassing 12 publications. This cluster took spatial and management-oriented approaches to heavy metal risk in rice growing areas. Studies mapped soil and grain levels around industrial regions, agricultural strips and river basins, highlighting spatial variability in levels of risk (Zhao *et al*., 2010; Li *et al*., 2014b; Tang *et al*., 2019; Hu *et al*., 2019). Soil testing and extraction methods were used to improve the accuracy of spatial assessments (Lindsay & Norvell, 1978; Liu *et al*., 2010). Additional studies suggested risk indices and classifications, and quantitative inventories of metal inputs as a basis for regulatory setting across regions (Mao *et al*., 2019; Lei *et al*., 2015; Zheng *et al*., 2020). Broader research dealt with environmental issues, emphasizing long-term remediation of farmland (Rai *et al*., 2019; Tóth *et al*., 2016; Nagajyoti *et al*., 2010).

Table 6 presents the co-citation clusters on heavy metal contamination in rice. The table displays the cluster labels, publication counts, and all associated publications that underpin each thematic community.

Table 6 Co-citation clusters on heavy metal contamination in rice.

Cluster	Cluster label	Number of publications	Publications
1 (red)	Human Exposure Pathways	16	Zhuang *et al*. (2009); Hang *et al*. (2009); Cheng *et al*. (2006); Zheng *et al*. (2007); Liu *et al*. (2005); Khan *et al*. (2008); Chary *et al*. (2008); Liu *et al*. (2011); Wang *et al*. (2005); Li *et al*. (2012); Singh *et al*. (2011); Järup (2003); McLaughlin *et al*. (1999); Yu *et al*. (2006); Sharma *et al*. (2007); Liu *et al*. (2003)
2 (green)	Soil Pollution Dynamics	16	Zeng *et al*. (2011); Zhao *et al*. (2015); Hakanson (1980); Liu *et al*. (2007); Li *et al*. (2014a); Tessier *et al*. (1979); Zhou *et al*. (2015); Wong *et al*. (2002); Chen *et al*. (2015); Uraguchi *et al*. (2009); Luo *et al*. (2009); Honma *et al*. (2016); Li *et al*. (2017); Kashem & Singh (2001); Sasaki *et al*. (2012); Ueno *et al*. (2010)
3 (blue)	Dietary Exposure Profiling	14	Zeng *et al*. (2015); Williams *et al*. (2007); Satpathy *et al*. (2014); Rahman *et al*. (2012).
4 (yellow)	Spatial Risk Governance	12	Zhao *et al*. (2010); Mao *et al*. (2019); Tang *et al*. (2019); Lei *et al*. (2015); Li *et al*. (2014b); Hu *et al*. (2019); Zheng *et al*. (2020); Lindsay & Norvell (1978); Rai *et al*. (2019); Tóth *et al*. (2016); Nagajyoti *et al*. (2010); Liu *et al*. (2010)

Source: Author's interpretation derived from VOSviewer analysis

3.6.2 Co-word analysis

A total of 59 keywords met the minimum occurrence threshold of 19 and were included in the co-occurrence network. The analysis showed that "cadmium" was the most dominant term (221 occurrences), followed by "rice" (179 occurrences) and "heavy metals" (167 occurrences). The high-frequency keywords indicate consistent research interest in metal toxicity, crop contamination, and soil–rice systems. The top 15 keywords (Table 7) were generated based on prevalence and total link strength.

Table 7 The top 15 keywords in the keyword co-occurrence analysis

Rank	Keyword	Occurrences	Total link strength
1	cadmium	221	1112
2	rice	179	816
3	heavy metals	167	739
4	contamination	111	610
5	accumulation	115	580
6	soil	105	555
7	lead	90	498
8	heavy metal	78	400
9	pollution	77	379
10	cd	65	363
11	plants	78	332
12	heavy metals	59	324
13	bioavailability	51	294
14	zinc	54	273
15	oryza-sativa l.	46	252

Figure 7 shows the resulting network structure, where closely associated terms form visible thematic clusters. These clusters capture the field's major conceptual directions, which are elaborated in the subsequent section.

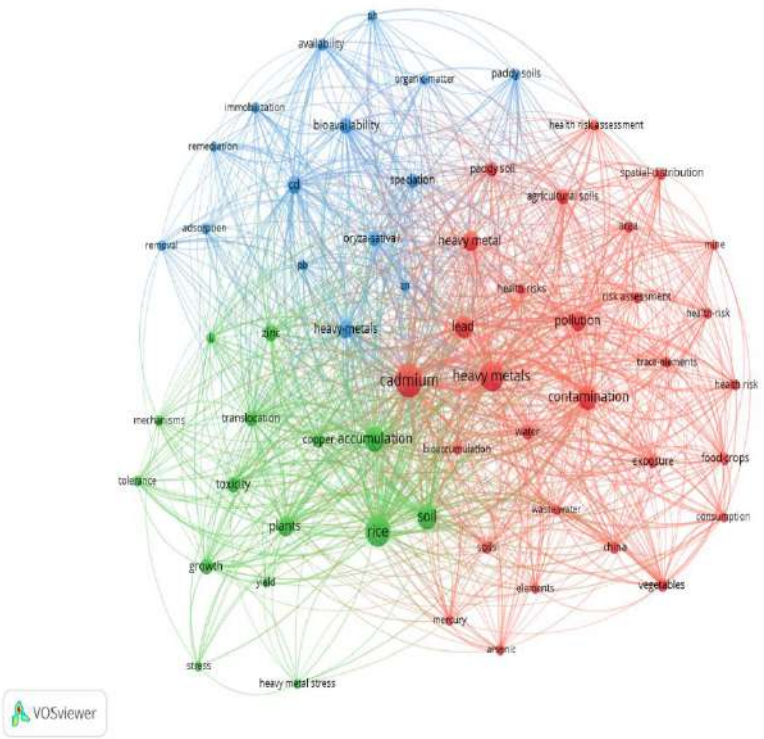

Figure 7 Co-word analysis on heavy metal contamination in rice (VOSviewer visualization).

- **Cluster 1 (red)** develops the theme of **"Diffuse Environmental Pathways of Human Risk"**, encompassing 29 keywords. This cluster illustrates the relationship between metal pollution and its point sources, such as industrial discharge, mining operations, and irrigation sources contaminated with metals, before dispersing through the soil–water–crop interface (Wu *et al*., 2022). Previous studies suggested that pollutants such as Cd, Pb, and As can move through the soil in agricultural areas and eventually entering the human diet through food products such as rice (Ahn *et al*., 2017). Subsequent studies have expanded our understanding of cumulative exposure, as exposure can occur both from direct soil contamination and atmospheric deposition, wastewater irrigation, and long-term bioaccumulation through food chains (Zhang *et al*., 2025). Researchers have also used geospatial mapping and health-based risk-assessment approaches to identify risk areas and populations at highest risk (Yang *et al*., 2021). This transition marks a significant shift from identifying isolated contamination events towards evaluating integrated pathways of exposure through environmental locations based upon human consumption patterns.

- **Cluster 2 (green)** centres on the theme of **"Plant Uptake Dynamics in Soil–Rice Systems"** and covers 15 keywords. This cluster illustrates the concept that recent studies have used

molecular techniques in rice (Fang *et al*., 2022). Early studies considered how variation in soil chemistry, fertility status, climate, and pollutant chemistry govern mobility and root absorption (Zhao & Wang, 2020). Gradually moving to the organismal level, researchers began recognising the importance of tolerance mechanisms, cellular transport, and grain translocation pathways that regulate contamination of edible tissues and husks (Uraguchi *et al*., 2017). Comparative studies have shown that differences in soil texture, redox conditions, and mineral composition produce significant variation in uptake intensity among rice varieties (Li *et al*., 2023). Recent studies utilize molecular techniques to refine the plant response to contaminants, producing yield-contaminated crops (Zhang *et al*., 2018).

- **Cluster 3 (blue)** presents the theme of **"Chemical Behaviour and Remediation Potentials in Paddy Environments"**, comprising 15 keywords. This cluster revolves around the fate and transformation of heavy metals in flooded rice systems and and strategies for reducing their bioavailability? (Lin *et al*., 2020) Work in this field began with an understanding that soil acidity, organic matter, and interactions with minerals affect the speciation and mobility of such toxic elements (Kosolsaksakul *et al*., 2018). As the field advanced, researchers examined how metals bind to soil particles, shift between chemical forms, and re-enter biological pathways under fluctuating waterlogged conditions characteristic of paddy fields (Hamid *et al*., 2018). Concurrent studies explored the use of soil amendment and adsorption remediation techniques designed to bring down pollutant availability during cultivation (Cecire *et al*., 2024). More recently, biochar-based and mineral composite materials such as nano zero-valent iron–modified biochar have demonstrated strong potential to simultaneously immobilize multiple contaminants and enhance soil microbial activity in rice systems (Xiang *et al*., 2024).

Table 8 presents the results of the co-word analysis on heavy metal contamination in rice, outlining the keyword frequencies, representative terms, and assigned thematic cluster categories.

Table 8 Co-word analysis on heavy metal contamination in rice.

Cluster No.	Cluster label	Number of keywords	Representative Keywords (all)
1 (red)	Diffuse Environmental Pathways of Human Risk	29	"cadmium", "heavy metals", "contamination", "lead", "heavy metal", "pollution", "agricultural soils", "water", "paddy soil", "vegetables", "exposure", "food crops", "risk assessment", "soils", "area", "china", "health risk", "health risk assessment", "trace-elements", "consumption", "spatial-distribution", "mine", "arsenic", "bioaccumulation", "health-risk", "health-risks", "mercury", "elements", "waste-water"
2 (green)	Plant Uptake Dynamics in Soil–Rice Systems	15	"rice", "accumulation", "soil", "plants", "zinc", "translocation", "toxicity", "growth", "copper", "l.", "tolerance", "mechanisms", "stress", "yield", "heavy metal stress"
3 (blue)	Chemical Behaviour and Remediation Potentials	15	"cd", "heavy-metals", "bioavailability", "oryza-sativa l.", "speciation", "availability", "paddy soils", "immobilization", "ph", "pb", "zn", "organic-matter", "remediation", "removal", "adsorption"

Source: Author's interpretation based on VOSviewer examination.

3.6.3 Implications of Bibliometric Analysis

The implications of the results of our bibliometric analysis for research development, methodological development, and policy and decision-making in the field of heavy metal contamination in rice are widely discussed. By synthesizing activities over the past 50 years through co-citation and co-word analyses, this study offers a structured understanding of how knowledge in this domain has evolved and where future efforts should be directed.

From a research and theoretical perspective, these identified co-citation clusters suggest that the literature on human exposure to heavy metals in rice has been organised onto discrete but related domains of human exposure pathways, the geochemical risk of soil pollution, profiling patterns of dietary exposure, and spatial governance of risk. Each cluster has developed considerable coherence within itself, but the limited co-referencing between clusters implies that research on heavy metal contamination in rice remains fragmented. Studies that explore the geochemistry of soil and availability in plants (Hakanson, 1980; Tessier *et al*., 1979; Uraguchi *et al*., 2009) can be conceptually disconnected from health risk assessment, and food ingestion models (Zhuang *et al*., 2009; Hang *et al*., 2009; Fu *et al*., 2008). This 'fragmentary' nature serves as a prompt for future studies to adopt and employ frameworks which more explicitly integrate soil processes, plant physiology, dietary ingestion and public health outcomes. Such integration would strengthen causal interpretation and enhance the explanatory power of contamination studies, particularly in regions where rice is a staple food and a primary exposure pathway for toxic metals (McLaughlin *et al*., 1999; Järup, 2003).

The methodological dimensions are no less striking. The co-word analysis is rich in keywords pertinent to Cd, bioavailability, accumulation, and soil–rice interactions denoting that empirical work has focused predominantly on contamination detection and exposure quantification. These approaches are critical to understanding the scale and severity of the issue (Zeng *et al*., 2011; Hu *et al*., 2019; Wu *et al*., 2022), but the relative infrequency of terms engaging with longitudinal monitoring, behavioral exposure mitigation, and governance suggests a gap in these strategies. Empirical scholars may build upon cross-sectional surveys of contamination with longitudinal monitoring, intervention-based designs and multi-source models of exposure in relation to dietary patterns, water access, and socio-spatial vulnerability (Yang *et al*., 2021; Zhang *et al*., 2025). From a bibliometric standpoint, this study also highlights the value in merging co-citation and co-word techniques to reveal not only existing intellectual roots but also potential trajectories for the field, providing a reusable methodological blueprint for other

environmental and food safety domains (Shi *et al*., 2022; Zou *et al*., 2025).

In policy and regulatory terms, the cluster of papers on dietary exposure and management of spatial risk indicates the importance of bibliometric evidence to food safety regulation and land use. The cluster of research conducted on rice contamination in China and other Asian settings highlights not only the intensity of research in these geographical areas but also the vulnerability of populations for whom rice is a staple food (Zhao *et al*., 2015; Li *et al*., 2014b). The spatially oriented literature suggests the role of zoning, soil monitoring, and region-specific remediation to reduce exposure (Zhao *et al*., 2010; Mao *et al*., 2019; Tang *et al*., 2019). Policymakers may therefore use the evidence synthesized in this bibliometric analysis to target surveillance of high risk areas, aid remediation programmes in contaminated soil, and align agricultural practices on food safety regulations that look at cumulative exposure rather than isolated contaminant thresholds (Lei *et al*., 2015; Rai *et al*., 2019).

Finally, the findings provide a guideline for future remediation and sustainability-oriented studies. The growing visibility of keywords and papers associated with bioavailability reduction, immobilization, and soil amendments, are signs of an evolution toward solution-oriented research (Hamid *et al*., 2018; Kosolsaksakul *et al*., 2018; Cecire *et al*., 2024). The bibliometric patterns suggest that remediation studies are still not sufficiently integrative with risk assessment and policy evaluations. Future studies could better link remediation efforts with reductions in dietary exposures and long-term health risks under different cultivation and water-management regimes (Li *et al*., 2023; Zhao & Wang, 2020; Xiang *et al*., 2024). Similar patterns of heavy-metal accumulation and translocation have been reported in Oryza sativa, demonstrating that rice plants can absorb metals from contaminated soils and distribute them among different plant tissues (Katiyar et al., 2022).

Conclusion

The current study highlighted an important food safety and environmental governance problem: heavy metal contamination in rice systems can endanger public health, yet the site-specific available evidence in Perak is scarce, and empirical comparisons before and after the pandemic are rare. These results showed clear tissue partitioning and metal-specific mobility: Cu, As, Cd and Pb were predominantly retained in roots, consistent with the protective role of the root zone limiting transfer to edible grain, while Mn was accumulated more strongly in above-ground tissues, consistent with the physiological role of this metal and its relatively high mobility at paddy redox conditions. Enrichment analysis indicated that Cd and Mn exhibited the most pronounced enrichment from sediment to grain were Cd and Mn. This suggests that even when absolute grain concentrations remain low, transfer from soil to grain can still be enhanced under specific local soil and agricultural management scenarios. In comparing the pre- and post-pandemic patterns, the most notable result was a very large decline in As, Pb, Cu and Cd concentrations across most paddy tissues post-pandemic, which is mirrored by substantial declines in average daily dose, hazard quotient and hazard index for adults and children.

From a public health perspective, the current non-carcinogenic risks from rice consumption at the sampled sites in Perak appear negligible; post-pandemic HQ and HI outputs were <1 for adults and children. This is practically encouraging in terms of ongoing suitability of rice from the sites that we studied yet implies that surveillance work should not be neglected. Trajectories from tightened sediment inputs may precede any future change on plant uptake. The findings imply that interventions should be spatially targeted rather than uniform; Hilir Perak sediments should be monitored for As, Cu, and Pb contaminations; Kerian is of interest for Cd and Mn uptake efficiency where the mechanism may be responsive to water management, soil pH optimization, and amendment-based fixation strategies. At the field-to-policy interface, the bibliometric synthesis adopts a practical approach to begin to strengthen the argument for integrated risk governance, globally the literature clusters into somewhat dissociated domains, with weaker conceptual linkage across soil chemistry, plant uptake, dietary exposure modelling, and tools for governance. This fragmentation suggests that Malaysian efforts going forward could derive high value added by explicitly linking detailed mechanistic evidence from soil to plant, into realistic exposure scenarios and decision-ready management pathways.

In general, heavy metal risks from rice in Perak are presently at low levels, but the study is restricted by its narrow scope and a one-off sampling. Therefore, future efforts will need to focus on long-term monitoring, and on actionable measures which can directly reduce metals in the grain.

Conflict Of Interest

The authors declare that there are no conflicts of interest.

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Contribution Of Authors

Cheng Wan Hee, Yan Ji Teoh, Walton Wider, Kumar Krishnan, and Chee Kong Yap were involved in the research design, experimental work, manuscript preparation, analysis, and data interpretation. Leilei Jiang, Yixiao Cao, Rong Zou, Hao Wu Qijin, Kok Song Lai and Lina Gozali were involved in the data analysis, review and editing.

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