Asian Journal of Agriculture and Biology
https://doi.org/10.35495/ajab.2024.135

Original Article

Heavy metal accumulation in paddy plants and health risks: Insights from southern peninsular Malaysia and global research trends

Yan Ji Teoh[1,2], Wan Hee Cheng[1,2]*, Walton Wider[3,4], Kumar Krishnan[1,2], Chee Kong Yap[5], Qijin Chen[6], Leilei Jiang[6], Thomas Man Tat Lei[7], Tawatchai Tanee[8,9], Runglawan Sudmoon[10], Shiou Yih Lee[1,2]

[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, Negeri Sembilan, Malaysia
[4]Department of Applied Economic Sciences, Wekerle Sandor Uzleti Foiskola, Budapest, Hungary
[5]Department of Biology, Faculty of Science, Universiti Putra Malaysia, 43400 UPM Serdang, Serdang, Selangor, Malaysia
[6]Faculty of Education and Liberal Arts, INTI International University, Nilai, Negeri Sembilan, Malaysia
[7]Institute of Science and Environment, University of Saint Joseph, Macau, 999078, China
[8]Faculty of Environmental and Resource Studies, Mahasarakham University, Mahasarakham 44150, Thailand
[9]One Health Research Unit, Mahasarakham University, Maha Sarakham 44000, Thailand
[10]Faculty of Law, Khon Kaen University, Khon Kaen 40002, Thailand

**Corresponding author's email*: wanhee.cheng@newinti.edu.my
Received: 05 September 2024 / Accepted: 29 November 2024 / Published Online: 23 January 2025

Abstract

This current study assessed the toxicity of selected heavy metals in paddy and sediments of non-major production sites in Southern Peninsular Malaysia, complemented by bibliometric analysis of research trends and health implications of rice contamination. Paddy (grains, stems, roots) and soil samples were collected from seven selected sites in the Southern parts of Peninsular Malaysia and analyzed for their heavy metals content. The health risk assessments were conducted based on estimated daily intake, and the Web of Science database was used for bibliometric analysis. The results indicated elevated levels of manganese, Mn (0.4 ± 0.07), especially in the roots, compared to other heavy metals. Generally, the heavy metal levels in paddy grains were below FAO/WHO's tolerable daily intake levels, indicating minimal non-carcinogenic risks to both adults and children. The bibliometric analysis indicated a significant increase in related publications, reflecting growing academic interest. This study highlights the potential of non-major sites to produce rice with lower contamination levels, provides insights into research trends, and identifies future investigation areas, especially for major production sites and post-COVID-19 periods. Therefore, this study offers a robust scientific context, identifies research gaps, benchmarks findings, and guides future research directions, ensuring an in-depth perception on heavy metal contamination and its health risks.

Keywords: Heavy metals risk assessment, ICP-MS, Bibliometric analysis, Rice contamination, Human health

How to cite this article:
Teoh YJ, Cheng WH, Wider W, Krishnan K, Yap CK, Chen Q, Jiang L, Lei TMT, Tanee T, Sudmoon R and Lee SY. Heavy metal accumulation in paddy plants and health risks: Insights from southern peninsular Malaysia and global research trends. Asian J. Agric. Biol. 2025: 2024135. DOI: https://doi.org/10.35495/ajab.2024.135

This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 License. (https://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Introduction

Rice (*Oryza sativa* L.) is a key energy source, rich in complex carbohydrates, moderate protein, and micronutrients such as vitamin B (Yuan et al., 2017; Kong et al., 2019; Zulkafflee et al., 2021). Rice is not only considered as one of the most important foods for daily consumption globally (Pishgar-Komleh et al., 2011; Abbas et al., 2011; Fukagawa and Ziska, 2019; Sen et al., 2020), but it is also the staple food in Asian countries (OECD and FAO, 2022). Therefore, there is a rising concern on the detrimental effects of heavy metals on the consumption of rice as well as to the environment (Rodriguez et al., 2007).

Khairiah et al. (2013) and Syahariza et al. (2013) reported massive use of synthetic fertilisers and agrochemicals containing harmful metals such as arsenic (As), cadmium (Cd), and lead (Pb) among paddy farmers to boost their crop yields. These metals can bioaccumulate, biomagnify and translocate in these crops (Clemens and Ma, 2016; Kanu et al., 2017; Zulkafflee et al., 2021; Saeed et al., 2023) leading to metal toxicity cases if consumed by human (Zulkafflee et al., 2019; Liu et al., 2022; Sudmoon et al., 2024). Thus, comprehensive monitoring and mitigation strategies to improve heavy metal pollution in the agricultural ecosystem is crucial.

Bibliometric analysis is used in this study to assess the possible health risks associated with heavy metal accumulation in rice. The primary objective is to highlight key results and identify areas that requires further research. It is a quantitative technique that has been widely used to discern the academic landscape surrounding heavy metal contamination in rice production (Dahlal et al., 2024; Ungureanu et al., 2023). This analysis evaluates research patterns, dynamic changes, and organisational structures in academic literature relevant to a particular discipline using statistical techniques (Linnenluecke et., 2020; Wider et al., 2023; Zakaria et al., 2023). The patterns of publication, citations, authorship, and keyword frequencies are analysed to understand the scientific environment, evaluate research outcomes, seek collaborations, and identify both well-established and novel themes (Wider et al., 2024; Wider et al., 2023; Fauzi, 2022). Apart from that, it also offers a brief synopsis of the evolution of the field, key research, and possible future paths which are important strategy formulation resources for academics, legislators, and organisations.

Current trends can be assessed by using bibliographic coupling analysis, which involves looking at studies with shared references (Chandrakumar et al., 2024). This process uncovers interrelated research domains, prevailing themes, methodologies, and noteworthy contributions. On top of that, this approach may allow better understanding on the geographical distribution of studies, isolating specific areas where heavy metal contamination of rice is a significant issue. This study also makes use of co-word analysis to map the co-occurrences of keywords, revealing unexplored research areas and suggests new research pathways (Fauzi et al., 2024). Public health, agricultural science, environmental science, and toxicology are just a few of the fields that could benefit from interdisciplinary collaboration, as this analysis shows.

Combining these bibliometric approaches yields a thorough understanding of the heavy metal research field as it relates to rice, illuminating prevalent trends and suggesting future directions for study. Using an all-encompassing strategy advances our grasp of the field's status and future research efforts, allowing a deeper comprehension of health implications on heavy metal contamination and the issues that surround it.

Previous reported studies in Malaysia emphasized on main paddy production areas while many non-major production areas are not well studies (Rahman et al., 2014; Ruzdi et al., 2018; Zulkafflee et al., 2019). Thus, the current study focuses on the heavy metal accumulation in soils and paddies of non-major producing areas in the southern part of Peninsular Malaysia. To further assess the possible health risks, we applied a bibliometric analysis of previously published research on the topic. By analysing the impact of prior studies and revealing gaps in the literature, bibliometric analysis provides a holistic view of our research trends. In doing so, the result of the analysis sets a benchmark for our findings, situate it within the larger scientific discussion and point the way for further studies on the dangers of heavy metal contamination to human health. The aim of this study is to (i) determine concentrations of metals in the paddy soils and different parts of paddy (root, stalk, and grain) from selected paddy fields of the southern part of Peninsular Malaysia; (ii) assess the health risk of paddy consumption via risk indices; (iii) evaluate current trends in the study of heavy metal accumulation in rice and associated health risk assessments; (iv) determining novel research avenues concerning the accumulation of heavy metals in rice in relation of health risks.

Material and Methods

Sample collections

Paddy field samples were collected from non-major paddy production sites located in the southern part of Peninsular Malaysia. Samples such as paddy grains, stems, roots, and the surrounding soil were collected from eight locations: Bahau (2°48'59.6"N 102°20'55.1"E), Mersing (2°36'11.9"N 102°35'30.0"E), Endau (2°37'50.0"N 103°38'15.1"E), Kuala Rompin (2°39'51.2"N 103°34'53.3"E), Sungai Mati (2°10'27.4"N 102°30'35.4"E), Gemas (2°36'11.9"N 102°35'30.0"E), Gerisek (2°14'23.9"N 102°40'35.5"E), and Semerah (1°53'05.2"N 102°45'53.1"E). For trace metal analysis, all samples were collected from the specific sites using a wooden scoop with hands covered with rubber gloves, and samples were kept using clean, labeled plastic bags. All samples are collected randomly from each site with three replications and returned to laboratory for further analysis preparation.

Samples treatments and metal determination

All the paddy samples, which included paddy grain, stem, and root, were collected and brought to the laboratory, where they were separated by hand. All samples are separated using labeled aluminum foil and dried at 60˚C in the oven to a constant dry weight. All samples were sent to ALS Technichem (M) Sdn. Bhd. for heavy metal concentration determination by using AGILENT - 7700 series, Inductively Coupled Plasma-mass Spectrometer for As, Cd, Cu, Li, Mn, and Pb. The detection limit is 1 mg/kg (As, Cd, Cu, Mn, and Pb) and 5 mg/kg (Li).

Trace metals data treatment

The Human Risk Assessment (HRA) values, including hazard quotient (HQ) and hazard index (HI), were calculated based on the equation presented by USEPA 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).

$$HQ = \frac{ADD}{RfD}$$

Where,
ADD = average daily dose;
RfD = reference dose.

$$HI = \sum HQ$$

Where,
HI < 1 denotes possible chronic risks;
HI > 1 denotes possible noncancerous risks.

Statistical analysis

Mean calculation was applied to the data from the metal determination while the significance of differences among samples of different sites were determined with ANOVA analysis by using MS Excel (version 2013, Microsoft, Redmond, WA, USA).

Bibliometric analysis

We utilized the WoS database to conduct a comprehensive evaluation with close attention on the SCIE and SSCI (Wider et al., 2024). Many reputable academic journals from various disciplines, such as social and natural sciences, via this method and all articles published up until December 31, 2023, were excluded from our investigation. The "TOPIC" search function is used to identify titles, abstracts, and keywords related to our area of interest. The following keywords were used to achieve this objective: ("Heavy Metal Accumulator*" OR "Heavy metal deposit*" OR "heavy metal*") AND (rice OR paddy OR "paddy soil" OR "paddy sediment") AND ("health risk assessment*" OR "human health risk" OR "average daily dose*" OR "average daily intake*"). Our analysis was limited to documents written in English to cater to our primary audience and conform to the prevailing convention of scientific communication. Following the application of the inclusion and exclusion criteria, the screening process retained 505 articles in total.

Results

Comparative analysis of trace metal levels in paddy plants from southern Malaysia

The provided data originates from eight distinct paddy fields throughout central to southern Malaysia. The mean concentration of all heavy metals (Cu, As, Cd, Pb, Li, and Mn) in the different air-dried paddy parts from eight different paddy fields was determined and displayed in Figure 1. Nonetheless, information regarding metal accumulation in the paddy grain from Sawah Ring is unavailable due to challenges in coordinating harvest timing with the local farmers.

https://doi.org/10.35495/ajab.2024.135

Heavy metals in different paddy plant parts and sediments

Generally, all the mean values for copper (Cu) ranged from 0.0005 – 0.0794, 0.0011 – 0.0410, 0.0025 – 0.0223, and 0 – 0.0032 mg/kg for roots, stem, grain, and sediments. The concentration of Cu in roots (0.0199 ± 0.009 mg/kg) was shown to be higher than other paddy parts and sediments, while samples collected from Bahau (0.0794 ± 0.073 mg/kg) have the highest record among all locations (P<0.05).

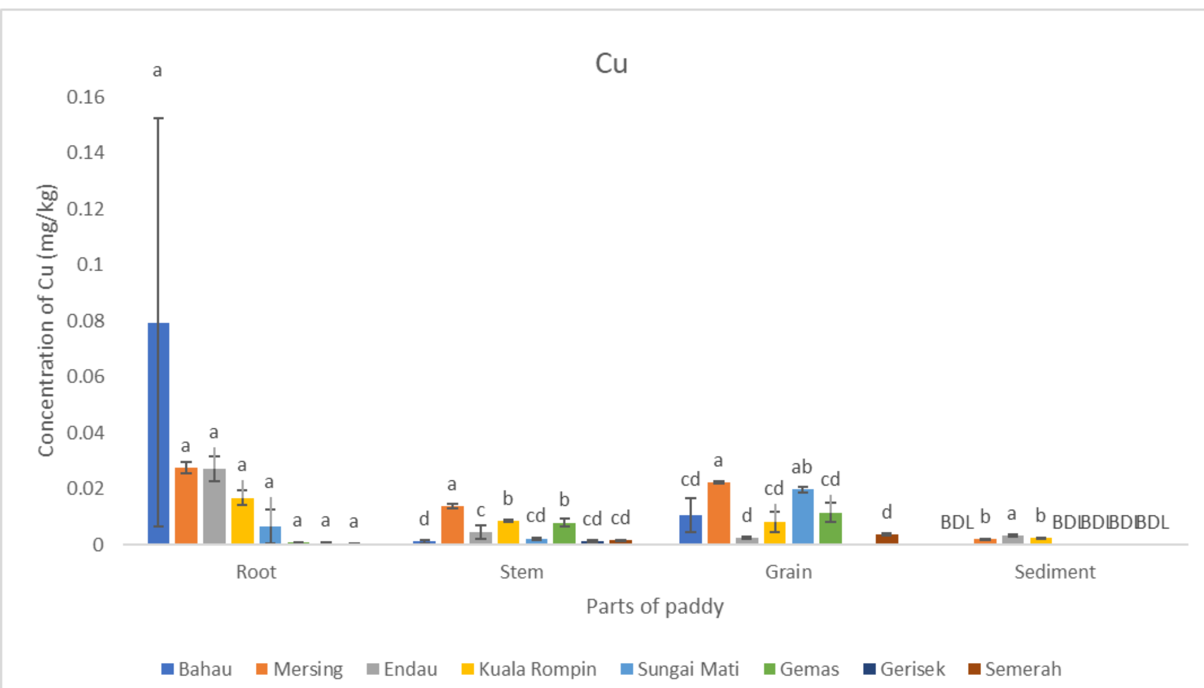
Arsenic (As) mean values ranged from 0.0111 – 0.1320, 0.0005 – 0.0063, 0.0003 – 0.0015, 0 – 0.0155 mg/kg for roots, stem, grain, and sediment. The concentration of As (0.0389 ± 0.014 mg/kg) in roots showed the highest accumulation than other paddy parts and sediments, while samples collected from Gemas (0.132 ± 0.045 mg/kg) have the highest record among all other locations (P<0.05).

Cadmium (Cd) mean values ranged from 0.0003 – 0.0018, 0.0001 – 0.0008, 0.0001 – 0.0006, BDL – 0.00009 mg/kg for roots, stem, grain, and sediment. Concentration of Cd (0.00074 ± 0.0001 mg/kg) in roots shown the highest accumulation than other paddy parts and sediments, while samples collected from Bahau (0.0018 ± 0.0007 mg/kg) have the highest record among all other locations (P<0.05).

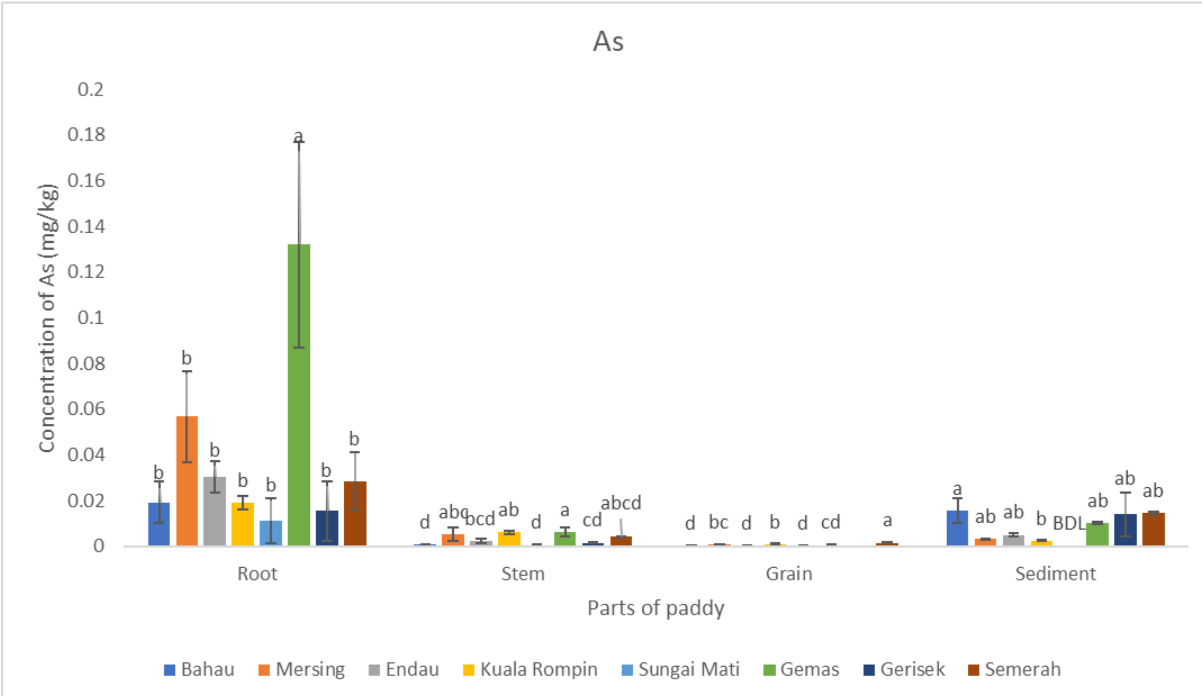
Lead (Pb) mean values ranged from 0.0354 – 0.0743, 0.0004 – 0.0107, 0.0001 – 0.0006, 0.013 – 0.0327 mg/kg for roots, stem, grain, and sediment. The concentration of Pb (0.0493 ± 0.005 mg/kg) in roots showed the highest accumulation than other paddy parts and sediments, while samples collected from Mersing (0.0743 ± 0.0038 mg/kg) have the highest record among all other locations (P<0.05).

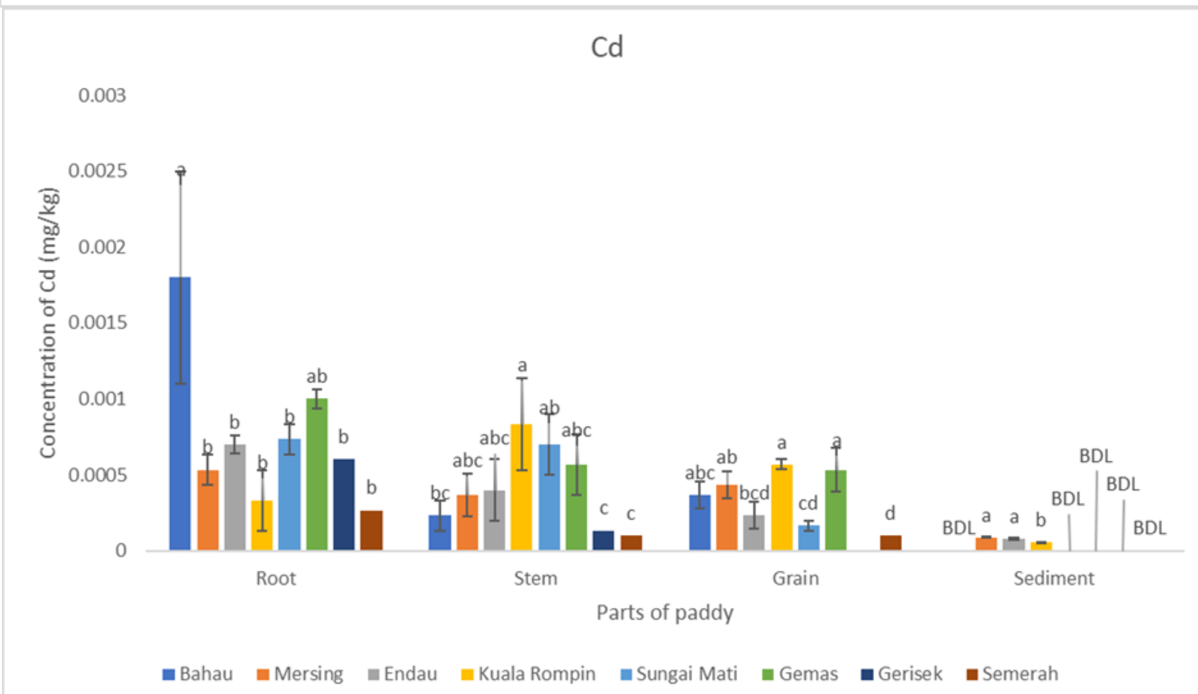
Lithium (Li) mean values ranged from 0.0003 – 0.0111, BDL – 0.0008, BDL – 0.0004, BDL – 0.034 mg/kg for roots, stem, grain, and sediment. Interestingly, the concentration of Li (0.0038 ± 0.0016 mg/kg) in sediments showed the highest accumulation than other paddy parts and sediments, while samples collected from Sungai Mati (0.034 ± 0.0028 mg/kg) have the highest record among all other locations (P<0.05).

Manganese (Mn) mean values ranged from 0.2197 – 0.803, 0.308 – 1.86, 0.1036 – 0.4463, 0.0063 – 0.0908 mg/kg for roots, stem, grain, and sediment. Surprisingly, Mn concentration (0.934±0.186 mg/kg) shows the highest accumulation in stem compared to other paddy parts and sediments, while samples collected from Sungai Mati (1.86 ± 0.336 mg/kg) have the highest record among all other locations (P<0.05).

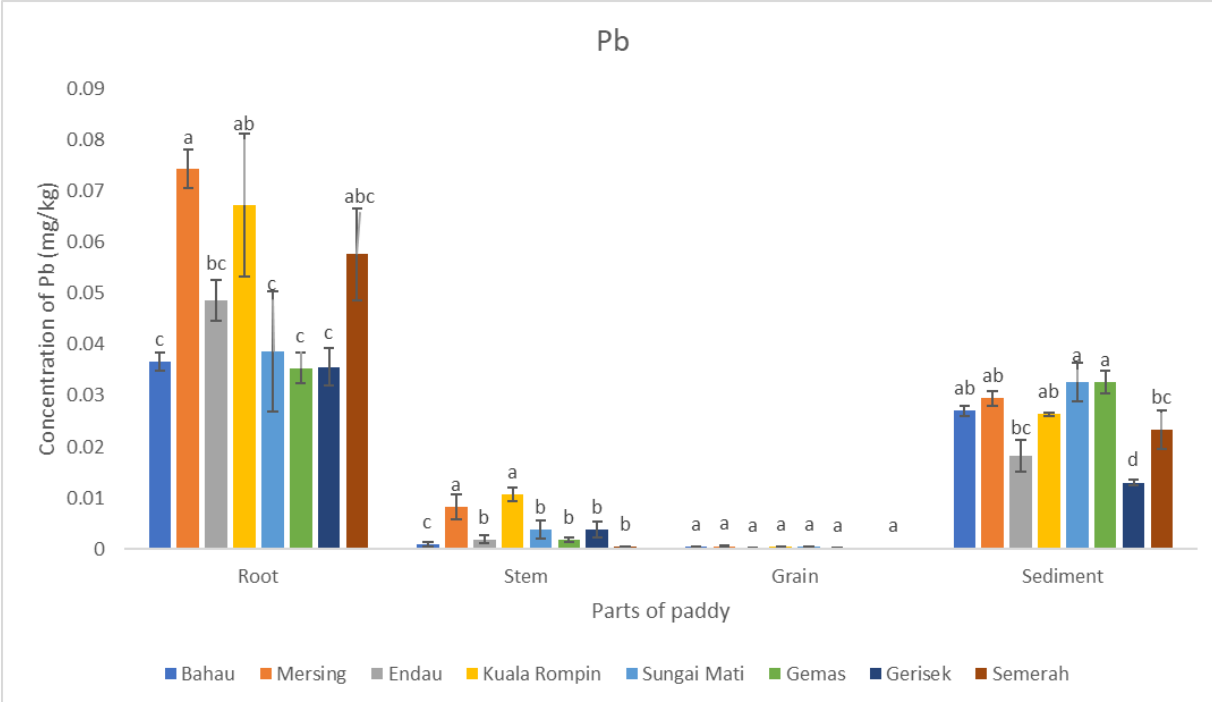


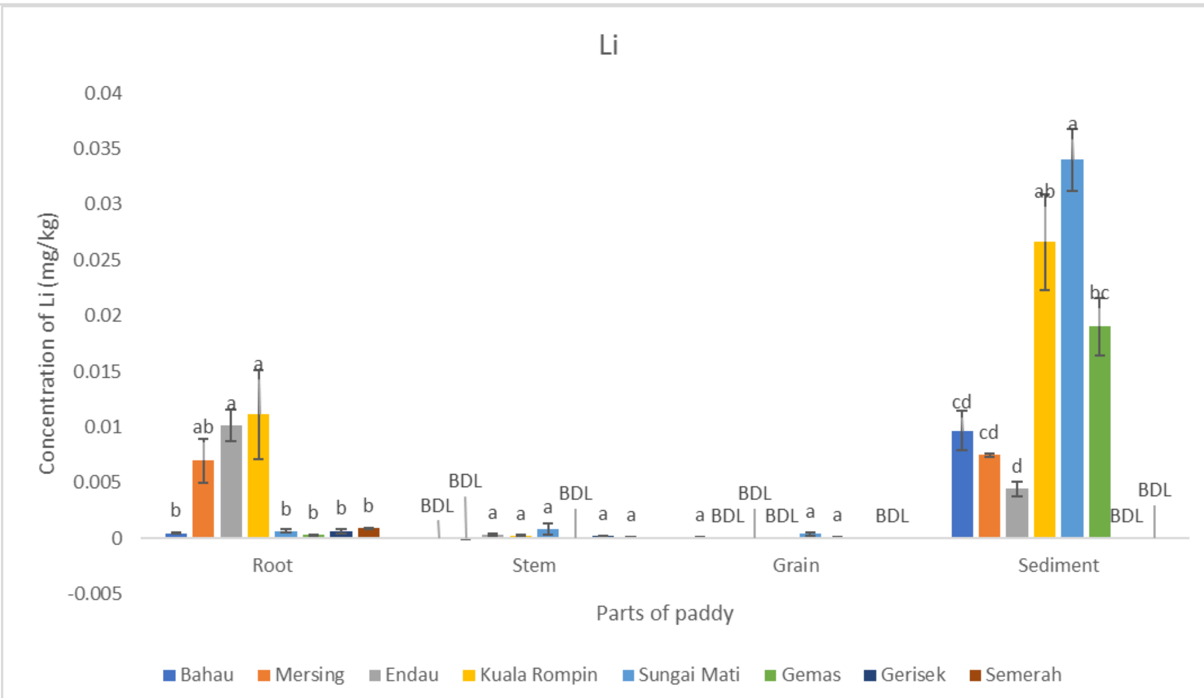
https://doi.org/10.35495/ajab.2024.135





https://doi.org/10.35495/ajab.2024.135


Pb
Concentration of Pb (mg/kg)
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Root
Stem
Grain
Sediment
Parts of paddy
Bahau
Mersing
Endau
Kuala Rompin
Sungai Mati
Gemas
Gerisek
Semerah


Li
Concentration of Li (mg/kg)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
BDL
Root
Stem
Grain
Sediment
Parts of paddy
Bahau
Mersing
Endau
Kuala Rompin
Sungai Mati
Gemas
Gerisek
Semerah

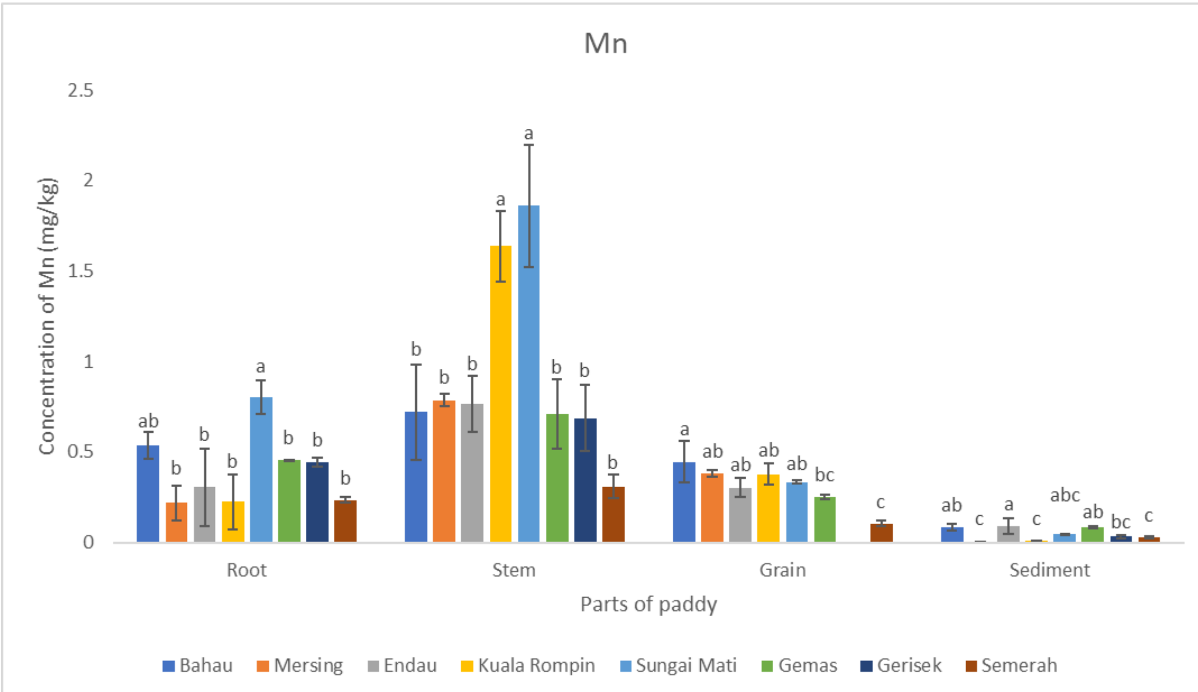


Figure-1. Mean concentrations (mg/kg) of Cu (a), As (b), Cd (c), Pb (d), Li (e) and Mn (f) in different paddy parts collected from selected sites of Southern Peninsular Malaysia.
* BDL = Below Detection Level
* The different alphabets on top of the bar represent significant differences at $p<0.05$.

Human health risk assessment (HRA)

Average daily dose (ADD)

The primary pathway through which humans are exposed to toxic trace metals is via the consumption of rice, wherein these metals accumulate within the grains. Tables 1 and 2 demonstrate the ADD of trace metals among Malaysian adults and children through rice consumption, tolerable daily intake (TDI) values, and maximum allowable concentration (MAC) values. The TDI values used in this study are Cu, As, Cd, and Pb were 0.0714, 0.0021, 0.001, and 0.0036 mg/kg (Khanam et al., 2020; Myat Soe et al., 2023). The pattern of ADD for both consumers is in the ascending order of Mn > Cu > As > Cd > Pb. All ADD values (adult and children) for Cu, As, Cd, Pb, and Mn in paddy grains were lower than the corresponding TDI and MAC values.

Table-1. The ADD (mg/kg) for heavy metals for adults through consumption of paddy grain from selected sites of Southern Peninsular Malaysia.

	Cu	**As**	**Cd**	**Pb**	**Mn**
Bahau	0.00009	0.0000032	0.0000035	0.0000042	0.0043
Mersing	0.00021	0.0000076	0.0000042	0.0000054	0.0037
Endau	0.00002	0.0000025	0.0000022	0.0000015	0.0029
Kuala Rompin	0.00007	0.0000086	0.0000054	0.0000040	0.0036
Sungai Mati	0.00018	0.0000028	0.0000016	0.0000037	0.0032
Gemas	0.00011	0.0000051	0.0000051	0.0000028	0.0024
Semerah	0.00004	0.0000140	0.0000009	0.0000012	0.0010
TDI (mg/kg)	0.0714	0.0021	0.001	0.0036	N/A
MAC (mg/kg)	20	0.2	0.2	0.2	N/A

TDI: Tolerable daily intake in mg/kg
MAC: Maximum allowable concentration (FAO, 2006) in mg/kg

Table-2. The ADD (mg/kg) for heavy metals by children through consumption of paddy grain from selected sites of Southern Peninsular Malaysia.

	Cu	As	Cd	Pb	Mn
Bahau	0.00011	0.0000034	0.0000037	0.0000045	0.0045
Mersing	0.00023	0.0000081	0.0000044	0.0000057	0.0039
Endau	0.00003	0.0000027	0.0000024	0.0000016	0.0031
Kuala Rompin	0.00008	0.0000091	0.0000058	0.0000042	0.0038
Sungai Mati	0.00020	0.0000030	0.0000017	0.0000039	0.0034
Gemas	0.00012	0.0000054	0.0000054	0.0000029	0.0027
Semerah	0.00004	0.0000149	0.0000010	0.0000013	0.0011
TDI	0.0714	0.0021	0.001	0.0036	N/A
MAC	20	0.2	0.2	0.2	N/A

TDI: Tolerable daily intake in mg/kg
MAC: Maximum allowable concentration (FAO, 2006) in mg/kg

Noncarcinogenic risk

ADD was used to calculate the hazard quotient (HQ), an indicator that assesses the potential noncarcinogenic risk to human health. The HQ results for the heavy metals through consumption of rice-selected paddy fields in Malaysia by adults and children were presented in Table 3 and Table 4. The results trend for adults and children are similar, with the descending order of Mn > As > Cd > Cu > Pb. According to Tables 4.3 and 4.4, the HQ for Mn is the highest, in the ranges of 0.0071 – 0.0305 and 0.0075 – 0.0323 for both adults and children as comes after Mn, which ranges from 0.0085 – 0.0468 and 0.0090 – 0.0496 for adults and children. Even though Mn and As were rated to be the two highest HQ values, together with other trace metal contaminants, they still did not exceed 1 and exhibited no obvious individual risk.

According to Table 3, the hazard index (HI) for both adults and children showed similar patterns in the samples collected from Kuala Rompin (adult = 0.0630; children = 0.0630) followed by Mersing (adult = 0.0626; children = 0.0664), Semerah (adult = 0.0561; children = 0.0595), Bahau (adult = 0.0484; children = 0.0513), Gemas (adult = 0.0429; children = 0.0456), Sungai Mati (adult = 0.0399; children = 0.0423), and Endau (adult = 0.0399; children = 0.0345).

Table-3. Hazard quotient (HQ) & Hazard Index (HI) for adults based on paddy grains consumption at the sampling sites.

	HQ					HI
	Cu	As	Cd	Pb	Mn	
Bahau	0.0025	0.0106	0.0035	0.0012	0.0305	**0.0484**
Mersing	0.0053	0.0255	0.0041	0.0015	0.0260	**0.0626**
Endau	0.0006	0.0085	0.0022	0.0004	0.0208	**0.0326**
Kuala Rompin	0.0019	0.0287	0.0054	0.0011	0.0258	**0.0630**
Sungai Mati	0.0047	0.0096	0.0016	0.0010	0.0229	**0.0399**
Gemas	0.0028	0.0170	0.0051	0.0008	0.0173	**0.0429**
Semerah	0.0009	0.0468	0.0010	0.0003	0.0071	**0.0561**

Table-4. Hazard quotient (HQ) & Hazard Index (HI) for children based on paddy grains consumption at the sampling sites.

	HQ					HI
	Cu	As	Cd	Pb	Mn	
Bahau	0.0026	0.0113	0.0037	0.0013	0.0324	**0.0513**
Mersing	0.0057	0.0271	0.0044	0.0016	0.0277	**0.0664**
Endau	0.0006	0.0090	0.0024	0.0005	0.0220	**0.0345**
Kuala Rompin	0.0021	0.0305	0.0058	0.0012	0.0273	**0.0668**
Sungai Mati	0.0050	0.0102	0.0017	0.0011	0.0243	**0.0423**
Gemas	0.0029	0.0181	0.0054	0.0008	0.0183	**0.0456**
Semerah	0.0009	0.0496	0.0010	0.0004	0.0075	**0.0595**

Bibliometric Analysis

Publication trend and descriptive analysis

Out of the 505 publications for the selected papers, the Web of Science (WoS) database found 15,986 citations, of which 14,573 were self-citations. An average of 31.66 citations were attributed to each article, resulting in an H-index of 60. The data from the examination of 505 articles indicates a growing interest in the body of literature concerning the accumulation of heavy metals in rice and the corresponding assessments of health risks. Although the research field originated in 1997, substantial contributions did not surface until 2014. Subsequently, the volume of publications has exhibited a consistent upward trend, ascending from 10 publications in 2014 to a significantly greater surge of 99 publications by 2022. Nevertheless, a marginal decline in the overall quantity of publications is observed in 2023. The observed trend suggests that there will probably be a significant surge in academic attention toward accumulating heavy metals in rice and evaluating the associated health risks. Figure 2 illustrates the trajectory of article publication and the corresponding citation counts spanning the period from 1997 to December 31, 2023.

Bibliographic coupling

The bibliographic coupling analysis's results, which adhered to a minimum citation threshold of 60, comprised 60 references. As illustrated in Figure 3, the network analysis was derived from the references. Table 5 presents the ranking of the ten most-cited references according to their total link strength. The publications of Zakaria et al. (2021); Ali et al. (2020) and Sharafi et al. (2019b) are particularly noteworthy, having received 63, 109, and 83 citations, respectively.

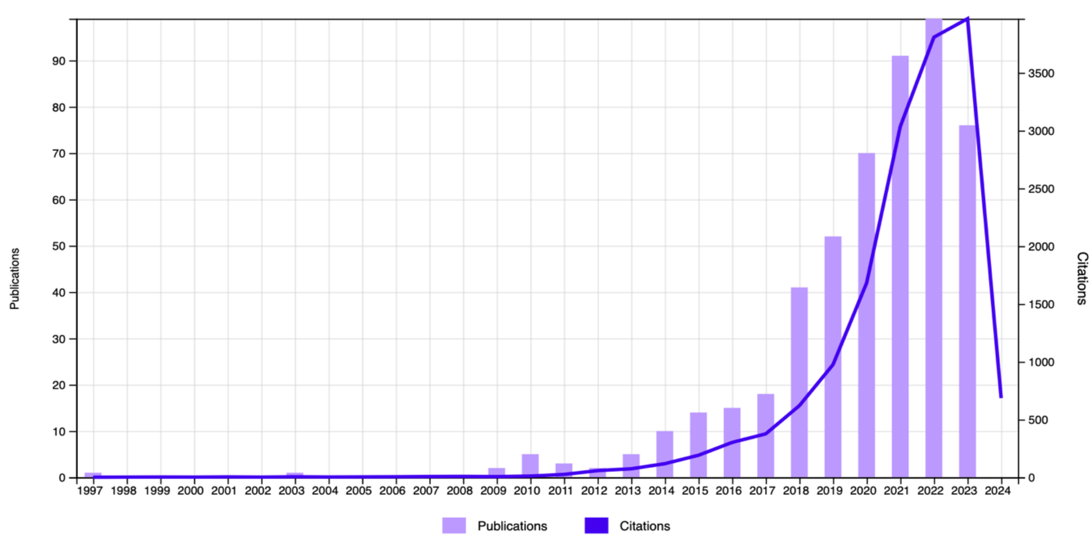


Figure-2. Citations and publications regarding heavy metal accumulation in rice and the associated health risks from 1997 to December 31, 2023**.**

Table-5. The publications rank highest in terms of total link strength and bibliographic coupling.

No.	Documents	Citation	Total link strength
1	Zakaria Z, Zulkafflee NS, Mohd Redzuan NA, Selamat J, Ismail MR, Praveena SM, Toth G and Abdull Razis AF, 2021. Understanding potential heavy metal contamination, absorption, translocation and accumulation in rice and human health risks. Plants, 10(6): 1070.	63	177
2	Ali W, Mao K, Zhang H, Junaid M, Xu N, Rasool A, Feng X and Yang Z, 2020. Comprehensive review of the basic chemical behaviours, sources, processes, and endpoints of trace element contamination in paddy soil-rice systems in rice-growing countries. Journal of Hazardous Materials, 397: 122720.	109	130
3	Sharafi K, Yunesian M, Nodehi RN, Mahvi AH and Pirsaheb M, 2019b. A systematic literature review for some toxic metals in widely consumed rice types (domestic and imported) in Iran: human health risk assessment, uncertainty and sensitivity analysis. Ecotoxicology and Environmental Safety, 176: 64-75.	83	103
4	Du Y, Chen L, Ding P, Liu L, He Q, Chen B and Duan Y, 2019. Different exposure profile of heavy metal and health risk between residents near a Pb-Zn mine and a Mn mine in Huayuan county, South China. Chemosphere, 216: 352-364.	64	101
5	Zhuang P, Lu H, Li Z, Zou B and McBride MB, 2014. Multiple exposure and effects assessment of heavy metals in the population near mining area in South China. PloS One, 9(4): e94484.	106	89
6	Sharafi K, Nodehi RN, Yunesian M, Mahvi AH, Pirsaheb M and Nazmara S, 2019a. Human health risk assessment for some toxic metals in widely consumed rice brands (domestic and imported) in Tehran, Iran: uncertainty and sensitivity analysis. Food Chemistry, 277: 145-155.	74	85
7	Liang Y, Yi X, Dang Z, Wang Q, Luo H and Tang J, 2017. Heavy metal contamination and health risk assessment in the vicinity of a tailing pond in Guangdong, China. International Journal of Environmental Research and Public Health, 14(12): 1557.	126	82
8	Cao H, Chen J, Zhang J, Zhang H, Qiao L and Men Y, 2010. Heavy metals in rice and garden vegetables and their potential health risks to inhabitants in the vicinity of an industrial zone in Jiangsu, China. Journal of Environmental Sciences, 22(11): 1792-1799.	263	82
9	Mao C, Song Y, Chen L, Ji J, Li J, Yuan X, Yang Z, Ayoko GA, Frost RL and 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.	202	79
10	Fan Y, Zhu T, Li M, He J and Huang R, 2017. Heavy metal contamination in soil and brown rice and human health risk assessment near three mining areas in central China. Journal of Healthcare Engineering, 2017.	124	79

By employing bibliographic coupling analysis, it was possible to identify four distinct clusters. These clusters represent discrete areas of emphasis in the body of literature pertaining to the accumulation of heavy metals in rice and the corresponding assessments of health risks. These clusters represent publications' compilations connected by the bibliographic coupling method and stemming from a similar thematic background. A method is used where the nodes are publications that belong to a certain cluster, and each node is highlighted with a certain colour to distinguish each other and to analyse easily

(Dong et al., 2023). The following are the classifications and descriptions offered for each cluster, with an emphasis on the themes that they encompass:

•**Cluster 1 (Red)** examines "Environmental Health Risks from Agricultural Contaminants," primarily focusing on heavy metal buildup in agricultural soils near industrial and mining sites, which enters the food chain, notably through rice. Studies by Zheng et al. (2020) underscore this contamination path, while Praveena and Omar (2017) emphasize bioavailability's role in assessing health risks through skin contact, inhalation, and ingestion. Increased environmental policies and food safety standards, as discussed by Zakaria et al. (2021), are crucial for managing these risks, with multidisciplinary approaches involving health risk assessment and toxicology (Singh et al., 2010; Zhuang et al., 2014).

•**Cluster 2 (Green)** addresses "Environmental Health Risks from Agricultural Contaminants" focusing on regional variations in contamination due to farming practices and geography. Research by Hu et al. (2020) notes bioaccumulation in crops like rice as a primary exposure route. Wen et al. (2021) suggests region-specific prevention strategies, while Qin et al. (2021) explore technologies for metal extraction from soils. Efforts to reduce heavy metal phytoavailability are highlighted by Xiang et al. (2021), and organic amendments to promote food safety and reduce toxic uptake (Khan et al., 2018).

•**Cluster 3 (Blue)** focuses on "Comprehensive Assessment of Dietary Heavy Metal Exposure and Human Health Risks," discussing food contamination, particularly rice, and its global health implications. Djahed et al. (2018) highlight significant health hazards, while Ebrahimi-Najafabadi et al. (2019) improve analytical methods for risk assessment. Advanced models, like Monte Carlo simulations by Pirsaheb et al. (2021), address uncertainties in exposure, emphasizing the importance of interdisciplinary collaboration to strengthen regulations and protect the food supply.

•**Cluster 4 (Yellow)** explores "Heavy Metal Transfer from Soil to Plants and Human Health Impact," focusing on urban areas where crops absorb metals like Cu and Pb from industrial sites. Studies by Cai et al. (2019) analyze metal transfer, with Du et al. (2020) underscoring risks for vulnerable populations like children. Research from Rahman et al. (2014) advocates for stricter surveillance and food safety standards to protect public health, particularly in regions like China, Bangladesh, and India.

Table 6 summarizes the bibliographic coupling analysis related to the research on heavy metal accumulation in rice and related health risk assessments. The information provided consists of the labels assigned to each cluster, the total count of publications within each cluster, and examples of key publications that represent the thematic focus of each cluster.

Co-occurrence of keyword

The co-word analysis found that each of the 49 identified keywords had a minimum frequency of 23 occurrences in the literature. The term "rice" was mentioned 205 times, while the term "cadmium" was mentioned 180 times. Additionally, the term "heavy metals" was mentioned 194 times. Table 7 presents a compilation of the top fifteen keywords that appear most frequently, emphasizing the main subjects of focus in studies concerning the research on heavy metal accumulation in rice and related health risk assessments.

https://doi.org/10.35495/ajab.2024.135

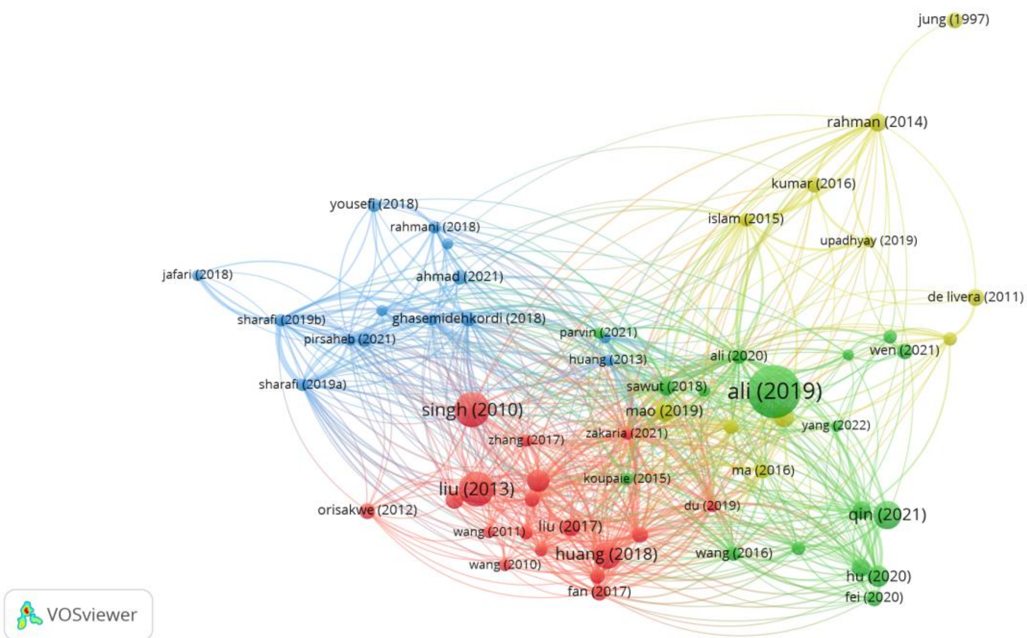


Figure-3. Bibliographic coupling

Table-6. Bibliographic coupling clusters

Cluster	Cluster label	Number of publications	Representative publications
1 (Red)	Environmental Health Risks from Agricultural Contaminants	18	Zheng et al. (2020); Praveena and Omar (2017); Zakaria et al. (2021); Singh et al. (2010); Zhuang et al. (2014).
2 (Green)	Environmental Health Risks from Agricultural Contaminants	17	Hu et al. (2020); Wen et al. (2021); Qin et al. (2021); Xiang et al. (2021); Khan et al. (2018).
3 (Blue)	Comprehensive Assessment of Dietary Heavy Metal Exposure and Human Health Risks	14	Djahed et al. (2018); Ebrahimi-Najafabadi et al. (2019); Pirsaheb et al. (2021).
4 (Yellow)	Heavy Metal Transfer from Soil to Plant and Its Implications for Human Health	11	Cai et al. (2019); Du et al. (2020); Rahman et al. (2014).

Source: The interpretation of the author by means of VOSviewer

Table-7. The top 15 most frequently used keywords.

Rank	Keyword	Occurrences	Total link strength
1	Rice	205	1167
2	Cadmium	180	1051
3	Heavy-metals	194	974
4	Soil	138	837
5	Accumulation	119	685
6	Lead	106	659
7	Vegetables	104	619
8	Health risk assessment	101	600

9	Pollution	96	588
10	Exposure	104	551
11	Health-risk assessment	86	519
12	Consumption	84	513
13	Heavy metal	100	466
14	Water	67	429
15	Agricultural soils	74	425

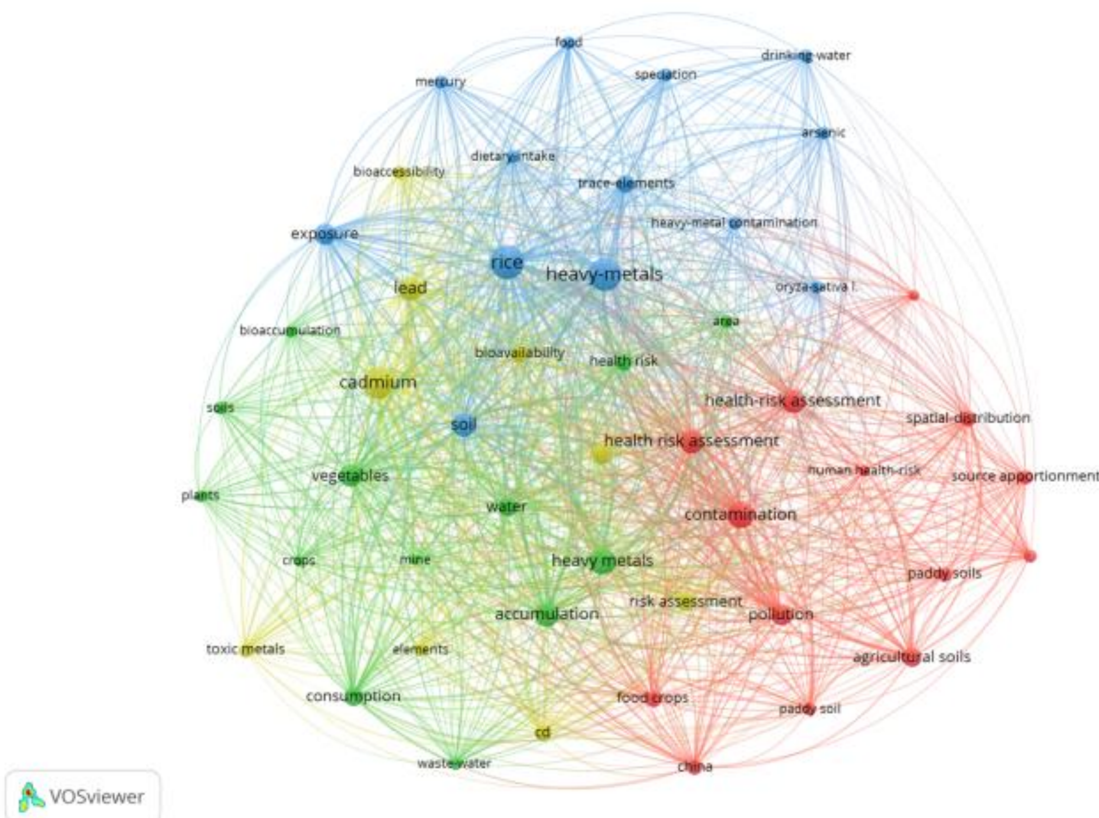


Figure-4. Co-word analysis.

The network illustrated in Figure 4 displays three interconnected clusters of keyword co-occurrences. Further analysis and discussion of each cluster's features and thematic focuses shed light on the interconnected areas of study within this field.

- **Cluster 1 (red)** examines "Spatial Dynamics of Heavy Metal Contamination in Rice Cultivation" to identify contamination hotspots and improve risk assessment models. Research by Karmakkar et al. (2024) emphasizes the need to mitigate the public health risks posed by increasing industrial activities and agricultural practices in developing nations like China (Wei et al., 2023). Future efforts should prioritize sustainable food systems and ecosystem protection strategies to address pollution and its health impacts effectively (He et al., 2023).
- **Cluster 2 (green)** focuses on "Heavy Metal Pathways from Environmental Exposure to Health Outcomes," detailing the toxicological implications of heavy metal pollution on human health, especially from wastewater and mining (Lin et al., 2023). Pollutants accumulate in plants, posing risks when consumed (Cui et al., 2023). This cluster underscores the need for a multidisciplinary approach involving environmental science, agriculture, and health to address the spatial aspects of pollution around

mining areas, informing policies and legal frameworks (Liu et al., 2023).

- **Cluster 3 (blue)** addresses "Arsenic and Mercury in the Food Chain," specifically their uptake by rice, which poses dietary risks due to rice's capacity to absorb high levels of these metals (Endah et al., 2023). The cluster reveals the importance of distinguishing metal speciation to assess dietary health threats and form preventive strategies. Future research aims to inform government policy and improve agricultural practices to shield populations from toxic exposure.
- **Cluster 4 (yellow)** explores "Bioavailability and Health Impacts of Heavy Metals" in agricultural systems, focusing on cadmium (Cd) and lead (Pb) in rice, with particular concern over their bioaccessibility and long-term health effects (Wang et al., 2023). These metals are associated with severe health disorders, including kidney and neurological diseases (Ma et al., 2022). Research here will likely seek to refine contamination measurement techniques and explore remediation methods, addressing health risks based on dietary exposure patterns and genetic factors.

Table 8 compiles the insights from the co-word analysis on human heavy metal studies. It specifies the title of each cluster, the quantity of keywords that make up that cluster, and the representative keywords that encapsulate the fundamental themes of each cluster.

Table-8. Co-word analysis on heavy metals on humans.

Cluster No and colour	Cluster label	Number of keywords	Representative Keywords
1 (Red)	Spatial Dynamics of Heavy Metal	14	Agricultural soils, China, contamination, food crops, health risk assessment, human health-risk, paddy soils, pollution, potentially toxic elements, source apportionment, source identification, spatial-distribution
2 (Green)	Heavy Metal Pathways from Environmental Exposure to Health Outcomes	13	Accumulation, area, bioaccumulation, consumption, crops, health risk, heavy metals, mine, plants, soils, vegetables, waste-water.
3 (Blue)	Arsenic and Mercury in the Food Chain: Exposure Risks and Mitigation Strategies	13	Arsenic, dieatary-intake, drinking-water, exposure, food, heavy-metal contamination, mercury, Oryza sativa L, rice, soil, speciation, trace-elements.
4 (Yellow)	Advancing Understanding of Heavy Metal Bioavailability and Health Impacts in Agricultural Systems	9	Bioaccesibility, bioavailability, cadmium, elements, heavy metal, lead, risk assessment, toxic metals.

Source: The interpretation of the author by means of VOSviewer

Discussion

Generally, Cu, As, Cd, Pb, and Mn accumulation were found to be high concentrations in the roots of the paddy plant (Figure 1). According to Zakaria et al. (2021), it has been observed that the metals within rice plants tend to accumulate primarily in the roots, as opposed to other parts such as stalks and grains. The roots exhibit the highest As metal uptake in sampling sites. This study is in line with a case study conducted in Alor Setar, Kedah, Malaysia, which also found that the concentration of As (4.62 mg/kg), Cd (0.29 mg/kg), and Pb (1.35 mg/kg) was found to be higher in roots than in the stem and grain (Looi et al., 2014). The reason for high As in roots is likely due to the prevalence of iron plaque on the root surface, which results in high As accumulation (Looi et al., 2014). Liu et al. (2006) explained that oxygen and oxidant release in the rhizosphere environment stimulates iron plaque formation–high affinity for As. Apart from Malaysia cases, studies near Zhengzhou City of China found that paddy roots tend to accumulate As, Cd, and Hg from paddy soil, which also aligned with the results from Liu et al. (2007).

The current study also found higher Cd concentration in the paddy plants as compared to sediments. These are similar to the findings of earlier studies (Liu et al., 2007; Du et al., 2013). It was suggested that the Cd content in paddy is mainly influenced by its availability rather than the total soil amount. According to Du et al. (2013), the pH of the soil shows a significant positive correlation with the HCL-Cd (Cd availability) concentration in soil, thus suggesting that the predominance of acidic soils in Hunan can potentially increase the mobility of the Cd from soil to paddy plants. This is supported by Liao et al. (1999), who proposed that when pH exceeds 6, Cd forms complexes with certain soil groups, with higher pH levels resulting in increased Cd fixation. Conversely, when the pH falls below 6 but remains above the zero-charge point, Cd predominantly binds to the soil via electrostatic adsorption. In relation to that, Malaysian paddy soils are predominantly lower in pH ranging from 4-5 (Maidin et al., 2023). This may explain the high concentration of Cd in paddy roots.

As for Cu, a recent study in Perlis has shown that Cu accumulation is high in root samples collected from Kurong Anai (transportation hub) (Aziz et al., 2023). Cu accumulation is almost at the same level in the roots and grain in Sena (Industrial point). As copper is a vital nutrient for metabolic processes, it is also important in root metabolism, leading to its prevalent concentration in plant roots, which contrasts with other tissues. Moreover, Cu exhibits a robust affinity towards the outer membranes, displacing other ions from exchange sites within the roots (Yusefi-Tanha et al., 2020). However, there is a disagreement from a study in India (Singh et al., 2011). It was found that Cu contents are higher in the cultivated soils than in different parts of the paddy due to its adsorptive nature in soil.

Interestingly, Mn content is recorded to be the highest in paddy shoots compared to other paddy parts and sediments. One of the key mechanisms to regulate the acquisition from soil is the uptake by specific transporters into the cells of the roots (Alejandro et al., 2020). The same results were shown in a study conducted by Yu et al. (2021), stating that two transporters (OsNRAMP5 & OsMTP9) that are polarly localized at both exodermis and endodermis of the paddy roots are the main contributors to high Mn accumulation in shoots. In addition, a study conducted in the agricultural area of Jhang, Pakistan, also agreed with our findings, with the highest concentration of Mn in paddy shoots.

The current study showed higher Li content in soils is higher as compared to other paddy parts indicating that this metal is mostly unavailable for plant uptake. These results align with Török et al. (2021), which found that Li was observed to be high in soil from certain locations, but due to its low bioconcentration factor (BCF), it was mostly unavailable for plant uptake and bioaccumulation. However, the Li uptake, bioavailability, and accumulation could be impacted by several factors (moisture, pH, metal content, etc.) related to soil (Hayyat et al., 2021). Török et al. (2021) also discovered that soil samples exhibiting high nitrogen content were associated with elevated Li BCF values. However, other elements such as K, Mg, and Ca may induce synergetic effects on the update of Na and the antagonistic effects on Li (Török et al., 2021). Seven rural non-main paddy production sites in Malaysia showed Cu, As, Cd, Pb, and Mn levels below FAO/WHO standards for both adults and children, indicating no significant health risk. This is consistent with findings from Omor rice field in Nigeria, where industrial activity is minimal. The HQ of heavy metals was less than one, indicating no probable potential non-carcinogenic health risks from the Omor rice field (Ihedioha et al., 2021). On the other hand, previous studies have concluded that heavy metal contamination in certain locations still poses potential health risks to the residents (Qu et al., 2012; Sibuar et al., 2022). According to Sibuar et al. (2022), the HQ for As was reported to be the highest and exceeded 1. This proposal presents possible noncarcinogenic hazards for the local population in Perak, encompassing both adults and children. However, this could be attributed to Perak's past mining activity. This finding mirrors a prior study indicating that heavy metal contamination could potentially endanger the health of nearby residents, particularly those residing near mining sites (Qu et al., 2012). Another possible explanation for this phenomenon might be the different sampling time frames (Pre-Covid-19 & Post-Covid-19 pandemic). The impact of the COVID-19 lockdown has greatly reduced anthropogenic activities and, hence, reduced the input of heavy metals. Similar findings in South India where the non-carcinogenic risk (HI>1) has reduced from 93% to 87% (children), from 87% to 80% (women), and from 80% to 73% (males), respectively_due to the lock-down effect (Arainthasamy et al., 2021).

The recent bibliographic coupling in this research area uses the example of heavy metal contamination from agricultural practices to underscore an intense focus on managing and mitigating such risks. Indeed, a significant part of the research shows the harmful influence of agricultural contamination combined with industrial pollution; heavy metals in agricultural soils affect food safety, mainly for crops like rice. This needs stringent environmental policies and a teamwork approach integrating toxicology, environmental science, and health risk assessments.

Important recent developments for reducing the phytoavailability of heavy metals in agricultural systems deal with bioaccumulation and the emphasis on risk management strategies that are tailor-made to the spatial heterogeneity of the contamination. Innovations for reducing the phytoavailability of heavy metals and increasing soil health with organic amendments are important. Finally, advancements within a comprehensive assessment of dietary exposure to heavy metals relate to analytical techniques, improvement of risk assessment models toward global impacts on health, and uncertainties in exposure management.

These research trends will also mean that the regulatory requirements, in terms of stringent systems and necessary international cooperation, need to be in place to ensure food safety regulations. Because this is a problem that transcends borders, both monitoring and mitigation strategies have to be planned to proactively avert a contamination incident; this points to an integrative, interdisciplinary approach to protecting public health from the prevalent risk of heavy metal contamination.

As summarized into four focused clusters, future research in environmental health promises to advance our understanding of heavy metal contamination in agricultural systems and the subsequent broader implications for public health. Key areas are spatial dynamics of contamination in rice cultivation; it emphasizes the need for advanced risk assessment models and effective mitigation strategies to combat food security threats in fast-developing regions.

The other important research areas involve direct human health impacts due to environmental heavy metal exposure, in which regional and crop-specific studies are important for designing appropriate interventions. Research aimed at studying arsenic and mercury in the food chain is in progress; there is a shift toward speciation studies so that bioavailability and toxicity can be better understood and eventually used in setting up food safety regulations.

In addition, new remedial measures and integrated risk evaluation techniques are being made to investigate the bioavailability and utilization of toxic metals, like Cd and Pb, in crops and their related health effects. These research trends highlight the need for a combined approach involving environmental science, toxicology, agriculture, and public health to address and mitigate the persistent heavy metal contamination challenges.

Conclusion

Overall, the data showed that roots tend to accumulate more heavy metals than other paddy parts, with Mn being the most abundant. Nevertheless, this study's concentration of heavy metals in the paddy grain is still below the TDI established by FAO/WHO. Health risk assessment also revealed no potential for noncarcinogenic risks in adults and children. The current study revealed that non-major paddy production sites have the potential to produce paddy with low heavy metals contamination, hence securing the health of the consumers, but also suggested that there will probably be a significant surge in academic attention toward the accumulation of heavy metals in rice and the evaluation of the health risks in the future, based on the bibliometric analysis of publications in 1997-2023. The integration of metal studies and bibliometric data in this paper supplement each other by providing a thorough scientific context, identifying research gaps, benchmarking our results, and guiding future research directions. Hence, more findings will need to focus on Malaysia's major paddy production site and compare the pre and post-COVID-19 pandemic period.

Disclaimer: None.
Conflict of Interest: None.
Source of Funding: The current work was funded by Fundamental Research Grant Scheme (FRGS/1/2022/STG01/INTI/02/1) from the Ministry of Higher Education (MOHE), Malaysia.

Contribution of Authors

Teoh YJ, Cheng WH, Wider W, Krishnan K and Kong YC: Planning and design of research, conducting the research, write up, analysis and data interpretation.
Chen Q, Jiang L, Lei TMT, Tanee T, Sudmoon R and Lee SY: Review, editing and approval of drafts.

References

Abbas A, Murtaza S, Aslam F, Khawar A, Rafique S and Naheed S, 2011. Effect of processing on nutritional value of rice (Oryza sativa). World J. Med. Sci. 6: 68–73.

Alejandro S, Höller S, Meier B and Peiter E, 2020. Manganese in Plants: From Acquisition to Subcellular Allocation. Front. Plant Sci. 11:300. DOI: https://doi.org/10.3389/fpls.2020.00300.

Ali W, Mao K, Zhang H, Junaid M, Xu N, Rasool A, Feng X and Yang Z, 2020. Comprehensive review of the basic chemical behaviours, sources, processes, and endpoints of trace element contamination in paddy soil-rice systems in rice-growing countries. J. Hazard. Mater. 397: 122720. DOI: https://doi.org/10.1016/j.jhazmat.2020.122720.

Arainthasamy P, Karunanidhi D, Shankar K, Subramani T, Setia R, Bhattacharya P and Das S, 2021. COVID-19 lockdown impacts on heavy metals and microbes in shallow groundwater and expected health risks in an industrial city of South India. Environ. Nanotechnol. Monit. Manag. 16: 1-9. DOI: https://doi.org/10.1016/j.enmm.2021.100472.

Aziz RA, Yiwen M, Saleh M, Salleh MN, Gopinath SCB, Giap SGE, Chinni SV and Gobinath R, 2023. Bioaccumulation and Translocation of Heavy Metals in Paddy (*Oryza sativa* L.) and Soil in Different Land Use Practices. Sustainability. 15:13426. DOI: https://10.3390/su151813426.

Cai LM, Wang QS, Luo J, Chen LG, Zhu RL, Wang S and Tang CH, 2019. Heavy metal contamination and health risk assessment for children near a large Cu-smelter in central China. Sci. Total Environ. 650: 725-733. DOI: https://doi.org/10.1016/j.scitotenv.2018.09.081.

Cao H, Chen J, Zhang J, Zhang H, Qiao L and Men Y, 2010. Heavy metals in rice and garden vegetables and their potential health risks to inhabitants in the vicinity of an industrial zone in Jiangsu, China. J. Environ. Sci. 22(11): 1792-1799. DOI: 10.1016/s1001-0742(09)60321-1

Chandrakumar D, Arumugam V and Vasudevan A, 2024. Exploring presenteeism trends: a comprehensive bibliometric and content analysis. Front. Psychol. 15:1352602. https://doi.org/10.3389/fpsyg.2024.1352602

Clemens S and Ma JF, 2016. Toxic heavy metal and metalloid accumulation in crop plants and foods. Annu. Rev. Plant Biol. 67: 489–512. DOI: https://doi.org/10.1146/annurev-arplant-043015-112301.

Cui W, Mei Y, Liu S and Zhang X, 2023. Health risk assessment of heavy metal pollution and its sources in agricultural soils near Hongfeng Lake in the mining area of Guizhou Province, China. Front. Public Health. 11:1276925. DOI: https://doi.org/10.3389/fpubh.2023.1276925.

Dahlal ND, Hasan WNW, Rahim HA and Amid A, 2024. Research Trends on Rice Paddy Agriculture: A Bibliometric analysis. J. Sustain. Dev. 1: 1-9.

Djahed B, Taghavi M, Farzadkia M, Norzaee S and Miri M, 2018. Stochastic exposure and health risk assessment of rice contamination to the heavy metals in the market of Iranshahr, Iran. Food Chem. Toxicol. 115: 405-412. DOI: https://doi.org/10.1016/j.fct.2018.03.040.

Dong M, Li F and Chang H, 2023. Trends and hotspots in critical thinking research over the past two decades: Insights from a bibliometric analysis. Heliyon, *9*(6), e16934.

Du Y, Hu XF, Wu XH, Shu Y, Jiang Y and Yan XJ, 2013. Effects of mining activities on Cd pollution to the paddy soils and rice grain in Hunan province, Central South China. 185:9843-56. Environ. Monit. Assess. DOI: https://10.1007/s10661-013-3296-y.

Du Y, Chen L, Ding P, Liu L, He Q, Chen B and Duan Y, 2019. Different exposure profile of heavy metal and health risk between residents near a Pb-Zn mine and a Mn mine in Huayuan county, South China. Chemosphere. 216: 352-364. DOI: 10.1016/j.chemosphere.2018.10.142

Du B, Zhou J, Lu B, Zhang C, Li D, Zhou J, Jiao S, Zhao K and Zhang H, 2020. Environmental and human health risks from cadmium exposure near an active lead-zinc mine and a copper smelter, China. Sci. Total Environ. 720: 137585. DOI: https://doi.org/10.1016/j.scitotenv.2020.137585.

Ebrahimi-Najafabadi H, Pasdaran A, Bezenjani RR and Bozorgzadeh E, 2019. Determination of toxic heavy metals in rice samples using ultrasound assisted emulsification microextraction combined with inductively coupled plasma optical emission spectroscopy. Food Chem. 289: 26-32. DOI: https://doi.org/10.1016/j.foodchem.2019.03.046.

Endah WN, Henry S, Inandin NP, Irene KM and Mahalul A, 2023. Heavy Metals Contamination of Local and Imported Rice in Semarang, Central Java, Indonesia. J. Ecol. Eng. 24: 49-60. DOI: https://doi.org/10.12911/22998993/163308.

Fan Y, Zhu T, Li M, He J and Huang R, 2017. Heavy metal contamination in soil and brown rice and human health risk assessment near three mining areas in central China. J. Healthc. Eng. 2017: DOI: 10.1155/2017/4124302 4124302.

FAO (Food Administrative Organization), 2006. Report of the 29th session of the Codex Alimentarius commission. FAO, Rome, Italy.

Fauzi MA, 2022. E-learning in higher education institutions during COVID-19 pandemic: Current and future trends through bibliometric analysis. Heliyon. 8: e09433. DOI: https://doi.org/10.1016/j.heliyon.2022.e09433.

Fauzi MA, Ali Z, Satari Z, Megat Ramli PA and Omer M, 2024. Social media influencer marketing: science mapping of the present and future trends. Int. J. Qual. Serv. Sci. DOI: https://doi.org/10.1108/IJQSS-10-2023-0174

Fukagawa NK and Ziska LH, 2019. Rice: Importance for Global Nutrition. J Nutr Sci Vitaminol (Tokyo). 65: S2-S3. DOI: 10.3177/jnsv.65.S2. PMID: 31619630.

Hang X, Wang H, Zhou J, Ma C, Du C and 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. Environ. Pollut. 157: 2542-2549. DOI: https://doi.org/10.1016/j.envpol.2009.03.002.

Hayyat MU, Nawaz R, Siddiq Z, Shakoor MB, Mushtaq M, Ahmad SR, Ali S, Hussain A, Irshad MA and Alsahli AA, 2021. Investigation of Lithium Application and Effect of Organic Matter on Soil Health. Sustainability. 13: 1705. DOI: https://doi.org/10.3390/su13041705.

He Q, Sun Y and Yi M, 2023. Evolutionary Game of Pesticide Reduction Management for Sustainable Agriculture: An Analysis Based on Local Governments, Farmers, and Consumers. Sustainability, 15: 9173. DOI: https://doi.org/10.3390/su15129173.

Hu B, Shao S, Ni H, Fu Z, Hu L, Zhou Y, Min X, She S, Chen S, Huang M, Zhou L, Li Y and Shi Z, 2020. Current status, spatial features, health risks, and potential driving factors of soil heavy metal pollution in China at province level. Environ. Pollut. 266: 114961. DOI: https://doi.org/10.1016/j.envpol.2020.114961.

Ihedioha JN, Abugu H, Ujam OT and Ekere NR, 2021. Ecological and human health risk evaluation of potential toxic metals in paddy soil, rice plants, and rice grains (Oryza sativa) of Omor Rice Field, Nigeria. Environ. Monit. Assess. 196: 620. DOI: https://doi.org/10.1007/s10661-021-09386-3.

Kanu AS, Ashraf U, Mo Z, Fuseini I, Mansaray LR, Duan M, Pan S and Tang X, 2017. Cadmium (Cd) uptake and distribution in fragrant rice genotypes and related consequences on yield and grain quality traits. J. Chem. 1405878. DOI: https://doi.org/10.1155/2017/1405878

Khairiah J, Ramlee AR, Jamil H, Ismail Z and Ismail BS, 2013. Heavy Metal Content of Paddy Plants in Langkawi, Kedah, Malaysia. Aust. J. Basic Appl. Sci. 7: 123–127.

Khan MA, Ding X, Khan S, Brusseau ML, Khan A and Nawab J, 2018. The influence of various organic amendments on the bioavailability and plant uptake of cadmium present in mine-degraded soil. Sci. Total Environ. 636: 810-817. DOI: https://doi.org/10.1016/j.scitotenv.2018.04.299.

Khanam R, Kumar A, Nayak AK, Shahid M, Tripathi R, Vijayakumar S, Bhaduri D, Kumar U, Mohanty S, Panneerselvam P, Chatterjee D, Satapathy BS and Pathak H, 2020. Metal(loid)s (As, Hg, Se, Pb and Cd) in paddy soil: Bioavailability and potential risk to human health. Sci. Total Environ. 699: 134330. DOI: https://doi.org/10.1016/j.scitotenv.2019.134330.

Kong W, Zhong H, Gong Z, Fang X, Sun T, Deng X and Li Y, 2019. Meta-analysis of salt stress transcriptome responses in different rice genotypes at the seedling stage. Plants. 8: 64. DOI: https://doi.org/10.3390/plants8030064.

Liang Y, Yi X, Dang Z, Wang Q, Luo H and Tang J, 2017. Heavy metal contamination and health risk assessment in the vicinity of a tailing pond in Guangdong, China. Int. J. Environ. Res. Public Health. 14(12): 1557. DOI: 10.3390/ijerph14121557

Liao M, Huang CY and Xie ZM, 1999. Effect of pH on transformation of cadmium in soil water system. J. Environ. Sci.19: 81–86.

Lin C, Wang W, Hu G, Yu R, Huang H and Liao D,

2023. Incorporating source apportionment and bioaccessibility into human health risk assessment of heavy metals in a soil-rice system in the Jiulong River basin, southeast China. J. Food Compos. Anal. 124: 105692. DOI: https://doi.org/10.1016/j.jfca.2023.105692.

Linnenluecke MK, Marrone M and Singh AK, 2020. Conducting systematic literature reviews and bibliometric analysis. Aust. J. Manag. 45: 175-194. DOI: https://doi.org/10.1177/0312896219877678.

Liu WJ, Zhu YG, Hu Y, Williams PN, Gault AG, Meherg AA, Charnock JM and Smith FA, 2006. Arsenic sequestration in iron plaque, its accumulation and speciation in mature rice plants (*Oryza sativa* L.). Environ. Sci. Technol. 40: 5730-5736. DOI: https://doi.org/10.1021/es060800v.

Liu WX, Shen LF, Liu JW, Wang YW and Li SR, 2007. Uptake of toxic heavy metals by rice (Oryza sativa L.) cultivated in the agricultural soil near Zhengzhou city, China. *Bull. Environ. Contam. Toxicol*. 79**:** 209-213. DOI: https://doi.org/10.1007/s00128-007-9164-0.

Liu Y, Cao X, Hu Y and Cheng H, 2022. Pollution, Risk and Transfer of Heavy Metals in Soil and Rice: A Case Study in a Typical Industrialized Region in South China. Sustainability 14: 10225. DOI: https://doi.org/10.3390/su141610225.

Liu H, Xie J, Cheng Z and Wu X, 2023. Characteristics, Chemical Speciation and Health Risk Assessment of Heavy Metals in Paddy Soil and Rice around an Abandoned High-Arsenic Coal Mine Area, Southwest China. Minerals. 13: 629. DOI: https://doi.org/10.3390/min13050629.

Looi LY, Aris AZ, Lim WY and Haris H, 2014. Bioconcentration and Translocation Efficiency of Metals in Paddy (*Oryza Sativa*): A Case Study from Alor Setar, Kedah, Malaysia. Sains Malays. 43: 521-528.

Ma Y, Su Q, Yue C, Zou H, Zhu J, Zhao H, Song R and Liu Z, 2022. The Effect of Oxidative Stress-Induced Autophagy by Cadmium Exposure in Kidney, Liver, and Bone Damage, and Neurotoxicity. Int. J. Mol. Sci. 23: 13491. DOI: https://doi.org/10.3390/ijms232113491.

Mao C, Song Y, Chen L, Ji J, Li J, Yuan X, Yang Z, Ayoko GA, Frost RL and 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.

Maidin MKH, Kamaruddin R and Applanaidu SD, 2023. Influence of Soil Properties on Technical Efficiency of Paddy Production: Evidence from Malaysia. *J. Ekon. Malays*. 57: 123-133. DOI: http://dx.doi.org/10.17576/JEM-2023-5702-09.

Myat Soe AM, Mu AA and Toyoda K, 2023. Arsenic and trace metal contents in white rice samples from rainfed paddy fields in Yangon division, Myanmar—Natural background levels? PLoS One. 18: e0283420. DOI: https://doi.org/10.1371/journal.pone.0283420.

OECD and FAO, (Economic Co-operation and Development and Food Administrative Organization), 2022. Oecd-Fao Agricultural Outlook 2022-2031. OECD & FAO.

Pirsaheb M, Hadei M and Sharafi K, 2021. Human health risk assessment by Monte Carlo simulation method for heavy metals of commonly consumed cereals in Iran-Uncertainty and sensitivity analysis. J. Food Compos. Anal. 96: 103697. DOI: https://doi.org/10.1016/j.jfca.2020.103697.

Pishgar-Komleh SH, Sefeedpari P and Rafiee S, 2011. Energy and economic analysis of rice production under different farm levels in Guilan province of Iran. Energy 36: 5824–5831. DOI: https://doi.org/10.1016/j.energy.2011.08.044.

Praveena SM and Omar NA, 2017. Heavy metal exposure form cooked rice grain ingestion and its potential health risk to humans from total and bioavailable forms analysis. Food Chem. 235: 203-211. DOI: https://doi.org/10.1016/j.foodchem.2017.05.049.

Qin G, Niu Z, Yu J, Li Z, Ma J and Xiang P, 2021. Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. Chemosphere, 267: 129205. DOI: https://doi.org/10.1016/j.chemosphere.2020.129205.

Qu CS, Ma ZW, Yang J, Liu Y, Bi J and Huang L, 2012. Human exposure pathways of heavy metals in a lead-zinc mining area, Jiangsu Province, China. PLoS One. 7: e46793. DOI: https://doi.org/10.1371/journal.pone.0046793.

Rahman MA, Rahman MM, Reichman SM, Lim RP and Naidu R, 2014. Heavy metals in Australian grown and imported rice and vegetables on sale in Australia: health hazard. Ecotoxicol. Environ. Saf. 100: 53-60. DOI: https://doi.org/10.1016/j.ecoenv.2013.11.024.

Rodriguez L, Rincon J, Asencio I and Rodrı´guez-Castellanos L, 2007. Capability of selected crop plants for shoot mercury accumulation from polluted soils: phytoremediation perspectives. *Int. J. Phytoremediation.* 9: 1–13. DOI: https://doi.org/10.1080/15226510601139359.

Ruzdi SK, Ho YB and Kharni IIA, 2018. Heavy Metals Contamination in Paddy Soil and Water and Associated Dermal Health Risk Among Farmers. Malays. J. Med. Health Sci. 14: 2-10.

Saeed SH, Gillani GMS, Gazder U, Shaheen S, Gul A, Arifuzzaman M, Asif AH, Nasrin A, Asaduzzaman M and Mahmood Q, 2024. Interactive effects of toxic metals on the total phenolic and flavonoid in Hydrocotyle umbellata L. Asian J. Agric. Biol. 2024(2): 2023122. DOI: https://doi.org/10.35495/ajab.2023.122

Sen S, Chakraborty R and Kalita P, 2020. Rice - not just a staple food: A comprehensive review on its phytochemicals and therapeutic potential. Trends Food Sci Technol. 97: 265-285. DOI: https://doi.org/10.1016/j.tifs.2020.01.022.

Sharafi K, Nodehi RN, Yunesian M, Mahvi AH, Pirsaheb M and Nazmara S, 2019a. Human health risk assessment for some toxic metals in widely consumed rice brands (domestic and imported) in Tehran, Iran: uncertainty and sensitivity analysis. Food Chem. 277: 145-155. DOI: https://doi.org/10.1016/j.foodchem.2018.10.090.

Sharafi K, Yunesian M, Nodehi RN, Mahvi AH and Pirsaheb M, 2019b. A systematic literature review for some toxic metals in widely consumed rice types (domestic and imported) in Iran: human health risk assessment, uncertainty and sensitivity analysis. Ecotoxicol. Environ. Saf. 176: 64-75. DOI: 10.1016/j.ecoenv.2019.03.072

Sibuar AA, Zulkafflee NS, Selamat J, Ismail MR, Lee SY and Abdull Razis AF, 2022. Quantitative Analysis and Human Health Risk Assessment of Heavy Metals in Paddy Plants Collected from Perak, Malaysia. Int. J. Environ. Res. Public Health. 19: 731. DOI: https://doi.org/10.3390/ijerph19020731.

Singh A, Sharma RK, Agrawal M and Marshall FM, 2010. Health risk assessment of heavy metals via dietary intake of foodstuffs from the wastewater irrigated site of a dry tropical area of India. Food Chem. Toxicol. 48: 611-619. DOI: https://doi.org/10.1016/j.fct.2009.11.041

Singh J, Upadhyay SK, Pathak RK and Gupta V, 2011. Accumulation of heavy metals in soil and paddy crop (*Oryza sativa*), irrigated with water of Ramgarh Lake, Gorakhpur, UP, India. Toxicol. Environ. Chem. 93: 462–473. DOI: https://doi.org/ 10.1080/02772248.2010.546559.

Sudmoon R, Chaveerach A, Ameamsri U, Thamsenanupap P, Pumipuntu N, Lee SY, Hock OG and Tanee T, 2024. Lead (Pb) accumulation in rice and its impact on DNA stability. Asian J. Agric. Biol. 2024(4): 2024031. DOI: https://doi.org/10.35495/ajab.2024.031

Syahariza ZA, Sar S, Hasjim J, Tizzotti MJ and Gilbert RG, 2013. The importance of amylose and amylopectin fine structures for starch digestibility in cooked rice grains. Food Chem. 136: 742–749. DOI: https://doi.org/10.1016/j.foodchem.2012.08.053.

Török AI, Moldovan A, Levei EA, Cadar O, Tănăselia C and Moldovan OT, 2021. Assessment of Lithium, Macro- and Microelements in Water, Soil and Plant Samples from Karst Areas in Romania. Materials. 14:4002. DOI: https://doi.org/10.3390/ma14144002.

Ungureanu EL, Mocanu AL, Stroe CA, Duta DE and Mustatea G, 2023. Assessing Health Risks Associated with Heavy Metals in Food: A Bibliometric Analysis. Foods. 12: 3974. DOI: https://doi.org/10.3390/foods12213974.

Wang J, Deng P, Wei X, Zhang X, Liu J, Huang Y, She J, Liu Y, Wan Y, Hu H, Zhong W and Chen D, 2023. Hidden risks from potentially toxic metal(loid)s in paddy soils-rice and source apportionment using lead isotopes: A case study from China. Sci. Total Environ. 856: 158883. DOI: https://doi.org/10.1016/j.scitotenv.2022.158883.

Wei R, Chen C and Kou M, 2023. Heavy metal concentrations in rice that meet safety standards can still pose a risk to human health. Commun. Earth Environ. 4: 84. DOI: https://doi.org/10.1038/s43247-023-00723-7.

Wen E, Yang X, Chen H, Shaheen SM, Sarkar B, Xu S, Song H, Liang Y, Rinklebe J, Hou D, Li Y, Wu F, Pohorely M, Wong JWC and Wang H, 2021. Iron-modified biochar and water management regime-induced changes in plant growth, enzyme activities, and phytoavailability of arsenic, cadmium and lead in a paddy soil. J. Hazard. Mater. 407: 124344. DOI: https://doi.org/10.1016/j.jhazmat.2020.124344.

Wider W, Fauzi MA, Gan SW, Yap CC, Khadri MWABA and Maidin SS, 2023. A bibliometric analysis of emerging adulthood in the context of higher education institutions: A psychological perspective. Heliyon. 9: e16988. DOI: https://doi.org/10.1016/j.heliyon.2023.e16988.

Wider W, Tan FP, Tan YP, Lin J, Fauzi MA, Wong LS, Tanucan JCM and Hossain SFA, 2024. Service quality (SERVQUAL) model in private higher education institutions: A bibliometric analysis of past, present, and future prospects. Soc. Sci. Humanit. 9: 100805. DOI: https://doi.org/10.1016/j.ssaho.2024.100805.

Xiang M, Li Y, Yang J, Lei K, Li Y, Li F, Zheng D, Fang X and Cao Y, 2021. Heavy metal contamination risk assessment and correlation analysis of heavy metal contents in soil and crops. Environ. Pollut. 278: 116911. DOI: https://doi.org/10.1016/j.envpol.2021.116911.

Yu E, Yamaji N, Mao C, Wang H and Ma JF, 2021. Lateral roots but not root hairs contribute to high uptake of manganese and cadmium in rice. J. Exp. Bot. 72: 7219-7228. DOI: https://doi.org/10.1093/jxb/erab329.

Yuan S, Peng S and Li T, 2017. Evaluation and application of the ORYZA rice model under different crop managements with high yielding rice cultivars in central China. Field Crops Res. 212: 115–125. DOI: https://doi.org/10.1016/j.fcr.2017.07.010.

Yusefi-Tanha E, Fallah S, Rostamnejad A and Pokhrel LR, 2020. Root System Architecture, Copper Uptake and Tissue Distribution in Soybean (Glycine max (L.) Merr.) Grown in Copper Oxide Nanoparticle (CuONP)-Amended Soil and Implications for Human Nutrition. Plants 9: 1326. DOI: https://doi.org/10.3390/plants9101326.

Zakaria Z, Zulkafflee NS, Mohd Redzuan NA, Selamat J, Ismail MR, Praveena SM, Toth G and Abdull Razis AF, 2021. Understanding potential heavy metal contamination, absorption, translocation and accumulation in rice and human health risks. Plants, 10: 1070. DOI: https://doi.org/10.3390/plants10061070.

Zakaria H, Kamarudin D, Fauzi MA and Wider W, 2023. Mapping the helix model of innovation influence on education: A bibliometric review. Front. Educ. 8:1142502. DOI: https://doi.org/10.3389/feduc.2023.1142502.

Zheng S, Wang Q, Yuan Y and Sun W, 2020. Human health risk assessment of heavy metals in soil and food crops in the Pearl River Delta urban agglomeration of China. Food Chem. 316: 126213. DOI: https://doi.org/10.1016/j.foodchem.2020.126213.

Zhuang P, Lu H, Li Z, Zou B and McBride MB, 2014. Multiple exposure and effects assessment of heavy metals in the population near mining area in South China. PloS one, 9: e94484. DOI: https://doi.org/10.1371/journal.pone.0094484.

Zulkafflee NS, Redzuan NAM, Hanafi Z, Selamat J, Ismail MR, Praveena SM and Razis AFA, 2019. Heavy Metal in Paddy Soil and its Bioavailability in Rice Using In Vitro Digestion Model for Health Risk Assessment. Int J Environ Res Public Health. 16: 4769. DOI: https://doi.org/10.3390/ijerph16234769.

Zulkafflee NS, Redzuan NAM, Selamat J, Ismail MR, Praveena SM and Razis AFA, 2021. Evaluation of heavy metal contamination in paddy plants at the northern region of Malaysia using ICPMS and its risk assessment. Plants. 10: 3. DOI: https://doi.org/10.3390/plants10010003.