

LEAD CONTAMINATION IN PADDY SOILS AND RICE GRAINS FROM KELANTAN: ASSESSING RISKS TO FOOD SECURITY AND PUBLIC HEALTH

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Abstract: This study assesses lead (Pb) contamination in paddy soils and rice grains from two rice-growing regions in Kelantan, Malaysia: Kemuning and Kelaweh. By evaluating estimated daily intake (EDI) and target hazard quotient (THQ) values for Pb in adults and children, the study aims to quantify the health risks associated with rice consumption in these regions. The highest Pb concentrations were observed in the "Outlet" zones of Kelaweh, where the THQ for Pb in adults reached 69.3 and for children reached 37.9, indicating significant potential health risks. In contrast, Kemuning exhibited lower Pb contamination, though the "Outlet" zone still presented moderate risks, with THQ values of 11.4 for adults and 8.11 for children. The study underscores the need for immediate intervention through environmental management and sustainable agricultural practices to reduce Pb contamination, ensuring rice consumption's safety and protecting the region's public health. The findings of this study are intended to inform future public health interventions and agricultural practices to mitigate Pb contamination, ensuring that rice production remains safe and sustainable in the long term.

Keywords: Lead contamination, target hazard quotient, food security, rice grains, Kelantan

1. INTRODUCTION

Lead (Pb) is a toxic heavy metal that poses significant environmental and public health risks when present in high concentrations in soils and crops. Among the various food sources, rice (*Oryza sativa* L.), a staple food for more than half of the world's population, has been identified as a key route for human exposure to Pb (Wu et al., 2015; Mlangeni et al., 2023; Bora and Devi, 2024). The unique growing conditions of rice, particularly in flooded paddy fields, increase its susceptibility to the uptake of heavy metals like Pb from contaminated soils and irrigation water (Wang et al., 2019; Sun et al., 2015; Deng et al., 2017). This is a serious concern for populations that depend heavily on rice as a dietary staple, as prolonged consumption of Pb-contaminated rice can result in chronic exposure and severe health consequences (Wang et al., 2023; Lei et al., 2010; Bian et al., 2015).

Pb toxicity in humans has been widely studied,

and it is known to cause a range of adverse health effects. Even at low levels of exposure, Pb can result in neurological impairments, especially in children, including developmental delays, cognitive deficits, and behavioral problems (Ma et al., 2010; Zhou et al., 2016). Chronic exposure to Pb can also cause kidney dysfunction, cardiovascular diseases, and in severe cases, Pb poisoning (Reddy et al., 2013; Liu et al., 2014; Lim et al., 2016). Unlike other essential metals, Pb has no known beneficial role in biological systems, making any level of exposure potentially harmful (Gao et al., 2022; Wu et al., 2023). As such, the contamination of rice by Pb represents a critical issue for food safety and broader public health (Jiang et al., 2019; Liang et al., 2019; Hong et al., 2022).

Several factors contribute to the accumulation of Pb in paddy fields, including using contaminated water for irrigation, industrial runoff, atmospheric deposition, and Pb-containing fertilizers or pesticides (Kim et al., 2014; Khanam et al., 2020; Zhao et al.,

2021). Paddy soils, which are often anaerobic and have high organic content, create conditions that facilitate Pb's mobilization, making them more bioavailable to rice plants (Bashir et al., 2018; Khaliq et al., 2019; Miao & Yang, 2012). Once absorbed by the plant, Pb can accumulate in various tissues, including the roots, stems, leaves, and, most concerning, in consumed grains (He et al., 2024; Yang et al., 2016; Wang et al., 2022a, 2022b). This makes rice a primary vector for Pb exposure in regions with high contamination levels (Kim et al., 2013; Iqbal et al., 2018; Wan et al., 2019).

The situation is particularly concerning in developing countries, where industrialization, mining, and inadequate environmental regulation contribute to higher levels of Pb contamination in agricultural fields (Xie et al., 2006; Moon et al., 2018; Jing et al., 2020). In Malaysia, where rice is a staple food, several regions, including Kelantan, have reported elevated levels of heavy metals in paddy soils, raising alarms about food safety and health risks (Merismon et al., 2017; Wu et al., 2023). Pb contamination in rice is hazardous because rice is often consumed in large quantities, increasing the likelihood of Pb intake beyond safe levels (Gao et al., 2016; Wu et al., 2015; Jeon et al., 2015a). The risk is further compounded for vulnerable populations, such as children and pregnant women, who are more susceptible to the toxic effects of Pb (Jung & Thornton, 1997; Kim et al., 2016).

This study aims to evaluate the levels of Pb contamination in paddy soils and rice grains from two major rice-growing regions in Kelantan, Peninsular Malaysia – Kemuning and Kelaweh. By determining the estimated daily intake (EDI) and target hazard quotient (THQ) values for both adults and children, the study aims to assess the potential health risks associated with Pb exposure through rice consumption. Furthermore, the research seeks to identify the zones within the paddy fields ("Inlet," "Middle," and "Outlet") with the highest contamination levels, providing critical insights into the spatial distribution of Pb and its implications for food safety. The ultimate goal is to offer recommendations for sustainable agricultural practices and public health interventions to mitigate the risks of Pb exposure and ensure the safety of rice consumption in the region.

2. MATERIALS AND METHODS

2.1. Study Area and Sample Collection

This study was conducted in two distinct paddy cultivation regions located in Kelantan, Malaysia: Kemuning and Kelaweh. These regions were selected due to their significant contributions to rice production and potential exposure to heavy metal contamination

from various environmental sources, including industrial runoff, agricultural inputs, and proximity to highways and plantations. The sampling locations were strategically chosen based on environmental characteristics and known contamination risks to assess comprehensively heavy metal accumulation in the paddy fields.

2.1.1. Site Descriptions

Kemuning is located approximately 1.7 km from a major highway and is characterized by a lack of nearby houses or buildings, reducing potential contamination from human settlements. The geographical isolation of this site makes it a valuable comparison point for evaluating the impact of industrial runoff versus residential or agricultural sources of contamination. Sampling in Kemuning was realized on August 10, 2014, during clear, sunny weather. The sampling period extended from 11:00 AM to 1:30 PM, with rice plants at the site being approximately 130 days old at the time of collection. Kelaweh, in contrast, is situated near residential housing areas and adjacent to a rubber plantation, with the nearest contamination source located approximately 0.8 km away. This site represents a more agriculturally intensive region with possible additional contamination from both residential and plantation activities. Sampling in Kelaweh was conducted on December 11, 2015, similarly under sunny conditions. The collection period ranged from 10:00 AM to 1:00 PM, and the rice plants were around 110 days old during sampling. The proximity to housing and plantations makes Kelaweh a key area of interest for assessing the interaction between agricultural practices and environmental contamination (Table 1).

Table 1. The sampling information for paddy fields at Kemuning and Kelaweh in Kelantan (Malaysia).

	Kemuning (5°44'45.2"N 102°13'11.9"E)	Kelaweh (6°01'28.2"N 102°15'31.4"E)
Dates	10-Aug-14	11-Dec-15
Weather	Sunny	Sunny
Time	11:00 AM – 1:30 PM	10:00 AM – 1:00 PM
Rice age	~130 days	~110 days
Distance from the main source of contamination	1.7 km	0.8 km to plantation area
Site description	1.7 km from the highway, lack of houses and buildings	Near the housing area, next to the rubber plantation

2.2. Sampling Strategy

At both Kemuning and Kelaweh, soil and plant samples were collected from three distinct zones within the paddy fields, corresponding to the flow of water within the plots: "Inlet," "Middle," and "Outlet" (Figure 1). These zones represent the points where irrigation water enters, moves through, and exits the paddy fields, potentially carrying and depositing contaminants. This sampling strategy was employed to capture the spatial variation in heavy metal concentrations within the paddy fields, ensuring that areas receiving and discharging water were thoroughly analyzed. This methodology allows for an assessment of the horizontal and vertical distribution of metals in both the soil and subsequently in plant tissues.

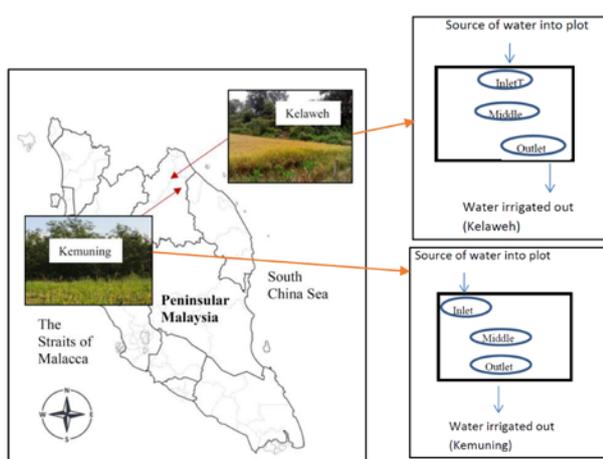


Figure 1. Sampling sites of paddy and surface soil samples from Kemuning and Kelaweh, Kelantan, Peninsular Malaysia. Note: The paddy planted at the two sites is the same variety MR263.

2.3. Sample Collection

At least nine mature paddy plants were collected from each point of Inlet, Middle, and Outlet. Therefore, there were a least 18 paddy plants were collected from one sampling farm. Since there are two farms, there were at least 36 paddy plants were collected from this study. In each sampling point of Inlet, Middle, and Outlet, the Grains, Husks, Leaves, Stems, and Roots were separated from 9 paddy plants and they are pooled. Later, they were dried together and homogenized into powder forms, and three replicates from each pooled part were analyzed for metals. In addition to the plant samples, 18 soil samples were collected from each site, taken at two different depths: 0-15 cm for the upper layer and 15-30 cm for the lower layer. This vertical stratification allowed for the examination of metal deposition at different soil levels, which is important for

understanding the interaction between soil characteristics and metal mobility.

At each sampling zone ("Inlet," "Middle," and "Outlet"), soil samples were collected using a stainless steel soil auger to avoid contamination. The soil samples were placed in labeled polyethylene bags and transported to the laboratory for air-drying and further processing. Plant samples were harvested using clean stainless steel shears to prevent cross-contamination between samples. The samples were also placed in labeled polyethylene bags and transported to the laboratory for washing, drying, and grinding before digestion and metal content analysis.

Vertical (soil depth) and horizontal (water flow zones) sampling ensures a comprehensive analysis of metal concentrations and distribution across the paddy field environment. This methodology accounts for the potential influence of water movement on metal transport within the field while also considering the uptake of metals into different parts of the rice plants. Collecting plants during their different growth stages, weather conditions, and geographic positions provides valuable insights into the dynamics of metal contamination in rice cultivation, helping to identify specific zones and conditions where contamination risk is highest.

The paddy plant samples and their habitat topsoils were collected from points of inlet, middle, and outlet in the two paddy farming sites. The specific results of our study will allow for the formulation of recommendations for sustainable agricultural practices and environmental management in agricultural systems in rice fields exposed to heavy metal pollution.

2.4. Sample Preparation and Analysis

The rice grain samples were first washed thoroughly with deionized water to remove surface impurities, air-dried at room temperature, and oven-dried at 70 °C until a constant weight was achieved. Then the dried samples were ground into a fine powder using a stainless steel grinder. Soil samples were air-dried, homogenized, and sieved through a 2 mm mesh to remove larger particles and debris.

Before digestion, rice grain samples were treated with concentrated nitric acid (HNO₃). Approximately 0.5 g of each powdered rice sample was placed into digestion tubes and digested in a hot block digester. The temperature was initially set at 40 °C for one hour to allow the acid to gently break down organic matter, followed by an increase to 140 °C for three hours to complete the digestion.

For soil samples, a mixture of concentrated nitric acid (HNO₃) and perchloric acid (HClO₄) in a

4:1 ratio was used. Approximately 0.5 g of soil was digested in the same manner as the rice samples. The hot block digester was set at 40 °C for one hour, and the temperature was then raised to 140 °C for an additional three hours to ensure the complete breakdown of soil particles and the release of metals bound to organic matter or soil minerals.

Once digestion was complete, both rice and soil digests were cooled, filtered through Whatman filter paper, and diluted with deionized water to a known volume for analysis. Pb and Fe concentrations were determined using an air-acetylene flame technique Atomic Absorption Spectrophotometry (AAS) Model AAnalyst 800.

To ensure the accuracy of the metal concentration data, certified reference materials (CRMs) were used to verify the results. Table 2 provides a comparison of certified values (CV) and measured values (MV) for the metals analyzed in this study, including Pb and Fe. The recovery percentages (RP) were calculated as the ratio of the measured value to the certified value, expressed as a percentage:

Table 2. Comparison of metal concentrations (µg/g dry weight) between certified (CV) and measured (MV) values of the certified reference materials, and their recovery percentages (RP, %).

Metal	Samples	CV	MV	RP (MV/CV × 100)
Fe	MESS-3	4340	4012	92.5
	Peach Leaves	218	211±3.32	97.0
Pb	MESS-3	21.1±0.7	19.92±0.7	94.4
	Peach Leaves	0.87	1.11±0.14	128

The recovery percentages for the metal analysis ranged from 92.5 % to 128 %, demonstrating the accuracy and reliability of the analytical method used for measuring metal concentrations in the rice and soil samples.

2.5. Geoaccumulation Index (I_{geo}), Contamination Factor (C_f), and Ecological Risk Index (Er)

The possible anthropogenic accumulation of Pb by *Oryza sativa* can be analyzed by calculating the degree of enrichment of an element. The method is done using the formula as follows:

$$EF = \left(\frac{Me}{Fe} \right)_{sample} \div (Me/Fe)_{background}$$

where *Me* is the concentration of the potentially

enriched element studied and *Fe* is the concentration of the iron in the sediment sample. The background value for each metal is as suggested by Hakanson (1980), which is 70 for Pb. Sutherland (2000) categorized the contamination into five categories based on enrichment factor (EF) in which $EF < 2$ shows depletion to minimal enrichment, $2 \leq EF < 5$ of moderate enrichment, $5 \leq EF < 20$ shows significant enrichment, $20 \leq EF < 40$ shows very high enrichment, and $EF > 40$ shows extremely high enrichment.

The quantitative analysis for the assessment of trace elements can be done using the Index of Geoaccumulation (I_{geo}) and the ER Index. The I_{geo} as proposed by Muller (1969) is calculated by:

$$I_{geo} = \text{Log}_2 (\text{Sample} / (K \times \text{Background}))$$

where Background value is the value of the preindustrial level as reported Hakanson (1980), $K = 1.5$ is the constant to include the possible differences in the background values due to lithological factor. The ranking practically goes as $I_{geo} \leq 0$ is practically uncontaminated, $0 < I_{geo} \leq 1$ is uncontaminated to moderately contaminated, $1 < I_{geo} \leq 2$ is moderately contaminated, $2 < I_{geo} \leq 3$ moderately to heavily contaminated, $3 < I_{geo} \leq 4$ is heavily contaminated, $4 < I_{geo} \leq 5$ is heavy to very heavily contaminated and $I_{geo} > 5$ is very heavily contaminated.

Meanwhile, the ER discusses the contamination factor, the toxicity of the metal, also its abundance and it can be calculated as follows:

$$C_f^i = C_s^i \div C_n^i$$

$$E_r^i = T_r^i \times C_f^i$$

$$RI = \sum_i^n E_r^i$$

where C_f^i = Contaminative factor of element, C_s^i = Examined element in the samples, C_n^i = Background value, E_r^i = Potential ecological risk of the element, T_r^i = Toxicity parameter of element (Pb, 5), and RI is the index of potential ecological risk of total hazardous trace elements.

2.6. Health Risk Assessment: Estimated Daily Intake (EDI), Target Hazard Quotient (THQ)

To assess the health risks associated with Pb contamination from rice consumption, we calculated the EDI and THQ

The EDI was calculated as:

$$EDI=(C_{Pb} \times DRC)/ BW$$

where C_{Pb} is the Pb concentration in rice ($\mu\text{g/g}$ wet weight) in which the dry weight basis was converted into wet weight basis using conversion factors (CFs) of 0.86 for stored rice and 0.61 for steamed rice; DRC is the daily rice consumption (300 g/day for adults, 231.5 g/day for children); BW is the average body weight (60 kg for adults, 32.7 kg for children).

The THQ was calculated to assess the potential health risk associated with Pb exposure. The THQ was computed using the following equation:

$$THQ=EDI/RfD$$

where RfD is the oral reference dose for Pb, set at 0.004 mg/kg/day by the U.S. Environmental Protection Agency (USEPA, 2004). A THQ value greater than 1 indicates a potential health risk due to Pb exposure (USEPA 2004).

2.7. Statistical Analysis

Descriptive statistics were used to summarize Pb concentrations in rice grains and soils from Kemuning and Kelaweh. Analysis of variance (ANOVA) was conducted to determine significant differences in Pb concentrations between the "Inlet," "Middle," and "Outlet" zones, and between the two sites. Pearson correlation analysis was performed to evaluate the relationship between Pb concentrations in soils and rice grains. All statistical analyses were performed using SPSS software, with a significance level set at $p < 0.05$.

3. RESULTS

3.1. Concentrations of Pb and Fe in the paddy parts and their habitat topsoils

Table 3 presents the mean concentrations of Pb and Fe in different parts of the paddy plant (grain, husk, leaf, stem, and root) and their associated topsoils collected from Kemuning and Kelaweh are presented in Table 4. The data demonstrate significant Fe and Pb concentration variations between the sites and across different plant parts.

3.1.1. Lead (Pb) Concentrations

Pb concentrations followed a similar trend, with higher accumulation in the grains and leaves of plants from Kelaweh compared to Kemuning. Pb concentrations in the grains of Kelaweh ranged from 42.0 $\mu\text{g/g}$ in the "Inlet" zone to 53.4 $\mu\text{g/g}$ in the

"Outlet" zone, while Kemuning reported lower values of 6.08 $\mu\text{g/g}$ to 8.20 $\mu\text{g/g}$. The husk and stem of plants in Kelaweh also exhibited higher Pb concentrations, with the "Inlet" zone showing up to 41.6 $\mu\text{g/g}$ Pb in the husk and 118 $\mu\text{g/g}$ in the stem.

In soils, Pb concentrations were higher in Kelaweh than in Kemuning, with Kelaweh recording a peak of 78.2 $\mu\text{g/g}$ in the "Inlet" zone, compared to Kemuning's 65.8 $\mu\text{g/g}$ in the same zone. This trend was consistent across all zones, indicating a greater accumulation of Pb in Kelaweh's soils.

3.1.2. Iron (Fe) Concentrations

Fe concentrations were notably higher in both sites' roots than in other plant parts. In Kemuning, Fe concentrations in the roots ranged from 45.170 $\mu\text{g/g}$ to 54.661 $\mu\text{g/g}$, while in Kelaweh, concentrations were slightly lower, ranging from 34.679 $\mu\text{g/g}$ to 41.645 $\mu\text{g/g}$. The leaves also accumulated high Fe concentrations, particularly in Kelaweh, where values reached 1.091 $\mu\text{g/g}$ in the "Outlet" zone. The lowest Fe concentrations were found in the grains, with Kemuning reporting values between 3.34 $\mu\text{g/g}$ and 7.74 $\mu\text{g/g}$, and Kelaweh showing higher values ranging from 16.3 $\mu\text{g/g}$ to 28.5 $\mu\text{g/g}$.

Table 3. Mean concentrations ($\mu\text{g/g}$ dry weight) of Fe and Pb in the different parts of paddy fields and their habitat topsoils collected from Kemuning and Kelaweh in Kelantan.

Site		Fe		Pb	
		KM	KL	KM	KL
Grain	Inlet	7.74	28.5	6.08	42.0
	Middle	3.34	26.9	7.21	49.7
	Outlet	3.96	16.3	8.20	53.4
Husk	Inlet	10.9	187	8.76	41.6
	Middle	15.4	200	4.27	34.4
	Outlet	10.3	314	2.86	28.6
Leaf	Inlet	125	899	3.98	104
	Middle	159	1054	1.55	95.9
	Outlet	90.1	1091	2.17	107
Stem	Inlet	116	541	2.57	118
	Middle	106	454	2.20	127
	Outlet	61.79	608	2.47	134
Root	Inlet	45170	41645	62.0	37.7
	Middle	54661	36276	74.1	42.0
	Outlet	50622	34679	73.0	66.7
Soil	Inlet	13697	24036	65.8	78.2
	Middle	7691	31540	49.2	76.9
	Outlet	9487	23098	49.4	75.6

Note: KM= Kemuning; KL= Kelaweh

Regarding soil Fe content, the highest concentration was recorded in the "Inlet" zone of Kelaweh (24.036 µg/g), while Kemuning showed lower Fe levels, with a peak of 13.697 µg/g in the same zone. Across all zones, Kelaweh exhibited higher Fe concentrations in soils compared to Kemuning.

Table 4. Mean concentrations (µg/g dry weight) of Pb and Fe (%) in the habitat topsoils of paddy fields collected from Kemuning and Kelaweh in Kelantan.

Site		Fe		Pb	
		KM	KL	KM	KL
Inlet	Upper	1.37	2.40	65.76	78.19
	Lower	1.13	3.10	67.01	79.46
Middle	Upper	0.77	3.15	49.20	76.87
	Lower	1.01	2.89	59.10	77.87
Outlet	Upper	0.95	2.31	49.38	75.56
	Lower	0.95	3.28	56.30	80.92

Note: KM= Kemuning; KL= Kelaweh.

3.2. Enrichment Factor (EF), Index of geoaccumulation (Igeo), contamination factor (Cf), ecological risk (Er)

Table 5 presents the values of the enrichment factor (EF), index of geoaccumulation (Igeo), contamination factor (Cf), and ER for Pb in the habitat topsoils collected from Kemuning (KM) and Kelaweh (KW), Kelantan. These values were calculated for both upper (U) and lower (L) levels of the topsoil, allowing for an assessment of metal contamination across different depths.

The EF values for Pb in Kemuning ranged from 5.93 to 7.90 across the different zones, indicating moderate enrichment, with the highest EF value observed in the middle zone of the upper soil layer (7.90). In Kelaweh, the EF values were slightly lower, ranging from 3.02 to 4.33, suggesting moderate enrichment in this site as well. The "Inlet" zone in Kelaweh had an EF of 4.03 in the upper level, while the lower level of the "Outlet" zone showed an EF of 3.05. These EF values indicate that both sites are experiencing Pb enrichment, though it is more pronounced in Kemuning.

The Igeo values for Pb in Kemuning ranged from 0.39 to 0.84, indicating low to moderate contamination. The highest Igeo value of 0.84 was recorded in the lower level of the "Inlet" zone. In Kelaweh, the Igeo values ranged from 1.01 to 1.11, indicating moderate contamination across the site, with the highest values found in the lower level of the "Outlet" zone (1.11). The higher Igeo values in Kelaweh suggest a greater degree of Pb

contamination in this area compared to Kemuning.

The contamination factor (Cf) values in Kemuning ranged from 1.97 to 2.68, indicating moderate contamination. The highest Cf value was recorded in the lower level of the "Inlet" zone (2.68). In Kelaweh, Cf values were higher, ranging from 3.02 to 3.24, indicating moderate to considerable contamination, with the highest value observed in the lower level of the "Outlet" zone (3.24). These results suggest that Kelaweh has a higher level of Pb contamination than Kemuning, particularly in the deeper soil layers.

The ER values for Pb in Kemuning ranged from 9.84 to 13.50, reflecting low to moderate ecological risk. The highest Er value was found in the lower level of the "Inlet" zone (13.50). In Kelaweh, Er values were higher, ranging from 15.11 to 16.18, indicating moderate ecological risk. The highest Er value was observed in the lower level of the "Outlet" zone (16.18). These results highlight that Kelaweh is at a higher ecological risk from Pb contamination compared to Kemuning, particularly in the lower soil layers.

In conclusion, the results indicate that both Kemuning and Kelaweh experience moderate Pb enrichment and contamination. However, Kelaweh consistently exhibited higher values for most indicators (Igeo, Cf, Er, PERI), especially in the deeper soil layers, reflecting a greater ecological risk. These findings highlight the need for targeted interventions in Kelaweh to address Pb contamination and reduce potential environmental and health risks.

Table 5. The values of enrichment factor (EF), index of geoaccumulation (Igeo), contamination factor (Cf), ecological risk (Er), and potential ecological risk index (PERI) of Pb in the habitat topsoils collected from Kemuning and Kelaweh in Kelantan.

			EF	Igeo	CF	ER
KM	Inlet	U	5.93	0.81	2.63	13.15
		L	7.33	0.84	2.68	13.40
	Middle	U	7.90	0.39	1.97	9.84
		L	7.23	0.66	2.36	11.82
	Outlet	U	6.42	0.40	1.98	9.88
		L	7.32	0.59	2.25	11.26
KW	Inlet	U	4.03	1.06	3.13	15.64
		L	3.17	1.08	3.18	15.89
	Middle	U	3.02	1.04	3.07	15.37
		L	3.33	1.05	3.11	15.57
	Outlet	U	4.04	1.01	3.02	15.11
		L	3.05	1.11	3.24	16.18

Note: U= Upper level with 5 cm upper from a total of 10 cm topsoil; L= Lower level with 5 cm lower from a total of 10 cm topsoil.

3.3. Estimated daily intake (EDI) values and target hazard quotients (THQ)

Table 6 shows the values of EDI and THQ for Fe and Pb in grains collected from Kemuning and Kelaweh, based on adult and children consumption rates. The calculations are performed using stored rice (conversion factor of 0.86) and steamed rice (conversion factor of 0.61), reflecting the potential health risks associated with consuming rice contaminated with Fe and Pb.

Table 6. Estimated daily intake (EDI) values and target hazard quotients (THQ) values of Fe and Pb in comparison to adult and children reported daily consumption (g/day), using wet weight of grains ($\mu\text{g/g ww}$), collected from Kemuning and Kelaweh in Kelantan.

WW	Cf=		Fe		Pb	
			KM	KL	KM	KL
0.86	Inlet	EDI (adult)	43.16	158.96	33.90	234
		THQ (Adult)	0.062	0.227	8.475	58.6
	Middle	EDI (adult)	18.62	149.99	40.20	277
		THQ (Adult)	0.027	0.214	10.05	69.3
	Outlet	EDI (adult)	22.08	90.72	45.72	297
		THQ (Adult)	0.032	0.13	11.43	74.4
0.61	Inlet	EDI (adult)	30.6	113	24.05	166
		THQ (Adult)	0.04	0.16	6.011	41.6
	Middle	EDI (adult)	13.2	106	28.51	197
		THQ (Adult)	0.02	0.15	7.129	49.2
	Outlet	EDI (adult)	15.7	64.4	32.43	211
		THQ (Adult)	0.02	0.09	8.107	52.8
0.86	Inlet	EDI (Children)	21.9	80.9	17.3	119.3
		THQ (children)	0.03	0.12	4.31	29.8
	Middle	EDI (Children)	9.48	76.3	20.5	141
		THQ (children)	0.01	0.11	5.12	35.3
	Outlet	EDI (Children)	11.2	46.2	23.3	151
		THQ (children)	0.02	0.07	5.82	37.9
0.61	Inlet	EDI (Children)	15.6	57.4	12.2	84.6

Inlet	THQ (children)	0.02	0.08	3.06	21.2
Middle	EDI (Children)	6.72	54.2	14.5	100
	THQ (children)	0.01	0.08	3.63	25.0
Outlet	EDI (Children)	7.97	32.8	16.5	107
	THQ (children)	0.01	0.05	4.13	26.9

Note: Reported daily consumption rates for adults and children are 389 and 198 g/day, respectively (Hang *et al.*, 2009). The wet weight basis is converted using a reported conversion factor of 0.86 for stored rice (Zhuang *et al.*, 2009) and an estimated conversion factor of 0.61 for steamed rice from the present study. Toxic response values used are Fe: 700 and Pb: 4.00. Note: KM= Kemuning; KL= Kelaweh.

The EDI values for Fe varied significantly between Kemuning and Kelaweh. For adults, Fe intake from stored rice in the "Inlet" zone of Kelaweh was the highest at 158.96 $\mu\text{g/day}$, while Kemuning's intake was substantially lower at 43.16 $\mu\text{g/day}$. Similarly, the "Outlet" zone in Kelaweh showed an EDI of 90.72 $\mu\text{g/day}$, compared to 22.08 $\mu\text{g/day}$ in Kemuning. When using the steamed rice conversion factor, the EDI values decreased, but the trend remained the same, with Kelaweh showing higher intake levels across all zones.

The EDI values for children were lower than for adults but still reflected higher intake levels in Kelaweh compared to Kemuning. The highest Fe intake for children was recorded in the "Inlet" zone of Kelaweh at 80.91 $\mu\text{g/day}$, while Kemuning showed an intake of 21.97 $\mu\text{g/day}$ in the same zone. Across all zones, children in Kelaweh had a higher Fe intake than those in Kemuning.

Pb intake (EDI) values followed a similar trend, with Kelaweh showing higher values than Kemuning. For adults, the highest Pb intake from stored rice was observed in the "Inlet" zone of Kelaweh at 234.35 $\mu\text{g/day}$, compared to 33.90 $\mu\text{g/day}$ in Kemuning. In the "Outlet" zone, Kelaweh had an EDI of 297.57 $\mu\text{g/day}$, whereas Kemuning reported 45.72 $\mu\text{g/day}$. The EDI values for steamed rice were lower but followed the same pattern, with Kelaweh consistently showing higher Pb intake levels.

For children, Pb intake was significantly higher in Kelaweh, particularly in the "Inlet" and "Outlet" zones, where EDI values reached 119.28 $\mu\text{g/day}$ and 151.46 $\mu\text{g/day}$, respectively. In comparison, Kemuning showed much lower intake levels, with the highest EDI recorded in the "Outlet" zone at 23.27 $\mu\text{g/day}$.

The THQ for Fe in both adults and children were well below the safety threshold of 1, indicating no immediate health risk from Fe intake. For adults,

the THQ for Fe in Kemuning ranged from 0.022 to 0.062, while in Kelaweh, the THQ ranged from 0.092 to 0.227. The highest THQ for Fe was observed in the "Inlet" zone of Kelaweh for adults at 0.227, which remains below the threshold. Similarly, for children, the THQ for Fe in Kelaweh was higher than in Kemuning, with the highest THQ in the "Inlet" zone at 0.116, still below the safety threshold.

In contrast to Fe, the THQ values for Pb were much higher, particularly in Kelaweh, and exceeded the safety threshold of 1 in several zones, indicating potential health risks. For adults, the THQ for Pb in Kelaweh ranged from 41.555 to 69.306 across the different zones, with the highest THQ recorded in the "Inlet" zone (THQ = 58.586) and "Outlet" zone (THQ = 69.306). In comparison, Kemuning showed lower THQ values, ranging from 8.107 to 11.430, still below the threshold but indicating moderate risk.

For children, the THQ for Pb in Kelaweh also exceeded the threshold in all zones, with the highest values recorded in the "Inlet" zone (THQ = 29.820) and "Outlet" zone (THQ = 37.866). In contrast, Kemuning's THQ values for children were lower, ranging from 3.060 to 8.127, remaining below the threshold but still posing a potential health risk.

The results indicate that Kelaweh consistently exhibits higher EDI and THQ values for both Fe and Pb compared to Kemuning. While Fe intake poses no immediate health risk, the elevated THQ values for Pb in Kelaweh, especially in the "Inlet" and "Outlet" zones, exceed the safety threshold for both adults and children, highlighting a potential health concern. This suggests that rice consumption from Kelaweh, particularly in these zones, may pose a significant risk of Pb exposure, warranting further investigation and potential mitigation strategies.

4. DISCUSSION

4.1. Comparison of Fe and Pb in Paddy Plants and Soils

The study highlights distinct patterns of Fe and Pb accumulation in both paddy plants and soils from Kemuning and Kelaweh. Fe accumulation was highest in the roots, followed by the leaves and stems, while Pb concentrations were most pronounced in the grains and leaves, particularly in Kelaweh. The results indicate significant variations between the two sites, with Kelaweh exhibiting consistently higher levels of both Fe and Pb in the soil and plant tissues than Kemuning. These variations can be attributed to differences in soil composition, irrigation practices, and external contamination sources (Sun *et al.*, 2015;

Wang *et al.*, 2019; Arunakumara *et al.*, 2013; Reddy *et al.*, 2013).

Fe is an essential micronutrient for plants, and its accumulation was notably higher in the roots, as the roots are the primary site for metal uptake from the soil (Sun *et al.*, 2012; Li *et al.*, 2016; Zarcinas *et al.*, 2004; Song *et al.*, 2020). The elevated Fe concentrations in Kelaweh, especially in the "Inlet" and "Outlet" zones, suggest that irrigation practices and water flow dynamics may contribute to the redistribution of Fe within the fields (Wu *et al.*, 2023; Zeng *et al.*, 2011; Tang *et al.*, 2021). Soil samples from Kelaweh exhibited higher Fe concentrations, particularly in the deeper layers, indicating that Fe is bioavailable to the plants and prone to accumulation over time (Wang *et al.*, 2016; Wei *et al.*, 2018; Zhao *et al.*, 2021). While Fe is critical for plant growth, excessive levels can interfere with the absorption of other essential nutrients, potentially impairing plant health and productivity if not carefully managed (Marschner, 2012; Wu & Zhang, 2010).

The findings align with previous studies indicating that waterlogged conditions in paddy fields can enhance the solubility and mobility of Fe, leading to increased bioavailability for plant uptake (Jiang *et al.*, 2019; Wu *et al.*, 2015; Zarcinas *et al.*, 2003). In Kemuning, Fe accumulation was moderate and remained below critical thresholds for plant health and human consumption, suggesting that the area may not be as prone to metal mobilization as Kelaweh (Wu *et al.*, 2015).

Pb, in contrast, is a toxic metal with no biological function in plants or humans. The significant accumulation of Pb in Kelaweh's paddy grains and leaves, particularly in the "Outlet" zones, raises critical food safety concerns (Kim *et al.*, 2014; Hang *et al.*, 2009). Pb concentrations in Kelaweh's grains reached up to 53.4 µg/g, which far exceeds the levels observed in Kemuning (6.08–8.20 µg/g) (Bashir *et al.*, 2018). These high levels of Pb in edible plant parts pose a serious risk to human health, especially for children who are more susceptible to Pb toxicity (Järup, 2003; Halim *et al.*, 2014; Yin *et al.*, 2016).

The consistently higher Pb levels in Kelaweh, particularly in the "Inlet" and "Outlet" zones, suggest that external sources of contamination, such as industrial runoff or the use of Pb-containing agrochemicals, may be contributing to the elevated Pb levels in the soils (Jeon *et al.*, 2015b; Bian *et al.*, 2015; Nadimi-Goki *et al.*, 2014). Pb is known for its ability to accumulate in waterlogged soils, where it becomes more bioavailable for plant uptake (Jiang *et al.*, 2019; Rogan *et al.*, 2009). This study's findings emphasize the need for immediate interventions to mitigate Pb

contamination in Kelaweh, as chronic exposure to Pb through rice consumption can lead to severe health problems, including neurological and developmental issues (Khan et al., 2020; Lei et al., 2010).

4.2. Distribution of Fe and Pb in Different Parts of the Paddy Plant and Its Significance in Biomonitoring and Ecotoxicological Studies

The distribution of Fe and Pb in different parts of the paddy plant provides crucial information for biomonitoring and ecotoxicological assessments, particularly in regions like Kelantan where heavy metal contamination is a concern (Wu et al., 2010; Jalali & Hemati, 2013; Merismon et al., 2017). Fe, an essential nutrient for plant growth, and Pb, a non-essential and highly toxic metal, behave differently in their absorption and translocation within the plant system (Wu et al., 2015; Yap & Wong, 2011). The patterns of accumulation observed in this study offer insights into the ecological impact of metal contamination and the potential risks posed to human health and the environment (Wu et al., 2023; Zarcinas et al., 2003; Wu et al., 2016).

Fe, an essential micronutrient, accumulated predominantly in the roots, followed by the leaves and stems, with significantly lower concentrations in the grains (Li et al., 2016; Xiong et al., 2024). This distribution pattern aligns with the general understanding that Fe is actively absorbed by the roots from the soil and stored in plant tissues, where it is used in vital physiological processes such as chlorophyll synthesis and enzyme function (Marschner, 2012; Xu et al., 2017; Nziguheba & Smolders, 2008). The high Fe concentrations in the roots indicate that the plant efficiently sequesters Fe, preventing excess translocation to the aerial parts of the plant, particularly the grains (Zhao et al., 2021; Sun et al., 2015; Yang et al., 2017).

From a biomonitoring perspective, the concentration of Fe in the roots makes the paddy plant a valuable tool for assessing soil Fe levels and monitoring changes in soil metal content over time (Reddy et al., 2013; Li et al., 2013; Ye et al., 2018). Since Fe is essential for plant growth, monitoring Fe levels in the paddy plant can serve as an indicator of the overall health of the soil and agricultural ecosystem (Arunakumara et al., 2013; Zhang et al., 2016). High levels of Fe in the roots, as observed in Kelaweh, suggest that irrigation practices and soil composition may be contributing to Fe accumulation in this region (Sun et al., 2015; Wu et al., 2023). Biomonitoring of Fe in the roots can provide early warning signals of potential soil degradation or nutrient imbalances that could affect crop yields and

soil fertility in the long term (Li et al., 2016; Yap & Wong, 2011).

The distribution of Pb in the paddy plant was significantly different from that of Fe, with higher concentrations found in the grains and leaves, particularly in the "Outlet" zones of Kelaweh (Miao & Yang, 2012; Halim et al., 2014). Pb is a highly toxic metal with no known biological function in plants or animals, and its accumulation in edible plant parts, such as rice grains, poses a serious risk to human health (Kim et al., 2014; Zhao et al., 2010). The Pb concentrations in Kelaweh's grains, reaching up to 53.4 µg/g, far exceed the concentrations observed in Kemuning and are significantly above safe consumption limits (Khan et al., 2020; Reddy et al., 2013).

From an ecotoxicological perspective, the high mobility and bioavailability of Pb in paddy fields under waterlogged conditions result in significant translocation of Pb from the soil to the aerial parts of the plant (Jeon et al., 2015a; Rogan et al., 2009). This suggests that irrigation water and soil composition play a critical role in Pb contamination (Sun et al., 2015; Halim et al., 2014). The higher Pb concentrations in the "Outlet" zones further support the idea that Pb is transported through water flow and accumulates in lower-lying areas of the paddy fields (Jiang et al., 2019; Li et al., 2013; Zou et al., 2021). This pattern of Pb distribution highlights the importance of monitoring water sources and irrigation practices to prevent the spread of Pb contamination in agricultural systems (Wu et al., 2023; Miao & Yang, 2012).

The translocation of Pb from the roots to the grains has significant implications for biomonitoring and ecotoxicological studies. Paddy plants can serve as effective biomonitors for detecting Pb contamination in soils and assessing the risk of Pb entering the food chain (Bashir et al., 2018; Wu et al., 2010). The high Pb concentrations in the grains suggest that human populations relying on rice as a staple food source are at risk of Pb exposure, necessitating regular monitoring of Pb levels in both soils and crops (Khan et al., 2020; Halim et al., 2014). Ecotoxicological assessments should focus on the impact of Pb contamination on plant health, soil fertility, and the broader ecosystem, as prolonged exposure to Pb can lead to reduced biodiversity and disruption of soil microorganisms (Kim et al., 2016; Li et al., 2016).

4.3. The Relationships Between ER and Metal Accumulation in Paddy Parts

The relationship between metals' ER and their

accumulation in different parts of the paddy plant is key to understanding how metal contamination impacts plant health and the broader ecosystem. In this study, Pb shows distinct patterns of accumulation in the paddy plant's roots, stems, leaves, and grains. These patterns offer insights into the bioavailability and mobility of metals in the environment and how they contribute to ecological risk (Sun et al., 2015; Jiang et al., 2019; Halim et al., 2014).

The accumulation of metals in different parts of the paddy plant—roots, stems, leaves, and grains—indicates how metals are absorbed from the soil and redistributed throughout the plant (Jeon et al., 2015a; Arunakumara et al., 2013; Rogan et al., 2009). Pb, being a toxic and non-essential metal, was found to accumulate in higher concentrations in the grains and leaves, while Fe, an essential nutrient, was predominantly stored in the roots and stems. This differential accumulation is critical because it suggests that Pb is more likely to pose a direct risk to human health via food consumption, while Fe, though important for plant growth, could impact soil and plant health if present in excessive amounts (Wu et al., 2023; Lei et al., 2010).

Regarding ecological risk (Er), Pb presents a higher risk due to its toxic nature and ability to bioaccumulate in edible parts of the plant, particularly the grains. The Er values for Pb in this study were elevated in areas such as the "Outlet" zones of Kelaweh, where irrigation runoff likely increased the bioavailability of Pb in the soil. This, in turn, led to higher concentrations of Pb in the paddy grains, which poses significant health risks to consumers (Reddy et al., 2013; Bashir et al., 2018). Previous studies have shown that Pb contamination in paddy fields can be linked to industrial runoff and the use of Pb-based agrochemicals, which exacerbate the ecological risk posed by this metal (Khan et al., 2020; Jeon et al., 2015b; Li et al., 2013).

The ER of metals such as Pb and Fe is directly influenced by their bioavailability in the soil and their ability to be absorbed by plants (Miao & Yang, 2012; Sun et al., 2015). In paddy fields, waterlogged conditions increase the solubility of certain metals, making them more available for plant uptake. The higher Er values for Pb in the soil are reflected in its higher accumulation in the grains and leaves of the paddy plant, particularly in the "Outlet" zones, where metals tend to accumulate due to water flow dynamics (Sun et al., 2015; Rogan et al., 2009).

In contrast, Fe, despite being an essential nutrient, also poses an ecological risk when present in excessive amounts. In this study, Fe was primarily concentrated in the roots, which suggests that the plant can store Fe in non-edible parts, thereby

reducing its risk to human health. However, elevated Fe levels in the soil can lead to imbalances in nutrient availability, potentially affecting crop yields and soil health (Marschner, 2012; Arunakumara et al., 2013). The relationship between Fe accumulation and Er is less concerning than that of Pb, but it still requires monitoring to prevent long-term environmental impacts (Li et al., 2016; Hang et al., 2009).

The accumulation of Pb in the grains directly impacts human health, as rice is a staple food in many regions, including Kelantan. The elevated Er values for Pb in this study indicate that humans consuming rice from contaminated areas are at risk of Pb exposure. This is particularly concerning for children, who are more susceptible to the toxic effects of Pb, such as cognitive impairment and developmental delays (Khan et al., 2020; Halim et al., 2014). The relationship between high Er values for Pb and its accumulation in the grains underscores the need for targeted interventions to reduce metal contamination in paddy fields, such as improving irrigation practices and limiting the use of Pb-containing agrochemicals (Kim et al., 2014; Bian et al., 2015).

Regarding biomonitoring, the patterns of metal accumulation in different parts of the paddy plant can be used to assess the ecological risk of metal contamination in agricultural systems (Mlangeni et al., 2023; Yap & Wong, 2011). Roots, which tend to store essential metals like Fe, can be monitored to evaluate soil health and nutrient availability, while grains and leaves are critical for assessing the risk posed by toxic metals like Pb. The findings from this study suggest that regular monitoring of metal concentrations in both soil and plant tissues is essential for managing ecological risks and ensuring food safety (Wu et al., 2023; Bashir et al., 2018).

4.4. High Pb Levels in Edible Paddy: Public Health Risk, Food Security, and Planetary Health

The high levels of Pb detected in the edible parts of the paddy plant, particularly the grains, present significant risks to public health, food security, and planetary health. Pb is a toxic metal with no known biological function, and its accumulation in staple crops such as rice poses direct threats to human health, especially in populations that rely heavily on rice as a dietary staple (Bashir et al., 2018; Hang et al., 2009). The findings from this study highlight the urgency of addressing Pb contamination in rice-producing regions like Kelantan to prevent long-term consequences on human well-being, food supply, and environmental sustainability (Khan et al., 2020; Kim

et al., 2014).

Pb contamination in rice presents a severe public health issue, especially in regions where rice is consumed in large quantities, such as Southeast Asia (Kim et al., 2014; Sun et al., 2015). The elevated Pb levels in Kelaweh, where concentrations in the grains reached up to 53.4 µg/g, far exceed the safe limits set by international food safety authorities (Järup, 2003). Chronic exposure to Pb through rice consumption can lead to serious health problems, including neurological impairments, cognitive deficits, developmental delays in children, and kidney dysfunction in adults (Alloway, 2013; Jiang et al., 2019). Children, in particular, are more vulnerable to Pb toxicity due to their developing nervous systems, which makes even low levels of exposure particularly harmful (Khan et al., 2020).

The high Pb concentrations in edible grains mean that every meal consumed by individuals in contaminated areas contributes to their overall Pb burden. This bioaccumulation of Pb can lead to long-term health effects that are difficult to mitigate once exposure has occurred (Jiang et al., 2019; Lei et al., 2010). Pb is known for its persistence in the body, and prolonged exposure exacerbates its toxic effects, creating a public health crisis for populations living near contaminated agricultural zones (Dolenec et al., 2007; Jeon et al., 2015a; Mlangeni et al., 2023). To protect public health, immediate interventions are necessary to reduce Pb levels in rice fields through improved agricultural practices and remediation strategies that limit Pb uptake by rice plants (Garrido et al., 2020; Wu et al., 2023).

The contamination of rice, a staple food for billions of people globally, directly threatens food security. Rice is not only a major source of calories but also provides essential nutrients to many populations (Sun et al., 2015; Hang et al., 2009). The high levels of Pb contamination in rice grains found in Kelaweh undermine the safety and nutritional value of this essential food source. If rice from contaminated areas is deemed unsafe for consumption, it could lead to a reduction in food availability, forcing communities to rely on alternative, possibly more expensive, food sources (Alloway, 2013; Kim et al., 2016). This situation could exacerbate food insecurity, particularly in rural and low-income populations that have limited access to diverse food supplies (Khan et al., 2020; Bian et al., 2015).

Moreover, Pb contamination in rice fields can negatively affect crop productivity. Heavy metals like Pb can disrupt nutrient absorption in plants, reduce yields, and lead to poor crop quality (Mlangeni et al., 2023; Rogan et al., 2009). In the long term,

contaminated soils may become less fertile, further threatening the sustainability of rice farming in affected regions (Zarcinas et al., 2003; Miao & Yang, 2012; Jiang et al., 2014). Ensuring food security in these areas will require comprehensive measures to reduce metal contamination in soils and prevent the uptake of toxic metals by food crops (Ali et al., 2013; Yap & Wong, 2011).

The concept of planetary health, which links human health to the health of the natural ecosystems that sustain life, is deeply interconnected with the issues of environmental contamination and agricultural sustainability (Ceci et al., 2019). The high Pb levels in rice-producing regions like Kelaweh not only threaten human health and food security but also have broader implications for planetary health. Pb contamination in soils degrades ecosystem integrity by altering soil chemistry, reducing microbial biodiversity, and impairing the natural processes that support plant growth and soil fertility (Sun et al., 2015; Nziguheba & Smolders, 2008).

The persistence of heavy metals in agricultural soils also contributes to long-term environmental degradation. Once Pb accumulates in the soil, it remains for extended periods, affecting both current and future generations of plants and animals (Jiang et al., 2019; Reddy et al., 2013). This contamination can spread beyond the agricultural fields through water runoff, further polluting nearby ecosystems, rivers, and wetlands (Jeon et al., 2015b; Rinklebe et al., 2016; Wu & Zhang, 2010). These cumulative impacts undermine the resilience of ecosystems and their capacity to sustainably support human populations (Ali et al., 2013; Lei et al., 2010; Nopriani et al., 2023).

Addressing Pb contamination is essential not only for safeguarding human health but also for protecting the ecological systems that are vital to planetary health. Sustainable agricultural practices that minimize the use of metal-containing agrochemicals, improve water quality, and promote soil health are crucial for maintaining the balance between human activity and environmental sustainability (Kim et al., 2016; Mlangeni et al., 2023). By tackling Pb contamination in paddy fields, we can ensure the long-term viability of rice production while preserving the health of ecosystems that are critical for planetary health (Wu et al., 2023; Zarcinas et al., 2004; Li et al., 2018; Nong et al., 2020).

4.5. Future Recommendations

The findings of this study highlight the urgent need for addressing Pb contamination in paddy fields,

particularly in areas like Kelaweh, where Pb levels in the edible parts of the rice plant exceed safe thresholds. Several recommendations should be implemented to mitigate these risks and ensure the sustainability of rice production, both at the policy level and in agricultural practices.

4.5.1. Enhanced Monitoring and Regular Risk Assessments

Monitoring heavy metal concentrations in soil, water, and plant tissues is critical to ensuring food safety and protecting public health. It is recommended that a systematic monitoring program be established, focusing on key contaminants such as Pb, cadmium (Cd), and mercury (Hg) (Mlangeni et al., 2023). This will allow early detection of contamination hotspots and enable timely interventions. Moreover, implementing risk assessment models such as the THQ and the Cf can help assess the severity of the contamination and its potential impact on human health and the environment (Ceci et al., 2019; Li et al., 2016; Wijewardana et al., 2022).

4.5.2. Adoption of Phytoremediation and Soil Amendment Techniques

Phytoremediation, using specific plants to absorb and concentrate metals from contaminated soils, offers a sustainable solution for reducing metal concentrations in agricultural land (Shi et al., 2011; Ali et al., 2013; Rosariastuti et al., 2019). Fast-growing hyperaccumulators such as *Brassica juncea* (Indian mustard) or *Pteris vittata* (Chinese brake fern) can be introduced during fallow periods to cleanse the soil of excessive Pb. In conjunction with phytoremediation, soil amendments such as the addition of biochar, lime, or organic matter can reduce the bioavailability of Pb, thus minimizing its uptake by paddy plants (Jiang et al., 2019; Bashir et al., 2018). These techniques enhance soil health, improve crop productivity, and contribute to long-term agricultural sustainability (Guo et al., 2018; Kim et al., 2016).

4.5.3. Improvement of Water Management Systems

The study highlighted the role of water flow in redistributing Pb across the paddy fields, with higher concentrations observed in the "Outlet" zones (Sun et al., 2015; Hou et al., 2023). To address this, improved water management systems should be developed to control the flow of contaminated water. Implementing constructed wetlands or buffer zones can help filter out contaminants before irrigation water enters paddy fields (Garrido et al., 2020). Additionally, introducing controlled irrigation practices such as alternate wetting and drying (AWD) may reduce metal solubility and

bioavailability in flooded soils, thereby limiting metal uptake by plants (Kim et al., 2014).

4.5.4. Use of Pb-Free Agrochemicals and Fertilizers

Pb-containing agrochemicals are a known contributor to soil contamination in agricultural regions (Miao & Yang, 2012). Policymakers should enforce stricter regulations on the use of metal-based fertilizers and pesticides, promoting the use of safer alternatives (Jiang et al., 2019). Education campaigns for farmers on the harmful effects of Pb contamination and guidance on best practices for minimizing metal inputs into the environment can further reduce the risk of contamination. Additionally, promoting the use of organic farming practices, which avoid synthetic chemicals, can play a vital role in preventing metal buildup in agricultural soils (Alloway, 2013; Huang et al., 2023).

4.5.5. Strengthening Food Safety Regulations and Public Health Initiatives

Governments and regulatory bodies must strengthen food safety regulations by limiting allowable metal concentrations in agricultural products (Bashir et al., 2018). These regulations should be regularly updated to reflect emerging scientific knowledge on metal toxicity and human health risks. Alongside these regulatory measures, public health initiatives should focus on raising awareness about the risks of consuming contaminated rice and promoting dietary diversification to reduce dependence on rice as a sole staple in regions with known contamination issues (Khan et al., 2021; Divisekara et al., 2018).

4.5.6. Research and Development of Contamination Mitigation Technologies

Further research is needed to develop innovative contamination mitigation technologies that are cost-effective and scalable. This includes exploring advanced methods of soil remediation, such as electrokinetic remediation, which uses electric currents to remove metals from soils (Jeon et al., 2015b), and nanotechnology-based solutions for metal sequestration (Sun et al., 2015; Diao et al., 2022). Additionally, investigating crop varieties that are less prone to metal uptake or can tolerate contaminated environments without translocating metals to edible parts can help secure the safety of food supplies in contaminated regions (Kim et al., 2016; Mlangeni et al., 2023; Ceci et al., 2019).

5. CONCLUSIONS

This study highlights the significant health

risks associated with Pb contamination in paddy soils and rice grains in Kelantan, particularly in the Kelaweh region, where Pb concentrations far exceeded safe consumption limits. The elevated Pb levels in the edible parts of the plant pose severe risks to public health, especially for children and vulnerable populations, due to the long-term effects of Pb toxicity. In addition, the higher levels of Pb in soils and its bioaccumulation in rice grains underscore the urgent need for mitigation strategies to prevent further contamination of agricultural lands. These findings also raise concerns about food security, as rice is a staple crop, and continued contamination could reduce the availability of safe, nutritious food for local populations.

The broader implications of this study extend to planetary health, as heavy metal contamination in agricultural ecosystems disrupts human health and the integrity of soil and water systems. Sustainable agricultural practices, such as improved water management, the use of Pb-free agrochemicals, and soil remediation techniques, are crucial for mitigating contamination and preserving ecosystem health. By addressing these challenges through concerted policy efforts, public health interventions, and continued research, the region can ensure safer food production and contribute to long-term environmental sustainability.

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REFERENCES

- Arunakumara, K. K. I. U., Walpola, B. C., & Yoon, M. H.**, 2013. *Current status of heavy metal contamination in Asia's rice lands*. *Reviews in Environmental Science and Bio/Technology*, 12(4), 355-377, <https://doi.org/10.1007/s11157-013-9312-6>.
- Bashir, S., Shaaban, M., Hussain, Q., Mehmood, S., Zhu, J., Fu, Q., Aziz, O., & Hu, H.**, 2018. *Influence of organic and inorganic passivators on Cd and Pb stabilization and microbial biomass in a contaminated paddy soil*. *Journal of Soils and Sediments*, 18(1), 2948-2959, <https://doi.org/10.1007/s11368-018-1971-7>.
- Bian, B., Zhou, L. J., Li, L., Lv, L., & Fan, Y. M.**, 2015. *Risk assessment of heavy metals in air, water, vegetables, grains, and related soils irrigated with biogas slurry in Taihu Basin, China*. *Environmental Science and Pollution Research*, 22, 7794-7807.
- Bora, P., & Devi, N. N.**, 2024. *Bioremediation of heavy metal lead (Pb) by enteric bacteria and metagenomic analysis of an endogenic earthworm *Metaphire nanaoensis* found in the semi-urban paddy fields of Kamrup District, Assam*. *Water, Air, and Soil Pollution*, 235(6), 1-19.
- Deng, X., Li, Q., Mi, Y., Duan, H., Chen, L., Zhang, W., & Wei, M.**, 2017. *Immobilization remediation of Pb-contaminated paddy soils in Gejiu Mining Area, Yunnan*. *Chinese Journal of Environmental Engineering*, 11(8), 4831-4837.
- Diao, Y., Wang, X., Zhou, L., Dan, Y., Sang, W., Usman, M., Luo, G., & Zhang, Y.**, 2022. *Simultaneously immobilization of Cd and Pb in paddy soil by magnetic modified biochar based on textile dyeing sludge: Metal speciation and soil microbial community evolution*. *Journal of Soils and Sediments*, 22(10), 2765-2776.
- Divisekara, T., Navaratne, A. N., & Abeysekara, A. S. K.**, 2018. *Impact of a commercial glyphosate formulation on adsorption of Cd(II) and Pb(II) ions on paddy soil*. *Chemosphere*, 198, 334-341.
- Dolenec, T., Serafimovski, T., Tasev, G., Dobnikar, M., Dolenec, M., & Rogan, N.**, 2007. *Major and trace elements in paddy soil contaminated by Pb-Zn mining: A case study of Kočani Field, Macedonia*. *Environmental Geochemistry and Health*, 29(1), 21-32.
- Gao, R., Zhu, P., Guo, G., Hu, H., Zhu, J., & Fu, Q.**, 2016. *Efficiency of several leaching reagents on removal of Cu, Pb, Cd, and Zn from highly contaminated paddy soil*. *Environmental Science and Pollution Research*, 23(22), 23271-23280, <https://doi.org/10.1007/s11356-016-7560-x>
- Gao, Y., Jiang, X., Wu, H., Tong, J., Ren, X., Ren, J., Wu, Q., Ye, J., Li, C., & Shi, J.**, 2022. *Colonization of *Penicillium oxalicum* SL2 in Pb-contaminated paddy soil and its immobilization effect on soil Pb*. *Journal of Environmental Sciences (China)*, 120, 53-62, <https://doi.org/10.1016/j.jes.2021.12.045>.
- Guo, Z., Ran, H., Feng, W., Xiao, X., Shi, L., & Xue, Q.**, 2018. *Effect of impeding main exogenous heavy metal input on accumulation of Cd and Pb in paddy soil-rice system*. *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, 34(16), 232-237, <https://doi.org/10.11975/j.issn.1002-6819.2018.16.030>
- Hakanson, L.**, 1980. *An ecological risk index for aquatic pollution control. A sedimentological approach*. *Water Research*, 14(8), 975-1001.
- Halim, M. A., Majumder, R. K., & Zaman, M. N.**, 2014. *Paddy soil heavy metal contamination and uptake in rice plants from the adjacent area of Barapukuria coal mine, northwest Bangladesh*. *Arabian Journal of Geosciences*, 7, 3911-3920, <https://doi.org/10.1007/>

s12517-013-1123-3.

- 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), 2542–2549, <https://doi.org/10.1016/j.envpol.2009.03.002>.
- He, H., Zhou, J., Xiao, A., Yan, Y., Chen, A., & Han, B.,** 2024. *A two-year study of bioorganic fertilizer on the content of Pb and As in brown rice and rice yield in a contaminated paddy field*. Agriculture (Switzerland), 14(7), 1061, <https://doi.org/10.3390/agriculture14071061>.
- Hong, Y.-K., Kim, J.-W., Lee, S.-P., Yang, J., & Kim, S.-C.,** 2022. *Effect of combined soil amendment on immobilization of bioavailable As and Pb in paddy soil*. Toxics, 10(2), Article 90, <https://doi.org/10.3390/toxics10020090>.
- Hou, Z.-W., Li, J.-H., Li, C.-S., Zhang, J.-M., Lin, Q.-H., Zhao, Q.-J., Wu, Z.-P., & Wang, Y.,** 2023. *Effect of coconut fiber biochar and its nitrate modification on Pb passivation in paddy soils*. Huanjing Kexue/Environmental Science, 44(8), 4497–4506. <https://doi.org/10.13227/j.hjkk.202208042>.
- Huang, H., Mao, J., Tan, J., Zhong, K., Chen, J., Huang, D., Gu, X., & Zhang, C.,** 2023. *Heavy metal contamination, accumulation, and risk assessment in a paddy field near Pb-Zn mine, in Guangxi Province, China*. Journal of Soils and Sediments, 23(3), 1345–1355, <https://doi.org/10.1007/s11368-022-03366-x>.
- Iqbal, M. M., Murtaza, G., Naz, T., Hussain, A., Button, M., & Du Laing, G.,** 2018. *Pb fractionation and redistribution as affected by applied inorganic amendments under different soil moisture regimes and incubation time in saline-sodic Pb-polluted paddy soil*. Paddy and Water Environment, 16(4), 875–885, <https://doi.org/10.1007/s10333-018-0676-5>.
- Jalali, M., & Hemati, N.,** 2013. *Chemical fractionation of seven heavy metals (Cd, Cu, Fe, Mn, Ni, Pb, and Zn) in selected paddy soils of Iran*. Paddy and Water Environment, 11(1-4), 299–309, <https://doi.org/10.1007/s10333-012-0320-8>.
- Jeon, E.-K., Jung, J.-M., Kim, W.-S., Ko, S.-H., & Baek, K.,** 2015a. *In situ electrokinetic remediation of As-, Cu-, and Pb-contaminated paddy soil using hexagonal electrode configuration: A full-scale study*. Environmental Science and Pollution Research, 22(1), 711–720, <https://doi.org/10.1007/s11356-014-3363-0>.
- Jeon, E.-K., Jung, J.-M., Ryu, S.-R., & Baek, K.,** 2015a. *In situ field application of electrokinetic remediation for an As-, Cu-, and Pb-contaminated rice paddy site using parallel electrode configuration*. Environmental Science and Pollution Research, 22(20), 15763–15771, <https://doi.org/10.1007/s11356-015-4765-3>.
- Jiang, Q.-J., Zhang, Y.-Q., Zhang, L.-M., Zhou, X.-B., & Shi, X.-J.,** 2014. *Microbial characteristics of purple paddy soil in response to Pb pollution*. Pakistan Journal of Pharmaceutical Sciences, 27(3), 643–648.
- Jiang, Y., Jiang, S., Li, Z., Yan, X., Qin, Z., & Huang, R.,** 2019. *Field scale remediation of Cd and Pb contaminated paddy soil using three mulberry (Morus alba L.) cultivars*. Ecological Engineering, 129, 38–44, <https://doi.org/10.1016/j.ecoleng.2019.01.009>.
- Jing, F., Chen, X., Wen, X., Liu, W., Hu, S., Yang, Z., Guo, B., Luo, Y., Yu, Q., & Xu, Y.,** 2020. *Biochar effects on soil chemical properties and mobilization of cadmium (Cd) and lead (Pb) in paddy soil*. Soil Use and Management, 36(2), 320–327, <https://doi.org/10.1111/sum.12557>.
- Jung, M. C., & Thornton, I.,** 1997. *Environmental contamination and seasonal variation of metals in soils, plants, and waters in the paddy fields around a Pb-Zn mine in Korea*. Science of the Total Environment, 198(2), 105–121. [https://doi.org/10.1016/S0048-9697\(97\)05434-X](https://doi.org/10.1016/S0048-9697(97)05434-X).
- Khalique, M. A., Khan Tarin, M. W., Jingxia, G., Yanhui, C., & Guo, W.,** 2019. *Soil liming effects on CH₄, N₂O emission, and Cd, Pb accumulation in upland and paddy rice*. Environmental Pollution, 248, 408–420, <https://doi.org/10.1016/j.envpol.2019.02.036>.
- Khanam, R., Kumar, A., Nayak, A. K., Shahid, M., Tripathi, R., Vijayakumar, S., Bhaduri, D., Kumar, U., Mohanty, S., Panneerselvam, P., Chatterjee, D., Satapathy, B. S., & Pathak, H.,** 2020. *Metal(loid)s (As, Hg, Se, Pb, and Cd) in paddy soil: Bioavailability and potential risk to human health*. Science of the Total Environment, 699, Article 134330, <https://doi.org/10.1016/j.scitotenv.2019.134330>.
- Kim, B.-K., Park, G.-Y., Jeon, E.-K., Jung, J.-M., Jung, H.-B., Ko, S.-H., & Baek, K.,** 2013. *Field application of in situ electrokinetic remediation for As-, Cu-, and Pb-contaminated paddy soil*. Water, Air, and Soil Pollution, 224(9), Article 1698, <https://doi.org/10.1007/s11270-013-1698-7>.
- Kim, S.-C., Kim, H. S., Seo, B.-H., Owens, G., & Kim, K.-R.,** 2016. *Phytoavailability control-based management for paddy soil contaminated with Cd and Pb: Implications for safer rice production*. Geoderma, 270, 83–88, <https://doi.org/10.1016/j.geoderma.2015.11.031>.
- Kim, W.-S., Yoo, J.-C., Jeon, E.-K., Yang, J.-S., & Baek, K.,** 2014. *Stepwise sequential extraction of As-, Cu-, and Pb-contaminated paddy soil*. Clean - Soil, Air, Water, 42(12), 1785–1789, <https://doi.org/10.1002/clen.201300355>.
- Lei, M., Zhang, Y., Khan, S., Qin, P.-F., & Liao, B.-H.,** 2010. *Pollution, fractionation, and mobility of Pb, Cd, Cu, and Zn in garden and paddy soils from a Pb/Zn mining area*. Environmental Monitoring and Assessment, 168(1-4), 215–222, <https://doi.org/10.1007/s10661-009-1105-4>.
- Li, F.-L., Yang, C.-M., Syu, C.-H., Lee, D.-Y., Tsuang, B.-J., & Juang, K.-W.,** 2016. *Combined effect of rice genotypes and soil characteristics on iron plaque formation related to Pb uptake by rice in paddy soils*.

- Journal of Soils and Sediments, 16(1), 150–158, <https://doi.org/10.1007/s11368-015-1169-4>.
- Li, H.-L., Li, X.-Z., Nie, S.-A., Li, Y.-Y., Zheng, C.-Y., & Wang, G.,** 2018. *Effects of two flooding methods on bio-available Cd-Pb-Zn contents of contaminated paddy soil and bacteria community in rice rhizosphere.* Journal of Agro-Environment Science, 37(7), 1456–1467, <https://doi.org/10.11654/jaes.2018-0726>.
- Li, T., Jiang, H., Yang, X., & He, Z.,** 2013. *Competitive sorption and desorption of cadmium and lead in paddy soils of eastern China.* Environmental Earth Sciences, 68(6), 1599–1607, <https://doi.org/10.1007/s12665-012-1855-1>.
- Liang, F., Guo, Z.-H., Men, S.-H., Xiao, X.-Y., Peng, C., Wu, L.-H., & Christie, P.,** 2019. *Extraction of Cd and Pb from contaminated-paddy soil with EDTA, DTPA, citric acid, and FeCl₃ and effects on soil fertility.* Journal of Central South University, 26(11), 2987–2997, <https://doi.org/10.1007/s11771-019-4230-4>.
- Lim, G.-H., Seo, B.-H., Kim, K.-H., Kim, H.-S., Kim, W.-L., Owens, G., & Kim, K.-R.,** 2016. *Transfer functions for estimating phytoavailable Cd and Pb in metal-contaminated paddy and upland soils: Implications for phytoavailability-based land management.* Geoderma, 270, 89–97, <https://doi.org/10.1016/j.geoderma.2015.11.021>.
- Liu, Y., Peng, P.-Q., Zhu, X.-L., & Ding, X.-Q.,** 2014. *Effect of paper mill sludge on adsorption and desorption of Cd(II) and Pb(II) in paddy soils.* Advanced Materials Research, 955–959, 2539–2545, <https://doi.org/10.4028/www.scientific.net/AMR.955-959.2539>.
- Ma, L., Xu, R., & Jiang, J.,** 2010. *Adsorption and desorption of Cu(II) and Pb(II) in paddy soils cultivated for various years in subtropical China.* Journal of Environmental Sciences, 22(5), 689–695, [https://doi.org/10.1016/S1001-0742\(09\)60164-9](https://doi.org/10.1016/S1001-0742(09)60164-9).
- Merison, Budianta, D., Napoleon, A., & Hermansyah.,** 2017. *The contamination of Pb and Cd in the intensive paddy field at Musi Rawas Regency, South Sumatera-Indonesia.* Pollution Research, 36(3), 381–386.
- Miao, D., & Yang, W.,** 2012. *Speciation distributions and availability of Zn, Pb, Cu, and Ni in mine drainage contaminated paddy soils.* Advanced Materials Research, 347–353, 826–831, <https://doi.org/10.4028/www.scientific.net/AMR.347-353.826>.
- Mlangeni, A. T., Chinthenga, E., Kapito, N. J., Namaumbo, S., Feldmann, J., & Raab, A.,** 2023. *Safety of African grown rice: Comparative review of As, Cd, and Pb contamination in African rice and paddy fields.* Heliyon, 9(7), Article e18314, <https://doi.org/10.1016/j.heliyon.2023.e18314>.
- Moon, D. H., Hwang, I., Koutsospyros, A., Cheong, K. H., Ok, Y. S., Ji, W. H., & Park, J.-H.,** 2018. *Stabilization of lead (Pb) and zinc (Zn) in contaminated rice paddy soil using starfish: A preliminary study.* Chemosphere, 199, 459–467, <https://doi.org/10.1016/j.chemosphere.2018.01.090>.
- Muller, G.,** 1969. *Index of geoaccumulation in sediments of the Rhine River.* Geojournal, 2, 108–118.
- Nadimi-Goki, M., Wahsha, M., Bini, C., Kato, Y., Vianello, G., & Antisari, L. V.,** 2014. *Assessment of total soil and plant elements in rice-based production systems in NE Italy.* Journal of Geochemical Exploration, 147, 200–214, <https://doi.org/10.1016/j.gexplo.2014.06.007>.
- Nong, X., Zhang, C., Chen, H., Rong, Q., Gao, H., & Jin, X.,** 2020. *Remediation of Cd, Pb, and As co-contaminated paddy soil by applying different amendments.* Bulletin of Environmental Contamination and Toxicology, 105(2), 283–290, <https://doi.org/10.1007/s00128-020-02940-8>.
- Nopriani, L. S., Prayogo, C., Soemarno, Atikah, & Kusuma, Z.,** 2023. *Models of Pb distribution and uptake in inundated paddy and maize cropping systems.* Journal of Degraded and Mining Lands Management, 11(1), 4927–4934, <https://doi.org/10.15243/jdmlm.2023.111.4927>.
- Nziguheba, G., & Smolders, E.,** 2008. *Inputs of trace elements in agricultural soils via phosphate fertilizers in European countries.* Science of the Total Environment, 390(1), 53–57, <https://doi.org/10.1016/j.scitotenv.2007.09.031>.
- Reddy, M. V., Satpathy, D., & Dhiviya, K. S.,** 2013. *Assessment of heavy metals (Cd and Pb) and micronutrients (Cu, Mn, and Zn) of paddy (Oryza sativa L.) field surface soil and inlet a predominantly paddy-cultivated area at Puducherry (Pondicherry, India), and effects of the agricultural runoff on the elemental concentrations of a receiving rivulet.* Environmental Monitoring and Assessment, 185(8), 6693–6704, <https://doi.org/10.1007/s10661-012-3057-3>.
- Rinklebe, J., Shaheen, S. M., & Yu, K.,** 2016. *Release of As, Ba, Cd, Cu, Pb, and Sr under pre-definite redox conditions in different rice paddy soils originating from the U.S.A. and Asia.* Geoderma, 270, 21–32, <https://doi.org/10.1016/j.geoderma.2015.10.011>.
- Rogan, N., Serafimovski, T., Dolenc, M., Tasev, G., & Dolenc, T.,** 2009. *Heavy metal contamination of paddy soils and rice (Oryza sativa L.) from Kočani Field (Macedonia).* Environmental Geochemistry and Health, 31(4), 439–451, <https://doi.org/10.1007/s10653-009-9233-3>.
- Rosariastuti, R., Mahardika, D. P., Supriyadi, Purwanto, & Hartati, S.,** 2019. *Soil bioremediation of lead (Pb) polluted paddy field using Mendong (Fimbristylis globulosa), Rhizobium Sp13, compost, and inorganic fertilizer.* IOP Conference Series: Earth and Environmental Science, 230(1), Article 012014, <https://doi.org/10.1088/1755-1315/230/1/012014>.
- Shi, J., Lin, H., Yuan, X., & Zhao, Y.,** 2011. *Isolation and characterization of a novel sulfur-oxidizing chemolithoautotroph Halothiobacillus from Pb polluted paddy soil.* African Journal of Biotechnology, 10(20), 4121–4126.
- Song, D., He, Z., Dong, Y., Dai, W., Yang, X., Cao, L., &**

- Sha, Z.**, 2020. *Nitrogen losses and Cu, Pb changes of paddy field affected by adding duckweed under biogas slurry application*. Chinese Journal of Eco-Agriculture, 28(4), 608–618, <https://doi.org/10.13930/j.cnki.cjea.190825>.
- Sun, R., Shu, F., Sun, W., Hao, W., & Li, L.**, 2012. *Heavy metal contamination in paddy soils around a Pb-Zn mining and smelting area and its relation with soil physicochemical properties*. Beijing Daxue Xuebao (Ziran Kexue Ban)/Acta Scientiarum Naturalium Universitatis Pekinensis, 48(1), 139–146.
- Sun, Y., Li, Y., Xu, Y., Liang, X., & Wang, L.**, 2015. *In situ stabilization remediation of cadmium (Cd) and lead (Pb) co-contaminated paddy soil using bentonite*. Applied Clay Science, 105–106, 200–206, <https://doi.org/10.1016/j.clay.2014.12.031>.
- Sutherland, R. A.**, 2000. *Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii*. Environmental Geology, 39(6), 611–627.
- Tang, J.-Q., Zhang, X., Huang, G.-Y., & Hu, H.-Q.**, 2021. *Effect of water regimes on Pb and Cd immobilization by biochar in contaminated paddy soil*. Huanjing Kexue/Environmental Science, 42(3), 1185–1190, <https://doi.org/10.13227/j.hj.kx.202010127>.
- US EPA (United States Environmental Protection Agency)**, 2010. *Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual*, EPA/540/1-89/002.
- Wan, Y., Huang, Q., Camara, A. Y., Wang, Q., & Li, H.**, 2019. *Water management impacts on the solubility of Cd, Pb, As, and Cr and their uptake by rice in two contaminated paddy soils*. Chemosphere, 228, 360–369, <https://doi.org/10.1016/j.chemosphere.2019.04.133>.
- Wang, C., Wang, J., Zhao, Y., & Zhong, C.**, 2019. *The vertical migration and speciation of the Pb in the paddy soil: A case study of the Yangtze River Delta, China*. Environmental Research, 179, Article 108741.
- Wang, H., Zhou, L., Dan, Y., Wang, X., Diao, Y., Liu, F., & Sang, W.**, 2022a. *Impact of pyrolysis temperature and application amount of sewage sludge biochar on the speciation and bioavailability of Cd and Pb in paddy soil*. Water, Air, and Soil Pollution, 233(6), Article 209, <https://doi.org/10.1007/s11270-022-05659-w>.
- Wang, Y., Shen, X., Bian, R., Liu, X., Zheng, J., Cheng, K., Xuhui, Z., Li, L., & Pan, G.**, 2022b. *Effect of pyrolysis temperature of biochar on Cd, Pb, and As bioavailability and bacterial community composition in contaminated paddy soil*. Ecotoxicology and Environmental Safety, 247, Article 114237, <https://doi.org/10.1016/j.ecoenv.2022.114237>.
- Wang, Y., Wang, X., Ai, F., Du, W., Yin, Y., & Guo, H.**, 2023. *Climatic CO₂ level-driven changes in the bioavailability, accumulation, and health risks of Cd and Pb in paddy soil–rice systems*. Environmental Pollution, 324, Article 121396, <https://doi.org/10.1016/j.envpol.2023.121396>.
- Wang, Y.-J., Zou, J.-L., Yang, W.-T., Zhou, H., & Liao, B.-H.**, 2016. *Synergetic control of bioavailability of Pb, Cd, and As in the rice paddy system by combined amendments*. Huanjing Kexue/Environmental Science, 37(10), 4004–4010, <https://doi.org/10.13227/j.hj.kx.2016.10.044>.
- Wei, X., Liu, Y., Zhan, Q., Zhang, P., Zhao, D., Xu, B., Bocharnikova, E., & Matichenkov, V.**, 2018. *Effect of Si soil amendments on As, Cd, and Pb bioavailability in contaminated paddy soils*. Paddy and Water Environment, 16(1), 173–181, <https://doi.org/10.1007/s10333-017-0629-4>.
- Wijewardana, P., Nanayakkara, N., Gunasekara, C., Karunaratna, A., Law, D., & Pramanik, B. K.**, 2022. *Removal of Cu, Pb, and Zn from stormwater using an industrially manufactured sawdust and paddy husk derived biochar*. Environmental Technology and Innovation, 28, Article 102640, <https://doi.org/10.1016/j.eti.2022.102640>.
- Wu, C., & Zhang, L.**, 2010. *Heavy metal concentrations and their possible sources in paddy soils of a modern agricultural zone, southeastern China*. Environmental Earth Sciences, 60(1), 45–56, <https://doi.org/10.1007/s12665-009-0161-2>.
- Wu, M., Dan, Y., Miao, J., Wang, X., Liu, F., & Sang, W.**, 2023. *Interactions of moisture content, pH, and HA on the immobilization of Pb and Zn in paddy soil using magnetic-chitosan hydrochar*. Water, Air, and Soil Pollution, 234(2), Article 104, <https://doi.org/10.1007/s11270-023-06107-z>.
- Wu, Q., Leung, J. Y. S., Pérez, A. L., Huang, X., & Wang, W.**, 2015. *Contamination and vertical distribution of As, Cd, Cr, Cu, Pb, Tl, and Zn in paddy soil irrigated with untreated leachate from tailings retention ponds*. Toxicological and Environmental Chemistry, 97(6), 710–722, <https://doi.org/10.1080/02772248.2015.1062484>.
- Wu, Y.-J., Zhou, H., Yang, W.-T., Zou, Z.-J., Zhu, W., Gu, J.-F., Peng, P.-Q., Zhang, P., Zeng, M., & Liao, B.-H.**, 2016. *Comparison of the persistence of a combined amendment stabilizing Pb, Cd, Cu, and Zn in polluted paddy soil*. Huanjing Kexue/Environmental Science, 37(7), 2791–2798, <https://doi.org/10.13227/j.hj.kx.2016.07.048>.
- Xie, D., Xu, R.-K., Jiang, X., & Bian, Y.-R.**, 2006. *Desorption kinetics of Cu(II) and Pb(II) in two paddy soils*. Journal of Ecology and Rural Environment, 22(3), 65–69.
- Xiong, M., Dai, G. Q., Sun, R. G., & Zhao, Z.**, 2024. *Passivation effect of corn vinasse biochar on heavy metal lead in paddy soil of Pb-Zn mining area*. Nature Environment and Pollution Technology, 23(1), 419–426, <https://doi.org/10.46488/NEPT.2024.v23i01.036>.
- Xu, D.-M., Yan, B., Chen, T., Lei, C., Lin, H.-Z., & Xiao, X.-M.**, 2017. *Contaminant characteristics and environmental risk assessment of heavy metals in the paddy soils from lead (Pb)-zinc (Zn) mining areas in Guangdong Province, South China*. Environmental Science and Pollution Research, 24(31), 24387–24399, <https://doi.org/10.1007/s11356-017-0052-9>.

- Yang, W., Zhou, H., Deng, G., Zhu, W., Wu, Y., Zou, Z., Wang, Y., & Liao, B.**, 2016. *Effects of combined amendment on bioavailability of Pb, Cd, and As in polluted paddy soil*. *Huanjing Kexue Xuebao/Acta Scientiae Circumstantiae*, 36(1), 257–263, <https://doi.org/10.13671/j.hjkxxb.2015.0133>.
- Yang, W.-T., Zhou, H., Gu, J.-F., Liao, B.-H., Peng, P.-Q., & Zeng, Q.-R.**, 2017. *Effects of a combined amendment on Pb, Cd, and As availability and accumulation in rice planted in contaminated paddy soil*. *Soil and Sediment Contamination*, 26(1), 70–83, <https://doi.org/10.1080/15320383.2017.1235132>.
- Yap, C. K., & Wong, C. H.**, 2011. *Assessment of Cu, Ni and Zn pollution in the surface sediments in the Southern Peninsular Malaysia using cluster analysis, ratios of geochemical nonresistant to resistant fractions, and geochemical indices*. *Environment Asia*, 4(1), 53–61.
- Ye, X., Li, H., Zhang, L., Chai, R., Tu, R., & Gao, H.**, 2018. *Amendment damages the function of continuous flooding in decreasing Cd and Pb uptake by rice in acid paddy soil*. *Ecotoxicology and Environmental Safety*, 147, 708–714, <https://doi.org/10.1016/j.ecoenv.2017.09.034>.
- Yin, D., Wang, X., Chen, C., Peng, B., Tan, C., & Li, H.**, 2016. *Varying effect of biochar on Cd, Pb, and As mobility in a multi-metal contaminated paddy soil*. *Chemosphere*, 152, 196–206, <https://doi.org/10.1016/j.chemosphere.2016.01.044>.
- Zarcinas, B. A., Ishak, C. F., McLaughlin, M. J., & Cozens, G.**, 2003. *Assessment of pollution of agricultural soils and crops in southeast Asia by heavy metals. 1. Peninsular Malaysia*. *Environmental Geochemistry and Health*, 25(3), 331–344, <https://doi.org/10.1023/A:1023908005616>
- Zarcinas, B. A., Pongsakul, P., McLaughlin, M. J., & Cozens, G.**, 2004. *Heavy metals in soils and crops in Southeast Asia. 2. Thailand*. *Environmental Geochemistry and Health*, 26(4), 359–371, <https://doi.org/10.1007/s10653-005-4673-0>.
- 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, <https://doi.org/10.1016/j.envpol.2010.09.019>.
- Zhang, P., Zhang, C., Pan, L., Yang, W., Li, C., Xu, G., Li, F., & Lu, M.**, 2016. *Effects of amendments and water conditions on the chemical speciation of Cd and Pb in contaminated paddy soil in a mining area*. *Soil and Sediment Contamination*, 25(7), 717–726, <https://doi.org/10.1080/15320383.2016.1204530>.
- Zhao, H., Huang, X., Liu, F., Hu, X., Zhao, X., Wang, L., Gao, P., Li, X., & Ji, P.**, 2021. *Potential of using a new aluminosilicate amendment for the remediation of paddy soil co-contaminated with Cd and Pb*. *Environmental Pollution*, 269, Article 116198, <https://doi.org/10.1016/j.envpol.2020.116198>.
- Zhao, K., 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), 778–787, <https://doi.org/10.1016/j.jhazmat.2010.05.081>.
- Zhou, G., Xia, X., Wang, H., Li, L., Wang, G., Zheng, S., & Liao, S.**, 2016. *Immobilization of lead by *Alishewanella* sp. WH16-1 in pot experiments of Pb-contaminated paddy soil*. *Water, Air, and Soil Pollution*, 227(9), 339, <https://doi.org/10.1007/s11270-016-3040-7>.
- Zhuang, P., Murray, B.M., Xia, H.P., Li, N.Y., Li, Z.** 2009. *Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China*. *Science of Total Environment*, 407, 1551–1561.
- Zou, L., Lu, Y., Dai, Y., Khan, M. I., Gustave, W., Nie, J., Liao, Y., Tang, X., Shi, J., & Xu, J.**, 2021. *Spatial variation in microbial community in response to As and Pb contamination in paddy soils near a Pb-Zn mining site*. *Frontiers in Environmental Science*, 9, Article 630668, <https://doi.org/10.3389/fenvs.2021.630668>.

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