ASSESSMENT OF COPPER AND ZINC CONTAMINATION IN PADDY SOILS AND GRAINS FROM KEMUNING AND KELAWEH, KELANTAN: IMPLICATIONS FOR SUSTAINABILITY AND PLANETARY HEALTH

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Abstract. This study aimed to investigated the concentrations of copper (Cu) and zinc (Zn) in paddy tissues and associated topsoils from Kemuning and Kelaweh, Kelantan. It assessed the potential ecological and health risks linked to metal accumulation. The results revealed significantly ($P < 0.05$) higher Cu and Zn concentrations in Kelaweh than Kemuning, particularly in the outlet zones, where metal accumulation was the most pronounced. The contamination factor and ecological risk index indicated that Kelaweh has a greater contamination potential, with Cu target hazard quotient (THQ) values exceeding the safe threshold for adults, suggesting a potential health risk. Zn levels, though elevated, did not pose an immediate health concern, as THQ values remained below risk thresholds. These findings highlighted the need for sustainable agricultural practices, improved water management, and continuous monitoring to ensure food safety and protect planetary health. The study emphasized the critical link between soil health, food security, and ecosystem sustainability in the context of rising environmental pressures. By understanding the current levels of metal contamination and the associated risks, policymakers and farmers can implement targeted interventions to ensure that paddy cultivation remains sustainable and contributes positively to planetary health.
Keywords: *heavy metal accumulation, agroecosystem health, environmental risk assessment, food security, sustainable agriculture*

Introduction

The contamination of agricultural soils with heavy metals, such as copper (Cu) and zinc (Zn), has become an increasing concern globally due to its implications for food safety, environmental sustainability, and human health (Satpathy et al., 2014; Huang et al., 2019; Shan et al., 2021; Xiao and Li, 2022). Paddy fields, which are a staple agricultural system in many parts of Asia, are particularly vulnerable to metal contamination through irrigation, industrial runoff, and the use of metal-based fertilizers and pesticides (Lu et al., 2018; Wang et al., 2021; Guo et al., 2024). These metals can accumulate in plant tissues and soil, potentially entering the food chain and posing significant health risks to consumers (Zarcinas et al., 2003, 2004; Liu et al., 2011). Understanding the distribution and risk of heavy metals in agricultural settings is essential for developing sustainable practices that protect human health and the environment (Tang et al., 2018; Deng et al., 2019; Kang et al., 2020).

Cu and Zn are essential micronutrients required for plant growth and development. However, in excessive amounts, these metals can become toxic to plants and harmful to

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human health (Mao et al., 2019; Huang et al., 2020). Prolonged exposure to high levels of Cu can cause liver and kidney damage, while elevated Zn levels, though generally less toxic, can disrupt the balance of other essential minerals in the human body (Zhao et al., 2009). In paddy cultivation systems, these metals can accumulate in different parts of the plant, such as grains, leaves, stems, and roots, depending on the bioavailability of the metals in the soil (Xu et al., 2017; Zulkafflee et al., 2019; Chen et al., 2021). The accumulation of these metals in food crops like rice, which is a staple food for billions of people worldwide, raises critical concerns about food security and public health (Zhao et al., 2010; Wang et al., 2023).

Assessing metal contamination in agricultural soils and crops is crucial for identifying potential risks and implementing measures to reduce exposure (Ogunkunle et al., 2016). This study focuses on two regions in Kelantan, Malaysia—Kemuning and Kelaweh—where paddy farming is a major economic activity. Previous studies have indicated that agricultural soils in Malaysia are increasingly vulnerable to metal contamination due to industrialization and intensified agricultural practices (Satpathy et al., 2014; Zulkafflee et al., 2021). However, limited research has focused on the accumulation of Cu and Zn in paddy soils and their potential impact on food safety and sustainability in Kelantan. By examining the levels of Cu and Zn in both plant tissues and soils, this study aims to fill this knowledge gap and provide insights into the environmental and health implications of metal contamination in these regions.

The growing global emphasis on sustainability and planetary health highlights the need to integrate environmental health with human well-being (Liu et al., 2006; Kang et al., 2020). Planetary health, which emphasizes the interconnectedness of human health and natural ecosystems, calls for a reconsideration of agricultural practices to ensure that they are productive and ecologically sustainable (Kinimo et al., 2021; Liu et al., 2023). The contamination of soils with toxic metals not only affects crop yields and food quality but also degrades the health of ecosystems by disrupting soil microbiota, reducing biodiversity, and contaminating water systems (Mao et al., 2019; Wang et al., 2021). By exploring the levels of metal contamination in paddy fields, this study contributes to the broader understanding of how agricultural practices can impact planetary health and highlights the urgent need for sustainable approaches that reduce environmental footprints (Zheng et al., 2018).

This study aims to assess the concentrations of Cu and Zn in different parts (grain, husk, leaf, stem, and root) of the paddy plant. and associated topsoils from Kemuning and Kelaweh in Kelantan, Malaysia. Specifically, the study aims to determine the levels of Cu and Zn contamination in these regions, evaluate the ecological risk through geoaccumulation indices (I_{geo}), contamination factors (Cf), and ecological risk indices (Er), and assess the potential health risks posed to local populations by calculating the estimated daily intake (EDI) and target hazard quotients (THQ) for both adults and children. By achieving these objectives, the study seeks to provide insights into the implications of metal contamination for food safety, environmental sustainability, and planetary health, by offering recommendations for sustainable agricultural practices and long-term environmental management.

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Materials and methods

Study area and sample collection

This study was conducted in two rice-growing regions in Kelantan, Peninsular Malaysia: Kemuning and Kelaweh. These areas were chosen due to their importance in rice production and potential exposure to heavy metal contamination from nearby sources, such as agricultural practices, highway proximity, and plantation areas.

Soil and plant samples were collected from three distinct zones in each site: the inlet, middle, and outlet zones of the paddy fields (*Figure 1*), corresponding to the flow of water entering (Inlet), moving through (Middle), and exiting (Outlet) the field.

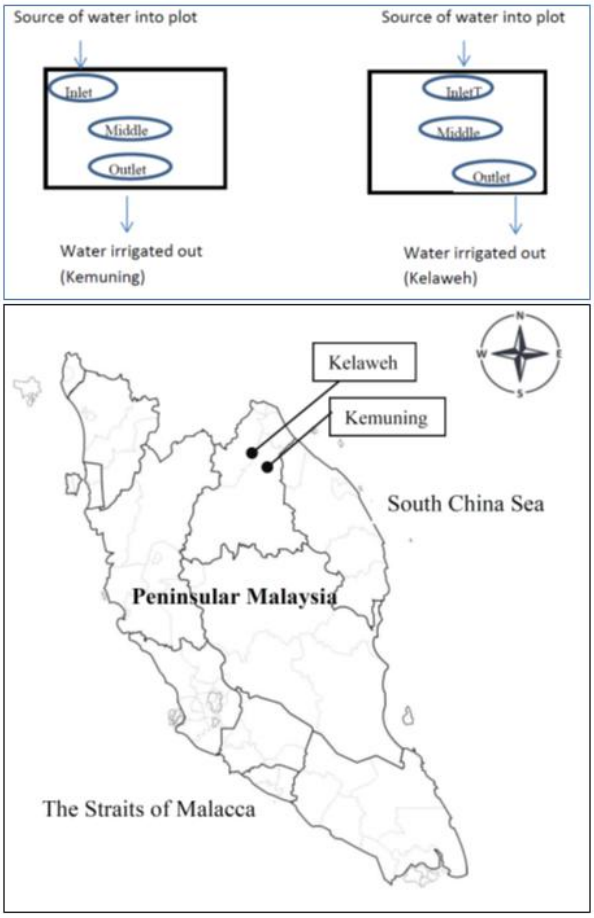

Figure 1. *Sampling sites of paddy and surface soil samples from Kemuning and Kelaweh, Kelantan, Peninsular Malaysia. Note: The paddy planted at the two sites are the same variety MR263*

The first sampling site, Kemuning, was located approximately 1.7 km away from the highway, with minimal nearby buildings or housing. Samples from this site were collected on August 10, 2014, under sunny weather conditions. Sampling was conducted between 11:00 AM and 1:30 PM. The rice plants at this site were around 130 days old at the time of sampling (*Table 1*).

The second sampling site, Kelaweh, was situated near a housing area and next to a rubber plantation, approximately 0.8 km away from a known contamination source.

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Sampling at this site occurred on December 11, 2015, also under sunny conditions. The sampling period was from 10:00 AM to 1:00 PM, with the rice plants being approximately 110 days old (*Table 1*). The two paddy plantation sites at Kelaweh and Kemuning are almost similar in terms of soil composition, irrigation practice, with the same variety MR263.

Table 1. *The sampling information for paddy at Kemuning and Kelaweh in Kelantan*

	Kemuning	**Kelaweh**
Sampling dates	10-Aug-14	11-Dec-15
Weather	Sunny	Sunny
Sampling time	11:00 AM – 1:30 PM	10:00 AM – 1:00 PM
Sample age	~130 days	~110 days
Distance from main source of contamination	1.7 km	0.8 km to plantation area
Site description	1.7 km from highway, lack of houses and buildings	Near housing area, next to rubber plantation

In total, 36 plant samples (comprising grains, husks, leaves, stems, and roots) and 18 topsoil samples (from upper and lower levels) were collected from both sites (Zhuang et al., 2009). All plant samples were harvested at full maturity, and soil samples were collected at two depths: 0-15 cm for the upper level and 15-30 cm for the lower level (Yap and Wong, 2011). These sample zones were selected to capture the vertical and horizontal distribution of metals in relation to the water flow pattern within the paddy fields, ensuring a comprehensive analysis of metal concentrations in different plant tissues and soil layers.

This methodology ensures that both the geographic and environmental factors, such as proximity to contamination sources and water irrigation patterns, are accounted for in the analysis of heavy metal contamination in rice and soil from both regions.

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 then oven-dried at 70°C until a constant weight was reached. The dried rice grains 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 debris and larger particles (Yap and Wong, 2010).

For digestion, rice grain samples were treated with concentrated nitric acid (HNO_3). Approximately 0.5 g of each powdered sample was placed in digestion tubes and digested using a hot block digester. The temperature was initially set at 40°C for one hour to gently break down the organic matter, followed by an increase to 140°C for three hours to complete digestion.

Soil samples underwent digestion using a 4:1 ratio of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$). Approximately 0.5 g of soil was treated with the acid mixture, digested at 40°C for one hour, and then heated to 140°C for three hours in the hot block digester. This ensured the complete breakdown of the soil matrix, releasing metals bound to organic matter or soil particles.

After digestion, both soil and rice samples were allowed to cool, filtered using Whatman filter paper, and diluted with deionized water to a known volume for analysis.

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Cu and Zn concentrations were determined using an air-acetylene technique Atomic Absorption Spectrophotometry (AAS) Model AAnalyst 800.

Certified reference materials (CRMs) were used as quality control measures to verify the accuracy of the metal concentration data. *Table 2* presents a comparison of certified values (CV) and measured values (MV) for Cu and Zn, along with their respective recovery percentages (RP), which were calculated as the ratio of MV to CV 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 x 100)
Cu	MESS-3	34 ± 1.6	31.3 ± 0.18	92.4
	Peach Leaves	3.7	4.67 ± 0.18	126.2
Zn	MESS-3	159 ± 8	157 ± 2.31	98.5
	Peach Leaves	17.9	18.4 ± 2.12	102.6

The recovery percentages for Cu and Zn ranged from 92.4% to 126.2%, demonstrating high accuracy and reliability of the analytical method employed in measuring metal concentrations in both rice grains and soil samples. These quality control measures ensure that the metal data obtained in this study are precise and suitable for further risk assessments (Yap and Wong, 2011).

Ecological risk assessment

The level of soil contamination was assessed using the I_{geo}, Cf, and Er. The I_{geo} was calculated using the following equation:

The quantitative analysis for assessment of trace elements can be done using Index of Geoaccumulation and the Potential Ecological Risk Index. The I_{geo} was proposed by Muller (1969), I_{geo} can be calculated by:

$$I_{geo} = \text{Log}_2 \left(\text{Sample} / (\text{K} \times \text{Background})\right) \quad \text{(Eq.1)}$$

where Background value is the value of 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, $< I_{geo} \leq 2$ 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 heavily to very heavily contaminated and $I_{geo} > 5$ is very heavily contaminated (Xu et al., 2008).

The Cf was calculated as the ratio of the concentration of metals in the soil to their respective background concentrations. The ecological risk index (Er) was derived using the formula:

$$\text{Er} = \text{Tr} \times \text{Cf} \quad \text{(Eq.2)}$$

where *Tr* is the toxic response factor for each metal (5 for Cu and 1 for Zn).

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Health risk assessment: estimated daily intake (EDI) and target hazard quotient (THQ)

The potential health risks of Cu and Zn exposure through rice consumption were evaluated by calculating the EDI, and THQ for both adults and children. The EDI was calculated using the formula:

$$EDI = (Cmetal \times CR) / BW \quad \text{(Eq.3)}$$

where *Cmetal* is the concentration of Cu or Zn in the rice grain in wet weight after conversion, *CR* is the daily rice consumption rate (for adults and children are 389 and 198 g/day, respectively (Hang et al., 2009); The conversion factors for stored rice (0.86; Zhuang et al., 2009) and steamed rice (0.61; from the present study), and *BW* is the average body weight (60 kg for adults and 32.7 kg for children) (Hang et al., 2009).

The THQ was calculated using the following equation:

$$THQ = EDI / RfD \quad \text{(Eq.4)}$$

where *RfD* is the oral reference dose (40 µg/kg/day for Cu and 300 µg/kg/day for Zn) (USEPA, 2010, 2024). A THQ greater than 1 indicates a potential health risk from metal exposure.

Statistical analysis

The data were analyzed using descriptive statistics to present the mean concentrations of Cu and Zn in plant tissues and soils from both sites. An independent t-test was conducted using JASP software (JASP Team, 2024; Version 0.18) to assess significant differences in metal concentrations between Kemuning and Kelaweh, as well as across different zones (inlet, middle, and water-out). Pearson's correlation analysis was applied to evaluate the relationship between metal concentrations in soils and plant tissues. Statistical significance was determined at a 95% confidence level ($p < 0.05$).

Results

Table 3 illustrates the mean concentrations of Cu and Zn in different parts of paddy plants and their associated topsoils collected from Kemuning and Kelaweh in Kelantan. The concentrations were measured in the grain, husk, leaf, stem, and root, with three zones analyzed in the habitat topsoils: inlet, middle, and outlet.

Cu concentrations

In the grains, Cu concentrations ranged from 2.86 to 14.70 µg/g dry weight, with Kelaweh generally exhibiting significantly ($P < 0.05$) higher values than Kemuning (*Table 4*). The husks followed a similar pattern, with concentrations ranging from 1.32 to 12.62 µg/g, showing elevated levels in Kelaweh. Leaf concentrations of Cu varied between 2.33 and 19.56 µg/g, with Kemuning showing the highest concentration of 5.12 µg/g in the outlet area and Kelaweh reaching up to 19.56 µg/g in the inlet area.

Cu levels in the stems were relatively lower than in other plant parts, ranging from 1.97 to 4.02 µg/g. The highest concentration was recorded in Kemuning in the outlet zone. Cu accumulated more significantly in the roots, especially in Kemuning, with

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concentrations between 4.02 and 7.10 µg/g, whereas Kelaweh had lower levels, peaking at 7.39 µg/g.

The topsoils showed considerable Cu variation, with concentrations in Kemuning ranging from 4.78 to 5.85 µg/g and Kelaweh reaching up to 12.81 µg/g in the outlet area, indicating a higher soil Cu content in Kelaweh.

Table 3. *Mean concentrations (mean ± SD, µg/g dry weight) of Cu, and Zn in the different parts of paddy and their habitat topsoils from Kemuning and Kelaweh in in Kelantan*

		Cu		**Zn**	
		Kemuning	**Kelaweh**	**Kemuning**	**Kelaweh**
Grain	Inlet	2.98 ± 0.68[a]	14.7 ± 1.20[b]	13.4 ± 2.40[a]	28.0 ± 3.22[b]
	Middle	2.86 ± 0.55[a]	7.93 ± 0.79[b]	14.0 ± 3.90[a]	23.9 ± 3.91[b]
	Outlet	3.62 ± 0.44[a]	9.18 ± 1.98[b]	11.6 ± 1.11[a]	24.2 ± 2.20[b]
Husk	Inlet	1.37 ± 0.11[a]	12.6 ± 1.34[b]	14.2 ± 2.21[a]	50.1 ± 4.21[b]
	Middle	1.32 ± 0.21[a]	8.58 ± 2.31[b]	14.3 ± 0.99[a]	32.4 ± 5.21[b]
	Outlet	1.40 ± 0.11[a]	10.1 ± 2.22[b]	9.87 ± 8.01[a]	44.3 ± 2.56[b]
Leaf	Inlet	2.33 ± 0.45[a]	19.6 ± 4.21[b]	39.8 ± 2.65[a]	70.8 ± 7.27[b]
	Middle	3.51 ± 0.55[a]	7.59 ± 0.76[b]	46.9 ± 7.01[a]	33.2 ± 2.45[b]
	Outlet	5.12 ± 0.87[a]	17.6 ± 2.11[b]	11.6 ± 2.34[a]	43.9 ± 1.99[b]
Stem	Inlet	1.97 ± 0.11[a]	5.03 ± 0.32[b]	52.8 ± 3.89[a]	40.6 ± 4.01[b]
	Middle	2.31 ± 0.32[a]	2.70 ± 0.77[b]	55.5 ± 2.78[a]	34.4 ± 1.21[b]
	Outlet	4.02 ± 0.65[a]	6.64 ± 0.56[b]	57.8 ± 7.77[a]	43.7 ± 4.00[b]
Root	Inlet	4.14 ± 0.32[a]	7.39 ± 1.02[b]	66.7 ± 6.91[a]	62.9 ± 3.01[b]
	Middle	2.90 ± 0.21[a]	6.25 ± 0.34[b]	61.3 ± 1.39[a]	56.9 ± 6.01[b]
	Outlet	7.10 ± 1.88[a]	10.5 ± 1.99[b]	54.8 ± 8.01[a]	52.9 ± 2.91[b]

Note: Different alphabets indicate the significant different at P< 0.05 using T-test

Table 4. *Mean concentrations (µg/g dry weight) of Cu and Zn in the habitat topsoils of paddy from Kemuning and Kelaweh in in Kelantan*

Site		**Cu**		**Zn**	
		Kemuning	**Kelaweh**	**Kemuning**	**Kelaweh**
Inlet	Upper	5.85 ± 0.88[a]	9.60 ± 0.21[b]	43.4 ± 4.08[a]	60.0 ± 7.08[b]
	Lower	5.45 ± 1.08[a]	9.51 ± 0.66[b]	42.8 ± 2.67[a]	60.3± 4.44[b]
Middle	Upper	4.78 ± 0.78[a]	9.95 ± 1.00[b]	35.2 ± 5.54[a]	58.8± 8.21[b]
	Lower	5.29 ± 0.67[a]	10.1 ± 2.55[b]	43.3 ± 3.33	56.9± 6.54[b]
Outlet	Upper	5.00 ± 1.01[a]	12.8 ± 2.81[b]	38.2 ± 5.21[a]	62.8± 2.36[b]
	Lower	5.23 ± 0.54[a]	13.7 ± 1.21[b]	41.5 ± 2.34[a]	64.2± 6.22[b]

Note: U= Upper level with 0-5 cm of habitat topsoil; L= Lower level with 6-10 cm of habitat topsoil

Zn concentrations

Zn concentrations in grains ranged from 11.56 to 28.01 µg/g, with Kelaweh consistently showing significantly (P< 0.05) higher values than Kemuning (*Table 4*). In husks, Zn levels ranged between 9.87 and 50.07 µg/g, with Kelaweh again having higher values, peaking at 50.07 µg/g. Leaves exhibited Zn concentrations of up to 70.76 µg/g in Kelaweh's outlet zone, while Kemuning's highest concentration was 39.79 µg/g.

The stems demonstrated high Zn concentrations in both sites, particularly in Kemuning, where levels reached 57.76 µg/g. Roots had Zn concentrations between 52.87

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and 66.74 µg/g in Kemuning and up to 62.90 µg/g in Kelaweh, showing significant metal accumulation in this part of the plant.

The habitat topsoils exhibited a Zn range of 35.17 to 62.82 µg/g, with Kelaweh recording the highest values in the outlet zone. The Zn concentrations were substantially higher in Kelaweh than Kemuning, indicating a potential environmental or anthropogenic influence on soil metal levels in this region.

Overall, the results indicate that Kelaweh tends to accumulate higher concentrations of Cu and Zn across all paddy plant tissues and associated topsoils compared to Kemuning, with the outlet zones showing the most significant metal accumulation.

Correlation analysis

Table 5 presents the Pearson's correlation coefficients of Cu and Zn between different paddy plant parts (grain, root, stem, leaf, and husk) and their habitat soils. The bold values indicate significant correlations at $P < 0.05$.

Table 5. *Pearson's correlation coefficients of metals (Cu and Zn) between the paddy parts (grain, root, stem, leaf and husk) and their habitat soils*

Cu	Grain	Root	Stem	Leaf	Husk	Soils
Grain	—					
Root	**0.604**	—				
Stem	**0.647**	**0.931**	—			
Leaf	**0.928**	**0.782**	**0.87**	—		
Husk	**0.963**	**0.682**	**0.676**	**0.923**	—	
Soils	**0.719**	**0.807**	**0.742**	**0.81**	**0.868**	—
Zn	**Grain**	**Root**	**Stem**	**Leaf**	**Husk**	**Soils**
Grain	—					
Root	-0.166	—				
Stem	**-0.903**	0.16	—			
Leaf	**0.654**	0.477	-0.42	—		
Husk	**0.976**	-0.183	**-0.803**	**0.688**	—	
Soils	**0.937**	-0.32	**-0.864**	0.483	**0.939**	—

Note: The values in bold are significant at P< 0.05

For Cu, the highest correlation is observed between the husk and grain (r = 0.963), followed by the leaf and grain (r = 0.928), and the husk and leaf (r = 0.923), suggesting a strong relationship between these plant compartments. Additionally, the correlation between soil and husk (r = 0.868) and soil and leaf (r = 0.81) indicate significant Cu transfer from soil to these plant parts. Notably, the root and stem also exhibit strong correlations (r = 0.931), further emphasizing the systemic transport of Cu within the plant.

For Zn, significant negative correlations are observed between the grain and stem (r = -0.903) and the soils and stem (r = -0.864), indicating an inverse relationship between Zn accumulation in these plant parts. Conversely, the husk shows a strong positive correlation with the grain (r = 0.976) and soils (r = 0.939), suggesting a preferential accumulation of Zn in the husk. The leaf and husk also exhibit a moderate correlation (r = 0.688), which may suggest a common uptake pathway for Zn.

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Index of geoaccumulation (Igeo), contamination factor (Cf), and ecological risk index (Er)

Table 6 presents the index of I_{geo}, Cf, and Er, for Cu and Zn in the habitat topsoils collected from Kemuning (KM) and Kelaweh (KW) in Kelantan. The analysis is conducted for both the upper and lower levels of the soil profile, examining potential contamination risks in the inlet, middle, and outlet zones of the paddy fields.

Table 6. *The values of the index of geoaccumulation (Igeo), contamination factor (Cf), and ecological risk (Er), of Cu and Zn in the habitat topsoils collected from Kemuning (KM) and Kelaweh (KW) in in Kelantan*

			Cu			Zn		
			Igeo	**CF**	**ER**	**Igeo**	**CF**	**ER**
KM	Inlet	U	-2.94	0.19	0.97	-1.47	0.54	0.54
		L	-3.05	0.18	0.91	-1.49	0.53	0.53
	Middle	U	-3.23	0.16	0.80	-1.77	0.44	0.44
		L	-3.09	0.18	0.88	-1.47	0.54	0.54
	Outlet	U	-3.17	0.17	0.83	-1.65	0.48	0.48
		L	-3.10	0.17	0.87	-1.53	0.52	0.52
KW	Inlet	U	-2.23	0.32	1.60	-1.00	0.75	0.75
		L	-2.24	0.32	1.58	-0.99	0.75	0.75
	Middle	U	-2.18	0.33	1.66	-1.03	0.74	0.74
		L	-2.15	0.34	1.69	-1.08	0.71	0.71
	Outlet	U	-1.81	0.43	2.13	-0.93	0.79	0.79
		L	-1.72	0.46	2.28	-0.90	0.80	0.80

Note: U= Upper level with 0-5 cm of habitat topsoil; L= Lower level with 6-10 cm of habitat topsoil

Cu geoaccumulation and risk

The I_{geo} values for Cu in Kemuning (KM) show negative values across all zones and levels, ranging from -2.94 to -3.23 in the upper level and from -3.05 to -3.09 in the lower level. These negative Igeo values indicate that the soil in Kemuning is unpolluted by Cu. Similarly, Kelaweh (KW) shows slightly less negative I_{geo} values, ranging from -2.23 to -1.81 in the upper level and from -2.24 to -1.72 in the lower level, suggesting a low level of Cu accumulation but still within unpolluted levels.

The Cf for Cu shows relatively low values across both sites. In Kemuning, Cf values range from 0.16 to 0.19, while in Kelaweh, they range from 0.32 to 0.46. These values indicate low contamination levels, with Kelaweh showing slightly higher Cf values, particularly in the outlet zone. The Er for Cu reflects low-risk levels, with Er values ranging from 0.80 to 0.97 in Kemuning and 1.60 to 2.28 in Kelaweh. Kelaweh’s outlet zone exhibits the highest Er values, suggesting a higher but still low ecological risk.

Zn geoaccumulation and risk

For Zn, the I_{geo} values are higher than those for Cu, but they remain negative, indicating no significant contamination in both sites. Kemuning (KM) shows Igeo values between -1.47 and -1.77, whereas Kelaweh (KW) has values ranging from -0.93 to -1.00 in the upper level and from -0.90 to -1.08 in the lower level. This indicates a low level of Zn accumulation, particularly in the outlet zone of Kelaweh.

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The Cf for Zn indicates moderate contamination at Kelaweh, with Cf values ranging from 0.75 to 0.80. In comparison, Kemuning shows lower Cf values between 0.44 and 0.54. The Er for Zn shows low to moderate risk across both sites. In Kemuning, Er values range from 0.44 to 0.54, while in Kelaweh, they range from 0.74 to 0.80. The highest ecological risk was recorded in the outlet zone of Kelaweh, with an Er value of 0.80.

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

Based on the converted data in wet weight basis (*Table 7*), *Table 8* presents the EDI values and THQ for Cu and Zn in grains collected from Kemuning and Kelaweh. The EDI and THQ were calculated for both adults and children, using reported daily consumption rates for rice, with conversion factors of 0.86 for stored rice and 0.61 for steamed rice. The values reflect the potential health risks associated with consuming rice contaminated with Cu and Zn.

Table 7. *Concentrations (µg/g wet weight) of Cu, Fe and Zn in grains collected from Kemuning and Kelaweh, converted from two different conversion factors (CF)*

CF	0.86			0.61		
Kemuning	**Cu**	**Fe**	**Zn**	**Cu**	**Fe**	**Zn**
Inlet	2.57	6.59	11.52	1.82	4.68	8.17
Middle	2.46	2.87	12.05	1.75	2.03	8.54
Outlet	3.11	3.40	9.97	2.21	2.41	7.07
Kelaweh	**Cu**	**Fe**	**Zn**	**Cu**	**Fe**	**Zn**
Inlet	12.64	24.52	24.09	8.97	17.39	17.08
Middle	6.81	23.13	20.63	4.84	16.41	14.63
Outlet	7.89	13.99	20.84	5.60	9.92	14.78

Note: Values are converted from dry weight to wet weight by using two conversion factors, 0.86 by Zhuang et al. (2009) and 0.61 (present study), which was calculated from the present study

The EDI values for Cu in Kemuning and Kelaweh vary significantly across the water zones. For adults consuming grains from the inlet zone, the EDI values are 16.6 µg/day for Kemuning and 81.9 µg/day for Kelaweh under the wet weight conversion factor of 0.86, suggesting a considerably higher Cu intake from Kelaweh. The THQ values for Cu in these zones are 0.42 and 2.05 for Kemuning and Kelaweh, respectively. The values for Kelaweh exceed the safe threshold (THQ > 1), indicating a potential health risk for adult consumers of rice from this area.

For children, the Cu EDI values range from 6.00 to 41.7 µg/day in Kemuning and Kelaweh. Similarly, the THQ values for children are lower than for adults but still concerning for Kelaweh, with a THQ of 1.04 in the inlet zone, indicating potential health risks. The THQ values for Kemuning are consistently below the threshold, suggesting minimal risk.

The EDI and THQ values under the conversion factor of 0.61 for steamed rice reflect lower intake levels but still show a significant difference between Kemuning and Kelaweh. The highest THQ values in Kelaweh (1.45 for adults and 0.74 for children) indicate the need for closer monitoring of Cu levels in grains from this area.

Zn EDI values for adults range from 52.9 to 156 µg/day across the water zones in Kemuning and Kelaweh under the wet weight conversion factor of 0.86. Kelaweh consistently shows higher Zn intake values, particularly in the inlet zone, with an EDI of

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156 µg/day compared to 74.7 µg/day in Kemuning. The THQ values for Zn remain below 1 in all zones, indicating a low risk to adults. The highest THQ value is 0.52 in the inlet zone of Kelaweh.

Table 8. *Estimated daily intake (EDI) values and target hazard quotients (THQ) values of Cu, and Zn in comparison to adult and children reported daily consumption (g/day), using wet weight of grains (µg/g ww), converted using a reported conversion factor of 0.86 for stored rice (Zhuang et al., 2009) and an estimated conversion factor of 0.61 (present study) for steamed rice from the present study, of grains collected from Kemuning and Kelaweh in Kelantan*

		Cu		**Zn**	
WW Cf= 0.86		**Kemuning**	**Kelaweh**	**Kemuning**	**Kelaweh**
Inlet	EDI (adult)	16.62	81.96	74.71	156.17
Inlet	THQ (Adult)	0.415	**2.049**	0.249	0.521
Middle	EDI (adult)	15.95	44.22	78.12	133.70
Middle	THQ (Adult)	0.399	**1.105**	0.260	0.446
Outlet	EDI (adult)	20.18	51.18	64.45	135.15
Outlet	THQ (Adult)	0.505	**1.280**	0.215	0.451
		Cu		**Zn**	
WW Cf= 0.61		**Kemuning**	**Kelaweh**	**Kemuning**	**Kelaweh**
Inlet	EDI (adult)	11.79	58.14	52.99	110.77
Inlet	THQ (Adult)	0.295	**1.453**	0.177	0.369
Middle	EDI (adult)	11.31	31.36	55.41	94.84
Middle	THQ (Adult)	0.283	0.784	0.185	0.316
Outlet	EDI (adult)	14.32	36.31	45.72	95.87
Outlet	THQ (Adult)	0.358	0.908	0.152	0.320
		Cu		**Zn**	
WW Cf= 0.86		**Kemuning**	**Kelaweh**	**Kemuning**	**Kelaweh**
Inlet	EDI (Children)	8.46	41.72	38.03	79.49
Inlet	THQ (children)	0.211	**1.043**	0.127	0.265
Middle	EDI (Children)	8.12	22.51	39.76	68.06
Middle	THQ (children)	0.203	0.563	0.133	0.227
Outlet	EDI (Children)	10.27	26.05	32.81	68.79
Outlet	THQ (children)	0.257	0.651	0.109	0.229
		Cu		**Zn**	
WW Cf= 0.61		**Kemuning**	**Kelaweh**	**Kemuning**	**Kelaweh**
Inlet	EDI (Children)	6.00	29.59	26.97	56.38
Inlet	THQ (children)	0.150	0.740	0.090	0.188
Middle	EDI (Children)	5.76	15.96	28.20	48.27
Middle	THQ (children)	0.144	0.399	0.094	0.161
Outlet	EDI (Children)	7.29	18.48	23.27	48.80
Outlet	THQ (children)	0.182	0.462	0.078	0.163

Note: The reported daily consumption rates for adults and children are 389 and 198 g/day, respectively (Hang et al., 2009). The toxic response values used are 40 µg/kg/day for Cu and 300 µg/kg/day for Zn (USEPA, 2010)

For children, the Zn EDI values range from 28.2 to 79.5 µg/day, with Kelaweh again showing higher intake levels. The THQ values for Zn in children are similarly low, with the highest value being 0.27 in the inlet zone of Kelaweh, indicating minimal health risk for children consuming rice from both locations.

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The results for Zn under the conversion factor of 0.61 for steamed rice follow a similar pattern, with lower intake and THQ values. The highest Zn EDI value in Kelaweh reaches 111 µg/day for adults and 56.4 µg/day for children. Despite the higher EDI values, the THQ values remain well below the threshold for both adults and children, suggesting that Zn contamination does not pose a significant health risk in this context.

Discussion

The distribution of Cu and Zn in different parts of paddy plants

The bioaccumulation patterns of Cu and Zn in different parts of paddy plants offer critical insights into how these essential micronutrients are absorbed, translocated, and stored in plant tissues. Both Cu and Zn are vital for numerous physiological processes, including enzyme activation, protein synthesis, and photosynthesis. However, their uptake and distribution vary significantly across plant parts, influencing both plant health and potential risks to human consumers (Liu et al., 2016; Guo et al., 2024).

Cu, a necessary cofactor for several enzymes involved in electron transport, photosynthetic pathways, and oxidative stress response, was predominantly found to accumulate in the roots (Satpathy et al., 2014; Zulkafflee et al., 2021). This suggests that the roots function as the primary site for Cu uptake and storage, likely due to their direct contact with Cu-rich soil and the plant's metal homeostasis mechanisms, which regulate the amount of Cu translocated to other tissues (Deng et al., 2019; Kinimo et al., 2021). The relatively low concentrations of Cu in the stems, leaves, and grains indicate that its movement from the roots to the aerial parts is tightly controlled (Xu et al., 2017; Zulkafflee et al., 2019). High levels of Cu in plant tissues can be toxic, leading to oxidative damage; thus, the plant's ability to compartmentalize Cu in the roots is essential for preventing toxicity in sensitive tissues like leaves and grains (Liu et al., 2006).

Zn, which is crucial for a range of biological functions such as DNA replication, gene expression, and protein stabilization, exhibited a similar accumulation pattern, though its mobility within the plant appeared to be greater than that of Cu (Xiao et al., 2019; Kinimo et al., 2021). Higher concentrations of Zn were detected in the leaves, where it plays an essential role in photosynthesis and other metabolic processes (Huang et al., 2020; Kang et al., 2020). Zn is particularly important for chloroplast development and the synthesis of chlorophyll. The elevated Zn levels in the leaves suggest that the plant actively transports Zn from the roots to the leaves to support these critical functions (Liu et al., 2020; Guo et al., 2024). This differential distribution between Cu and Zn reflects the plant's adaptive mechanisms for handling essential micronutrients, ensuring that they are available where needed while avoiding toxic accumulation in sensitive tissues (Zhao et al., 2009; Wang et al., 2021).

Understanding the distribution patterns of Cu and Zn is critical for optimizing their availability in crops like rice. The ability of roots to sequester metals and limit their movement to other plant parts helps the plant regulate metal toxicity (Satpathy et al., 2014; Zulkafflee et al., 2019). However, if metal concentrations in the soil rise due to contamination or excessive fertilizer use, these mechanisms may be overwhelmed, leading to higher concentrations in the grains, which could pose health risks to consumers (Ogunkunle et al., 2016; Adlane et al., 2020). Therefore, monitoring metal distribution in plants can help manage nutrient levels, ensuring crop safety and nutritional value (Shan et al., 2021).

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The comparison of Cu and Zn in the two sites

When comparing the concentrations of Cu and Zn between the two sites—Kemuning and Kelaweh—clear differences emerged, reflecting the influence of local environmental factors, such as soil composition, irrigation practices, and possible contamination sources (Huang et al., 2019; Zulkafflee et al., 2021). Kelaweh consistently exhibited higher concentrations of both Cu and Zn across all plant parts, particularly in the roots and stems, suggesting that environmental factors unique to this site may increase metal availability in the soil (Deng et al., 2019). Several factors may contribute to the higher Cu and Zn levels in Kelaweh. Soil composition plays a critical role in metal uptake by plants, with factors such as pH, organic matter content, and cation exchange capacity affecting the bioavailability of metals (Liu et al., 2011; Huang et al., 2020).

In Kelaweh, soil conditions may favour the solubility and mobility of Cu and Zn, leading to their increased uptake by plant roots (Liu et al., 2016). Additionally, irrigation practices could influence metal distribution, as water flow patterns may carry metals to certain field areas (Kinimo et al., 2021). For example, higher concentrations of Cu and Zn were observed in specific zones, suggesting that waterborne transport of metals could contribute to localized accumulation in specific field parts (Guo et al., 2024). In contrast, Kemuning exhibited lower overall metal concentrations, with Cu and Zn being more evenly distributed across plant tissues (Wang et al., 2021).

This more balanced distribution may reflect differences in soil properties, such as lower metal content or greater capacity for metal binding, reducing the bioavailability of Cu and Zn (Xu et al., 2017; Kang et al., 2020). Alternatively, Kemuning's agricultural practices, such as using organic farming methods or controlled irrigation, may help limit the uptake of these metals (Satpathy et al., 2014). The disparity between the two sites underscores the need for localized environmental assessments, as metal contamination is often site-specific and influenced by various factors (Kinimo et al., 2021). The higher metal concentrations in Kelaweh could also be attributed to anthropogenic inputs, such as metal-containing agrochemicals or industrial runoff (Zulkafflee et al., 2021). Previous studies have shown that agricultural regions near industrial zones or areas where metal-based fertilizers and pesticides are used tend to exhibit elevated metal concentrations in both soil and plants (Liu et al., 2006).

The potential for metal contamination from such sources highlights the importance of monitoring and regulating the use of agrochemicals to prevent excessive metal accumulation in paddy fields (Huang et al., 2020; Yin et al., 2023). Regular soil testing and adopting sustainable farming practices, such as crop rotation and organic fertilizers, could help mitigate the risks associated with metal contamination (Yang et al., 2008; Adlane et al., 2020). Therefore, comparing Cu and Zn levels between Kemuning and Kelaweh demonstrates the complex interplay of environmental and anthropogenic factors that influence metal accumulation in paddy plants (Guo et al., 2024). The higher concentrations observed in Kelaweh underscore the need for targeted interventions, such as soil remediation and improved water management, to reduce metal availability and protect both crop quality and human health (Shan et al., 2021).

Metal accumulation and translocation in paddy plants: insights from Cu and Zn correlation analysis

The correlation results for Cu reveal a strong and significant association among different plant parts, particularly between the husk and grain, leaf and grain, and husk and

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leaf. These findings suggest that Cu is effectively translocated within the paddy plant, with substantial accumulation occurring in reproductive and storage tissues such as the grain and husk. The strong correlation between soil and husk and soil and leaf indicates that Cu uptake from the soil plays a critical role in its bioaccumulation. The high correlation between root and stem further supports the systemic movement of Cu within the plant, possibly influenced by its role in enzymatic functions and photosynthesis. These results align with previous studies indicating that Cu is essential for plant metabolism but may accumulate in excess if present in high concentrations in soils, posing potential risks to human consumption (Bian et al., 2015).

In contrast, Zn exhibits a more complex accumulation pattern, with both positive and negative correlations across different plant parts. A significant negative correlation between the grain and stem and between soils and stem suggests that Zn is not efficiently transported from the vegetative tissues to the grain, which may indicate a restriction in its mobility within the plant (Peng et al., 2020). This is further supported by the moderate positive correlation between the leaf and husk, which suggests that Zn is retained in outer tissues rather than being translocated efficiently to storage organs (Zhuang et al., 2009). However, the strong positive correlation between the husk and grain and between husk and soil implies that Zn primarily accumulates in the husk, potentially acting as a protective barrier to prevent excessive Zn translocation to the edible grain. These findings suggest a preferential accumulation mechanism in paddy plants, which may be influenced by factors such as metal transport proteins and soil metal bioavailability (Jing et al., 2023).

Overall, the differential partitioning of Cu and Zn in paddy plants highlights the complex mechanisms governing metal uptake, translocation, and accumulation. The strong correlation between soil and certain plant parts suggests that soil metal concentrations significantly influence bioaccumulation, reinforcing the importance of soil quality management in rice cultivation (Aziz et al., 2023). The higher translocation of Cu across plant tissues, compared to Zn's selective retention in the husk, suggests that Cu may pose a greater risk of entering the food chain through rice consumption. These findings have important implications for food safety, particularly in metal-contaminated environments, where excessive metal accumulation in edible parts of crops could lead to potential health risks. Future studies should focus on the physiological mechanisms governing metal uptake and explore potential mitigation strategies, such as soil amendments or selective breeding, to minimize metal accumulation in rice grains (Jing et al., 2023).

The public health risk of Cu and Zn in edible paddy grains

Although Cu and Zn are essential trace elements for human health, their excessive intake can lead to toxicity, posing significant public health risks (Kinimo et al., 2021; Guo et al., 2024). Both elements play critical roles in various physiological processes—Cu in red blood cell formation, nerve function, and immune response, and Zn in immune system regulation, DNA synthesis, and protein production (Hashimoto and Kambe, 2015). However, when consumed in amounts exceeding the recommended daily intake, these metals can cause adverse health effects, particularly over prolonged exposure (Shan et al., 2021).

In this study, the concentrations of Cu and Zn in the edible paddy grains were found to be below the tolerable intake levels established by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), indicating that rice from these sites does not pose an immediate health risk (Liu et al., 2016; Huang et al., 2019).

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Specifically, the safe daily intake for Cu is around 2–3 mg for adults, and for Zn, it is approximately 8–11 mg per day (Liu et al., 2011; Kinimo et al., 2021). Despite this, prolonged rice consumption with elevated Cu and Zn levels—especially in regions such as Kelaweh, where higher concentrations were observed—could lead to cumulative exposure over time (Ihedioha et al., 2019, 2021; Xiao and Li, 2022).

Chronic exposure to elevated Cu levels can result in gastrointestinal disturbances, including nausea, vomiting, and abdominal pain. In extreme cases, it can lead to more severe conditions like liver damage and Cu poisoning, which can manifest as neurological symptoms (Ogunkunle et al., 2016). Prolonged Cu accumulation in the liver impairs its detoxification function, potentially leading to hepatic failure in cases of acute toxicity (Zulkafflee et al., 2019). Genetic conditions such as Wilson's disease also exacerbate Cu toxicity risks, making Cu monitoring in food even more critical for sensitive populations (Kinimo et al., 2021; Guo et al., 2024).

Excessive Zn intake, while less immediately harmful than Cu, can interfere with absorbing other critical minerals like iron and Cu (Liu et al., 2020). Chronic Zn toxicity can lead to immune suppression and disruptions in the metabolism of trace elements and hormones (Yap and Wong, 2011; Huang et al., 2020). Long-term Zn exposure can result in an imbalance in iron and Cu homeostasis, leading to anaemia, bone weakness, and fatigue (Satpathy et al., 2014; Ogunkunle et al., 2016). This makes it particularly important to monitor Zn levels in regions where rice is a staple food and a primary dietary Zn source (Zhang et al., 2019; Zulkafflee et al., 2021).

Although the metal concentrations in this study do not currently reach toxic thresholds, continuous monitoring is necessary (Xiao et al., 2019). The potential for bioaccumulation, especially in rice-eating populations with long-term, daily exposure, underscores the importance of regular surveillance (Liu et al., 2016). Prolonged, undetected increases in metal concentrations could pose risks to public health, particularly in regions with historical metal contamination, such as areas near industrial sites or where metal-based fertilizers are commonly used (Mao et al., 2019; Zulkafflee et al., 2019).

Biomonitoring of metals in paddy for the sustainability of future food security

With their unique ability to absorb and accumulate metals from the soil, Paddy plants serve as invaluable biomonitors for assessing metal bioavailability and contamination in agricultural ecosystems (Zhao et al., 2010; Reddy et al., 2013). By studying the accumulation patterns of metals such as Cu and Zn in various parts of the paddy plant—roots, stems, leaves, and grains—researchers and farmers can gain critical insights into the health of the soil, potential contamination levels, and the overall impact on crop quality (Huang et al., 2020; Kinimo et al., 2021). This capacity for metal uptake makes the paddy plant an effective tool for gauging the environmental and health risks posed by soil metal content, especially in regions where heavy metal pollution is a concern (Guo et al., 2024).

Sustained biomonitoring of Cu, Zn, and other potentially toxic metals is crucial for ensuring that paddy farming remains sustainable (Huang et al., 2019). Excessive accumulation of metals in soil not only affects plant growth and yield but also poses serious risks to the nutritional value and safety of rice—a staple food for billions of people globally (Liu et al., 2006; Satpathy et al., 2014). Elevated metal levels in paddy soils can reduce soil fertility, disrupt nutrient cycling, and lead to lower crop productivity over time (Xu et al., 2017; Xiao and Li, 2022).

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Moreover, the excessive presence of metals in paddy grains reduces the safety of rice consumption, threatening both food security and public health (Shan et al., 2021; Kinimo et al., 2021). To safeguard the sustainability of paddy farming and food security for future generations, ongoing monitoring of metal concentrations in both the soil and plant tissues is essential (Hang et al., 2009; Halim et al., 2014). This ensures that metal levels are kept within acceptable limits, preventing potential harm to consumers and protecting the long-term productivity of paddy fields (Satpathy et al., 2014). Furthermore, maintaining optimal levels of essential metals in the soil is critical for supporting healthy plant growth, as both Cu and Zn play vital roles in the biological functions of rice plants (Huang et al., 2020). However, their concentrations must be carefully managed to avoid the risks associated with toxicity (Shan et al., 2021).

Implementing sustainable farming practices, such as crop rotation, organic farming, and soil amendments, can significantly reduce the buildup of metals in agricultural soils (Zulkafflee et al., 2019; Navaretnam et al., 2023). Soil amendments like biochar, organic compost, and lime have been shown to reduce the bioavailability of metals by binding them in less accessible forms, thus limiting their uptake by plants (Mao et al., 2019; Kinimo et al., 2021). In addition, organic farming methods that avoid using metal-containing fertilizers and pesticides can help prevent the accumulation of Cu and Zn in soils, promoting healthier and more productive paddy ecosystems (Huang et al., 2020). These sustainable approaches improve crop yields and ensure that rice remains a safe and nutritious food source, supporting local and global food security (Xiao et al., 2019).

By integrating biomonitoring systems into agricultural practices and adopting strategies to mitigate metal contamination, we can protect the health of paddy ecosystems and ensure the continued viability of rice farming (Liu et al., 2011; Zulkafflee et al., 2021). This is particularly important in regions where rice is a dietary staple and where contamination from industrial or agricultural activities is more likely to occur (Satpathy et al., 2014; Shan et al., 2021). The long-term sustainability of paddy farming depends on our ability to monitor and manage metal levels effectively, ensuring that future generations can continue to rely on rice as a safe and secure food source (Liu et al., 2006; Huang et al., 2019).

Future studies and recommendations

Future research should expand the monitoring of potentially toxic metals across different rice-growing regions to understand contamination patterns in various environmental contexts (Ogunkunle et al., 2016; Zulkafflee et al., 2019). This includes identifying contamination sources such as industrial discharge, agrochemical use, and inherent soil properties, which will inform targeted strategies to reduce metal accumulation in paddy fields (Shan et al., 2021). In particular, future studies should evaluate the effectiveness of soil remediation techniques, including phytoremediation and biochar applications, for reducing metal bioavailability and promoting sustainable crop production (Kinimo et al., 2021).

Efforts to educate farmers and policymakers on the risks of metal contamination and the importance of sustainable agricultural practices are crucial (Liu et al., 2006; Deng et al., 2019). Implementing stricter regulations on metal-containing agrochemicals, combined with improved irrigation practices, will help minimize the buildup of metals in soils and crops (Huang et al., 2020; Zulkafflee et al., 2021). Raising public awareness about the potential long-term health risks of heavy metal exposure through rice consumption will also be vital in ensuring food safety and protecting public health

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(Satpathy et al., 2014; Kinimo et al., 2021). By fostering stakeholder collaboration, paddy farming can remain a safe and sustainable food source, supporting local communities and global food security (Shan et al., 2021; Guo et al., 2024).

Moreover, further studies should explore the long-term effects of metal contamination on soil health, crop physiology, and food security (Liu et al., 2011). This includes assessing the impacts of elevated Cu and Zn levels on crop rotation systems and examining whether certain rice varieties exhibit better tolerance to metal accumulation without compromising yield (Satpathy et al., 2014; Huang et al., 2020). Genetic approaches, such as breeding or engineering rice varieties with natural resistance to metal uptake, could offer promising solutions for mitigating contamination issues (Ao et al., 2019; Kinimo et al., 2021).

Policy-driven actions are essential to implement contamination prevention strategies at both local and national levels (Ogunkunle et al., 2016; Shan et al., 2021). Governments and agricultural bodies should collaborate to set regulatory standards for heavy metal concentrations in soils and crops and enforce them through regular inspections (Zulkafflee et al., 2019; Guo et al., 2024). Providing farmers with clear guidelines on safe farming practices and metal testing protocols will enable them to adopt preventive measures effectively (Satpathy et al., 2014; Kinimo et al., 2021). While current levels of Cu and Zn in rice may not pose immediate threats, ongoing monitoring and sustainable practices are critical to mitigating future risks (Shan et al., 2021). Integrating biomonitoring systems, sustainable soil management, and public education will safeguard public health and ensure the long-term resilience of paddy farming for food security (Kinimo et al., 2021).

Conclusion

This study highlights the importance of monitoring essential metals like Cu and Zn in paddy plants to safeguard public health, food security, and environmental sustainability. The findings showed that Cu and Zn primarily accumulated in the roots and leaves, with lower concentrations in the grains. Although the levels in the edible grains were within safe limits, continued exposure in regions with higher metal concentrations, such as Kelaweh, could pose health risks over time. Therefore, ongoing monitoring and interventions such as soil remediation and improved irrigation management are crucial for maintaining the productivity of paddy fields and ensuring safe food production.

The comparison between Kemuning and Kelaweh revealed higher concentrations of Cu and Zn in Kelaweh, with significant accumulation in the outlet zones, suggesting that environmental factors such as water flow patterns may contribute to metal redistribution in the fields. While the Cf and Er indicated low ecological risk, the THQ for Cu in Kelaweh exceeded safety thresholds, particularly for adults consuming rice. This underscores the need for targeted mitigation efforts to address Cu contamination. In contrast, Zn contamination was not immediately hazardous, but warrants continued monitoring to prevent future risks. Implementing localized management strategies, long-term monitoring, and sustainable farming practices will be essential to ensuring the ecological and public health viability of rice production in these regions.

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REFERENCES

[1] Adlane, B., Xu, Z., Xu, X., Liang, L., Han, J., Qiu, G. (2020): Evaluation of the potential risks of heavy metal contamination in rice paddy soils around an abandoned Hg mine area in Southwest China. – Acta Geochimica 39(1): 85-95. https://doi.org/10.1007/s11631-019-00364-8.

[2] Ao, M., Chai, G., Fan, C., Liu, G., Qin, S., Wang, P. (2019): Evaluation of potential pollution risk and source analysis of heavy metals in paddy soil and rice. – Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering 35(6): 198-205. https://doi.org/10.11975/j.issn.1002-6819.2019.06.024.

[3] Aziz, R. A., Yiwen, M., Saleh, M., Salleh, M. N., Gopinath, S. C., Giap, S. G. E., Chinni, S. V., Gobinath, R. (2023): Bioaccumulation and translocation of heavy metals in paddy (*Oryza sativa* L.) and soil in different land use practices. – Sustainability 15(18): 13426.

[4] 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. https://doi.org/10.1007/s11356-015-4710-5.

[5] Chen, J.-L., Xiang, M.-C., Tang, L.-X., Zhang, C.-H., Ge, Y. (2021): Assessing heavy metal pollution and human health risk of paddy soil with high geological background of transportation and deposition. – Chinese Journal of Ecology 40(8): 2334-2340. https://doi.org/10.13292/j.1000-4890.202108.010.

[6] Deng, Y., Jiang, L., Xu, L., Hao, X., Zhang, S., Xu, M., Zhu, P., Fu, S., Liang, Y., Yin, H., Liu, X., Bai, L., Jiang, H., Liu, H. (2019): Spatial distribution and risk assessment of heavy metals in contaminated paddy fields - A case study in Xiangtan City, southern China. – Ecotoxicology and Environmental Safety 171: 281-289. https://doi.org/10.1016/j.ecoenv.2018.12.060.

[7] Guo, Y., Yang, Y., Li, Y. (2024): Comprehensive perspective on contamination identification, source apportionment, and ecological risk assessment of heavy metals in paddy soils of a tropical island. – Agronomy 14(8): 1777. https://doi.org/10.3390/agronomy14081777.

[8] Hakanson, L. (1980): An ecological risk index for aquatic pollution control. A sedimentological approach. – Water Research 14(8): 975-1001. https://doi.org/10.1016/0043-1354(80)90143-8.

[9] 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 8: 3391-3401. https://doi.org/10.1007/s12517-014-1611-8.

[10] 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.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2303_43134334

[11] Hashimoto, A., Kambe, T. (2015): Mg, Zn and Cu transport proteins: A brief overview from physiological and molecular perspectives. – Journal of Nutritional Science and Vitaminology 61: S116-S118.

[12] Huang, H., Lin, C., Yu, R., Yan, Y., Hu, G., Li, H. (2019): Contamination assessment, source apportionment and health risk assessment of heavy metals in paddy soils of Jiulong River Basin, Southeast China. – RSC Advances 9(26): 14736-14744. https://doi.org/10.1039/c9ra02333j.

[13] Huang, A.-L., Fu, G.-H., Qin, S., Fan, C.-W., Liu, G.-H. (2020): Characteristics and ecological risk assessment of heavy metal pollution of Triassic osmotic paddy soil in the southwest of Guizhou province. – Journal of Ecology and Rural Environment 36(2): 193-201. https://doi.org/10.19741/j.issn.1673-4831.2019.0453.

[14] Ihedioha, J. N., Ogili, E. O., Ekere, N. R., Ezeofor, C. C. (2019): Risk assessment of heavy metal contamination of paddy soil and rice (*Oryza sativa*) from Abakaliki, Nigeria. – Environmental Monitoring and Assessment 191(6): 350. https://doi.org/10.1007/s10661-019-7491-3.

[15] Ihedioha, J. N., Abugu, H. O., Ujam, O. T., Ekere, N. R. (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. – Environmental Monitoring and Assessment 193(9): 620. https://doi.org/10.1007/s10661-021-09386-3.

[16] Jing, H., Yang, W., Chen, Y., Yang, L., Zhou, H., Yang, Y., Zhao, Z., Wu, P., Zia-ur-Rehman, M. (2023): Exploring the mechanism of Cd uptake and translocation in rice: Future perspectives of rice safety. – Science of the Total Environment 897: 165369.

[17] Kang, Z., Wang, S., Qin, J., Wu, R., Li, H. (2020): Pollution characteristics and ecological risk assessment of heavy metals in paddy fields of Fujian province, China. – Scientific Reports 10(1): 12244. https://doi.org/10.1038/s41598-020-69165-x.

[18] Kinimo, K. C., Yao, K. M., Marcotte, S., Kouassi, N. L. B., Trokourey, A. (2021): Trace metal(loid)s contamination in paddy rice (*Oryza sativa* L.) from wetlands near two gold mines in Côte d'Ivoire and health risk assessment. – Environmental Science and Pollution Research 28(18): 22779-22788. https://doi.org/10.1007/s11356-021-12360-8.

[19] Liu, X., Wu, J., Xu, J. (2006): Characterizing the risk assessment of heavy metals and sampling uncertainty analysis in paddy fields by geostatistics and GIS. – Environmental Pollution 141(2): 257-264. https://doi.org/10.1016/j.envpol.2005.08.048.

[20] Liu, J., Zhang, X.-H., Tran, H., Wang, D.-Q., Zhu, Y.-N. (2011): Heavy metal contamination and risk assessment in water, paddy soil, and rice around an electroplating plant. – Environmental Science and Pollution Research 18(9): 1623-1632. https://doi.org/10.1007/s11356-011-0523-3.

[21] Liu, G., Wang, J., Zhang, E., Hou, J., Liu, X. (2016): Heavy metal speciation and risk assessment in dry land and paddy soils near mining areas at Southern China. – Environmental Science and Pollution Research 23(9): 8709-8720. https://doi.org/10.1007/s11356-016-6114-6.

[22] Liu, W., Li, X., Zhang, K., Zhang, Q., Wang, Y. (2020): Ecological risk assessment of heavy metals in paddy soil based on improved Håkanson method. – Research of Environmental Sciences 33(11): 2613-2620. https://doi.org/10.13198/j.issn.1001-6929.2020.04.18.

[23] Liu, Y.-J., Li, C.-X., Mei, N., Zhang, M.-P., Zhang, C., Wang, D.-Y. (2023): Characteristics and risk evaluation of heavy metal contamination in paddy soils in the Three Gorges Reservoir Area. – Huanjing Kexue/Environmental Science 44(6): 3520-3530. https://doi.org/10.13227/j.hjkx.202207115.

[24] Lu, A., Li, B., Li, J., Chen, W., Xu, L. (2018): Heavy metals in paddy soil-rice systems of industrial and township areas from subtropical China: Levels, transfer and health risks. – Journal of Geochemical Exploration 194: 210-217. https://doi.org/10.1016/j.gexplo.2018.08.003.

[25] Mao, C., Song, Y., Chen, L., Ji, J., Li, J., Yuan, X., Yang, Z., Ayoko, G. A., Frost, R. L., Theiss, F. (2019): Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. – Catena 175: 339-348. https://doi.org/10.1016/j.catena.2018.12.029.
[26] Muller, G. (1969): Index of geoaccumulation in sediments of the Rhine River. – Geojournal 2: 108-118.
[27] Navaretnam, R., Soong, A. C., Goo, A. Q., Isa, N. M., Aris, A. Z., Haris, H., Looi, L. J. (2023): Human health risks associated with metals in paddy plant (*Oryza sativa*) based on target hazard quotient and target cancer risk. – Environmental Geochemistry and Health 45(5): 2309-2327. https://doi.org/10.1007/s10653-022-01344-3.
[28] Ogunkunle, C. O., Varun, M., Jimoh, M. A., Olorunmaiye, K. S., Fatoba, P. O. (2016): Evaluating the trace metal pollution of an urban paddy soil and bioaccumulation in rice (*Oryza sativa* L.) with the associated dietary risks to the local population: A case study of Ilorin, north-central Nigeria. – Environmental Earth Sciences 75(20): 1383. https://doi.org/10.1007/s12665-016-6203-3.
[29] Peng, C., Tong, H., Shen, C., Sun, L., Yuan, P., He, M., Shi, J. (2020): Bioavailability and translocation of metal oxide nanoparticles in the soil-rice plant system. – Science of the Total Environment 713: 136662.
[30] 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 water in 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/s10661-012-3078-x.
[31] Satpathy, D., Reddy, M. V., Dhal, S. P. (2014): Risk assessment of heavy metals contamination in paddy soil, plants, and grains (*Oryza sativa* L.) at the east coast of India. – BioMed Research International 2014: 545473. https://doi.org/10.1155/2014/545473.
[32] Shan, A., Pan, J., Kang, K. J., Pan, M., Wang, G., Wang, M., He, Z., Yang, X. (2021): Effects of straw return with N fertilizer reduction on crop yield, plant diseases and pests, and potential heavy metal risk in a Chinese rice paddy: A field study of two consecutive wheat-rice cycles. – Environmental Pollution 288: 117741. https://doi.org/10.1016/j.envpol.2021.117741.
[33] Tang, D.-D., Yuan, X.-Y., Wang, Y.-M., Ji, J.-F., Wen, Y.-B., Zhao, W.-F. (2018): Enrichment characteristics and risk prediction of heavy metals for rice grains growing in paddy soils with a high geological background. – Journal of Agro-Environment Science 37(1): 18-26. https://doi.org/10.11654/jaes.2017-0801.
[34] USEPA (United States Environmental Protection Agency). (2010): Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual. – EPA/540/1-89/002.
[35] USEPA (United States Environmental Protection Agency). (2024): Integrated Risk Information System (IRIS). Regional Screening Level (RSL) Summary Table, November 2024. – Retrieved from https://www.epa.gov/risk/regional-screening-levels-rsls-generic-tables (Accessed on 27 January 2025).
[36] Wang, X., Li, L., Guo, N., Xin, Z., Li, X., Sun, X., Li, Y. (2021): A comprehensive exploration on pollution characteristics and ecological risks of heavy metals in surface paddy soils around a large copper smelter, southeast China. – Sustainability 13(23): 13359. https://doi.org/10.3390/su132313359.
[37] Wang, J., Deng, P., Wei, X., Zhang, X., Liu, J., Huang, Y., She, J., Liu, Y., Wan, Y., Hu, H., Zhong, W., 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. – Science of the Total Environment 856: 158883. https://doi.org/10.1016/j.scitotenv.2022.158883.

[38] Xiao, R., Guo, D., Ali, A., Mi, S., Liu, T., Ren, C., Li, R., Zhang, Z. (2019): Accumulation, ecological-health risks assessment, and source apportionment of heavy metals in paddy soils: A case study in Hanzhong, Shaanxi, China. – Environmental Pollution 248: 349-357. https://doi.org/10.1016/j.envpol.2019.02.045.
[39] Xiao, M., Li, Y. (2022): Distribution characteristics and ecological risk assessment of heavy metals under reclaimed water irrigation and water level regulations in paddy fields. – Polish Journal of Environmental Studies 31(3): 2355-2365. https://doi.org/10.15244/pjoes/143294.
[40] Xu, Z. Q., Ni, S. J., Tuo, X. G., Zhang, C. J. (2008): Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. – Environmental Science & Technology 31(2): 112-115.
[41] 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.
[42] Yang, J. E., Ok, Y. S., Kim, W.-I., Lee, J.-S. (2008): Heavy metal pollution, risk assessment and remediation in paddy soil environment: Research experiences and perspectives in Korea. – Causes and Effects of Heavy Metal Pollution, pp. 341-367.
[43] Yap, C. K., Wong, C. H. (2011): Assessment 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.
[44] Yin, C. J., Hee, C. W., Shing, W. L., Hock, O. G., Subramaniam, G., Barasarathi, J. (2023): Assessment of heavy metal content and consumption risks at selected paddy fields in Malaysia: A review. – Journal of Experimental Biology and Agricultural Sciences 11(5): 791-799. https://doi.org/10.18006/2023.11(5).791.799.
[45] 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(2): 189-200. https://doi.org/10.1023/A:1022501813655.
[46] 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/s10653-005-4670-7.
[47] Zhang, Z., Zhang, N., Li, H., Lu, Y., Wang, Q., Yang, Z. (2019): Risk assessment, spatial distribution, and source identification of heavy metal(loid)s in paddy soils along the Zijiang River basin, Hunan Province, China. – Journal of Soils and Sediments 19(12): 4042-4051. https://doi.org/10.1007/s11368-019-02352-0.
[48] Zhao, K., Zhang, W., Zhou, L., Liu, X., Xu, J., Huang, P. (2009): Modelling transfer of heavy metals in soil-rice systems and their risk assessment in paddy fields. – Environmental Earth Sciences 59(3): 519-527. https://doi.org/10.1007/s12665-009-0049-x.
[49] 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.
[50] Zheng, K., Ren, Z.-L., Qin, X.-Q., Zhao, Y.-J., Zhu, Z.-Q., Lian, W.-L., Li, Y.-T. (2018): Status and risk assessment of heavy metal pollution in paddy soil and rice grains from the industrial and mining area of Shaoguan, Guangdong Province. – Journal of Agro-Environment Science 37(5): 915-925. https://doi.org/10.11654/jaes.2018-0224.
[51] Zhuang, P., McBride, M. B., Xia, H., Li, N., Li, Z. (2009): Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, South China. – Science of the Total Environment 407(5): 1551-1561. https://doi.org/10.1016/j.scitotenv.2008.10.061.

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[52] Zulkafflee, N. S., Redzuan, N. A. M., Hanafi, Z., Selamat, J., Ismail, M. R., Praveena, S. M., Razis, A. F. A. (2019): Heavy metal in paddy soil and its bioavailability in rice using an in vitro digestion model for health risk assessment. – International Journal of Environmental Research and Public Health 16(23): 4769. https://doi.org/10.3390/ijerph16234769.
[53] Zulkafflee, N. S., Redzuan, N. A. M., Selamat, J., Ismail, M. R., Praveena, S. M., Razis, A. F. A. (2021): Evaluation of heavy metal contamination in paddy plants at the northern region of Malaysia using ICPMS and its risk assessment. – Plants 10(1): 3. https://doi.org/10.3390/plants10010003.

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