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Original Article

Assessment of zinc accumulation in agricultural soil of common vegetables and its associated ecological risks in the west coast of Peninsular Malaysia

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Abstract

Zinc (Zn), an essential micronutrient that also poses a potential threat, necessitating a thorough investigation. This study analysed Zn in 18 local vegetable species (leafy greens, fruits, a tuber, and a legume) and their soils across two Malaysian farming sites: Ara Kuda and Sikamat. Soil is a critical environmental factor, directly influencing vegetable Zn uptake and food safety, as it's the primary medium for nutrient absorption. Results indicated significantly higher Zn levels in leafy vegetables, with soil Zn concentrations greater at Sikamat than at Penang. Enrichment factors showed moderate to significant soil Zn enrichment, while the geoaccumulation index classified soil from "unpolluted" to "unpolluted to moderately polluted." Targeted monitoring of soil and leafy vegetable Zn levels, particularly in Sikamat, is recommended, to ensure safety and mitigate accumulation risks. The study highlights soil contamination as a critical factor in vegetable Zn levels, emphasizing the need for effective management to protect human health.

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Keywords: zinc, vegetables, geoaccumulation index, enrichment factor, ecological risk assessment

1. Introduction

Zinc (Zn) is essential for various physiological processes, with its levels regulated through absorption in the small intestine and excretion via feces (Wan & Zhang, 2022). Adult men require 9.4 to 16.3 mg of this nutrient daily, whereas adult women need 7.5 to 12.7 mg per day. During pregnancy, an extra 1.6 mg/day is advised, and during lactation, an additional 2.9 mg/day is recommended to support the body's increased demands (EFSA Panel on Dietetic Products Nutrition and Allergies, 2014). Industrially, Zn is vital in applications like photocatalysis for wastewater treatment (Abdullah, Bakar, & Bakar, 2022), solvent extraction for ore processing (Cole & Sole, 2003), coatings for corrosion protection (Pop, Iepure, Titu, & Ravai-Nagy, 2023), Zn -based alloys for manufacturing (Pola, Tocci, & Goodwin, 2020), and Zn-ion batteries for energy storage (Cao *et al*., 2020). ZnO NPs are widely used in rubber, paint, coatings, and cosmetics. Their biocompatibility, affordability, and low toxicity make them valuable in biomedicine, particularly for anticancer, antibacterial, and antidiabetic applications (Jiang, Pi, & Cai, 2018).

They generate reactive oxygen species (ROS), release zinc ions, and induce apoptosis, enhancing therapeutic efficacy. Their luminescent properties also support bioimaging applications (Jiang *et al*., 2018). Zn accumulated in soil and plant leaves that does not affect plant growth is generally considered to be within the range of 15-20 mg/kg dry weight for most crops, with levels above this considered potentially toxic and causing growth inhibition; however, this can vary depending on the specific plant species and soil conditions (Natasha *et al*., 2022). Agricultural practices can increase Zn levels in crops mainly via systemic fertilization (Alkarkhi, Ismail, Ahmed, & Easa, 2008; Wong *et al*., 2017). Along with the declining effectiveness of Zn fertilizers over time, there is a potential need for increased application rates, raising the risk of Zn contamination (Li *et al*., 2022).

Hence, investigating Zn accumulation in vegetables and soils from Sikamat and Ara Kuda is crucial for ensuring food safety and assessing the ecological risks posed by anthropogenic Zn contamination in these agricultural regions. The objectives of this study are, 1) to assess the accumulation of Zn in the edible biomass of a variety of commercially available vegetables, as well as in the cultivation soils from Sikamat (Negeri Sembilan) and Ara Kuda (Penang); 2) to assess the degree of anthropogenic contamination and enrichment of Zn to the agricultural soils used to cultivate common vegetable species in Sikamat (Negeri Sembilan) and in Ara Kuda (Penang); and 3) to perform the Ecological Risk Assessment (ERA) of Zn in the agricultural soils of farming sites located in Sikamat (Negeri Sembilan) and in Ara Kuda (Penang).

2. Materials and Methods

2.1 Sampling and sample collection

Vegetable samples were collected from two commercial farms in Sikamat, Seremban, and Ara Kuda, Penang, in Malaysia from February 11th to 17th, 2018. These sites were chosen due to their proximity to neighbourhoods and marketability. Details of the sites and sampled vegetables are in Table 1, and their locations are shown in Figure 1. Topsoil samples (0-10 cm) were collected systematically across the agricultural area using a systematic random sampling technique to ensure representative coverage of the plant rooting zone for robust analysis of soil properties relevant to plant growth. Soil depths were determined by inserting a metal wire with a pre-measured length onto the farm soil ground when sample collection was conducted. The sampled vegetables and topsoil were placed in pre-cleaned plastic bags and chilled until they were brought back to the laboratory for sample processing and analysis. These samples have been refrigerated at -20°C in the laboratory until processing.

Table 1. The descriptive details, GPS coordinates, and sampling dates of the vegetable species collected

Sampling site (GPS Coordinates)	Sampling date	Taxonomy (common name)	Site description (source of irrigation)
Sikamat, Seremban, Negeri Sembilan (N 2°44.378', E 101°58.091')	11-Feb-18	*Allium cepa* (Spring onion)	Small size commercial farm that located near a small industrial and domestic neighbourhood (River stream and tap water supply)
	11-Feb-18	*Amaranthus viridis* (Green amaranth)	
	11-Feb-18	*Lactuca sativa* (Lettuce)	
	11-Feb-18	*Ipomoea aquatica* (Water spinach)	
Ara Kuda Penang, Taman Kekal Pengeluar Makanan, TKPM, Perak (N 05º 27', E 100º 31.583')	13-Feb-18	*Abelmoschus esculentus* (Okra)	Agriculture area surrounded by palm oil plantation, main road Penanti to Tasek Gelugor (Tube well and stream)
	13-Feb-18	*Amaranthus tricolor* (Red amaranth)	
	13-Feb-18	*Brassica rapa* (Bok choy)	
	17-Feb-18	*Capsicum annuum* (Red chilli)	
	13-Feb-18	*Cucurbita moshata* (Sweet pumpkin)	
	13-Feb-18	*Ipomoea batatas* (Sweet potatoes)	
	17-Feb-18	*Legenaria siceraria* (Calabash)	
	17-Feb-18	*Luffa acutangula* (Angle loofah)	
	13-Feb-18	*Momordica charantia* (Bitter gourd)	
	13-Feb-18	*Solanum melongena* (Brinjal)	
	13-Feb-18	*Tricosanthes celebica* (Snake gourd)	
	17-Feb-18	*Vigna sinensis* (Long bean)	
	17-Feb-18	*Sauropus androgynus* (Sweet shoot)	
	13-Feb-18	*Luffa aegyptiaca* (Spounge gourd)	

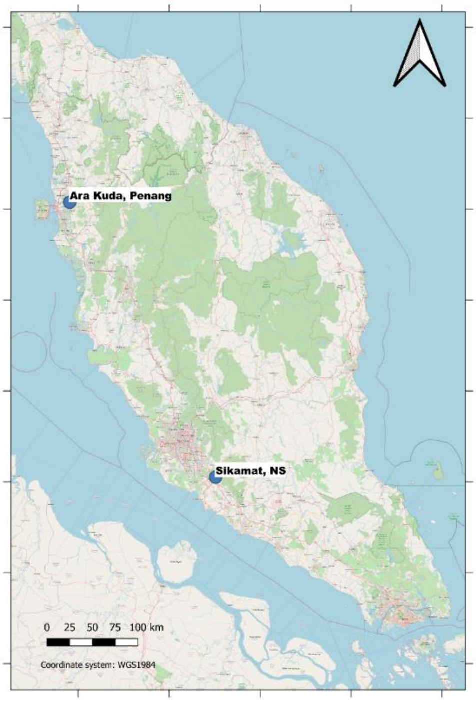

Figure 1. Map depicting the two locations where the vegetable samples were collected (Sikamat, Negeri Sembilan, Malaysia and Ara Kuda, Penang, Malaysia) (QGIS version 3.16)

2.2 Sample preparation

Vegetable and soil samples were dried in a 60°C oven until a stable dry weight was reached for digestion and analysis. The dried soil samples were ground with a mortar and pestle, then sieved through a 63µm stainless-steel sieve with vigorous shaking for homogeneity (Wong *et al*., 2017; Yap *et al*., 2002). Standardizing the soil's particle size is the primary purpose of this sieving procedure. The sieved soils were subsequently stored in a clean, labelled polypropylene zip bag and preserved at room temperature until the time of analysis (Wong *et al*., 2017). The dried soil samples were ground into a fine powder to ensure homogeneity (Cheng & Yap, 2015). These prepared samples were then stored at room temperature until further processing.

2.3 Sample treatment and digestion

Triplicate vegetable topsoil samples were digested with 10 mL of nitric acid; and with 10 mL of digestion reagent, namely nitric acid and aqua regia solution (mixture of nitric acid and perchloric acid in a 4:1 ratio), respectively. Sample-reagent mixtures were initially heated at 40 ºC for an hour, then at 140 ºC for three hours. The digested samples were diluted to 40 mL with ultrapure water and filtered through Whatman no. 1 filter paper to remove indigestible particles before metal analysis (Cheng & Yap, 2015). From an ecotoxicological view, analysing total Zn in soil better assesses overall metal contamination risk, long-term accumulation, and potential environmental toxicity, providing a comprehensive picture of Zn burden and its ecosystem health implications over time.

2.4 Zinc and Iron determination

The analysis of Zn and Fe concentrations in the processed samples was conducted using an air-acetylene flame atomic absorption spectrometer (FAAS, Thermo Scientific iCE 3000). To ensure the accuracy of the measurements, the FAAS instrument was calibrated with multiple level calibration standards during the measurement process.

Zn and Fe concentrations from FAAS were calculated based on dry weight. To compare studies, both dry and fresh weight based values are reported. Dry weight based Zn values were converted to fresh weight values using a conversion factor (CF), i.e. the ratio of dry to fresh weight (Cheng & Yap, 2015).

2.5 Determination of assessment indexes

2.5.1 Enrichment factor (EF)

The Enrichment Factor (EF) in ecotoxicology is a metric used to assess the degree of contamination or enrichment of a specific element or pollutant in a sample (e.g., soil, sediment, or water) compared to a background or reference level (Fe) (Loska, Cebula, Pelczar, Wiechuła, & Kwapuliński, 1997). In this study, EF was determined by using calculation formula defined is (Buat-Menard & Chesselet, 1979). The formula is as follows.

$$EF = (Zn/Fe)_{sample}/(Zn/Fe)_{PRV} \qquad \text{(Equation 1)}$$

Here, $(Zn/Fe)_{sample}$ is the ratio of Zn and Fe in the soil collected for this study and $(Zn/Fe)_{PRV}$ is the ratio between Zn and Fe by their preindustrial reference values (PRV) previously defined (Zn = 175 µg g^{-1}; Fe = 50,400 µg g^{-1}) (Hakanson, 1980; Rudnick & Gao, 2003). In the process of determination of EF, Fe was chosen as normalizer as it was recognized as a comparatively more conservative in nature and crustal weathering serves as a major source of it (Ong, Wong, Tan, & Yap, 2015). Additionally, Fe exists in nature environments consistently with a low variability of occurrence (Loska *et al*., 1997). The value of EF were interpreted as categorizations defined in (Ong *et al*., 2015).

2.5.2 Geoaccumulation index (I_{geo})

The Geoaccumulation Index (I_{geo}), was initially used to assess metal contamination in aquatic sediments (Muller, 1969). Over time, its application expanded to evaluating metal pollution in terrestrial soils (Yap *et al*., 2022). I_{geo} is crucial in assessing ZnO NP-related ecological risks, aiding research on their environmental impact and informing management strategies. As nanomaterial studies advance, integrating I_{geo} assessments remains vital for comprehensive ecotoxicology research. I_{geo} was determined as in Equation 2:

$$I_{geo} = Log_2(C_{Zn}/1.5 \times PRV_{Zn}) \qquad \text{(Equation 2)}$$

where C_{Zn} is the concentration of Zn in soil collected for this study, PRV_{Zn} is the preindustrial reference value of Zn (Hakanson, 1980). A factor of 1.5 was deployed as a correction factor for background matrixes, minimizing the variation due to lithogenic effects (Ong *et al*., 2015). The value of I_{geo} were interpreted with the categories defined in (Muller, 1969). The index values correspond to the following pollution levels: less than 0 indicates practically unpolluted, 0 to 1 indicates unpolluted to moderately polluted, 1 to 2 indicates moderately polluted, 2 to 3 indicates moderately to strongly polluted, 3 to 4 indicates strongly polluted, 4 to 5 indicates strongly to very strongly polluted, and greater than 5 indicates very strongly polluted.

2.5.3 Ecological risk assessment by contamination factor and risk index

Contamination factor and risk index assessments are vital for quantifying pollution levels and evaluating their potential ecological harm, thus informing effective environmental management (Hakanson, 1980). Contamination factor (C_f^{Zn}) was defined to describe a contamination level of a toxic substance in an environment (Hakanson, 1980). The definition of C_f^{Zn} is given in Equation 3.

$$C_f^{Zn} = Zn_{soil}/Zn_{PRV} \qquad \text{(Equation 3)}$$

Here C_f^{Zn} is the contamination factor for Zn, Zn_{soil} is the Zn concentration in soil collected for this study, and Zn_{PRV} is the preindustrial reference value for Zn (Hakanson, 1980). The values of C_f^{Zn} were interpreted by the categories defined in (Hakanson, 1980).

Potential risk index (RI_{Zn}) for Zn was defined as contamination factor for Zn by a toxic response factor (Equation 4).

$$RI_{Zn} = T_r^{Zn} \times C_f^{Zn} \qquad \text{(Equation 4)}$$

Here RI_{Zn} is the risk index for Zn, C_f^{Zn} is the contamination factor for Zn in soil, and T_r^{Zn} is the toxic response factor for Zn ($T_r^{Zn} = 1$) (Hakanson, 1980). The RI_{Zn} were interpreted as described by Hakanson (1980).

2.6 Quality assurance

All acid-proof glassware and apparatus were soaked in a 5% nitric acid bath for 72 hours and rinsed with distilled water and ultrapure water to prevent contamination. The accuracy of Zn measurements in vegetable and soil samples was verified using certified reference materials (CRMs): BCR-060 Aquatic Plant by the Joint Research Centre, EU, and MESS-3 Marine Sediment by the National Research Council of Canada. The measured values for the CRMs agreed satisfactorily with their certified values, with recoveries of 86.76% and 81.62%, respectively.

3. Results

3.1 Concentrations of Zn in vegetables' respective habitat soils

The Zn levels (µg g^{-1} dw) of respective vegetables' cultivating soils are shown in Table 2. Zn concentrations in soil vary greatly, with the lowest found in *Vigna sinensis*'s soil (42.2 µg g-1 dw) and the highest in *A. viridis*'s soil (452.378 µg g-1 dw). Higher Zn levels were generally found in soils from Sikamat, near a populated suburb of Seremban, compared to the more pristine Penang site. Similarly, vegetables from Sikamat had higher Zn levels. Higher level of Zn in soil was previously associated with industrial and agricultural activities due to its importance in these sectors (Fuge, 2013; Wong *et al*., 2017). It would be logical to ascribe this to the occurrence of anthropogenic activities surrounding Sikamat site, elevating Zn levels in soil and vegetables cultivated in that area.

The data reveal distinct patterns in soil Zn concentrations across vegetable categories in Malaysia. Leafy vegetables are typically associated with higher soil Zn levels, averaging 262.5 mg/kg, compared to fruiting vegetables at 117.9 mg/kg, though exceptions like *Capsicum annuum* blur this distinction. The tuber *Ipomoea batatas* also aligns with higher concentrations, while the legume *Vigna sinensis* marks the lower end of the spectrum. This variability suggests differing zinc accumulation dynamics in the habitats of these vegetables, potentially influenced by soil properties, plant uptake mechanisms, or agricultural practices specific to each species. Overall, the range from 42.183 mg/kg to 452.378 mg/kg highlights the diverse soil conditions supporting vegetable cultivation in Malaysia.

Different crops had varying abilities to absorb and accumulate Zn from the soil, with some species being more efficient than others. Crop-specific agricultural practices, such as the use of Zn-rich fertilizers, significantly increased Zn levels in the soil. Additionally, crop residues contributed to organic matter, which bound Zn, affecting its availability for subsequent crops. The type of crop and its management practices, including irrigation and fertilization, influenced Zn dynamics in the soil. For instance, Zn application to soil enhanced crop yields and increased Zn accumulation in grains while reducing the uptake of harmful elements like arsenic. Overall, crop plantation played a crucial role in managing Zn levels in the soil, impacting both soil fertility and crop nutritional quality.

Crop species exhibited varying capacities for Zn absorption and accumulation, with some crops being more efficient than others. For instance, soybeans were studied for their ability to accumulate Zn in seeds, with research identifying specific genomic regions and candidate genes responsible for this trait (Bellaloui *et al*., 2024). Crop-specific agricultural practices, such as the application of Zn-rich fertilizers, significantly elevated Zn concentrations in the soil, enhancing crop yields and nutritional quality (Chattha *et al*., 2022; Wong *et al*., 2017).

4. Discussion

4.1 Enrichment factor (EF)

The Enrichment Factor (EF) was used to assess the impact of pollution on soil's Zn levels, relative to its natural state. (Cheng & Yap, 2015; Ong *et al*., 2015; Wong *et al*., 2017). The EF of the soil samples collected in this study varied from 1.334 to 14.842 as shown in Table 2. When comparing sites, the Sikamat site exhibited a higher EF range of 5.037 – 14.842, in contrast to the Penang site which had an EF range of 1.334 – 14.157.

Table 2. Concentrations (µg/g dry weight) of Zn in the habitat soils of various vegetables in Malaysia and their respective geoaccumulation index (I_{geo}), enrichment factor (EF), contamination factor (C_f^{Zn}), and potential risk index (RI_{Zn}) for Zn in the cultivating soils of respective vegetables

Species	Part	Zn			Fe			I_{geo}	EF	C_f^{Zn}	RI_{Zn}
		Mean	±	SE	Mean	±	SE				
Allium cepa	Leafy	271.702	±	0.859	5272.16	±	260.04	0.050	14.842	1.553	1.553
Amaranthus viridis	Leafy	452.378	±	1.016	25867.24	±	5945.10	0.785	5.037	2.585	2.585
Ipomoea aquatica	Leafy	341.435	±	2.720	11438.13	±	412.19	0.379	8.597	1.951	1.951
Amaranthus tricolor	Leafy	108.816	±	1.746	5716.52	±	509.51	-1.270	5.482	0.622	0.622
Brassica rapa	Brassica	88.358	±	2.458	8579.40	±	1503.13	-1.571	2.966	0.505	0.505
Lactuca sativa	Leafy	298.955	±	0.383	12171.27	±	462.20	0.188	7.074	1.708	1.708
Sauropus androgynus	Leafy	275.643	±	2.182	5607.42	±	1217.75	0.070	14.157	1.575	1.575
Abelmoschus esculentus	Fruity	107.275	±	1.209	7246.24	±	687.48	-1.291	4.264	0.613	0.613
Capsicum annum	Fruity	271.137	±	1.461	6001.50	±	557.63	0.047	13.011	1.549	1.549
Cucurbita moschata	Fruity	99.862	±	1.112	21561.96	±	932.34	-1.394	1.334	0.571	0.571
Lagenaria siceraria	Fruity	176.345	±	1.595	5335.84	±	141.38	-0.574	9.518	1.008	1.008
Luffa acutangula	Fruity	154.004	±	1.402	5373.96	±	133.23	-0.769	8.253	0.880	0.880
Momordica charantia	Fruity	49.580	±	0.577	6415.08	±	301.27	-2.404	2.226	0.283	0.283
Solanum melongena	Fruity	49.854	±	2.331	4760.62	±	268.85	-2.397	3.016	0.285	0.285
Luffa aegyptiaca	Fruity	102.514	±	1.578	4719.56	±	478.27	-1.357	6.256	0.586	0.586
Tricosanthes celebica	Fruity	50.219	±	0.682	5111.93	±	230.59	-2.386	2.829	0.287	0.287
Ipomoea batatas	Tubers	337.128	±	1.084	20438.90	±	813.82	0.361	4.750	1.926	1.926
Vigna sinensis	legume	42.183	±	0.682	5532.31	±	345.15	-2.638	2.196	0.241	0.241

By Yongming *et al.* (2006)‘s standard, among the soil samples collected for current study, only soil for *Cucurbita moschata* can be categorized as “minimal enrichment” (EF < 2). Other samples fell into moderate enrichment (2 ≤ EF < 5) and significant enrichment (5 ≤ EF < 20) categories. Among these vegetables, soils of *Brassica rapa*, *Abelmoschus esculentus*, *Momordica charantia*, *Solanum melongena*, *Tricosanthes celebica*, *Ipomoea batatas* and *Vigna sinensis* have been found to be moderately enriched with Zn. In contrast, the cultivating soils of *Allium cepa*, *Amaranthus viridis*, *Ipomoea aquatica*, *Amaranthus tricolor*, *Lactuca sativa*, *Sauropus androgynus*, *Capsicum annum*, *Cucurbita moschata*, *lagenaria siceraria*, *Luffa acutangular* and *Luffa aegyptiaca* were found to be significantly enriched.

Anthropogenic activities have been suggested to increase heavy metal enrichment in geological materials, such as soils and sediments (Shafie *et al*., 2013; Wong *et al*., 2017). When compared with previous studies conducted in Peninsular Malaysia, the Enrichment Factor (EF) values range of the current study (1.334 – 14.842) aligns with the EF of Zn found in the Langat River (1.77 – 12.42) (Shafie *et al*., 2013), and is higher than in another study focused on the upper stream of the same river (0.63 – 1.49) (Wong *et al*., 2017). The Zn enrichment in soils sampled for this study was also found to be higher than in the mangrove area across the southwestern coast of Peninsular Malaysia (0.26 – 1.08) (Cheng & Yap, 2015). Adding Zn to agricultural fertilizers corrects soil micronutrient deficiencies, with Zn levels varying by type—e.g., $ZnSO_4$ differs in concentration, while Zn oxide is less soluble despite high Zn content. Though Zn percentages in fertilizers seem small, large-scale farming application rates can significantly increase soil Zn over time. Plants don’t fully absorb applied Zn, leaving some in the soil (Leite *et al*., 2020). Zn also appears in pesticides like fungicides, historically used against fungi, and while less common than fertilizers, their use adds to soil Zn levels based on application frequency and intensity (Luo *et al*., 2020).

4.2 Geoaccumulation index (I_{geo})

For the purpose of making it easy to compare the soils used to grow various vegetable varieties and the two sampling sites, I_{geo} was utilized in this study to objectively assess the extents of contamination (Muller, 1969). As shown in Table 2, the overall range of I_{geo} values is -2.638 to 0.785. In contrast to the pristine site in Penang (-2.638 – 0.361), the Sikamat site, which is in proximity to anthropogenic activity like traffic activity, has higher I_{geo} values (0.050 – 0.785). None of the I_{geo} values obtained in this study was above one (Muller, 1969). As a result of this, all the soil samples collected throughout this study have been categorised as “uncontaminated” ($I_{geo} \leq 0$) or “unpolluted to moderately polluted” ($0 < I_{geo} \leq 1$).

Of all soils collected, the soils of *Amaranthus tricolor, Brassica rapa, Abelmoschus esculentus, Cucurbita moschata, Lagenaria siceraria, Luffa acutangular, Momordica charantia, Solanum melongena, Luffa aegyptiaca, Tricosanthes celebica* and *Vigna sinensis* are practically unpolluted with Zn. *Allium cepa, Amaranthus viridis, Ipomoea aquatica, Lactuca sativa, Sauropus androgynus, Capsicum annum* and *Ipomoea batatas* soils were at a higher contamination level and fell into “unpolluted to moderately polluted” category.

In comparison of previous studies conducted in Peninsular Malaysia, the I_{geo} range of this study (-2.638 – 0.785) was found to be slightly wider than in a previous sedimental study conducted in Langat River, Malaysia, and in the mangrove area across southwest coast of Peninsular Malaysia (Cheng & Yap, 2015; Shafie *et al*., 2013; Wong *et al*., 2017). The EF for Cd and Pb was higher in eastern Dumai, Indonesia, compared to other locations, with Cd having the highest EF. Most locations indicated mild pollution, but moderate pollution was observed at the Cargo Port due to Cd. The heavy metal concentrations were like global averages, suggesting a mild to moderate pollution level in the coastal environment (Amin, Ismail, Arshad, Yap, & Kamarudin, 2009). Krishnan *et al*. (2022) assessed the ecological risk of heavy metals in the mangrove sediments of the Sepang Besar River using EF and I_{geo}. They found as to be the predominant pollutant.

4.3 Ecological risk assessment (ERA)

The values of contamination factor (C_f^{Zn}) and potential risk index (PRI) for Zn are presented in Table 2. The C_f^{Zn} values range from 0.241 to 2.585. According to Hakanson (1980)'s standard, the soil of *A. tricolor, B. rapa, A. esculentus, C. moschata*, *L. acutangula*, *M. charantia*, *A. melongena*, *L. aegyptiaca*, *T. celebica* and *V. sinensis* were categorized as “low contamination” ($C_f^{Zn} < 1$), while other vegetable species were categorized as moderate contamination ($1 \leq C_f^{Zn} < 3$).

RI_{Zn} is a risk assessment index involving the calculated C_f^{Zn} value multiplied with toxic response factor of Zn ($T_r^{Zn} = 1$). This multiplication is crucial in the Ecological Risk Assessment (ERA) process, as the potential ecological impact and toxicity vary among the pollutants or contaminants being investigated. The risk factor for Zn, T_r^{Zn}, is calculated by taking into account both the sedimentological toxic factor and the sensitivity requirement, expressed in terms of the bioproduction index (Hakanson, 1980). As indicated in Table 2, the Risk Index (RI_{Zn}) values in this study ranged from 0.241 to 2.585. None of the soil samples collected posed a significant potential ecological risk to the surrounding ecosystem or consumers, as all the soils fell into the “low potential ecological risk category” (RI_{Zn}). This suggests that despite the higher Enrichment Factor (EF) value for the soil of some vegetable varieties (as shown in Table 2), the potential ecological risk is not significant.

5. Conclusions

Leafy vegetables from the study accumulated significantly higher Zn levels (p<0.05) compared to other vegetable types, with the anthropogenically influenced Sikamat site showing higher Zn than Penang. Enrichment factor analysis indicated significant to moderate Zn enrichment in the soils, while the geoaccumulation index suggested unpolluted to moderately polluted conditions, indicating an insignificant ecological threat despite higher enrichment factors. Effective management of elevated Zn in Sikamat necessitates regular monitoring, adoption of best agricultural practices (crop rotation, organic fertilizers), phytoremediation, and public awareness to minimize ecological impact.

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Author Contributions

Koe Wei Wong: Methodology, Sampling, Investigation, Formal analysis, Writing – Original draft. Chee Kong Yap: Supervision, Conceptualization, Funding acquisition, Writing – Reviewing and Editing. Aziran Yaacob: Methodology, Sampling, Investigation, Validation. Rosimah Nulit: Methodology, Resources. Yoshifumi Horie: Software, Data curation. Hideo Okamura: Formal analysis, Validation. Meng Chuan Ong: Resources, Investigation. Mohamad Saupi Ismail: Resources, Data curation. Krishnan Kumar: Validation, Writing – Reviewing and Editing. Hesham M. H. Zakaly: Software, Formal analysis. Wan Mohd Syazwan: Investigation, Visualization. Wan Hee Cheng: Validation, Writing – Reviewing and Editing.

References

Abdullah, F. H., Bakar, N. H. H. A., & Bakar, M. A. (2022). Current advancements on the fabrication, modification, and industrial application of zinc oxide as photocatalyst in the removal of organic and inorganic contaminants in aquatic systems. *Journal of Hazardous Materials*, *424*, 127416. doi:10.1016/j.jhazmat.2021.127416

Alkarkhi, A. F. M., Ismail, N., Ahmed, A., & Easa, A. mat. (2008). Analysis of heavy metal concentrations in sediments of selected estuaries of Malaysia—A statistical assessment. *Environmental Monitoring and Assessment*, *153*(1), 179. doi:10.1007/s10661-008-0347-x

Amin, B., Ismail, A., Arshad, A., Yap, C. K., & Kamarudin, M. S. (2009). Anthropogenic impacts on heavy metal concentrations in the coastal sediments of Dumai, Indonesia. *Environmental Monitoring and Assessment*, *148*(1), 291–305. doi:10.1007/s10661-008-0159-z

Bellaloui, N., Knizia, D., Yuan, J., Song, Q., Betts, F., Register, T., . . . Kassem, M. A. (2024). Genomic regions and candidate genes for seed iron and seed zinc accumulation were identified in the soybean ‘Forrest’ by ‘Williams 82’ RIL population. *International Journal of Plant Biology*, *15*(2), 452–467. doi:10.3390/ijpb15020035

Buat-Menard, P., & Chesselet, R. (1979). Variable influence of the atmospheric flux on the trace metal chemistry of oceanic suspended matter. *Earth and Planetary Science Letters*, *42*(3), 399–411. doi:10.1016/0012-821X(79)90049-9

Cao, Z., Zhuang, P., Zhang, X., Ye, M., Shen, J., & Ajayan, P. M. (2020). Strategies for Dendrite-Free Anode in Aqueous Rechargeable Zinc Ion Batteries. *Advanced Energy Materials*, *10*(30), 2001599. doi:10.1002/aenm.202001599

Chattha, M. U., Amjad, T., Khan, I., Nawaz, M., Ali, M., Chattha, M. B., . . . Hassan, M. U. (2022). Mulberry based zinc nano-particles mitigate salinity induced toxic effects and improve the grain yield and zinc bio-fortification of wheat by improving antioxidant activities, photosynthetic performance, and accumulation of osmolytes and hormones. *Frontiers in Plant Science*, *13*, 920570. doi:10.3389/fpls.2022.920570

Cheng, W. H., & Yap, C. K. (2015). Potential human health risks from toxic metals via mangrove snail consumption and their ecological risk assessments in the habitat sediment from Peninsular Malaysia. *Chemosphere*, *135*, 156–165. doi:10.1016/j.chemosphere.2015.04.013

Cole, P. M., & Sole, K. C. (2003). Zinc solvent extraction in the process industries. *Mineral Processing and Extractive Metallurgy Review* (World). doi:10.1080/08827500306897

EFSA Panel on Dietetic Products Nutrition and Allergies. (2014). Scientific opinion on dietary reference values for zinc. *EFSA Journal*, *12*(10), 3844. doi:10.2903/j.efsa.2014.3844

Fuge, R. (2013). Anthropogenic sources. In O. Selinus, B. Alloway, J. A. Centeno, R. B. Finkelman, R. Fuge, U. Lindh, & P. Smedley (Eds.), *Essentials of Medical Geology* (pp. 59–74). Dordrecht, The Netherlands: Springer. doi:10.1007/978-94-007-4375-5_4

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

Han, Y., Du, P., Cao, J., & Posmentier, E. S. (2006). Multivariate analysis of heavy metal contamination in urban dusts of Xi'an, Central China. *Science of the Total Environment*, *355*(1), 176–186. doi:10.1016/j.scitotenv.2005.02.026

Jiang, J., Pi, J., & Cai, J. (2018). The advancing of zinc oxide nanoparticles for biomedical applications. *Bioinorganic Chemistry and Applications*, *2018*(1), 1062562. doi:10.1155/2018/1062562

Krishnan, K., Nadia, A., & Chong, M. (2022). Ecological risk assessment of heavy metal pollution in mangrove sediments of the Sepang Besar River, West Coast Peninsular Malaysia. *Environment and Ecology Research*, *10*, 497–507. doi:10.13189/eer.2022.100408

Leite, C. M. C., da Silva, A., César, F. R. C. F., Guimarães, G. G. F., Almeida, E., & Muraoka, T. (2020). Low efficiency of Zn uptake and translocation in plants provide poor micronutrient enrichment in rice and soybean grains. *Journal of Plant Nutrition*, *43*(1), 79–91. doi:10.1080/01904167.2019.1659341

Li, C., Wang, L., Wu, J., Blamey, F. P. C., Wang, N., Chen, Y., . . . Kopittke, P. M. (2022). Translocation of foliar absorbed Zn in sunflower (Helianthus annuus) Leaves. *Frontiers in Plant Science*, *13*. Retrieved from https://www.frontiersin.org/articles/10.3389/fpls.2022.757048

Loska, K., Cebula, J., Pelczar, J., Wiechuła, D., & Kwapuliński, J. (1997). Use of enrichment, and contamination factors together with geoaccumulation indexes to evaluate the content of Cd, Cu, and Ni in the Rybnik Water Reservoir in Poland. *Water, Air, and Soil Pollution*, *93*(1), 347–365. doi:10.1023/A:1022121615949

Luo, Y., Yao, A., Tan, M., Li, Z., Qing, L., & Yang, S. (2020). Effects of manganese and zinc on the growth process of Phytophthora nicotianae and the possible inhibitory mechanisms. *PeerJ*, *8*, e8613. doi:10.7717/peerj.8613

Muller, G. (1969). Index of geoaccumulation in sediments of the Rhine River. *Geojournal*, *2*, 108–118.

Natasha, N., Shahid, M., Bibi, I., Iqbal, J., Khalid, S., Murtaza, B., . . . Arshad, M. (2022). Zinc in soil-plant-human system: A data-analysis review. *Science of the Total Environment*, *808*, 152024. doi:10.1016/j.scitotenv.2021.152024

Ong, G. H., Wong, L. S., Tan, A. L., & Yap, C. K. (2015). Effects of metal-contaminated soils on the accumulation of heavy metals in Gotu Kola (*Centella asiatica*) and the potential health risks: A study in Peninsular Malaysia. *Environmental Monitoring and Assessment*, *188*(1), 40. doi:10.1007/s10661-015-5042-0

Pola, A., Tocci, M., & Goodwin, F. E. (2020). Review of microstructures and properties of zinc alloys. *Metals*, *10*(2), 253. doi:10.3390/met10020253

Pop, A. B., Iepure, G., Titu, A. M., & Ravai-Nagy, S. (2023). Characterization and corrosion behavior of zinc coatings for two anti-corrosive protections: A detailed study. *Coatings*, *13*(8), 1460. doi:10.3390/coatings13081460

Rudnick, R. L., & Gao, S. (2003). 3.01—Composition of the continental crust. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on Geochemistry* (pp. 1–64). Oxford, England: Pergamon. doi:10.1016/B0-08-043751-6/03016-4

Shafie, N. A., Aris, A. Z., Zakaria, M. P., Haris, H., Lim, W. Y., & Isa, N. M. (2013). Application of geoaccumulation index and enrichment factors on the assessment of heavy metal pollution in the sediments. *Journal of Environmental Science and Health, Part A*, *48*(2), 182–190. doi:10.1080/10934529.2012.717810

Wan, Y., & Zhang, B. (2022). The impact of zinc and zinc homeostasis on the intestinal mucosal barrier and intestinal diseases. *Biomolecules*, *12*(7), 900. doi:10.3390/biom12070900

Wong, K. W., Yap, C. K., Nulit, R., Hamzah, M. S., Chen, S. K., Cheng, W. H., . . . Al-Shami, S. A. (2017). Effects of anthropogenic activities on the heavy metal levels in the clams and sediments in a tropical river. *Environmental Science and Pollution Research*, *24*(1), 116–134. doi:10.1007/s11356-016-7951-z

Yap, C. K., Ismail, A., Tan, S. G., & Omar, H. (2002). Correlations between speciation of Cd, Cu, Pb and Zn in sediment and their concentrations in total soft tissue of green-lipped mussel *Perna viridis* from the west coast of Peninsular Malaysia. *Environment International*, *28*(1–2), 117–126. doi:10.1016/S0160-4120(02)00015-6

Yap, C. K., Tan, W. S., Cheng, W. H., Syazwan, W. M., Azrizal-Wahid, N., Krishnan, K., . . . Wong, L. S. (2022). Ecological–health risk of antimony and arsenic in *Centella asiatica*, topsoils, and mangrove sediments: A case study of Peninsular Malaysia. *Frontiers in Environmental Science*, *10*. Retrieved from https://www.frontiersin.org/articles/10.3389/fenvs.2022.939860