Health Risk Assessment of Heavy Metal(oid) in Paddy Rice (*Oryza sativa* L.) Around Ayutthaya Landfill Site

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ARTICLE INFO

Article history:
Received: 30 August 2024
Revised: 24 October 2024
Accepted: 25 Fubruary 2025
Online: 20 July 2026

Keywords:
Health risk assessment
Heavy metals
Paddy rice
Landfill

ABSTRACT

This study examines heavy metals and metalloid contamination in rice and assesses associated health risks from ingesting these contaminated rice products. The investigation involved measuring contamination levels across different rice components and evaluating health risks through non-carcinogenic and carcinogenic assessments. Non-carcinogenic risks were quantified using Hazard Quotient (HQ) and Hazard Index (HI) values, while carcinogenic risks were assessed using Carcinogenic Risk (CR) and Total Carcinogenic Risk (TCR) values. Rice samples were collected from high-risk agricultural areas near landfill sites during the storm season. Heavy metals(oid) were extracted using by acid digestion and analyzed by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) following USEPA methods 3050B and 6010D. Results indicated significant metalloid accumulation, with Arsenic (As) concentrated in rice grains (9.137 mg/kg) and other metals predominantly found in leaves and roots. Concentrations of Arsenic (As), Chromium (Cr), Copper (Cu), Iron (Fe), and Lead (Pb) in rice grains exceeded contamination standards set by Thailand, China, WHO, and FAO in 100%, 100%, 20%, 100%, and 80% of samples, respectively. Health risk assessments of multiple ingested elements showed unacceptable risks (HI $\geq$1, TCR $\geq 10^{-4}$) for children, adult males and adult females, with the highest risk in children (HI = 414.111, TCR = 3.867×10^{-1}).

1. INTRODUCTION

Rice (*Oryza sativa* L.) serves as a staple food for approximately 3.5 billion people globally [1], particularly for Asian populations [2, 3]. By 2030, the global demand for rice is projected to increase to around 567 million tons [4]. Consequently, ensuring the quality and safety of rice for consumption is critically important [5].

Currently, economic development in both the industrial and agricultural sectors has adversely affected rice quality [6]. This development has led to increased pollution in the soil and surrounding environment, and rice has the ability to accumulate toxic substances from both the soil and the environment into its tissues through the absorption of harmful environmental agents [7, 8]. Consequently, cultivating rice in soils with elevated levels of pollutant contamination can significantly increase the concentration of these pollutants in the rice itself [9]. This situation potentially exacerbates health risks for consumers, as pollutants can be transferred through the food chain from rice to humans [10].

A significant risk factor for pollutant contamination in rice and environment is waste management through landfilling [11], with inadequate engineering design for leachate management as a primary cause.

The surface runoff, if poorly managed, can contribute to dispersion of pollutant-containing leachate into surrounding environment [12] and agricultural areas [13], which leads to contamination of rice cultivated around landfill areas and adversely affects consumers' health. Furthermore, the spread of toxins from landfills contributes to soil contamination [14]. If contaminated soil is utilized for rice cultivation, the yield of the rice from such areas may be diminished [15], and the plants may exhibit abnormal growth patterns [16]. For instance, rice grown in soil with high cadmium contamination may have a lower germination rate, lack essential nutrients required for growth, and display shorter stems and roots, ultimately reducing photosynthetic efficiency [17].

Nowadays, the issue of contamination in agricultural products remain a global concern, including contaminated rice due to cultivation around landfills, as landfilling continues to be a prevalent waste management method in developing countries [18]. The varieties of heavy metals that can leach from landfills and can be absorbed by rice include arsenic, cadmium, chromium, nickel, and lead [19, 20].

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Levels and types of heavy metal(oid) contamination depend on composition of the waste disposed in each area [21]. Additionally, the pollutant contamination in rice results from the use of agricultural chemicals, including herbicides, insecticides, and chemical fertilizers [22]. These chemicals often contain heavy metal such as chromium, nickel, arsenic, and lead [23]. Excessive use of agricultural chemicals to boost crop yield can also exacerbate levels of heavy metal(oid) contamination in rice, consumption of which can lead to various health problems [24, 25].

Therefore, rice grown near landfill sites together with application of agricultural chemicals might contribute to a significant health risk for consumers. The health effects include: 1) non-carcinogenic effects such as gastrointestinal problems, neurological disturbances, and genetic damage; and 2) carcinogenic effects such as breast cancer, prostate cancer and stomach cancer [26]-[28]. The evaluation of health risks associated with the consumption of contaminated rice serves as a method to study the potential health impacts. Data obtained from this health risk assessment can indicate the levels of toxins ingested through exposure assessment, the degree of risk for non-carcinogenic diseases through non-carcinogenic health risk assessment, and the level of risk for developing cancers through carcinogenic health risk assessment [29]. Considering all the aforementioned factors, investigating heavy metal(oid) contamination in rice and assessing associated health risks for rice grown in areas impacted by landfills is critically important.

2. MATERIALS AND METHODS

2.1. Study area and sample collection

The study area is an agricultural area for rice cultivation located around the Ayutthaya landfill site in Bang Ban District, Phra Nakhon Si Ayutthaya Province, Thailand. The Ayutthaya landfill operates as a sanitary landfill, employing an oxidation pond system for leachate treatment and utilizes geosynthetic clay liners and geotextiles to reduce the levels of heavy metal contamination in the effluent released into the environment and to prevent leachate leakage. This landfill serves as a center for managing both municipal and hazardous waste generated within Ayutthaya Province [30]. A significant issue associated with the Ayutthaya landfill is the leakage of leachate due to surface runoff during the rainy season, which results in the contamination of pollutants in the surrounding environment, including groundwater, surface water, and soil [31, 32].

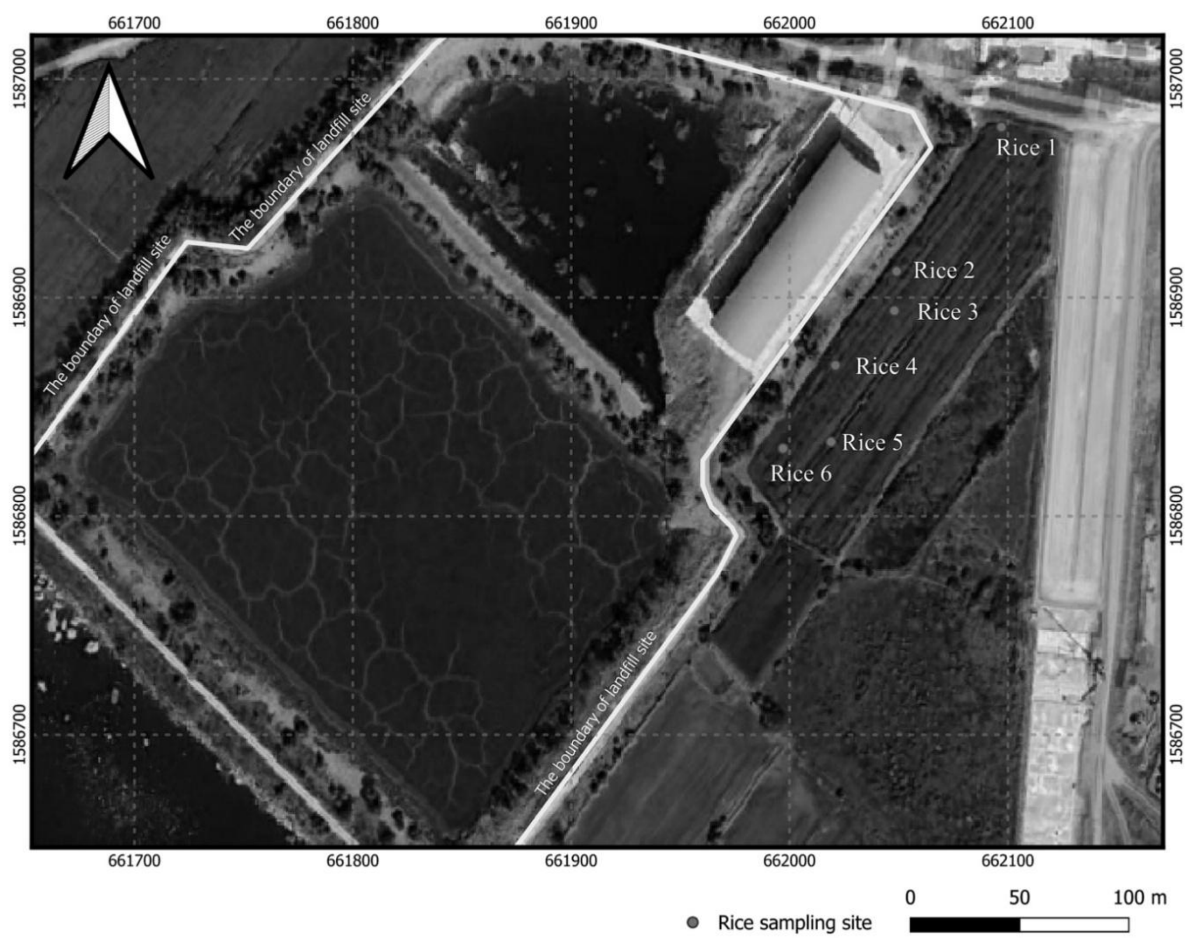

Fig. 1. Map of sampling locations and Sampling site coordinates in study area by QGIS.

The study site is situated to the north between the landfill and the main irrigation canal of Bang Ban District, which is identified as the highest-risk area for leachate accumulation in environment and rice due to its lower elevation compared to the landfill and surrounding areas. Additionally, the rice sampling area is located in close proximity to the boundary of landfill site and is approximately 200 meters from the operational waste disposal area. The geographical coordinates and sampling locations are illustrated in Fig. 1.

Rice samples were collected during the rainy season (May 2023) because this period is characterized by the highest levels of surface runoff, leading to increased leachate flow from the landfill to the surrounding environment and agricultural area. Rice selected for this study was in the pre-harvest phase [33].

A random sampling method was applied to collect rice samples, resulting in 6 samples representing the entire agricultural area [34]. These samples were stored in HDPE containers in the field. To prepare for extraction and heavy metal(oid) analysis in the laboratory, the samples were washed with deionized water and separated into different components, namely roots, leaves, and grains [35]. The washed and separated samples were then dried at 70°C for 24 hours until reaching a constant weight [36]. Then they were ground into fine powder and sieved using Sieve No.10. Afterwards, they were stored in HDPE containers at 4°C pending further laboratory analysis [37].

2.2. Sample preparation and analysis

The acid digestion process for heavy metal(oid) analysis in rice grains, leaves, and roots was conducted according to USEPA Method 3050B [38, 39]. 1 g of rice sample was accurately weighed and digested in the mixture of nitric acid (HNO_3, 65%), hydrochloric acid (HCl, 37%), and hydrogen peroxide (H_2O_2, 30%) in a volumetric ratio of 15 ml:10 ml:10 ml. During the digestion process, the samples were heated on a hot plate at 95 ± 5°C without boiling for 2 hours or until no brown fumes are released, signifying the completion of the oxidation reaction. After digestion, the sample was filtered through Whatman filter paper No. 42, and the filtrate was adjusted to a final volume of 100 ml. The concentration of heavy metal(oid), including arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn), was determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), PerkinElmer model 8300, following USEPA method 6010D [40] at Valaya Alongkorn Rajabhat University. The wavelengths used for the analysis were 193.696 nm for As, 226.502 nm for Cd, 267.716 nm for Cr, 324.754 nm for Cu, 259.940 nm for Fe, 257.610 nm for Mn, 231.60 nm for Ni, 220.353 nm for Pb, and 213.856 nm for Zn.

2.3. Quality assurance and quality control

Quality control of chemicals and glassware for analytical testing was conducted using the following procedures. 1) All glassware used in the analyses was soaked in 14% HNO_3 for 24 hours and subsequently rinsed with deionized water before use. 2) The chemicals used in the analysis including HCl (Thermo Fisher), HNO_3 (Kemaus), H_2O_2 (Thermo Fisher), and certified reference materials (CRM) for heavy metal(oid) (Sigma-Aldrich) must be produced through standardized processes to achieve quality certification in accordance with ISO 17034 standards.

To ensure quality control in the analytical testing, linearity was tested by constructing a standard curve with concentrations of 0, 0.25, 0.5, 1, 2.5, and 5 ppm before starting the analysis process each time. The correlation coefficients (r^2) for heavy metal(oid) including As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were greater than 0.995, which is within the acceptable range according to AOAC standards [41]. Accuracy was assessed through % recovery, with values ranging from 102.32% to 109.70%, which meets the AOAC acceptable range of 80-110% [42].

2.4. Translocation Factor

The Translocation Factor (TF) is utilized to evaluate the translocation of heavy metal(oid) from the roots to other plant tissues. It is determined by the ratio of heavy metal(oid) concentrations in various plant parts relative to their concentration in the roots [43], as defined by the equation (1).

$$TF = Cshoot / Croot \qquad (1)$$

where, TF represents translcation factor; Cshoot represents concentration of heavy metas in shoot (leaf and rice grain) (mg/kg); Croot represents concentration of heavy metal(oid) in root (mg/kg). When the TF is greater than 1, it indicates that the rice has a high capacity to move heavy metal(oid) from the roots to other parts of the plant. Conversely, when TF is less than 1, it signifies that the rice effectively accumulates heavy metal(oid) in the roots [44, 45].

2.5. Health risk assessment

Health risk assessment from rice consumption involves evaluating exposure through the calculation of the Average Daily Dose. The assessment of non-cancer health risks is performed by calculating the Hazard Quotient and Hazard Index. To evaluate cancer health risk, the Carcinogenic Risk and Total Carcinogenic Risk are calculated, following the methods by the USEPA [46].

2.5.1. Exposure assessment

Average daily dose value (ADD) of heavy metal(oid) elements was calculated using the following equation (2) [47]:

$$ADD = (C * IngR * EF * ED) / (BW * AT) \qquad (2)$$

where, ADD is average daily dose from ingestion (mg.kg/day); C is mean of heavy metal(oid) concentration in rice grain (mg/kg); IngR is ingestion rate of rice for Thai people (0.1984 kg/day for children, 0.43126 kg/day for adult male and 0.3198 kg/day for adult female); EF is exposure frequency (365 day/year); ED is exposure duration (6 years for children and 70 year for adult); BW is average body weight of Thai people (23.9 kg for children, 68.83 kg for adult male and 57.4 kg for adult female); AT is averaging time (ED x 365 day/year) [48]-[51]

2.5.1. Non-carcinogenic health risk assessment

The assessment of non-cancer health risk from consuming rice contaminated with heavy metal(oid) can be evaluated by calculating the Hazard Quotient (HQ) and Hazard Index (HI), as described by the following equations (3) and (4) [52]-[55]. The HQ is used to evaluate the health risk of single substances, while the HI assesses the cumulative health risk from exposure to multiple metal(oid).

$$HQ = ADD / RfD \quad (3)$$

$$HI = HQAs + HQCd + HQCr + HQCu + HQFe + HQMn + HQMn + HQNi + HQPb\ HQZn \quad (4)$$

where, HQ represents the Hazard Quotient; HI represents the Hazard Index; and RfD denotes the Reference Dose (mg/kg/day). The RfD values for As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn are 3.0×10^{-4}, 1.00×10^{-3}, 3.0×10^{-3}, 4.0×10^{-2}, 7.00×10^{-1}, 4.70×10^{-2}, 2.00×10^{-2}, 1.4×10^{-3}, and 0.3 mg/kg-bw/day [45], [56]-[58], respectively. When HQ or HI ≥ 1, it indicates that the heavy metal(oid) ingested can potentially cause health risk. Conversely, when HQ or HI < 1, it signifies that the ingested heavy metal(oid) is unlikely to result in non-carcinogenic health risk.

2.5.1. Carcinogenic health risk assessment

Carcinogenic risk denotes the elevated likelihood of cancer development over a person's lifetime (children, adult males and adult females) due to exposure to a suspected carcinogen, specifically As, Cd, Cr, Ni, and Pb [59]-[61]. Carcinogenic risk can be performed by calculating the Carcinogenic Risk value (CR) and Total Carcinogenic Risk value (TCR) using appropriate equation (5) and (6) [62]. The CR measures the cancer risk linked to exposure to each individual heavy metal(oid), whereas the TCR assesses the cumulative cancer risk resulting from exposure to multiple carcinogenic metal(oid).

$$CR = ADD * SF \quad (5)$$

$$TCR = CRAs + CRCd + CRCr + CRNi + CRPb \quad (6)$$

In this study, CR represents carcinogenic risk via ingestion, while TCR denotes the total carcinogenic risk. The slope factors (SF) for carcinogens such as As, Cd, Cr, Ni, and Pb are 1.5, 0.38, 0.5, 1.7, and 0.0085, respectively [63]-[66]. The evaluation criteria for carcinogenic risk are defined as follows: a TCR or CR value greater than 10^{-4} indicates an unacceptable risk level, suggesting a potential for cancer development; a TCR or CR value between 10^{-6} and 10^{-4} signifies a risk that is considered acceptable but still warrants attention; and a TCR or CR value less than 10^{-6} denotes negligible risk of cancer associated with the exposure to carcinogenic substances.

2.6. Statistic analysis

All statistical analyses were performed using SPSS (Version 29). Heavy metal(oid) contamination in rice and its various components was reported as mean values and standard deviations. To examine the relationships between different individual metals in rice grains, Pearson correlation coefficients were calculated [65]-[67]. Additionally, one-way ANOVA was employed to assess differences in heavy metal(oid) contamination among different rice components, including rice grains, rice husks, and rice bran [68].

3. RESULTS AND DISCUSSION

3.1. Contamination of heavy Metal(oid) in different parts of rice

The study of heavy metal(oid) accumulation (mg/kg dry weight) in various parts of rice (Table1) revealed the following results; 1) Fe (17093) represented the highest accumulation in the roots, followed by Mn (148.800) > Zn (98.925) > Cu (59.467) > Cr (40.100) > Ni (23.358) > Pb (13.533) > Cd (3.608) > As (1.550); 2) In the leaves, the accumulation of Fe is still the highest at 985, which was followed by Mn (375.450) > Cu (71.367) > Zn (46.558) > Pb (27.375) > Ni (21.533) > Cr (12.608) > As (6.874) > Cd (BDL); and 3) In the grains, the accumulation in descending order was Fe (2,336) > Mn (209.710) > Zn (45.847) > Cu (35.723) > Cr (14.962) > Ni (14.903) > As (9.137) > Pb (6.792) > Cd (BDL). The accumulation of As, Cd, Cr, Mn, Ni, and Zn varies significantly across different parts of rice plants ($p > 0.05$). Specifically, Cd, Cr, Ni, and Zn predominantly accumulate in the roots. Mn is mainly concentrated in the leaves and grains, whereas As is predominantly found in the grains. In contrast, the accumulation of Cu, Fe, and Pb does not show statistically significant differences between the leaves, grains, and roots ($p > 0.05$). The contamination of heavy metals in rice primarily results from the absorption of these metals from contaminated soil and water [71]. The sources of heavy metal contamination in the study area can be classified into two main categories. 1) Anthropogenic sources: These include activities associated with landfill operations and the application of agricultural chemicals in rice cultivation. Specifically, Cd and Pb are derived from leachate leakage, while Cu is produced from waste combustion.

Table 1. Contamination of Heavy Metal(oid) in parts of rice plant (Oryza sativa L.)

Rice sample No.	Parts of plant	Concentration of Heavy Metal and Metalloid (mg/kg)								
		As (Mean+SD)	Cd (Mean+SD)	Cr (Mean+SD)	Cu (Mean+SD)	Fe (Mean+SD)	Mn (Mean+SD)	Ni (Mean+SD)	Pb (Mean+SD)	Zn (Mean+SD)
Rice 1 (O. sativa L.)	Root (RR01)	3.300±5.425	4.000±0.510	50.850±0.155	77.400±1.735	22560±126	187.500±3.900	24.900±0.405	11.200±0.780	136.600±1.320
	Leaf (RL01)	9.300±4.350	BDL	10.300±0.420	17.000±0.310	1051±15	298.850±4.195	5.150±0.510	0.650±1.045	54.350±0.495
	Grain (RS01)	22.750±3.445	BDL	14.670±0.130	16.670±0.105	1537±5.900	296.500±0.935	8.920±0.600	BDL	59.580±0.170
Rice 2 (O. sativa L.)	Root (RR02)	3.050±2.345	3.950±0.160	51.750±0.340	51.350±0.640	22060±79	123.150±0.790	27.100±0.660	15.150±1.435	94.500±0.195
	Leaf (RL02)	11.100±3.855	BDL	9.850±0.305	24.450±0.080	1232±2.250	328.100±0.515	1.150±0.360	7.700±1.120	57.600±0.295
	Grain (RS02)	24.150±2.665	BDL	13.050±0.165	20.700±0.790	1884±49	395.450±10.38	BDL	15.400±1.850	50.900±0.370
Rice 3 (O. sativa L.)	Root (RR03)	2.950±8.965	2.650±0.195	38.000±0.515	94.300±1.485	16215±29	216.200±3.090	19.600±0.655	9.100±0.835	142.800±0.340
	Leaf (RL03)	15.500±3.585	BDL	12.600±0.225	23.800±0.325	1018±4.250	608±2.600	6.900±0.280	BDL	64.150±0.390
	Grain (RS03)	4.300±0.600	BDL	8.300±0.100	12.250±0.070	669±3.500	210.600±1.150	3.450±0.050	5±0.660	35.750±0.235
Rice 4 (O. sativa L.)	Root (RR04)	BDL	3.900±0.275	36.250±0.290	45.700±0.310	13960±53.500	126.300±1.180	23.350±0.145	13.800±0.875	73.900±0.490
	Leaf (RL04)	1.656±0.300	BDL	16.850±0.800	335.150±32.05	963±6.750	356.050±2.330	96.800±0.520	7.010±0.405	32.550±0.230
	Grain (RS04)	0.899±1.640	BDL	13.000±0.005	127.650±1.030	1454±15.250	124.150±1.340	34.900±0.235	12.200±0.430	32.600±0.140
Rice 5 (O. sativa L.)	Root (RR05)	BDL	4.500±0.125	33.250±0.275	60.550±0.995	15170±80.500	145.500±1.695	28±0.370	18.850±0.770	82.650±0.355
	Leaf (RL05)	2.262±0.620	BDL	8.900±0.090	10.900±0.145	845±5	327.800±2.030	4.050±0.140	139.850±1.035	34.200±0.150
	Grain (RS05)	0.316±3.190	BDL	29.100±0.200	24.800±0.290	7816±55.400	105.200±0.900	18.290±0.220	4.900±0.800	45.000±0.080
Rice 6 (O. sativa L.)	Root (RR06)	BDL	2.650±0.13	30.500±0.390	27.500±0.235	12590±20.500	94.150±0.445	17.200±0.085	13.100±1.250	63.100±0.510
	Leaf (RL06)	1.428±2.590	BDL	17.150±0.060	16.900±0.120	799±10.650	333.900±4.080	15.150±0.080	9.050±0.340	36.500±0.165
	Grain (RS06)	2.407±1.450	BDL	11.650+0.075	12.250 + 0.535	657±6.7	126.350±1.360	23.950±0.255	3.250±0.110	51.250±0.730
Average	Root	1.550 ±1.702	3.608±0.773	40.100±9.051	59.467±23.721	17093±4221	148.800±45.2	23.358 ±4.242	13.533 ±3.354	98.925 ±33.28
	Leaf	6.874 ±5.938	BDL	12.608±3.614	71.367±129.32	985±155.747	375.450±115.38	21.533±37.170	27.375 ±55.23	46.558 ±13.73
	Grain	9.137±11.181	BDL	14.962±7.250	35.723±45.308	2336±2729	209.710±115.9	14.903±13.280	6.792 ±5.811	45.847 ±10.21
One -way ANOVA	F value	5.233	345.046	96.150	1.035	193.108	29.213	0.768	2.176	40.481
	P value	0.009	< 0.001	< 0.001	0.363	< 0.001	< 0.001	0.469	0.124	< 0.001
Standard value										
Thailand national Standard	Maximum permissible limit in rice [72]	0.2 ppm	0.4 ppm	-	-	-	-	-	0.2 ppm	-
International Standard	Maximum Levels of Contaminants in Food (China): GB 2762-2022 [73]	0.2 ppm	0.2 ppm	1 ppm	-	-	-	-	0.5 ppm	-
	Maximum permissible levels in food crops and rice by WHO/FOA [74]-[78]	0.35 ppm	0.4 ppm	1.2 ppm	73 ppm	425 ppm	500 ppm	67 ppm	0.2 ppm	99.4 ppm
Concentration of heavy metals in rice grain in other countries										
Can Tho landfill, Vietnam [79]		-	ND	0.57	1.45	-	129	1.68	ND	17.7
Gunung Tugel dumpsite, Indonesia [80]		-	0.048	0.089	0.03	0.445	0.196	-	1.202	1.962
Nakhonlung dumpsite, Thailand [81]		-	-	5.62	7.4	174.43	21.77	7.32	1.48	24.66
Contaminated site in Taipei city, Taiwan [82]		0.001	-	-	-	-	-	-	-	-

BDL, below detection limit; ND, not detected

Table 2. Translocation factor of Metal(oid) in rice

Translocation factor	Metal and Metalloid								
	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
root to grain	5.895	0	0.373	0.601	0.137	1.409	0.638	0.502	0.463
root to leaf	4.435	0	0.314	1.200	0.058	2.523	0.922	2.023	0.471

Additionally, Cd contamination may also occur due to the use of phosphate fertilizers. 2) Natural sources: This category encompasses heavy metals that are naturally present in the soil, such as Zn, which is found in both natural soil and parent rock [83].

The results of the comparison between the average heavy metal contamination levels in rice grains from this study and those reported in various countries reveal that the average concentrations of As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn in rice cultivated near the Ayutthaya landfill are higher than those observed in rice grown around landfill sites and contaminated areas in Vietnam (Can Tho landfill), Indonesia (Gunung Tugel dumpsite), Thailand (Nakhonlung dumpsite), and Taiwan (contaminated site associated with wastewater disposal). Notably, Cd levels from the Can Tho landfill in Vietnam were found to be an exception. The reason for the higher levels of heavy metal contamination in rice from the Ayutthaya landfill area compared to other areas is the frequent leaching of leachate into the surrounding agricultural fields, particularly during the rainy season when surface runoff occurs.

Analysis of the TF to study the transfers of heavy metal(oid) from the roots to different parts of the rice plant (Table 2) indicated that rice effectively transfers As and Mn from the roots to the grains (TFroot to grain > 1) and As, Cu, Mn, and Pb from the roots to the leaves (TFroot to leave > 1). In contrast, Cd, Cr, Fe, Ni, and Zn showed lower transfer efficiency to the grains and leaves (TFroot to grain, leave <1). The TF values greater than 1 for As, Cu, Mn, and Pb suggest that rice acts as a hyperaccumulator for these elements, transferring them from roots to shoots (leave and grain) [84]. Heavy metals can translocate from the roots to the leaves and grains of rice via the xylem [85]. However, the internal mechanisms of the plant cause variations in the rates of translocation and accumulation of these metals to the leaves and rice grains. For example, Cd and Pb are sequestered in vacuoles of root, and Ni forms the stable complexes with amino acids in root. Consequently, these processes lead to a decreased translocation of heavy metals, resulting in lower levels of Cd and Ni in the leaves and roots, as well as diminished lead concentrations in the rice grains [90]-[92].

Health risk assessments comparing heavy metal(oid) contamination levels in rice grains to established standards indicated that the average concentrations of As, Cr, Fe, and Pb in rice grains exceeded the maximum permissible limits set by Thailand, China, and the WHO/FAO [69-75]. Consequently, the consumption of rice contaminated with these metal(oid)s poses significant health risks. Specifically, the contamination levels of As and Pb in rice grains surpass the standards established by Thailand, China, and the WHO/FAO, while Cr levels exceed the standards set by China and the WHO/FAO, and Fe levels exceed those established by the WHO/FAO.

Table 3: Pearson correlation coefficient of Metal(oid) in rice grain samples

Element	As	Cr	Cu	Fe	Mn	Ni	Pb	Zn
As	1	-.210	-.340	-.254	.941	-.669**	-.135	-.681**
Cr		1	-.040	.980**	-.337	.174	-.131	.134
Cu			1	-.065	-.351	.730**	.486*	-.620**
Fe				1	-.323	.088	-.057	.011
Mn					1	-.793**	.310	.498*
Ni						1	.007	-.384
Pb							1	-.402
Zn								1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 4: Average daily dose (mg/kg bw/day) for heavy metal(oid) through rice consumption in study area

Exposure assessment										
Group of exposed population		Average daily dose (mg/kg BW/day) of Metals and Metalloid (ADD)								
		As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn
Children (ADDingC)		7.585×10^{-2}	0	1.242×10^{-1}	2.965×10^{-1}	19.393	1.741	1.237×10^{-1}	5.638×10^{-2}	3.806×10^{-1}
Adult	Male (ADDingM)	5.725×10^{-2}	0	9.374×10^{-2}	2.238×10^{-1}	14.637	1.314	9.338×10^{-2}	4.255×10^{-2}	2.873×10^{-1}
	Female (ADDingFM)	5.082×10^{-2}	0	8.322×10^{-2}	1.987×10^{-1}	12.994	1.166	8.290×10^{-2}	3.778×10^{-2}	2.550×10^{-1}
Permissible daily dose intake										
Safe limit value [86]-[89]		3.00×10^{-3}	8.00×10^{-4}	3.00×10^{-3}	5.00×10^{-1}	8.00×10^{-1}	1.40×10^{-1}	2.00×10^{-2}	3.60×10^{-4}	60

Table 5: Non-carcinogenic risk assessment by risk index (Hazard quotient and Hazard index) for heavy Metal(oid) through rice consumption in study area

Non-carcinogenic health risk assessment											
Group of exposed population		Hazard quotient of Metals and Metalloid (HQ)									Hazard index (HI)
		As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	
Children		252.829	0	41.400	7.414	27.704	37.040	6.190	40.271	1.269	414.117
Adult	Male	190.829	0	31.248	5.596	20.910	27.956	4.669	30.396	0.958	312.562
	Female	169.411	0	27.741	4.968	18.563	24.819	4.145	26.984	0.851	266.482
HQ and HI result of relevant studies in previous study											
Children	Vietnam [79]	NA	NA	1.38x10^{-2}	7.77x10^{-4}	NA	3.75x10^{-2}	1.55x10^{-3}	NA	8.68x10^{-4}	5.44x10^{-1}
Adult		NA	NA	1.18x10^{-2}	6.65x10^{-4}	NA	3.21x10^{-2}	1.32x10^{-3}	NA	7.43x10^{-2}	4.66x10^{-1}
Children	Indonesia [80]	NA	0.109	0.068	6.00x10^{-4}	1.4x10^{-3}	3.20x10^{-3}	NA	0.778	0.015	NA
Adult		NA	0.148	0.092	7.00x10^{-4}	0.002	4.30x10^{-3}	NA	1.062	0.020	NA
Children	Thailand [81]	NA	NA	6.92x10^{-2}	1.50x10^{-3}	NA	3.47x10^{-3}	1.32x10^{-3}	1.19x10^{-2}	4.32x10^{-4}	8.78x10^{-2}
Adult		NA	NA	5.92x10^{-2}	1.28x10^{-3}	NA	2.97x10^{-3}	1.13x10^{-3}	1.01x10^{-2}	3.70x10^{-4}	7.51x10^{-2}
Adult	Nigeria [100]	NA	0.490	0.012	0.028	0.025	0.138	0.045	1.163	0.050	NA
Children	Pakistan [101]	2.11x10^{-3}	NA	2.09x10^{-2}	6.19x10^{-2}	2.51x10^{-1}	2.31x10^{-2}	2.72x10^{-3}	NA	1.28x10^{-2}	NA
Adult		1.78 x10^{-3}	NA	1.76x10^{-2}	5.22x10^{-2}	2.11x10^{-1}	1.95x10^{-2}	2.30x10^{-3}	NA	1.08x10^{-2}	NA
Children	China [102]	0.800	0.600	5.00 x10^{-4}	0.300	NA	NA	NA	0.100	NA	2.000
Adult		0.800	0.600	4.40 x10^{-4}	0.300	NA	NA	NA	0.100	NA	1.900

NA, not available

Table 6: Carcinogenic risk assessment by risk index (Carcinogenic risk value) for heavy metal(oid) through rice consumption in study area

Carcinogenic health risk assessment											
Group of exposed population		Carcinogenic risk of heavy metals and metalloid (CR)									Total carcinogen ic risk (TCR)
		As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Zn	
Children		1.138x10^{-1}	0	6.210 x10^{-2}	NC	NC	NC	2.103x10^{-1}	4.790x10^{-4}	NC	3.867x10^{-1}
Adult	Male	8.587x10^{-2}	0	4.690x10^{-2}	NC	NC	NC	1.587x10^{-1}	3.620x10^{-4}	NC	2.920x10^{-1}
	Female	7.624x10^{-2}	0	4.160x10^{-2}	NC	NC	NC	1.409x10^{-1}	3.210x10^{-4}	NC	2.591x10^{-1}
CR and TCR result of relevant studies in previous study											
Children	Indonesia [80]	NA	3.43x10^{-3}	5.04x10^{-4}	NA	NA	NA	NA	1.16x10^{-4}	NA	NA
Adult		NA	9.35x10^{-4}	1.38x10^{-4}	NA	NA	NA	NA	3.16x10^{-5}	NA	NA
Adullt	Thailand [81]	NA	NA	NA	NA	NA	NA	NA	5.31x10^{-8}	NA	5.31x10^{-8}
Children	Pakistan [101]	3.17x10^{-3}	NA	1.89x10^{-2}	NA	NA	NA	2.48x10^{-3}	NA	NA	2.27x10^{-2}
Adult		2.67x10^{-3}	NA	1.59x10^{-2}	NA	NA	NA	2.09x10^{-3}	NA	NA	2.07x10^{-2}
Children	China [102]	3.80x10^{-4}	NA	NA	NA	NA	NA	NA	NA	NA	NA
Adult		3.50 x10^{-4}	NA	NA	NA	NA	NA	NA	NA	NA	NA

NA, not available; NC, not calculated

The health effects of consuming rice contaminated with excessive levels of As, Cr, Pb, and Fe include: 1) excessive accumulation of Fe can damage various organs, potentially leading to diabetes and cardiovascular diseases [93]; 2) Pb exposure can cause dysfunction in kidneys, the reproductive system, and the nervous system. Children exposed to Pb are possibly vulnerable to learning disabilities [94]; 3) Cr exposure can impact the digestive system, causing bleeding disorders, and high levels of exposure may lead to death and heart failure. Moreover, chromium is a known carcinogen that can cause cancers and genetic mutations [95]; 4) Exposure can lead to symptoms such as vomiting, abdominal pain, and diarrhea, whereas long-term exposure may result in cancers, including bladder cancer, as well as genetic damage [96].

Correlation analysis using Pearson's coefficient (Table3) indicated strong positive correlations between As and Mn (r = 0.941), Cr and Fe (r = 0.980), and Cu and Ni (r = 0.730), suggesting a common or similar source of contamination [97, 98]. Conversely, metal(oid) such as As and Ni (r = -0.669), As and Zn (r = -0.681), Cu and Zn (r = -0.620), and Mn and Ni (r = -0.793) exhibited negative correlations, indicating distinct sources of contamination. Moderate positive correlations, such as Cu and Pb (r = 0.486) and Mn and Zn (r = 0.498), reflected complex relationships between the sources of contamination [99].

3.2 Exposure assessment

The transfer of heavy metal(oid) from rice to the human body through consumption was assessed using the ADD calculated in mg/kg/day, as illustrated in Table 4. The average ADD values for As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were $7.585x10^{-2}$, 0, $1.242x10^{-1}$, $2.965x10^{-1}$, 19.393, 1.741, $1.237x10^{-1}$, $5.638x10^{-2}$, and $3.806x10^{-1}$ mg/kg/day for children; $5.725x10^{-2}$, 0, $9.374x10^{-2}$, $2.238x10^{-1}$, 14.637, 1.314, $9.338x10^{-2}$, $4.255x10^{-2}$, and $2.873x10^{-1}$ mg/kg/day for adult males; and $5.082x10^{-2}$, 0, $8.322x10^{-2}$, $1.987x10^{-1}$, 12.994, 1.166, $8.290x10^{-2}$, $3.778x10^{-2}$, and $2.550x10^{-1}$ mg/kg/day for adult females. The ADD value of As, Cr, Fe, Mn, and Ni via ingestion pathway in children, adult males and adult females exceeded the standard limits. ADD values exceeding these safety standards indicate that consumption of contaminated rice can lead to both short-term and long-term health effects [86]-[89].

3.3 Non-carcinogenic health risk assessment

Calculated using HQ and HI values, the non-carcinogenic health risk assessment of heavy metal(oid) through rice consumption in children, adult males, and adult females are presented in Table 5. The HQ values of metal(oid) were As (HQ for children = 252.829, HQ for adult male = 190.829, HQ for adult female = 169.411) > Cr (HQ for children = 41.400, HQ for adult male = 31.248, HQ for adult female = 27.741) > Pb (HQ for children = 40.271, HQ for adult male = 30.396, HQ for adult female = 26.984) > Mn (HQ for children = 37.040, HQ for adult male = 27.956, HQ for adult female = 24.819) > Fe (HQ for children = 27.704, HQ for adult male = 20.910, HQ for adult female = 18.563) > Cu (HQ for children = 7.414, HQ for adult male = 5.596, HQ for adult female = 4.968) > Ni (HQ for children = 6.190, HQ for adult male = 4.669, HQ for adult female = 4.145) > Zn (HQ for children = 1.269, HQ for adult male = 0.958, HQ for adult female = 0.851) > Cd (HQ for children, adult male and adult female = 0). The HQ values of As, Cr, Cu, Fe, Mn, Ni, Pb and Zn in children, adult males, and adult females were greater than 1, indicating potential non-carcinogenic health risks.

Comparative analysis of HQ values across different groups of people indicated that children exhibit higher HQ values compared to adult males and adult females. The HQ values for heavy metal(oid) associated with rice consumption in this study are higher than those reported for health risks from heavy metal(oid) exposure in rice from areas near landfills and industrial zones in Indonesia, Vietnam, Thailand (Kalasin), Pakistan, Nigeria, and China [79]-[81], [100]-[102]. However, the HQ value for Cd was lower than in Pakistan for both children and adults. This suggests that human activities in the study area, such as waste disposal and the use of agricultural chemicals, contribute to higher health risks from rice consumption compared to other regions with similar pollution activities. Also, the assessment of non-carcinogenic risk from multiple heavy metal(oid) indicates that the health risk levels are deemed unacceptable (HI > 1) for children (HI = 414.117), adult males (HI = 312.562), and adult females (HI = 277.482). These HI values for children, adult males, and adult females suggest that the consumption of rice contaminated with multiple heavy metals poses significant health risks to consumers and may result in adverse health effects in the future.

3.4 Carcinogenic health risk assessment

Table 6 presents the carcinogenic health risk assessment of As, Cd, Cr, Ni, and Pb through rice consumption in children, adult males, and adult females, which was calculated using CR and TCR values.

The carcinogenic risk value for each heavy metal (oid) was as follows: Ni (CR for children = $2.103x10^{-1}$, CR for adult males = $1.587x10^{-1}$, CR for adult females = $1.409x10^{-1}$) > As (CR for children = $1.138x10^{-1}$,CR for adult males = $8.587x10^{-2}$, CR for adult females = $7.624x10^{-2}$) > Cr (CR for children = 6.210 $x10^{-2}$, CR for adult males = $4.690x10^{-2}$, CR for adult females = $4.160x10^{-2}$) > Pb (CR for children = $4.790x10^{-4}$, CR for adult males = $3.620x10^{-4}$, CR for adult females = $3.210x10^{-4}$) > Cd (CR for children, adult males, and adult females = 0). Comparative analysis of carcinogenic risk across different demographic groups revealed that children exhibited higher carcinogenic risks compared to adult males and adult females for Ni, As, Cr, and Pb. In contrast, the CR for Cd was negligible across all age groups. The individual metal(oid)s risk assessments indicated that all individual metal(oid), except for Cd, presented risk levels that exceeded acceptable thresholds (CR ≥ 10^{-4}) across all age groups. This suggests a potential carcinogenic risk associated with the consumption of contaminated rice over prolonged periods. In contrast, Cd does not exhibit a significant risk.

A comparative analysis of CR values from this study with other research locations impacted by heavy metal(oid) contamination in rice revealed that the CR values for As, Cr, Ni, and Pb in this study were higher than those reported in Indonesia, Thailand (Kalasin province), Pakistan and China, with the exception of Cd. However, the CR values for Cd in children and adults from research conducted in Indonesia were higher than those observed in this study, at 3.43 x 10^{-3} for children and 9.35 x 10^{-4} for adults. The evaluation of cancer risk associated with the ingestion of multiple elements, as measured by TCR values, indicated that the TCR for children, adult males, and adult females exceeded acceptable limits (TCR ≥ 10^{-4}), with the TCR for children being the highest at 3.867×10^{-1}, followed by adult males at 2.920×10^{-1} and adult females at 2.591×10^{-1}. These findings suggest that the risk of developing cancer due to the consumption of rice contaminated with multiple elements is significant for children, adult males, and adult females.

4. CONCLUSIONS

The average concentrations of heavy metal(oid) contamination indicated that Cd, Cr, Fe, Ni, and Zn were accumulated the highest in roots. Pb, Cu, and Mn are the most prominently accumulated in leaves, while As exhibits the highest accumulation in rice grains. The average contamination levels of As, Cr, Fe, and Pb in rice grains exceeded established safety standards. Among the metalloid, As had the highest translocation factor, reflecting its most significant movement from roots to leaves and grains. The evaluation of health risks related to the ingestion of individual metal(oid) from rice consumption indicated that non-carcinogenic health risks for As, Cr, Cu, Fe, Mn, and Pb in children, adult males, and adult females, as well as Zn in children, exceeded acceptable levels. Additionally, the carcinogenic health risks for As, Cr, Ni, and Pb also surpassed acceptable thresholds.

Furthermore, when considering the ingestion of multiple metal(oid), the assessment revealed that both non-carcinogenic and carcinogenic health risks remained unacceptable across all age groups. Specifically, the HI for non-carcinogenic risks exceeded 1, and the TCR exceeded 10^{-4} for carcinogenic risks.

To mitigate heavy metal(oid) contamination in rice and reduce health risks to consumers, it is imperative that government agencies take proactive measures. The following recommendations are proposed. 1) The government should implement regulations to control waste disposal sites, elevate standards for heavy metal(oid) contamination in rice, and provide training to farmers on proper agricultural chemical usage. 2) The government should design and enhance wastewater management systems to address leachate from waste disposal sites, including the development of treatment facilities, leachate collection systems, and measures to prevent surface runoff from these sites that may spread contaminants into the environment. 3)

To address heavy metal contamination in rice, the government should implement scientific approaches to remediate the environment, particularly the soil environment, to reduce the absorption of heavy metals by rice from contaminated soil. Suggested techniques for soil treatment include the use of nanoparticles, biosorption, and phytoremediation. These methods can effectively decrease heavy metal levels in agricultural settings, ultimately enhancing food safety and public health.

ACKNOWLEDGEMENTS

The research team would like to express their sincere gratitude to the Phra Nakhon Si Ayutthaya Provincial Administration Organization for facilitating the site surveys and sample collection. We also extend our appreciation to the Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, for providing the equipment, laboratory facilities, and scientific instruments essential for this research. Our special thanks also go to Mr. Nuttapong Rutamornchai, who proofread this research article.

REFERENCES

[1] Norhashila, H.; Maimunah, M.A.; Muhammad, R.M.; Ahmad, F.A.; Aimrun, W.; Muhamad, S.M.K.; and Askiah, J. 2024. Smart Farming for Sustainable Rice Production: An Insight into Application, Challenge, and Future Prospect. Rice Science 31(1): 47−61.

[2] Dhamira, A.; and Aminda, F.R. 2023. Rice production risk in main producing countries 1961-2021. Buletin Penelitian Sosial Ekonomi Pertanian Fakultas Pertanian Universitas Haluole 25(2): 143-150.

[3] Sujatanond, S.; Tibkaew, A.P.; and Hickey, M.W. 2017. Comparison the Sustainability and Rural Livelihood Assessment of Sang Yod Rice Production Groups in Phatthalung Province. GMSARN International Journal 11(4): 153-160.

[4] Nur, A.M.; Norhashila, H.; Rosnah, S.; and Hasfalina, C.M. 2022. Rice for Food Security: Revisiting Its Production, Diversity, Rice Milling Process and Nutrient Content. Agriculture 12: 741.

[5] FOA. (1995). CODEX STANDARD FOR RICE (Report No. CODEX STAN 198-1995). ROME: FOA.

[6] Prodipto, B.A.; Shafiul, I.; Shreejana, KC.; Arpan, D.; Nafisa, A.; Amrit, P.; and Shaharia, A.S. 2024. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon 10(2024): 28357.

[7] Jaafar, M.; Shrivastava, A.; Rai, B.S.; Felipe-Sotelo, M.; and Ward, N.I. 2021. Transfer of arsenic, manganese and iron from water to soil and rice plants: An evaluation of changes

in dietary intake caused by washing and cooking rice with groundwater from the Bengal Delta, India. J Food Comp Anal 96: 103748.

[8] Prodipto, B.A.; Shafiul, I.; Shreejana, K.C.; Arpan, D.; Nafisa, A.; Amrit, P.; and Shaharia, A.S. 2024. Sources, effects and present perspectives of heavy metals contamination: Soil, plants and human food chain. Heliyon 10: 28357.

[9] Watanabe, M.E. 1997. Phytoremediation on the Brink of Commercialization. Environmental Sciences and Technology 31: 182-186.

[10] Menghua, X.; and Yuanyuan, L. 2022. Distribution Characteristics and Ecological Risk Assessment of Heavy Metals under Reclaimed Water Irrigation and Water Level Regulations in Paddy Field. Pol. J. Environ. Stud. 31(3): 2355-2365.

[11] Ahmed, A.; Sara, T.A.; Sundas, R.Q.; and Man-Qun, W. 2021. Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. toxics 2021(9): 42.

[12] Jotaworn, S.; and Nitivattananon. V. 2021. Municipal Solid Waste Management for Coastal Tourism Destinations in Eastern Thailand: Challenges and Opportunities. GMSARN International Journal 15(4): 259-268.

[13] Amit, K.; Vinod, K.; Andres, R.S.; Raj, S.; Sumit, S.; Ashok, K.; Chandra, S.S.; and Renato, S. 2024. Appraisal of heavy metal(loid)s contamination in rice grain and associated health risks. Journal of Food Composition and Analysis 131(2024): 106215.

[14] Rouhani, A.; and Hejcman, M. 2024. A review of soil pollution around municipal solid waste landfills in Iran and comparable instances from other parts of the world. Int. J. Environ. Sci. Technol. 2024. https://doi.org/10.1007/s13762-024-05728-z.

[15] Temoor, A.; Muhammad, N.; Muhammad, R.; Shafaqat, A.; Muhammad, S.S.; and Bin, L. 2023. Recent progress on the heavy metals ameliorating potential of engineered nanomaterials in rice paddy: a comprehensive outlook on global food safety with nanotoxicitiy issues. Critical Reviews in Food Science and Nutrition 63(16): 2672-2686.

[16] Nur, E.W.; Henry, S.; Puteri, I.N.; Martha, I.K.; and Mahalul, A. 2023. Heavy Metals Contamination of Local and Imported Rice in Semarang, Central Java, Indonesia. Journal of Ecological Engineering 24(7): 49–60.

[17] Lal, C.M.; Sandeep, K.; Amrita, D.; and Sunita, Y. 2020. Heavy Metal Contamination: A Serious Hazard to Food-Chain. Food and Scientific Reports 1(4): 9-12.

[18] Hussein, I.A.S.; and Mona, S.M.M. 2018. Solid waste issue: Sources, composition, disposal, recycling, and valorization. Egyptian Journal of Petroleum 27: 1275–1290.

[19] Diane, M.; Gilbert, B.B.; Kalieu, W.A.I.; Patrice K.D.; Edouard, N.; and Serge, H.Z.T. 2024. Accumulation of Heavy Metals in Maga-Pouss Rice Fields (Far-North Region, Cameroon) and Transfer to Rice Grains. Agricultural Sciences 15: 311-326.

[20] Othman, R.; Mohd, L.N.H.; Baharuddin, Z.M.; Hashim, K.S.H.Y.; and Lukman H.M.L.H. 2019. Closed landfill heavy metal contamination distribution profiles at different soil depths and radiuses. Applied ecology and environmental research 17(4): 8059-8067.

[21] Nabulo, G.; Oryem, O.H.; Nasinyama, G.W.; and Cole, D. 2008. Assessment of Zn, Cu, Pb and Ni contamination in wetland soils and plants in the Lake Victoria basin. Int J Environ Sci Technol 5(1): 65–74.

[22] Usman, B. 2023. Heavy metals concentration in food crops irrigated with pesticides and their associated human health risks in Paki, Kaduna State, Nigeria. Cogent Food & Agriculture 9(1): 2191889.

[23] Defarge, N.; Spiroux de Vendomois, J.D.; and Séralini, G.E. 2018. Toxicity of Formulants and Heavy Metals in Glyphosate-Based Herbicides and Other Pesticides. Toxicology Reports 5: 156-163.

[24] Muyesaier, T.; Huada D.R.; Li, W.; Jia, L.; Ross, S.; Des, C.; Cordia, C.; and Dung, T.P. 2021. Agriculture Development, Pesticide Application and Its Impact on the Environment. Int J Environ Res Public Health 18(3): 1112.

[25] Bin, G.; Chunlai, H.; Wenbin, T.; Mingxing, X.; Chunlei, H.; Hanqin, Y.; Yicheng, L.; and Qinglin, F. 2020. Health risk assessment of heavy metal pollution in a soil-rice system: a case study in the Jin-Qu Basin of China. Sci. Rep. 10: 1–11.

[26] Zhuang, P.; McBride, M.B.; Xia, H.; Li, N.; and Li, Z. 2009. Health risk from heavy metals via consumption of food crops in the vicinity of Dabaoshan mine, south China. The Science of the Total Environment 407(5): 1551–1561.

[27] Briffa, J.; Sinagra, E.; and Blundell, R. 2020. Heavy Metal Pollution in the Environment and Their Toxicological Effects on Humans. Heliyon 6: 4691.

[28] Donatella, C.; Antonella, C.; Emanuela, A.; Ismaeil, M.A.M.; Maria, R.D.M.; Angelo, Z.; Ciriaco, C.; and Serenella, M. (2024). Heavy metals in biological samples of cancer patients: a systematic literature review. Biometals 37: 303-817.

[29] USEPA. 2005. Guidelines for Carcinogen Risk Assessment. Washington D.C.: USEPA.

[30] Department of Pollution Control. 2014. Project for Managing Waste Issues (Phra Nakhon Si Ayutthaya) (In Thai). Bangkok: Department of Pollution Control.

[31] Nisa, P., Nitipon, N., Datchpol, J., Archai, K., Somkid, T., and Sirapassorn, P., 2023. Environmental impact and flood risk mitigation by capacity building in flood resilience communities on the drainage area of Bang Ban-Bang Sai flood diversion channel project (Research report no. 005/2566) (In Thai). Pathumthani: Valaya Alongkorn Rajabhat University.

[32] Joseph, P.E.; Donald, I.I.; Edu, D.I.; Aniefiokmkpong, O.O.; Godwin, A.E.; and Nsikak, U.B. 2022. Occurrence and spatial distribution of heavy metals in landfill leachates and impacted freshwater ecosystem: An environmental and human health threat. PLoS ONE 17(2): 0263279.

[33] JF, Machiwa. 2012. Heavy Metal Levels in Paddy Soils and Rice (Oryza sativa (L)) from Wetlands of Lake Victoria Basin, Tanzania. AJOL. 36: 59-72.

[34] Chyad, A.A.; Saeed, A.M.; and Alhendi, A.S. 2022. Determination of Heavy Metals in Irrigation Water, Soil, Paddy, and Produced Rice of Some Paddy Fields of Iraq. Iraqi Journal of Science 63: 4637-4649.

[35] Mao, C.; Song, Y.; Chen, L.; Ji, J.; Li, J.; Yuan, X.; Yang, Z.; Ayoko, G.; Frost, R.; and Theiss, F. 2019. Human health risks of heavy metals in paddy rice based on transfer characteristics of heavy metals from soil to rice. Catena 175: 339-348.

[36] Deepmala, S.; Vikram, V.M.; and 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.

[37] Carolyn, P.; Aqilah, F, A.T.; and Tan, W.H. 2015. Heavy metals accumulation in paddy cultivation area of kompipinan, papar district, sabah. Journal of Sustainability Science and Management 10(1): 76-86.

[38] USEPA. 1996. Method 3050B: Acid Digestion of Sediments, Sludges, and Soils. Washington DC.: US EPA.

[39] Adzrin, A.Z.; Lee, H.L.; and Faizah, M. 2023. Comparative assessment of the heavy metal phytoextraction potential of vegetables from agricultural soils: A field experiment. Heliyon 9(2): 13547.

[40] USEPA. 2018. EPA Method 6010D (SW-846): Inductively coupled plasma—optical emission spectrometry. Washington DC.: USEPA.

[41] AOAC. 2015. Heavy Metals in Food. Inductively Coupled Plasma–Mass Spectrometry. Maryland: AOAC.

[42] AOAC. 2016. Guidelines for Standard Method Performance Requirements. Maryland: AOAC.

[43] Kim, I.S.; Kang, K.H.; Johnson-Green, P.; and Lee, E.J. 2003. Investigation of Heavy Metal Accumulation in Polygonum thunbergii for Phytoextraction. Environmental Pollution 126(2): 235-243.

[44] Eva, K.B.; Endre, D.; and Borba, L.B. 2021. Toxic metal phytoextraction potential and health-risk parameters of some cultivated plants when grown in metal- contaminated river sediment of Danube, near an industrial town. Environ Geochem Health 43: 2317–2330.

[45] Zojaji, F.; Hassani, A.H.; and Sayadi, M.H. 2015. A comparative study on heavy metal content of plants irrigated with tap and wastewater. Int. J. Environ. Sci. Technol. 12: 865-870.

[46] USEPA. 1989. Risk assessment guidance for superfund. Human health evaluation manual (Part A) (Vol. 1). Washington D.C.: USEPA.

[47] USEPA. 2013. Regional screening levels (RSL) for chemical contaminants at superfund sites. Washington D.C.: USEPA.

[48] Tanjira, K.; Benjaphorn, S.; and Preprame. P. 2017. Heavy Metal Concentration and Risk Assessment of Soil and Rice in and around an Open Dumpsite in Thailand. Environment Asia 10(2): 53-64.

[49] La-Up, A.; Wiwatanadate, P.; Pruenglampoo, S.; and Uthaikhup, S. 2017. Recommended rice intake levels based on average daily dose and urinary excretion of cadmium in a cadmium- contaminated area of northwestern Thailand. Toxicological Research 33(4): 291-297.

[50] Abdolkazem, N.; Majid, F.; Kambiz, A.A.; and Arefeh, S. 2024. Health risk assessment for consuming rice, bread, and vegetables in Hoveyzeh city. Toxicology Reports 12: 260-265.

[51] Mohammad, J.M.; Fatemeh, K.; Majid, F.; Saeed, G.; Davoodm J.; and Leila, M. 2024. Evaluation of carcinogenic risk of heavy metals due to consumption of rice in Southwestern Iran. Toxicology Reports 12: 578–583.

[52] Azam, M.; Mojgan, Z.; Mohammad, S.S.; and Sayed A.J. 2021. Investigating the Non-carcinogenic Risk and Hazard Quotient of Heavy Metals in High-traffic Districts of Tehran Metropolis, Iran. Journal of Advances in Environmental Health Research 9(4): 285-298.

[53] USEPA. 1991. Risk Assessment Guidance for Superfund Volume I-Human Health Evaluation Manual (Part B). Washington D.C.: USEPA.

[54] Yaping, L.; Xudong, C.; Yuanan, H.; and Hefa, C. 2022. Pollution, Risk and Transfer of Heavy Metals in Soil and Rice: A Case Study in a Typical Industrialized Region in South China. Sustainability 14: 10225.

[55] Hough, R.L.; Breward, N.; Young, S.D.; Crout, N.M.J.; Tye, A.M.; Moir, A.M.; and Thornton, I. 2004. Assessing potential risk of heavy metal exposure from consumption of home-produced vegetables by urban populations. Environment Health Perspect 112: 215-221.

[56] Doležalová, W.H..; Mihocová, S.; Chovanec, P.; and Pavlovský, J. 2019. Potential Ecological Risk and Human Health Risk Assessment of Heavy Metal Pollution in Industrial Affected Soils by Coal Mining and Metallurgy in Ostrava. Czech Republic. Int. J. Environ. Res. Public Health 16: 4495.

[57] Rehman, I.; Ishaq, M.; Ali, L.; Khan, S.; Ahmad, I.; Din, I.U.; and Ullah, H. 2018. Enrichment, Spatial Distribution of Potential Ecological and Human Health Risk Assessment via Toxic Metals in Soil and Surface Water Ingestion in the Vicinity of Sewakht Mines, District Chitral, Northern Pakistan. Ecotoxicol. Environ. Saf 154: 127–136.

[58] Taghavi, M.; Darvishiyan, M.; Momeni, M.; Eslami, H.; Fallahzadeh, R.A.; and Zarei, A. 2023. Ecological Risk Assessment of Trace Elements (TEs) Pollution and Human Health Risk Exposure in Agricultural Soils Used for Saffron Cultivation. Sci. Rep. 13: 4556.

[59] Cathleen, A.S.; Kanitthika, S.; Vladimir, S.; Prapat, P.; Narin, B.; Ranjna, J.; and Suwanna. K.B. 2024. Health risk assessment of soil contamination with heavy metals in a child care center co-located in vicinity to small scale industrial area: Case study of Thailand. Case Studies in Chemical and Environmental Engineering 9: 100727.

[60] Paweena, A.; Ramnaree, N.; Piriyaporn, T.; Sutha, K.; and Phitsanu, T. 2022. Carcinogenic Risk of Pb, Cd, Ni, and Cr and Critical Ecological Risk of Cd and Cu in Soil and Groundwater around the Municipal Solid Waste Open Dump in Central Thailand. Hindawi Journal of Environmental and Public Health 2022: 3062215.

[61] USEPA. 2009. Risk assessment guidance for superfund volume I: Human health evaluation manual (Part F, supplemental guidance for inhalation risk assessment). Washington D.C.: USEPA.

[62] He, M.; Shen, H.; Li, Z.; Wang, L.; Wang, F.; Zhao, K.; Liu, X.; Wendroth, O.; and Xu, J. 2019. Ten-year regional monitoring of soil-rice grain contamination by heavy metals with implications for target remediation and food safety, Environmental Pollution 244: 431-439.

[63] WHO. 2011. International agency for research on cancer (IARC) monographs on the identification of carcinogenic hazards to humans. Geneva: World Health Organization.

[64] Steven, S.; Alan, B.; and Steve, B. 2011. Oxford Handbook of Occupational Health. Oxford: Oxford university.

[65] OEHHA. 2009. Air Toxics Hot Spots Program Technical Support Document for Cancer Potencies. California: OEHHA.

[66] Tangkan, S.; and Sirapassorn, P. 2024. Health Risk and Contamination Assessment of Heavy Metals in Groundwater around Municipal Landfill, Ayutthaya Province. Huachiew Chalermprakiet Science and Technology Journal 10(2): 82-

97.
[67] Hasan, M. F.; Nur-E-Alam, M.; Salam, M.A.; Rahman, H.; Paul, S.C.; Rak, A.E.; Ambade, B.; and Towfiqul Islam, A.R.M. 2021. Health Risk and Water Quality Assessment of Surface Water in an Urban River of Bangladesh. Sustainability 13: 6832.
[68] Wang, K; Aji. D.; Li, P.; and Hu, C. 2024. Characterization of heavy metal contamination in wetland sediments of Bosten lake and evaluation of potential ecological risk. China. Front. Environ. Sci. 12: 1398849.
[69] Mohanty, S.; Nayak, R.K.; Jena, B.; Padhan, K.; Mohapatra, K.K.; Sahoo, S.K.; Dash, P.K.; Das, J.; Behera, S.K.; Sahu, A.; Nayak, J.K.; Padhan, S.; and Datta, D. 2023. Heavy metal contamination in rice, pulses, and vegetables from CKDu-endemic areas in Cuttack district, India: a health risk assessment. Front. Environ. Sci. 11:1248373.
[70] Adzrin, A.Z.; Lee, H.L.; and Faizah, M. 2023. Comparative assessment of the heavy metal phytoextraction potential of vegetables from agricultural soils: A field experiment. Heliyon 9: 13547.
[71] Tangkan, S.; Sirisetpop, C.; Phanthasa, S.; Chamnanphudsa, O.; Ngamnon, Y.; and Klomsungcharoen, W. in press. Evaluation of Heavy Metal Contamination and Health Risk Analysis in Landfill and Agricultural Soils. Mongolia Journal of Chemistry 26(53): 1–12. https://doi.org/ 10.5564/mjc.v26i53.3742.
[72] Ministry of Public Health. 2020. Standard of contaminants in food No. 414 (In Thai). Bangkok, Thailand.
[73] Chinese Ministry of Health. 2017. National Food Safety Standard Maximum Levels of Contaminants in Food: GB 2762-2017. Beijing: Chinese Ministry of Health.
[74] FAO/WHO. 2018. Food Safety and Quality Situation in the Countries of the Region: JOINT FAO/WHO Food standards programme codex committee on contaminants in foods No. CF/12 INF/1. Rome: Codex Alimentarius.
[75] WHO. 1999. Permissible limits of heavy metals in soil and plants. Geneva: World Health Organization.
[76] FAO/WHO. 2002. General Standard for Contaminants and Toxins in Food and Feed. Shedule 1 Maximum and Guidline Levels for Contaminants and Toxins in Food. Reference CX/FAC 02/16. Rotterdam: Codex Alimentarius.
[77] FAO/WHO. 2002. Joint FAO/WHO Food Standards Program Codex Committee on Contaminants in Food, Food CF/5INF/1. Fifth Session. Rome: FAO/WHO
[78] WHO. 1989. Report of 33rd meeting, Joint FAO/WHO Joint Expert Committee on Food Additives, Toxicological evaluation of certain food additives and contaminants No. 24, International Programme on Chemical Safety. Geneva: World Health Organization.
[79] Nguyen, T.G. 2020. Potential Health Risk Assessment for the Occurrence of Heavy Metals in Rice field Influenced by Landfill Activity in Can Tho City, Vietnam. International Journal of Environment, Agriculture and Biotechnology 5(4): 928-935.
[80] Fajri, M.I.; Suphia, R.; Dhandhun, W.; Kasam, K.; Ratna, K.S.; and Minoru. Y. 2021. Heavy metals exposure and risk assessment of cooked rice from the field near the old dumpsite in indonesia. International Journal of GEOMATE 20(80): 36-44.
[81] Tanjira, K.; Benjaphorn, S.; and Preprame, P. 2017. Heavy Metal Concentration and Risk Assessment of Soil and Rice in and around an Open Dumpsite in Thailand. Environment Asia 10(2): 53-64.
[82] Lin, S.C.; Chang, T.K.; Huang, W.D.; Lur, H.S.; and Shyu, G.S. 2015. Accumulation of arsenic in rice plant: a study of an arsenic-contaminated site in Taiwan. Paddy Water Environ 13: 11-18.
[83] Philomene, N.; Komariah; and Sajidan. 2021. Harmful Impacts of Heavy Metal Contamination in the Soil and Crops Grown Around Dumpsites. Reviews in Agricultural Science 9: 271-282.
[84] Rezvani, M.; and Zaefarian, F. 2011. Bioaccumulation and Translocation Factors of Cadmium and Lead in Aeluropus littoralis. Aust. J. Agric. Eng. 2: 114–119.
[85] José, M.B.; and Tatiana, B. Arsenic translocation in rice cultivation and its implication for human health. Chilean Journal of Agricultural research 76(1): 114-122.
[86] JECFA. 2011. Evaluation of certain food additives and contaminants: Summary and conclusion on the seventy-third meeting. Geneva: FAO/WHO.
[87] JECFA. 2010a. 72th Report of the Joint FAO/WHO Expert Committee on Food Additive. Geneva: FAO/WHO.
[88] JECFA. 2010b. 73th Report of the Joint FAO/WHO Expert Committee on Food Additive. Geneva: FAO/WHO.
[89] JECFA. 2012. Joint FAO/WHO expert committee on food additives seventy-sixth meeting. Geneva: FAO/WHO.
[90] Sara, P.E.; Peter, G.; Gerry, M.; and Zhongqi, C. 2020. The limits of lead (Pb) phytoextraction and possibilities of phytostabilization in contaminated soil: a critical review. International journal of phytoremediation 22(9): 916-930.
[91] Jie, Z.; Enrico, M.; and Youngsook, L. 2018. Vacuolar Transporters for Cadmium and Arsenic in Plants and their Applications in Phytoremediation and Crop Development. Plant Cell Physiol. 59(7): 1317–1325.
[92] Mengel, K.; Kosegarten, H.; Kirkby, E.A.; and Appel, T. 2001. Principles of Plant Nutrition. Dordrecht: Springer.
[93] Rahman, I.; Wahab, M.; Akter, M.; and Mahanta, T. 2023. Iron in Drinking Water and its Impact on Human Health –A Study in Selected Units of Jalalabad Cantonment. Bangladesh Armed Forces Med J. 56(2): 58-64.
[94] Cerazy, J.; and Cottingham, S. 2010. Lead Babies: how Heavy Metals Are Causing Our Children's Autism, ADHD, Learning Disabilities, Low IQ and Behavior Problems. Lead Babies How heavy metals. Indiana: iUniverse.
[95] Ganga, R.P.; and Galaxy, P. 2022. Effect of Chromium on Human-Health: A Review. BMC Journal of Scientific Research 5(1): 27-35.
[96] WHO. 2019. Exposure to arsenic: a major public health concern. Geneva: World Health Organization.
[97] Giri, S.; and Singh, A.K. 2015. Human health risk assessment via drinking water pathway due to metal contamination in the groundwater of Subarnarekha River Basin, India. Environ. Monit. Assessment 187(3): 63.
[98] Hasan, M. F.; Nur-E-Alam, M.; Salam, M.A.; Rahman, H.; Paul, S.C.; Rak, A.E.; Ambade, B.; and Towfiqul Islam, A.R.M. 2021. Health Risk and Water Quality Assessment of Surface Water in an Urban River of Bangladesh. Sustainability 13: 6832.
[99] Haodong, Z.; Yan, W.; Xiping, L.; Yuhong, Y.; Xiaonan, W.; and Liyu, D. 2022. Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution

level. Scientific Reports 12: 3552.

[100] Chidinma, C.E.; Janefrances N.I.; Oguejiofo T.U.; Nwachukwu, R.E.; and Charles O.N. 2019. Human health risk assessment of potential toxic elements in paddy soil and rice (Oryza sativa) from Ugbawka fields, Enugu, Nigeria. Open Chemistry 17: 1050-1060.

[101] Asghar, K.; Muhammad, S.K.; Munib, A.S.; Qaisar, K.; Ghulam, S. 2024. Assessment of potentially toxic and mineral elements in paddy soils and their uptake by rice (Oryza sativa L.) with associated health hazards in district Malakand, Pakistan. Heliyon 10: 28043.

[102] Fu, Q.; Li, L.; Achal, V.; Jiao, A.; and Liu, Y. 2015. Concentrations of Heavy Metals and Arsenic in Market Rice Grainand Their Potential Health Risks to the Population of Fuzhou, China. Hum. Ecol. Risk Assess. 21: 117–128.