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Unveiling the path from sediment trace elements to bioaccumulation in edible mussels: ecological and human health risk in Lake Singkarak, Indonesia

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ABSTRACT

Lake Singkarak is one of the tectonic lakes on Sumatera Island and is classified as a national priority lake in Indonesia. Our study aimed to investigate the accumulation level of trace elements in the bottom sediments and edible bivalves *Corbicula sumatrana* in Lake Singkarak, Indonesia. The study also assessed the ecological and health risks associated with the presence of these elements. Surficial sediments and mussels were taken from seven sites of Lake Singkarak in September and November 2022. The levels of several elements were determined in sediments and mussel soft tissues. Our results suggest that the lake sediments were uncontaminated to moderately contaminated by Cd according to the geo-accumulation index (Igeo). The contamination factor (CF) results exhibited moderate to considerable contaminated sediments in terms of Cd metal. Ecological risk evaluation posed by seven different trace elements identified Singkarak sediments as having low to moderate risk. Biota-sediment accumulation factor (BSAF) values indicated *Corbicula sumatrana* as a potential biomonitor for sediment chemical elements, especially Ag, Mo, Sb, Au, Pb, and Sn. Furthermore, human exposure to trace elements in sediments through dermal absorption poses no non-cancer risk, but lifetime exposure to Cr and Cd increases cancer risk (Cr: 29.04–70.80%, Cd: up to 30.26%). Consumption of Pb-containing mussels poses a risk of non-cancer effects, while prolonged exposure to Cr, Cd, Pb, Ni, and As increases cancer risk. Our findings highlight the importance of educating the public about the risks of consuming contaminated mussels and implementing safer eating practices to reduce exposure to toxic elements.

Keywords: cancer risk, *Corbicula sumatrana*, ecological risk, lake sediment, trace element.

INTRODUCTION

Trace elements are parts of the Earth's crust, which is composed of both essential and non-essential elements (Murthy et al., 2024). Trace elements enter the aquatic environments from both natural and anthropogenic sources. Atmospheric deposition and geologic weathering are primary natural sources of trace elements (Çevik et al., 2009). While, anthropogenic sources are agricultural practices, wastewater discharge, mining (Ali et al., 2019), dam construction (Çevik et al., 2009), and many others.

Lake environments are the most important routes for the migration, transformation, and enrichment of trace elements (Wang et al., 2024). Various elements entering aquatic environment can be adsorbed on particles and deposited onto sediments, causing sediments to be considered as major reservoirs for trace elements (He et al., 2022). On the other hand, trace elements can be a source of pollutants in aquatic environments due to their toxicity, persistence, and bioaccumulation, making them a major environmental challenge worldwide (Juncos et al., 2023). The accumulation of trace elements in bottom sediments can result in the release of these elements into the water column above, which will cause secondary source of pollution (Apestegui et al., 2023). Thus, sediment resuspension (anthropogenic or natural origin) can impact on ecosystem structure and functioning.

Lake sediments can record trace element variations that result from environmental changes and human activities over time (Wei et al., 2022). The levels of trace elements in sediments can reveal significant information about the source and pollution level, which is vital for monitoring aquatic habitats (Wang et al., 2024). Consequently, sediment became an effective indicator for evaluating pollution levels of lake ecosystems associated with potential ecological risks (Kormoker et al., 2019). This can contribute to the conservation of aquatic environments, in which trace elements pollution in sediment represents a major problem in developing countries (Kumar et al., 2020).

Aquatic sediment quality can be evaluated using single and integrated index approaches. Single index such as Igeo and CF are widely applied to assess contamination levels of elements in sediment. Meanwhile, the risk index (RI) combine the single index of the potential ecological risk factor (Er) for all trace elements in the sediment which represents the effects of multiple pollutants at the same time (Hakanson, 1980; Gupta et al., 2014).

Benthic organisms in lake waters, such as mussels, have the potential to accumulate bioavailable elements where sediments are their habitat and food source. Trace elements enter mussels via routes from direct contact with sediment particles, ingestion of water and dust, and consumption of contaminated food (Jia et al., 2018). This study chose *Corbicula sumatrana* because it is an important food source with high economic value in Lake Singkarak and a potential accumulator of sediment elements. Several studies have noted freshwater mussel *Corbicula* as a bioindicator for toxic element contamination in aquatic environments (Netpae and Phalaraksh, 2009).

The toxic effects of element pollutants have the potential to pose a risk to human health through the food chain, due to the processes of bioaccumulation and biomagnification (Sahu et al., 2023). One of the primary pathways of human exposure to toxic elements is through the consumption of contaminated aquatic biota (Jia et al., 2018). Trace elements in mussels may be measured to evaluate potential health risks associated with mussels-eating.

Previous findings have documented the accumulation of organochlorine pesticides residue in *C. sumatrana* in Lake Singkarak (Ibrahim et al., 2022) and residual pyrethroids content in lake sediment (Ibrahim et al., 2023). Meanwhile, elements accumulation in sediment and aquatic products is not yet documented. Likewise, ecological and health risk of trace elements in Indonesian lakes have yet to be widely reported. Since Lake Singkarak is one of the Indonesian priority lakes for management, a comprehensive study on trace elements contamination associated with potential risks is important. Therefore, this present work aims to (i) investigate the accumulation level of trace elements in the bottom sediments and edible bivalves *Corbicula sumatrana* in Lake Singkarak, Indonesia, (ii) assess the ecological and human health risks associated with the presence of these elements.

MATERIALS AND METHODS

Sample collection and analysis

Seven surficial sediment samples were taken in September and November 2022 from Lake Singkarak. Sampling locations are presented in Table 1 and Figure 1. Sediment samples were taken using a grab sampler and placed into plastic bags. The collection of mussels *C. sumatrana* was conducted from the same sites by diving into the lake's bottom and then crushing their shells to get soft tissues. All obtained samples were stored in a cooler box with ice packs and transferred to the laboratory for examination. The content of chemical elements in sediments and soft tissues were measured with an inductively coupled plasma – optical emission spectroscopy (ICP-OES) at the Central Laboratory of Universitas Padjadjaran.

Contamination assessment methods

Geo-accumulation index

Geo-accumulation (Igeo) index as single index was introduced by Muller (1969) to identify the accumulation and contamination status of elements in sediment considering background values. The *Igeo* of element is calculated as:

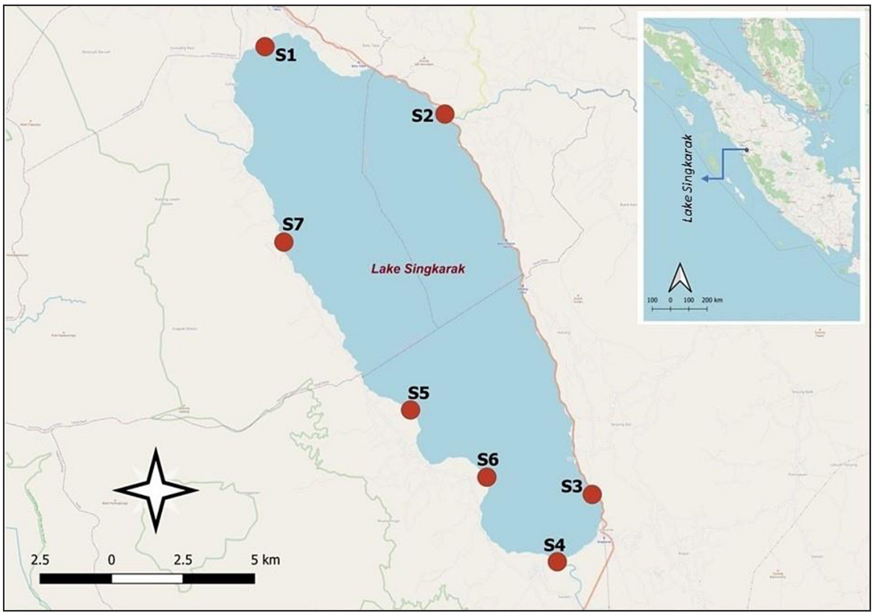


Figure 1. Research sites map in Lake Singkarak

$$Igeo = log_2(Ci/1.5Bi) \quad (1)$$

where: Ci and Bi represent concentration of element in the sediment and geochemical background concentration of element, respectively. The Factor 1.5 was applied to reduces the possible variation of lithogenic effects and to detect minimum anthropogenic influence (Onjefu et al., 2020). The background values of several elements to calculate this index refer to Turekian and Wedephol (1961) (Table 2).

Contamination factor

Contamination factor (CF) is also single index represents the ratio of an individual element value to the background values in sediment (Shen et al., 2020). The CF of element is calculated as follows:

$$CFi = Ci/Bi \quad (2)$$

Ecological risk assessment methods

Potential ecological risk factor

Potential ecological risk (Er) factor was applied to assess the probability of harmful effects of trace elements to environment. This single index depends on the toxic response (Tr) factor of elements and contamination factor. The Er of element is calculated as:

$$Er = \sum Tr_i\,(Ci/Bi) \quad (3)$$

Risk index

Risk index (RI) is expressed as the integrated index based on ecological risk factor of individual elements (Er_i) (Hakanson, 1980). (Table 3) This index was calculated:

$$RI = \sum Er_i = \sum Tr_i\,(Ci/Bi) \quad (4)$$

Table 1. Sampling sites in Lake Singkarak

Labels	Stations	Coordinate
S1	Sumpur	0°32’19.7”S 100°29’35.4”E
S2	Ombilin	0°33’35.6”S 100°32’58.8”E
S3	Tikalak	0°40’44.2”S 100°35’45.5”E
S4	Sumani	0°42’00.0”S 100°35’06.0”E
S5	Paninggahan	0°39’09.0”S 100°32’20.0”E
S6	Muaro Pingai	0°40’24.7”S 100°33’46.3”E
S7	Intake PLTA	0°35’59.9”S 100°29’56.7”E

Table 2. Criteria for geo-accumulation index (Muller, 1981; Ghrefat, 2011)

Igeo values	Criteria
Igeo ≤ 0	Uncontaminated
0 < Igeo < 1	Uncontaminated to moderately contaminated
1 < Igeo < 2	Moderately contaminated
2 < Igeo < 3	Moderately to heavily contaminated
3 < Igeo < 4	Heavily contaminated
4 < Igeo < 5	Heavily to extremely contaminated
5 ≤ Igeo	Extremely contaminated

Table 3. Criteria for CF, Er, and RI value (Hakanson, 1980; Apori et al., 2024)

CF	Criteria	Er	RI	Criteria
CF < 1	Low contamination	Er < 40	RI < 95	Low risk
1 ≤ CF < 3	Moderate contamination	40 ≤ Er < 80	95 ≤ RI < 190	Moderate risk
3 ≤ CF < 6	Considerable contamination	80 ≤ Er < 160	190 ≤ RI < 380	Considerable risk
CF ≥ 6	High contamination	160 ≤ Er < 320	-	High risk
		Er ≥ 320	RI ≥ 380	Very high risk

Biota-sediment accumulation factor (BSAF)

In order to assess accumulation profiles of elements in aquatic organisms, the BSAF was calculated by the following equations (Szefer et al., 1999):

$$BSAF = Cb/Ci \quad (5)$$

where: *Cb* and *Ci* is the average concentration of element in *C. sumatrana* (mg kg^{-1}) and sediment (mg kg^{-1}), respectively. (Table 4).

Human health risk assessment methods

Exposure to trace elements in sediments through the dermal absorption pathway

In addition to serving as a source of clean water, Lake Singkarak is utilized by the local community as a tourist destination and for water-based recreation activities such as fishing, swimming, as well as fisheries activities (Idris, 2013). In this case, individuals who come into direct contact with lake sediments are potentially exposed to trace elements through the dermal absorption pathway (Nasr et al., 2023).

Exposure to trace elements at concentrations exceeding the threshold may result in adverse health effects, including non-carcinogenic and cancer risks (Abd-Elghany et al., 2024). Non-carcinogenic health risks typically emerge following short-term exposure (Demissie et al., 2024), contingent on exposure concentration. In contrast, cancer health risks may manifest after prolonged exposure (Eze et al., 2021).

The method for calculating non-carcinogenic risks via the dermal absorption pathway in adults and children begins with calculating chronic daily intake (CDI), expressed in mg/kg/day. Once the CDI has been obtained, a non-carcinogenic health risk analysis is performed using the hazard quotient (HQ). Subsequently, the hazard index (HI) is calculated to assess the non-carcinogenic risks associated with several metals. The equation applied in our study refers to previous studies conducted by several researchers (Nasr et al., 2023; Fahimah et al., 2023; Oginawati et al., 2023).

Table 4. Criteria for BSAF (Dallinger, 1993)

BSAF	Criteria
BSAF < 1	Deconcentrator
1 < BSAF < 2	Microconcentrator
BSAF > 2	Macroconcentrator

$$CDI_{dermal} = \frac{C_{sed} \times SA \times AF \times ABS \times EF \times ED \times ET}{BW \times AT} \times 10^{-6} \quad (6)$$

$$HQ = \frac{CDI_{dermal}}{RfD_{dermal}} \quad (7)$$

$$THQ\ additif = \sum_i^n HQ_i \quad (8)$$

In the calculation, Csed is the concentration of trace elements in lake sediment (mg/kg), SA represents the surface area of exposed skin (cm²/day), EF is the frequency of exposure (days/year), AF is the adhesion factor or a measure of how much trace elements can adhere to the skin surface (mg/cm²), ED represents the exposure duration (years), ET is the exposure time (days/day), BW is the body weight (kg), ABS is the dermal absorption fraction (unitless), and AT is the averaging time (unitless). RfD is the reference dose for each element by dermal absorption, calculated using the equation RfD Dermal = RfD Ingestion × GIABS, where GIABS is the dimensionless fraction of gastrointestinal absorption (Fahimah et al., 2023). The THQ additive represents the cumulative risk level of all elements. A conversion factor is required to calculate the dermal CDI, which is 10^{-6}. The values of each parameter are given in Tables 5 and 6. If the value of HQ/HI is greater than 1, there are potential adverse non-cancer health effects, whereas if the value is less than 1, non-cancer effects are not expected (Das et al., 2024).

The equation applied to calculate cancer risk is as follows (Shetaia et al., 2023). This study analysed six elements in relation to cancer risk, namely As, Cd, Cr, Hg, Ni, and Pb.

$$CR_{dermal} = CDI_{dermal} \times CSF \qquad (9)$$

$$TCR\ additif = \sum_{i}^{n} CR_i \qquad (10)$$

where: CR_{dermal} represents the carcinogenic risk resulting from dermal absorption of trace elements from sediment, while CSF denotes the cancer slope factor. In calculating dermal CSF, the GIABS value is used (dermal CSF = oral CSF/GIABS) (Reli et al., 2019; Cheatwood and Staigerwald, 2012). The additive TCR represents the cumulative risk level associated with exposure to all elements. The values of each parameter are presented in Tables 5, 6, and 7. A CR value of 10^{-6} or lower indicates no carcinogenic risk (Das et al., 2024).

Exposure to trace elements in mussels through the ingestion pathway

Freshwater mussels (locally known as 'pensi') from Lake Singkarak represent a common food source for tourists and local communities.

Table 5. Values used for human health risk assessment

Parameter	Unit	Value			Data source
		Adult female	Adult male	Children	
SA	cm^2	15,733.07	16,375.14	9510.35	Fahimah et al. (2023)
EF	day/year	365	365	365	Fahimah et al. (2023)
ET	day/day	0.17	0.17	0.17	Assumed length of time spent on water-based recreation activities and fishing, i.e. 4 hours per day, converted to days/day, i.e. 4/24 days/day.
AF	$mg/cm^2/day$	0.07	0.07	0.2	Nasr et al. (2023)
ED	year	76.65	71.75	10	Life Expectancy Rate by Gender (BPS West Sumatera, 2023)
BW	kg	57.86	59.03	26.4	Fahimah et al. (2023)
AT	day	27,977.25	26,188.75	3650	AT = 365 × ED

Table 6. The RfD, GIABS, and ABS values of each element (Shomar and Reshkeev, 2021)

HMs	RfD_{oral} (mg/kg/day)	GIABS	ABS	RfD dermal (RfD Oral × GIABS) (mg/kg/day)
Al	1	1	0.001	1
Ba	20	0.07	0.001	1.4
Be	0.002[a]	0.007[a]	0.001[b]	0.000014
Ag	0.0005	0.04	0.001	0.00002
Mo	0.005	1	0.001	0.005
Sb	0.0004	0.15	0.001	0.00006
Au	*	*	0.001[b]	*
As	0.0003	1	0.03	0.0003
Cd	0.0005	0.025	0.001	0.0000125
Co	0.0003	1	0.001	0.0003
Cr	1.5	0.013	0.001	0.0195
Cu	0.04	1	0.001	0.04
Fe	0.7	1	0.001	0.7
Hg	0.0003	1	0.001	0.0003
Mn	0.024	0.04	0.001	0.00096
Ni	0.02[a]	0.04[a]	0.001[b]	0.0008
Pb	-	1.00[a]	0.001	0.04
Sn	0.6	1	0.001	0.6
Zn	0.3	1	0.001	0.3

Note: (a) IRIS USEPA (2024), (b) Nasr et al. (2023), (*) limited data.

Table 7. CSF values of each type of cancer-causing trace elements

HMs	CSF oral (mg/kg/day)	Data source	CSF dermal (CSF oral / GIABS) (mg/kg/day)
As	1.50	Uddin et al. (2024)	1.0
Cd	6.10	Uddin et al. (2024)	244
Cr	0.50	Wu et al. (2024)	38.46
Hg	0.01	Uddin et al. (2024)	0.01
Ni	0.84	Mohammadi et al. (2024)	21.00
Pb	0.01	Uddin et al. (2024)	0.01

The presence of elements in the mussels may potentially pose a health risk to consumers. A risk assessment was conducted to evaluate the potential non-carcinogenic and carcinogenic effects associated with the consumption of raw freshwater mussels. Several elements were present at higher levels in raw mussels than in cooked samples (de Pinho et al., 2024).

Estimated daily intake (EDI) and estimated weekly intake (EWI) were calculated using the following formula (Li et al., 2021; de Pinho et al., 2024):

$$EDI = \frac{C_{mussel} \times F_{IR}}{BW} \tag{11}$$

$$EWI = EDI \times 7 \tag{12}$$

C_{mussel} indicates the element content in the analysed raw mussels (mg/kg), FIR indicates the amount of food consumed daily (gr/day converted to kg/day), which is 0.0426 kg/day (Purnomo, 2018), and BW represents the reference body weight (kg) (Table 5).

Non-carcinogenic risk (HQ) and carcinogenic risk (CR) were calculated with the following equation.

$$HQ = \frac{EDI \times EF \times ED}{RfD_{oral} \times AT} \tag{13}$$

$$CR = \frac{EDI \times EF \times ED \times CSF}{AT} \tag{14}$$

EF is the frequency of exposure to trace elements (days/year), ED represents the duration of exposure (years), RfD is the oral or ingestion reference dose (μg/g/day), CSF is the oral cancer slope factor for trace elements (mg/kg/day); AT is the average exposure time to carcinogens (days). The values of each parameter can be seen in Table 5 and Table 6. THQ and TCR are the cumulative risk levels of all elements. If THQ is more than 1, there is a non-carcinogenic risk, while TCR is more than 10^{-6}, there is a potential cancer risk.

RESULTS AND DISCUSSION

Trace elements in lake sediments

In our study, the total contents of 19 major and trace elements (Al, Ba, Be, Ag, Mo, Sb, Au, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sn, Zn) in surface sediments of Lake Singkarak are determined. The variation in element concentrations at each site is illustrated in Table 8. The average abundance of trace elements in the lake sediments followed the descending order of Fe > Al > Mn > Ba > Zn > Cr > Pb > Cu > Co > Ni > As > Cd > Au > Sn > Be > Hg > Ag = Mo = Sb. Iron (Fe) was recorded as the major element with the highest concentration among all the studied elements, with a range of 9923.05–39,093.97 mg kg^{-1} with an overall average of 27,579.82 mg kg^{-1}. The second most abundant element is alumunium (Al), with a range of 7293.65 to 33,800.2 mg kg^{-1} and an average of 13,790.95 mg kg^{-1}. Compared to other Indonesian lakes, the Fe content in this study is greater than the sediment Fe in Lake Maninjau, which ranges from 1173 to 3573 mg kg^{-1} (Syawal et al., 2021).

Table 9 depicts the sediment quality criteria for selected metals stipulated by the CCME (2001) and EPA (Onjeifu et al., 2020). Several metals, namely As, Cr, Cu, Hg, and Pb, exhibited levels that met the ISQG (Interim Sediment Quality Guideline) standards from CCME (2001) in all investigated sites. The content of Cd exceeded the ISQG levels at three sites (S2, S3, and S4). Comparing the concentration of studied elements with the guidelines from EPA (Onjeifu et al., 2020), it was observed that sediments in some sites were moderately polluted by Cr at one site (S3), As at four sites (S2, S4, S6, and S7), and Mn at four sites (S1, S3, S6, and S7). Sediment was also heavily polluted with Mn (631.44 mg kg^{-1}) at site S4. Meanwhile, five sites (S1 to S5) exhibited moderate polluted by

Table 8. Major and trace elements concentrations of surface sediments from Lake Singkarak

Elements	Elements concentrations (mg kg^{-1})							Average
	S1	S2	S3	S4	S5	S6	S7	
Al	12,007.41	8,948.67	13,340.00	7,641.73	13,505.02	7,293.65	33,800.2	13,790.95
Ba	54.63	43.66	43.99	52.10	31.02	14.43	111.84	50.24
Be	0.13	0.24	0.15	0.14	0.16	-	-	0.16
Ag	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-	-	< 0.0001
Mo	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-	-	< 0.0001
Sb	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	-	-	< 0.0001
Au	0.42	<0.0001	0.90	1.52	0.07	-	-	0.58
As	2.26	3.73	2.21	5.58	1.86	5.61	4.39	3.66
Cd	0.56	1.31	0.89	0.62	0.41	-	-	0.76
Co	1.74	4.74	9.11	6.16	2.27	6.99	6.1	5.30
Cr	3.42	14.88	27.11	13.39	6.37	20.71	11.9	13.97
Cu	7.59	20.80	15.35	10.95	9.84	9.86	10.68	12.15
Fe	10,348.62	32,628.66	39,093.97	34,364.49	9,923.05	34,554.14	32,145.84	27,579.82
Hg	< 0.0001	0.02	< 0.0001	0.02	0.03	-	-	0.01
Mn	301.50	260.87	440.88	631.44	155.46	488.27	348.15	375.22
Ni	3.92	5.46	5.31	6.63	3.03	5.38	4.74	4.93
Pb	7.13	30.38	5.70	7.73	3.76	11.23	19.8	12.25
Sn	< 0.0001	0.92	0.97	0.17	0.53	-	-	0.52
Zn	25.39	98.35	48.22	50.88	16.12	51.64	42.12	47.53

Table 9. The selected trace elements guidelines for sediments (mg kg^{-1}) (CCME, 2001; Onjeifu et al., 2020)

Elements	CCME		EPA			Present work
	ISQG	PEL	Not polluted	Moderately polluted	Heavily polluted	
As	5.9	17	< 3	3–8	> 8	1.86–5.61
Cd	0.6	3.5	-	< 6	> 6	0.41–1.31
Cr	37.3	90	< 25	25–75	> 75	3.42–27.11
Cu	35.7	197	< 25	25–50	> 50	7.59–20.8
Hg	0.17	0.486	-	-	-	<0.0001–0.03
Mn	-	-	< 300	300–500	> 500	155.46–488.27
Ni	-	-	< 20	20–50	> 50	3.03–6.63
Pb	35	91.3	< 40	40–60	> 60	3.76–30.38

Cd. The remaining three metals, namely Cu, Pb, and Ni, were found to comply with the EPA standard values for unpolluted sediment within the investigated area.

Compared to the findings reported by Nastuti et al. (2024) for Lake Maninjau, the present study reveals higher concentrations of certain elements, including Cr, Cd, Cu, and Pb. The concentrations of Cd and Cr observed in this study ranged from 0.41 (S5) to 1.31 mg·kg^{-1} (S2) and 3.42 (S1) to 27.11 mg·kg^{-1} (S6), respectively (Table 8). The concentrations of both elements in Lake Maninjau were found to be lower, with values ranging from 0.147 to 0.189 mg kg^{-1} for Cd and 0.301 to 0.365 mg kg^{-1} for Cr. Other findings revealed lower levels of both elements for Lake Rawa Pening. In this lake, the concentrations of Cd and Cr were < 0.005 mg kg^{-1} and < 0.030 mg·kg^{-1}, respectively (Hidayah et al., 2012).

The observed Cu concentration in sediment of Lake Singkarak exhibited a range of 7.59 (S1) to 20.80 mg·kg^{-1} (S2), which was notably higher than that observed concentration in Lake Maninjau, which ranged from 0.195 to 0.290 mg kg^{-1}. While, other Indonesian lakes, including Lake Tondano, Rawa Pening, and Saguling Reservoir had greater

Cu concentrations, ranging from 26–88 mg kg^{-1} and 29.06–43.06 mg·kg^{-1}, respectively (Sinolungan et al., 2008; Hidayah et al, 2012).

Similarly, the Pb concentration in this work showed a considerable range, varying from 3.76 (S5) to 30.38 mg·kg^{-1} (S2), higher than the observed Pb concentration in Lake Maninjau and Lake Rawa Pening. The concentration of Pb in the sediment of Lake Maninjau ranges from 0.325 mg·kg^{-1} to 0.412 mg·kg^{-1}, with an average concentration of 0.356 mg·kg^{-1}. Meanwhile, the sediment Pb in Lake Rawa Pening had levels less than 0.030 mg·kg^{-1}. The contents of other elements, such as Hg, were also found to be relatively lower than those observed in Lakes Tondano and Maninjau, with a range of 0.036–0.201 mg·kg^{-1} and 0.048–0.720 mg·kg^{-1}, respectively (Sinolungan et al., 2008; Komala et al., 2020).

Contamination of trace elements

In this study, Igeo and CF were calculated in order to quantify the pollution level of heavy metals in lake sediments. The calculated results for the Igeo are given in Table 10. A total of 11 elements exhibited an average value of less than 0, which is indicative of uncontaminated status. Only the Igeo for Cd resulted in a value of 0–1 for the average value and the respective values of sites S1, S3, and S4 with uncontaminated to moderately contaminated criteria. Meanwhile, site S2 showed the highest Igeo value among the other sites (1.54), indicating a moderately contaminated status by Cd metal. Compared with other Indonesian lakes, such as Lake Maninjau, the Igeo results also demonstrated values less than zero for Cd, Cr, Cu, and Pb metals (Nastuti et al., 2024). Fadlillah (2024) reported different findings where Lake Menjer showed a sediment Cd content below the detection limit, resulting in the absence of an Igeo value. In contrast, another study in Lake Longhu reported moderate and heavy contamination by Cd (1 ≤ Igeo < 3) (Uddin et al., 2021). Other tectonic lake, such as Lake Dal had the Igeo values for Cr of 1.27 representing moderate contamination degree (Shah et al., 2021). In general, the descending order of the average Igeo values in this work is as follow Cd > Fe > Pb > Zn > Mn > As > Cu > Co > Cr > Ni > Sn > Hg.

The CF, also called the anthropogenic factor (AF), is a quantitative measure indicating anthropogenic contamination in sediments. Of the 12 elements, the highest CF value was observed for Cd, showing moderate to considerable contamination (1.36-4.38), as illustrated in Figure 2. Furthermore, the lake sediment indicated moderate contamination by Pb and Zn at site S2 with CF values of 1.52 and 1.04, respectively. The other CF of Pb and Zn were less than 1 showing that the lake sediments was low contamination. Similarly, the CF of the remaining elements in all sites. Overall, the level of contamination indicated by CF is Cd > Pb > Fe > Zn > Mn > As > Co > Cu > Cr > Sn > Ni > Hg (high to low). Nastuti et al. (2024) noted low contamination level in Lake Maninjau for four elements in the order of Cd > Pb > Cu > Cr. Conversely, the sediments in Saguling Reservoir were highly contaminated with Cd, with CF values ranging from 31.43 to 68.38 (Wardhani et al., 2016). Shah et al (2021) reported that the CF values for Ni, Cr, and Cu in Lake Dal indicate moderate to considerable contamination,

Table 10. Geoaccumulation Index (Igeo) for studied elements in Lake Singkarak

Elements	S1	S2	S3	S4	S5	S6	S7	Average
As	-3.11	-2.38	-3.14	-1.80	-3.39	-1.80	-2.15	-2.54
Cd	0.32	1.54	0.99	0.47	-0.14	-	-	0.64
Co	-4.03	-2.59	-1.64	-2.21	-3.65	-2.03	-2.22	-2.63
Cr	-5.30	-3.18	-2.32	-3.33	-4.41	-2.70	-3.50	-3.54
Cu	-3.15	-1.70	-2.14	-2.62	-2.78	-2.78	-2.66	-2.55
Fe	-2.77	-1.12	-0.86	-1.04	-2.83	-1.03	-1.14	-1.54
Hg	-13.55	-4.84	-13.55	-4.74	-4.44	-	-	-8.22
Mn	-2.08	-2.29	-1.53	-1.01	-3.04	-1.38	-1.87	-1.89
Ni	-4.70	-4.22	-4.26	-3.94	-5.07	-4.24	-4.43	-4.41
Pb	-2.07	0.02	-2.39	-1.96	-3.00	-1.42	-0.60	-1.63
Sn	-17.46	-3.29	-3.21	-5.72	-4.10	-	-	-6.75
Zn	-2.49	-0.54	-1.56	-1.49	-3.14	-1.46	-1.76	-1.78

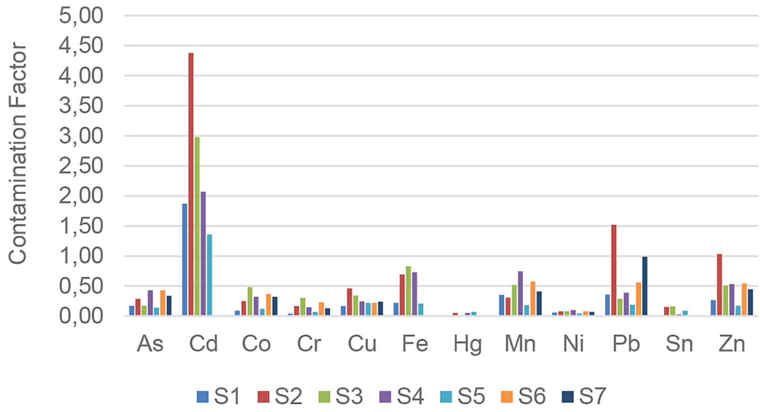


Figure 2. Contamination factor values for studied elements in Lake Singkarak

Table 11. Er values for studied elements in Lake Singkarak

Sites	As	Cd	Cr	Cu	Hg	Pb	Zn
S1	1.74	56.12	0.08	0.84	0.01	1.78	0.27
S2	2.87	131.30	0.33	2.31	2.10	7.59	1.04
S3	1.70	89.46	0.60	1.71	0.01	1.43	0.51
S4	4.29	62.12	0.30	1.22	2.24	1.93	0.54
S5	1.43	40.71	0.14	1.09	2.77	0.94	0.17
S6	4.32	-	0.46	1.10	-	2.81	0.54
S7	3.38	-	0.26	1.19	-	4.95	0.44
Average	2.82	75.94	0.31	1.35	1.42	3.06	0.50

while other elements (Fe, Co, Zn, Mn, and Pb) reflect low to moderate contamination.

The level of metal contamination in sediments of Lake Singkarak is influenced by anthropogenic sources, especially agriculture. Agricultural land occupies up to 56.49% of the lake's catchment area. There are almost no industries around the lake that have the potential to release heavy metals into the environment. The use of chemical fertilizers and pesticides contributes to the elevated Cd metal in lake sediments through leaching from farmland under rainfall and irrigation. In addition, fish feed used in floating net cages may contain cadmium, which deposited in bottom sediments (Li et al., 2017). The contamination of Zn and Pb metals at site S2 is also influenced by fertilizers application in the agricultural areas. Fuel combustion from fishing boats and automobile exhaust emissions have resulted in Pb contamination of lake sediments (Wang et al., 2019).

Ecological risk of trace elements

The Er and RI were employed to evaluate the ecological sensitivity of trace elements in sediments according to their toxicity and environmental responses (Devanesan et al., 2017). The Er calculation indicates that only the Cd element exhibits a moderate to considerable risk among the seven elements under investigation. The Cd element demonstrated moderate risk levels at S1, S4 and S5, while the remaining sites (S2 and S3) showed considerable risk, as indicated by the Er value in Table 11. Six other elements indicated low environmental risk with Er value below 40. The ranking of Er value from highest to lowest is Cd > Pb > Hg > As > Cu > Zn > Cr. Cheng et al. (2020) reported the presence of the metals Cd and Hg in seven freshwater tectonic lakes in China with a high ecological risk. Meanwhile, low risk degrees were found for the metals Cu, Cr, Zn, Pb, As and Ni. Furthermore, Ji et al. (2022) noted Cd has a greater potential ecological risk in the sediments of Lake Baiyangdian.

The RI measures the overall degree of ecological risk posed by the contamination of various trace elements in sediment. RI indicates the sensitivity of the organisms to the toxic substance (Gupta et al., 2014). A high RI value indicates a

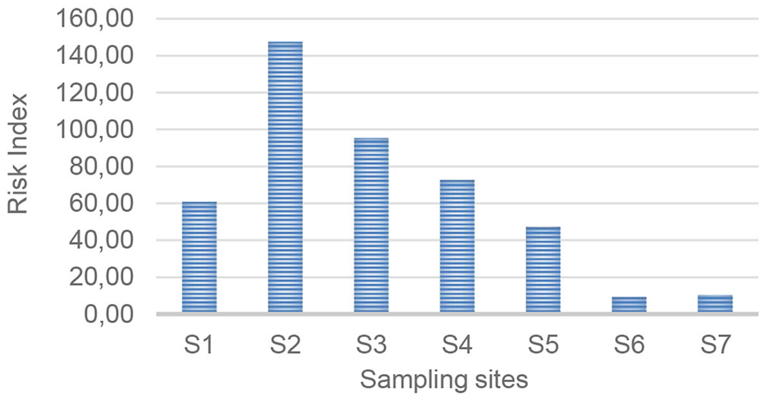


Figure 3. Risk index for studied elements in Lake Singkarak

high environmental risk. The calculated risk index of seven elements exhibits the highest value in S2 (147.54) and the lowest in S6 (9.22), as showed in Fig. 3. Based on the RI values, observed sites can be ranked as S2 > S3 > S4 > S1 > S5 > S7 > S6. The resulting RI values indicate a moderate ecological risk at two sites (S2 and S3) and a low risk at five others. Cd metal is the primary contributor to the RI values obtained in this study. Therefore, it is imperative to accord considerable attention to the long-term cadmium contamination of lake sediments. According to a previous study by Cheng (2020), four of the nine observed tectonic lakes were at low ecological risk, including Lugu, Yangzonnghai, Yilong and Chenghai lakes. The other two lakes (Dianchi and Xingyun) and Lake Fuxian were at considerable and moderate risk, respectively. The metals Cd and Hg in the sediments of these lakes contribute significantly to the RI values.

Accumulation of trace elements in mussels

Table 12 presented the variation of element content in the soft tissues of *C. sumatrana* during observations. The order of elements content in the *C. sumatrana* tissue is Pb > Fe > Zn > Mn > Al > Cu > As > Ba > Sn > Cr > Ni > Cd > Co > Mo > Au > Sb > Ag > Be > Hg. The *C. sumatrana* tissue had high concentration of Pb, especially at site S5 (74.65 mg kg^{-1}) with an average concentration of 19.41 mg kg^{-1}. *Corbicula sumatrana* exhibited relatively higher bioaccumulation of Pb in comparison to *Corbicula fluminea* from Taihu Lake and Dongting Lake, which showed Pb levels of 1.93 and 1.47 mg kg^{-1}, respectively (Kong et al., 2016; Li et al., 2019). The bioaccumulation of high Pb in mussels tissues indicates its bioavailability in sediments and water. Trace elements accumulation in mussels depends upon various biotic factors, including species, age, reproductive, dietary habits, and physiological condition (Boening, 1999). The abiotic factors were chemical element availability, temperature, pH, and filtration rate (Fernández-Tajes et al., 2011).

The content of Pb in the *C. sumatrana* tissue at two sites (S4 and S5) exceeded the maximum permitted limit proposed by the National Standardization Agency of Indonesia (1998) and FAO/WHO (2022) with content of 1.5 mg kg^{-1} and 2.0 mg kg^{-1}, respectively. Likewise, the As content from all sites was more than the Indonesian standard value of 1.0 mg kg^{-1}. The contents of Hg and Cd in the mussel tissues were below the Indonesian and FAO/WHO standard values of 1.0 mg kg^{-1}.

Table 13 demonstrates the BSAF values, which were determined to evaluate the uptake capacity of elements from aquatic sediments into the soft tissues of *C. sumatrana*. Understanding the bioaccumulation factor of elements is essential for comprehending their toxicity and fate in aquatic habitats and developing environmental protection strategies (EL-Shenawy et al., 2016). The majority of studied elements categorized the soft tissue of *C. sumatrana* as deconcentrators. Furthermore, the mussel's tissue was categorized as macroconcentrators for six elements include Ag, Mo, Sb, Au, Pb, and Sn. The BSAF value of As 1.0018 shows that *C. sumatrana* tissue is a microconcentrator of As. Our results suggest *C. sumatrana* is a potential biomonitor for assessing trace elements contamination. Li's (2019) findings noted that freshwater mussels *C. fluminea* have a BSAF value greater than 1 for Cu, Cd, Zn, and Ni. Thus, it is considered an adequate biomonitor for metal contamination.

Table 12. Elements concentrations in mussels and maximum permissible limits

Elements	Elements concentrations (mg kg^{-1})						Indonesian National Standard	FAO/WHO Standard
	S1	S2	S3	S4	S5	Average		
Al	2.71	3.42	11.80	< 0.0001	< 0.0001	3.59	-	-
Ba	3.34	1.48	1.14	0.32	0.68	1.39	-	-
Be	< 0.0001	0.001	< 0.0001	< 0.0001	< 0.0001	0.0002	-	-
Ag	0.005	0.01	< 0.0001	< 0.0001	< 0.0001	0.0028	-	-
Mo	< 0.0001	< 0.0001	0.06	< 0.0001	< 0.0001	0.01	-	-
Sb	< 0.0001	0.02	0.03	< 0.0001	< 0.0001	0.01	-	-
Au	0.01	0.02	0.02	< 0.0001	< 0.0001	0.01	-	-
As	2.40	2.90	2.41	1.59	3.33	2.53	1.0	-
Cd	0.06	0.05	0.04	< 0.0001	0.03	0.04	1.0	1.0
Co	0.03	0.03	0.05	< 0.0001	0.03	0.03	-	-
Cr	0.25	0.46	0.90	< 0.0001	0.94	0.51	-	-
Cu	2.98	2.81	2.96	1.31	2.81	2.57	-	-
Fe	31.86	31.20	32.15	< 0.0001	< 0.0001	19.04	-	-
Hg	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	1.0	1.0
Mn	22.71	2.41	2.27	< 0.0001	< 0.0001	5.48	-	-
Ni	0.15	0.04	0.20	< 0.0001	< 0.0001	0.08	-	-
Pb	< 0.0001	< 0.0001	0.05	22.36	74.65	19.41	1.5	2.0
Sn	0.48	0.75	0.46	< 0.0001	0.92	0.52	-	-
Zn	12.27	10.97	10.04	3.87	15.36	10.50	-	-

Table 13. Biota-sediment accumulation factor (BSAF) for trace elements in mussels

Elements	S1	S2	S3	S4	S5	Average
Al	0.0002	0.0004	0.0009	6.543E-09	3.702E-09	0.0003
Ba	0.0612	0.0339	0.0260	0.0062	0.0218	0.0298
Be	0.0004	0.0033	0.0003	0.0004	0.0003	0.0009
Ag	92.5000	183.5000	1.0000	1.0000	1.0000	55.8000
Mo	1.0000	1.0000	1238.5000	1.0000	1.0000	248.5000
Sb	1.0000	360.5000	525.5000	1.0000	1.0000	177.8000
Au	0.0350	413.0000	0.0176	3.290E-05	0.0007	82.6107
As	1.0598	0.7769	1.0933	0.2853	1.7937	1.0018
Cd	0.1085	0.0355	0.0496	8.049E-05	0.0757	0.0539
Co	0.0198	0.0069	0.0058	8.116E-06	0.0136	0.0092
Cr	0.0718	0.0308	0.0331	3.733E-06	0.1470	0.0565
Cu	0.3922	0.1349	0.1931	1.198E-01	0.2857	0.2252
Fe	0.0031	0.0010	0.0008	1.455E-09	0.0000	0.0010
Hg	1.0000	0.0024	1.0000	0.0022	0.0018	0.4013
Mn	0.0753	0.0093	0.0052	7.918E-08	3.216E-07	0.0179
Ni	0.0385	0.0065	0.0381	7.536E-06	1.650E-05	0.0166
Pb	7.011E-06	1.646E-06	0.0085	2.8919	19.8707	4.5542
Sn	9,509.0000	0.8103	0.4759	0.0003	1.7484	1,902.4070
Zn	0.4831	0.1115	0.2083	0.0760	0.9528	0.3664

Human health risk of trace elements

Health risk due to trace elements exposure in sediments through the dermal absorption pathway

The risk assessment for adults (subdivided by gender) and children (divided into non-cancer and cancer) through dermal absorption of Lake Singkarak sediment has been obtained by calculating CDI, HQ, THQ, CR, and TCR. The CDI values are presented in Table 14. The order of average CDI values, from highest to lowest is Fe > Al > Mn > As > Ba >

Table 14. CDI values of trace elements exposure in Lake Singkarak sediments through dermal absorption

Elements	CDI for adult - female (mg/kg/day)			CDI for adult - male (mg/kg/day)			CDI for children (mg/kg/day)		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Al	2.31E-05	1.07E-04	4.37E-05	2.36E-05	1.09E-04	4.46E-05	8.78E-05	4.07E-04	1.66E-04
Ba	4.58E-08	3.55E-07	1.59E-07	4.67E-08	3.62E-07	1.63E-07	1.74E-07	1.35E-06	6.05E-07
Be	4.08E-10	7.47E-10	5.20E-10	4.16E-10	7.62E-10	5.30E-10	1.55E-09	2.84E-09	1.97E-09
Ag	1.59E-13	1.59E-13	1.59E-13	1.62E-13	1.62E-13	1.62E-13	6.02E-13	6.02E-13	6.02E-13
Mo	1.59E-13	1.59E-13	1.59E-13	1.62E-13	1.62E-13	1.62E-13	6.02E-13	6.02E-13	6.02E-13
Sb	1.59E-13	1,59E-13	1.59E-13	1.62E-13	1.62E-13	1.62E-13	6.02E-13	6.02E-13	6.02E-13
As	1.77E-07	5.34E-07	3.49E-07	1.80E-07	5.45E-07	3.56E-07	6.70E-07	2.03E-06	1.32E-06
Cd	1.29E-09	4.17E-09	2.41E-09	1.32E-09	4.25E-09	2.46E-09	4.90E-09	1.58E-08	9.14E-09
Co	7.19E-09	3.01E-08	1.97E-08	7.33E-09	3.07E-08	2.01E-08	2.73E-08	1.14E-07	7.49E-08
Cr	1.08E-08	8.60E-08	4.43E-08	1.11E-08	8.77E-08	4.52E-08	4.11E-08	3.26E-07	1.68E-07
Cu	2.41E-08	6.60E-08	3.86E-08	2.46E-08	6.73E-08	3.93E-08	9.14E-08	2.50E-07	1.46E-07
Fe	3.15E-05	1.24E-04	8.75E-05	3.21E-05	1.27E-04	8.93E-05	1.19E-04	4.71E-04	3.32E-04
Hg	1.59E-13	8.79E-11	4.52E-11	1.62E-13	8.96E-11	4.61E-11	6.02E-13	3.33E-10	1.71E-10
Mn	4.93E-07	2.00E-06	1.19E-06	5.03E-07	2.04E-06	1.21E-06	1.87E-06	7.60E-06	4.52E-06
Ni	9.62E-09	2.10E-08	1.56E-08	9.81E-09	2.15E-08	1.59E-08	3.65E-08	7.98E-08	5.93E-08
Pb	1.19E-08	9.64E-08	3.89E-08	1.22E-08	9.83E-08	3.96E-08	4.52E-08	3.66E-07	1.47E-07
Sn	1.59E-13	3.08E-09	1.64E-09	1.62E-13	3.14E-09	1.68E-09	6.02E-13	1.17E-08	6.23E-09
Zn	5.11E-08	3.12E-07	1.51E-07	5.22E-08	3.18E-07	1.54E-07	1.94E-07	1.18E-06	5.72E-07

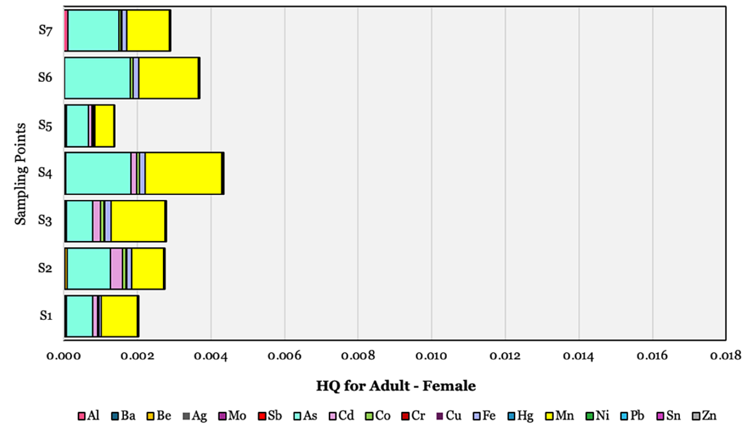
Zn > Cr > Pb > Cu > Co > Ni > Cd > Sn > Be > Hg > Ag = Mo = Sb. Fig. 4 depicts the HQ and THQ values associated with element exposure through dermal absorption in sediments. Of all the elements analysed, the HQ values for the entire study area are lower than 1 for children and adults, indicating no non-cancer risk associated with exposure to elements in lake sediments through dermal absorption. The order of HQ for elements is as follow: Mn > As > Cd > Fe > Co > Al > Be > Ni > Cr > Pb > Cu > Zn > Ba > Hg > Ag > Sn > Sb > Mo.

The carcinogenic risk (CR) via the dermal pathway was calculated for As, Cd, Cr, Hg, Ni, and Pb, as all six had cancer slope factor values. Fig. 5 depicts that the total cancer risk (TCR) from elements exposure via the dermal absorption pathway exceeded the safe limit at all sampling sites for both groups (adult females and males). Chromium (Cr) and cadmium (Cd) were the most significant contributors to the elevated cancer risk. Chromium accounted for 29.04% to 70.80% of the total cancer risk in the investigated area, while Cd contributed 0% to 30.26%.

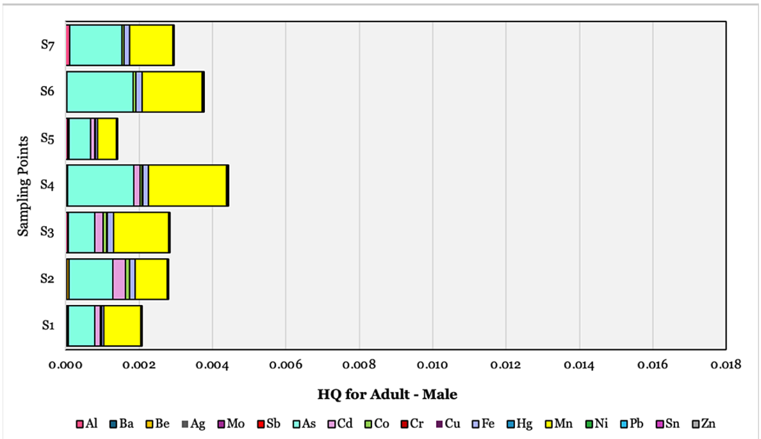
Health risk due to trace elements exposure in mussels through the ingestion pathway

This study has calculated the estimated weekly intake (EWI) values of 18 elements, the data are presented in Table 16. EWI values have been calculated based on EDI values, the results of which are presented in Table 15.

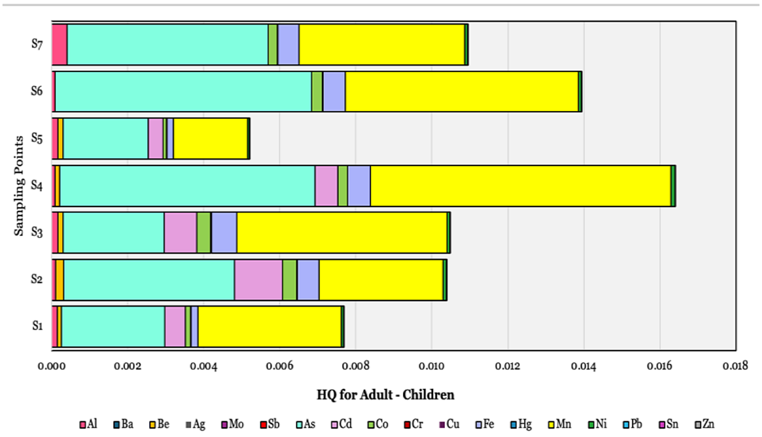
This study found that the highest mean EWI values (± SD) were for Fe, at $1.96 \times 10^{-1} \pm 1.78 \times 10^{-1}$ mg/kg/week for adult females and $1.92 \times 10^{-1} \pm 1.76 \times 10^{-1}$ mg/kg/week for adult males (Table 16). The lowest values were observed for mercury (Hg), with a mean of 2.58×10^{-7} mg/kg/week for adult females and 2.53×10^{-7} mg/kg/week for adult males. The low EWI values for Hg were a consequence of the Hg concentrations in mussels being below the limit of detection (LoD) (< 0.0001 mg/kg). The EWI assessment was based on the assumption that Hg concentrations in sediments are half the LoD. The order of EWI values from highest to lowest is Fe > Pb > Zn > Al > Mn > Cu > Ba > Sn > Cr > Ni > Cd > Co > Mo > Sb > As > Ag > Be > Hg. The EDI values have also been used to derive values of non-cancer risk (HQ, THQ) and cancer risk (CR, TCR) through



a) HQ for Adult-Female



b) HQ for Adult-Male



c) HQ for Adult-Children

Figure 4. HQ and THQ values for adult-female (a), adult-male (b), and children (c) of trace elements exposure in sediments via dermal absorption

the consumption of contaminated mussels in Lake Singkarak (Fig. 6 and Fig. 7, respectively).

Figure 6 illustrates the HQ and THQ values for elements contaminants in the mussel samples evaluated in this study. Based on the THQ values, the order of sample locations from highest to lowest (adult female and adult male, respectively) is as follows: S5 (15.5; 15.2) > S4 (4.61; 4.52) > S1 (1.12; 1.1) > S3 (0.72; 0.71) > S2 (0.59; 0.58). Sites S5, S4, and S1 were found to be at

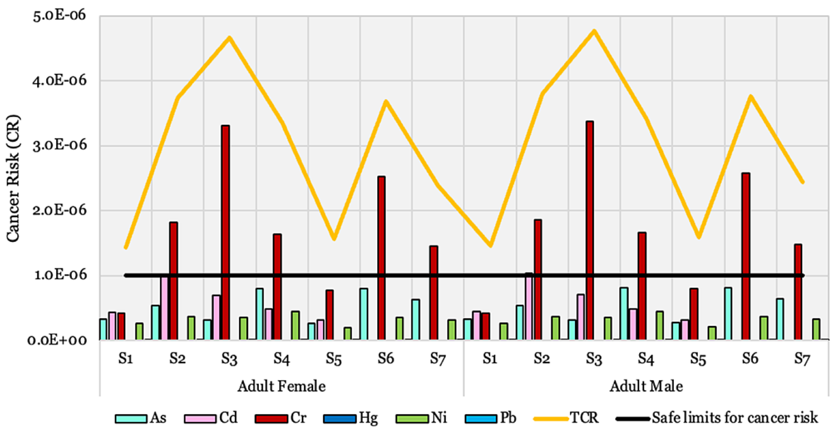


Figure 5. CR and TCR values of trace elements exposure in sediments via dermal absorption pathway

Table 15. Estimated daily intake (EDI) of trace elements in mussels via ingestion pathway

Elements	EDI for Adult - Female (mg/kg/day)			EDI for Adult - Male (mg/kg/day)		
	Min	Max	Average	Min	Max	Average
Al	3.68E-08	1.74E-02	5.28E-03	3.61E-08	1.70E-02	5.18E-03
Ba	2.38E-04	2.46E-03	1.02E-03	2.33E-04	2.41E-03	1.00E-03
Be	3.68E-08	1.10E-06	2.50E-07	3.61E-08	1.08E-06	2.45E-07
Ag	3.68E-08	1.35E-05	4.07E-06	3.61E-08	1.32E-05	3.99E-06
Mo	3.68E-08	9.11E-05	1.83E-05	3.61E-08	8.93E-05	1.79E-05
Sb	3.68E-08	3.87E-05	1.31E-05	3.61E-08	3.79E-05	1.28E-05
As	0.00E+00	2.32E-05	1.20E-05	0.00E+00	2.27E-05	1.17E-05
Cd	3.68E-08	4.48E-05	2.69E-05	3.61E-08	4.39E-05	2.64E-05
Co	3.68E-08	3.88E-05	2.22E-05	3.61E-08	3.80E-05	2.18E-05
Cr	3.68E-08	6.90E-04	3.74E-04	3.61E-08	6.76E-04	3.66E-04
Cu	9.66E-04	2.19E-03	1.90E-03	9.47E-04	2.15E-03	1.86E-03
Fe	3.68E-08	4.73E-02	2.80E-02	3.61E-08	4.64E-02	2.75E-02
Hg	3.68E-08	3.68E-08	3.68E-08	3.61E-08	3.61E-08	3.61E-08
Mn	3.68E-08	1.67E-02	4.72E-03	3.61E-08	1.64E-02	4.63E-03
Ni	3.68E-08	2.22E-04	8.47E-05	3.61E-08	2.18E-04	8.30E-05
Pb	3.68E-08	5.50E-02	1.43E-02	3.61E-08	5.39E-02	1.40E-02
Sn	3.68E-08	6.77E-04	3.83E-04	3.61E-08	6.64E-04	3.76E-04
Zn	2.85E-03	1.13E-02	7.73E-03	2.79E-03	1.11E-02	7.58E-03

non-cancer risk due to exposure to element in mussels at these sites (THQ value > 1). At site S5, the high non-cancer risk was mainly due to the contribution of Pb metal (HQ values were 15.3 for females and 15 for adult males, which accounted for about 98% of the THQ). Similar conditions were also found at site S4, where the non-cancer risk was dominated by Pb, with Pb accounting for about 99% of the THQ. Meanwhile, at site S1, the non-cancer risk is primarily due to the contribution of Mn, which accounts for about 62% of the THQ value at the site. Based on the average HQ values across the study sites, the order of the eighteen element based on their non-cancer risk levels from high to low is Pb (3.8932) > Mn (0.1929) > Co (0.0725) > Cd (0.0528) > Cu (0.0464) > Fe (0.0393) > As (0.0391) > Sb (0.0320) > Zn (0, 0253) > Ag (0.0080) > Al (0.0052) >Ni (0.0041) > Mo (0.0036) > Sn (0.0006) > Cr (0.0002) > Be = Hg = Ba (0.0001).

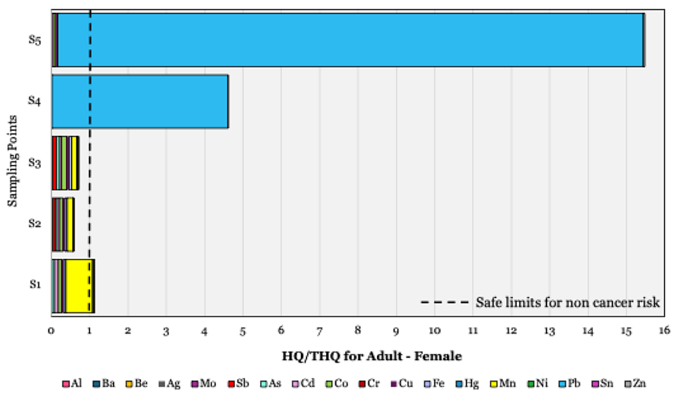
This finding confirms that exposure to element such as Pb through mussels consumption in some of the study sites requires special attention, especially to reduce the potentially non-carcinogenic health risks to populations that frequently collect and consume mussels from these areas.

Fig. 7 shows the CR and TCR values. TCR values at all sampling sites exceeded the USEPA threshold (> 10^{-6}), indicating that consumption of Lake Singkarak mussels over a lifetime of 76.65

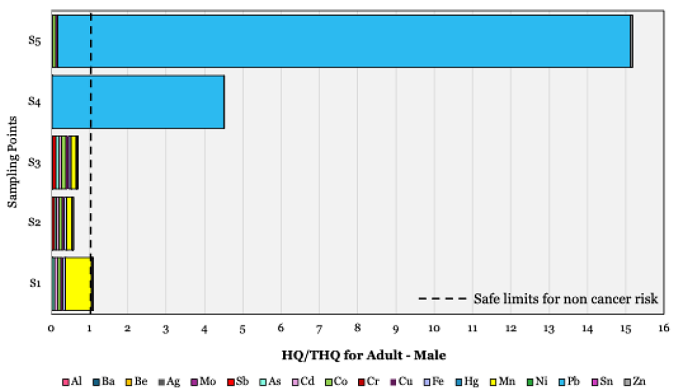
Table 16. Estimated weekly intake (EWI) of trace elements in mussels via ingestion pathway

Elements	EWI for Adult - Female (mg/kg/week)			EWI for Adult - Male (mg/kg/week)		
	Min	Max	Average	Min	Max	Average
Al	2.58E-07	1.22E-01	3.70E-02	2.53E-07	1.19E-01	3.62E-02
Ba	1.67E-03	1.72E-02	7.17E-03	1.63E-03	1.69E-02	7.03E-03
Be	2.58E-07	7.73E-06	1.75E-06	2.53E-07	7.58E-06	1.72E-06
Ag	2.58E-07	9.43E-05	2.85E-05	2.53E-07	9.24E-05	2.79E-05
Mo	2.58E-07	6.38E-04	1.28E-04	2.53E-07	6.25E-04	1.25E-04
Sb	2.58E-07	2.71E-04	9.14E-05	2.53E-07	2.65E-04	8.96E-05
As	0.00E+00	1.62E-04	8.38E-05	0.00E+00	1.59E-04	8.21E-05
Cd	2.58E-07	3.14E-04	1.88E-04	2.53E-07	3.08E-04	1.85E-04
Co	2.58E-07	2.71E-04	1.55E-04	2.53E-07	2.66E-04	1.52E-04
Cr	2.58E-07	4.83E-03	2.61E-03	2.53E-07	4.73E-03	2.56E-03
Cu	6.76E-03	1.53E-02	1.33E-02	6.63E-03	1.50E-02	1.30E-02
Fe	2.58E-07	3.31E-01	1.96E-01	2.53E-07	3.25E-01	1.92E-01
Hg	2.58E-07	2.58E-07	2.58E-07	2.53E-07	2.53E-07	2.53E-07
Mn	2.58E-07	1.17E-01	3.31E-02	2.53E-07	1.15E-01	3.24E-02
Ni	2.58E-07	1.56E-03	5.93E-04	2.53E-07	1.53E-03	5.81E-04
Pb	2.58E-07	3.85E-01	1.00E-01	2.53E-07	3.77E-01	9.81E-02
Sn	2.58E-07	4.74E-03	2.68E-03	2.53E-07	4.65E-03	2.63E-03
Zn	1.99E-02	7.91E-02	5.41E-02	1.95E-02	7.76E-02	5.30E-02

Note: <LOD = ½ LOD.



a) HQ/THQ for adult-female



b) HQ/THQ for adult-male

Figure 6. HQ and THQ values for adult-female (a) and adult-male (b) of trace elements exposure in mussels via ingestion pathway

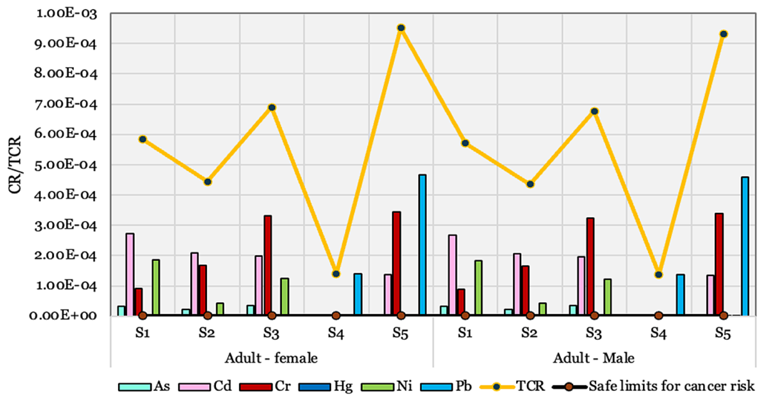


Figure 7. CR and TCR values of trace elements exposure in mussels via ingestion pathway

years for females and 71.75 years for males is associated with a carcinogenic risk. Of the five elements known to cause cancer, only mercury (Hg) was found in Lake Singkarak mussels at levels below the threshold (Fig. 7). High cancer risk due to element exposure from consumption of Lake Singkarak mussels may be caused by As, Cd, Cr, Ni and Pb, all of which had CR values above the threshold at some study sites. Based on the average HQ values across the study sites, the order of cancer risk levels from highest to lowest is as follows: Cr (1.85×10^{-4}) > Cd (1.63×10^{-4}) > Pb (1.20×10^{-4}) > Ni (7.04×10^{-5}) > As (1.78×10^{-5}) > Hg (4.01×10^{-10}, below the safe limit). Meanwhile, differences in risk between the sexes, with women at higher risk than men, may reflect differences in diet or body composition.

The results of this study raise serious concerns about the long-term health effects of eating mussels from this lake. To reduce the risk, efforts to raise awareness among local communities about the potential risks of consuming contaminated mussels and to promote safer food practices could help reduce exposure and protect vulnerable populations.

CONCLUSIONS

Our study revealed the occurrence of trace elements in sediment and their bioaccumulation in edible mussels *C. sumatrana* of Lake Singkarak. Risk assessment revealed that Cd in lake sediments produced moderate to considerable risks based on the Potential Ecological Risk Factor. Meanwhile, six other elements (Pb, As, Hg, Cu, Cr, and Zn) had a low risk. The Risk Index calculated from seven trace elements indicated a low to moderate ecological risk. A total of six elements (Ag, Mo, Sb, Au, Pb, and Sn) showed substantial bioaccumulation in *C. sumatrana* according to the BSAF. Furthermore, human exposure to trace elements in lake sediments through dermal absorption does not pose a risk of non-cancer effects. However, lifetime exposure to Cr and Cd increases cancer risk, with chromium contributing 29.04–70.80% and cadmium up to 30.26%. Consumption of mussels containing Pb increased the risk of non-cancer effects, while other elements did not show the same risk. However, prolonged exposure to Cr, Cd, Pb, Ni, and As through mussel consumption may increase cancer risk. The findings underline the importance of raising public awareness of the risks of consuming contaminated mussels and promoting safer eating practices to reduce exposure to toxic elements and protect vulnerable populations.

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