Aerosol and Air Quality Research (2025) 25:71
https://doi.org/10.1007/s44408-025-00073-3

RESEARCH

Health Risk Assessment of Heavy Metals Exposure in Household Dust: Relationships between Heavy Metals Concentrations, Household Characteristics and Daily Living Activities among Residents in Kampar, Malaysia

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Received: 29 July 2025 / Revised: 31 October 2025 / Accepted: 15 November 2025 / Published online: 28 November 2025

Abstract

Heavy metals (HM) emitted from anthropogenic activities pose serious environmental and health risks. However, limited research has been conducted on their health risks in former tin mining towns in Malaysia, such as Kampar. Therefore, this study aims to assess the health risk of HM exposure in household settled dust and to investigate the relationships between residents' daily activities and the concentration of HM in household dust in Kampar town, Malaysia. Survey questionnaires were distributed to the respondents (n = 200) from 51 households to collect their demographic data, household characteristics, and daily living activities. Household settle dust was collected from respective households using handheld vacuum cleaner, and concentrations of 10 HM (As, Zn, Fe, Ni, Pb, Al, Cd, Cu, Cr, Mn) in dust samples were measured using inductively coupled plasma optical emission spectrometry (ICP-OES). Non-carcinogenic risk and carcinogenic risk for HM exposure were estimated using Hazard Index (HI) and Total Lifetime Cancer Risk (TLCR), respectively. Associations of daily activities and concentrations of HM were analyzed using multi-level linear mixed model. The findings showed HI of arsenic exposure in children exceeded the acceptable threshold level (HI: 1.20). The carcinogenic risks of assessed HM were within the tolerable threshold of 1×10^{-4} to 1×10^{-6}. The presence of houseflies and mosquitoes was positively associated ($p < 0.05$) with concentrations of Cd (OR: 1.182) and Zn (OR: 1.757) in household dust. Frequent smoking (OR: 1.173), burning incense/mosquito coil/candle (OR: 1.202), and pan-frying practices (OR: 1.100) were positively related ($p < 0.05$) with higher concentrations of HM. However, the mitigation approaches like the use of air purifier (ORs: 0.698–0.763) and frequently vacuuming floor (OR: 0.899) significantly ($p < 0.05$) reduced the HM concentration. The daily practices and cleaning activities of building occupants were significantly related with their HM exposure in household settled dust.

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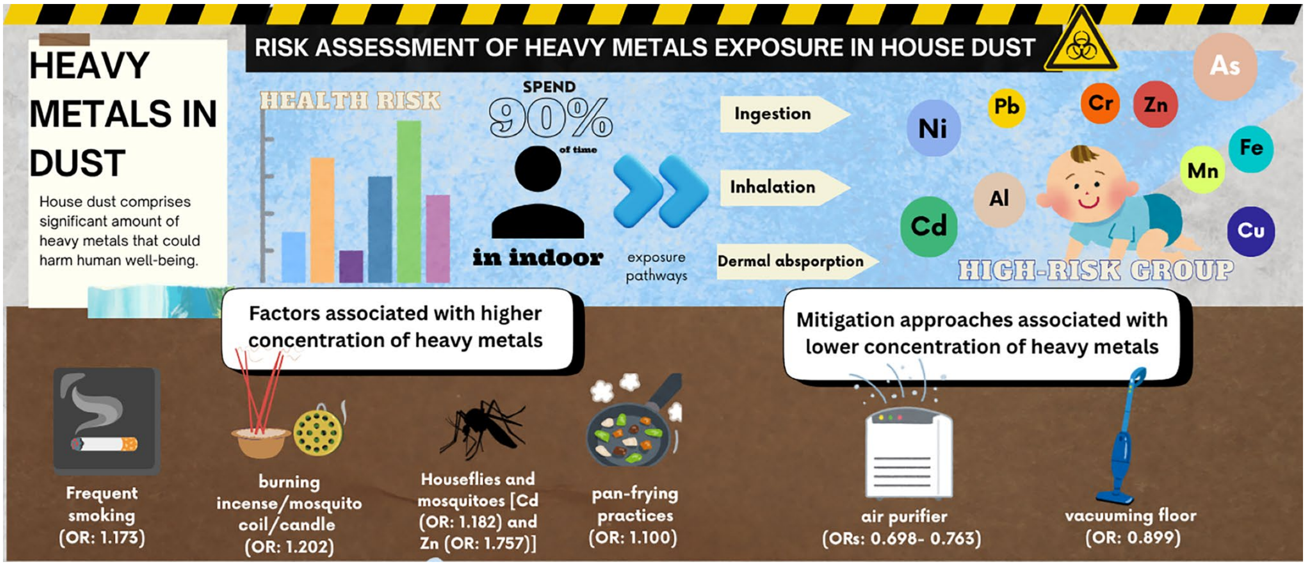
Graphical Abstract



Keywords Heavy metals · Indoor · Health risk assessment · House dust · Residents

1 Introduction

The growing population, rapid industrial development, and increasing number of vehicles have elevated environmental issues to an alarming status, especially in urban areas. These anthropogenic activities have generated street dust and fugitive dust that infiltrate into the indoor environment and settle down as indoor settled dust. Notably, approximately 85% of indoor dust originates from outdoor sources (Hassan et al. 2015). Thus, indoor air quality is gaining the public's concern as adults spend approximately 88% of their time indoors (Kurt-Karakus 2012).

Rapid urbanization and industrialization in Malaysia have raised significant concerns regarding heavy metal contamination in indoor environments. Numerous studies have reported elevated heavy metal concentrations in indoor dust across schools, nurseries, and residential settings (Latif et al. 2011; Praveena et al. 2015; Abdul Wahab et al. 2012). Vulnerable populations, particularly children, are at heightened risk due to their increased exposure through dust ingestion and hand-to-mouth activities. Among the detected elements, Fe and Al are commonly present at higher concentrations, reflecting their natural abundance in the Earth's crust (Latif et al. 2014). However, toxic heavy metals such as Pb, Cd, Zn, and Cr are primarily introduced into indoor environments through anthropogenic sources.

In Malaysia, traffic emissions have consistently been identified as a major contributor to indoor metal contamination, with road dust and vehicular activities facilitating the infiltration of Pb, Zn, and Cu into indoor spaces (Abdul Wahab et al. 2012; Tan et al. 2018). The use of Pb-based paints in older buildings, industrial emissions, agricultural fertilizers, deteriorating household materials, and electronic waste have also been documented as significant indoor emission sources (Yap et al. 2011; Sulaiman et al. 2017). Furthermore, studies have shown that indoor dust often contains higher concentrations of heavy metals compared to outdoor dust, due to household activities such as cooking, cleaning, and the use of mechanical appliances (Latif et al. 2011).

Dust can serve as a reservoir for organic and inorganic pollutants, including heavy metals. The sources of heavy metal in the dust could originate from natural sources or human activities (Kurt-Karakus 2012; Iwegbue et al. 2017). Additionally, building occupants' habits and daily activities such as renovations, smoking, cooking, burning incense, and using cleaning agents, significantly contribute to the enrichment of heavy metals in indoor house dust (Hassan 2012; Doyi et al. 2019).

Some trace elements like zinc, copper, manganese, aluminum, and iron are essential elements for human well-being, and they are harmless if in low levels of exposure. However, humans will face significant health risks when exposed to dust containing heavy metals due to their toxicity and excessive doses of exposure. Elements like arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni) are highly toxic even if humans are exposed in extremely low dosage because they act as cofactors for various cancers and diseases by interfering with the DNA sequence which cause gene mutation (Chattopadhyay et al. 2003).

Ingestion, inhalation, and skin absorption are the three primary pathways for heavy metal exposure in humans. Children have higher metabolism rates and lower renal clearance than adults which results in children facing higher health risks due to bioaccumulation and persistence of the heavy metals in their bodies (Zeng et al. 2016). According to the previous research findings, indoor dust exposure is the primary cause of lead poisoning among children in developing countries (Shi and Wang 2021). Lead poisoning will affect the neurological system, which could lead to neurologic deficit and affect the children's intelligence performance, hearing, sight impairment and behavioral change (Tan et al. 2016).

Most indoor studies on the health risks of heavy metal exposure have focused on settings such as classrooms, offices, and nurseries in metropolitan cities. However, limited research has been carried out at indoor home environment in developing countries, such as Malaysia. A previous study done at residential areas near the mining site in China (Cao et al. 2022; Li et al. 2019) revealed the enrichment of heavy metals in the household dust. Another study conducted in a residential area near a mining site in Pahang, Malaysia, revealed that Cd poses potential carcinogenic and non-carcinogenic risks to the local residents (Shafie and Mohtar 2021). Moreover, some studies also found the impact of persistent contamination of heavy metals in soil and water in ex-mining towns (Ashraf et al. 2011; Abdul Hamid et al. 2020). Thus, this study is crucial in identifying the concentrations of heavy metals in household settled dust and their associated health risks in ex-mining towns like Kampar, Perak.

This transition of Kampar from tin mining town into education hub in recent decades has contributed to population growth and increased traffic density which have affected the local air quality. Despite these developments, there remains a significant research gap regarding the health risk assessment of heavy metals in household dust and their enrichment levels in Kampar town. Therefore, this research aims to study the socio-demographics and daily activities of Kampar residents through survey questionnaires, to determine the heavy metal concentration (Al, Zn, Fe, Cu, Mn, As, Pb, Cr, Cd, Ni) in the household settled dust, to assess the carcinogenic and non-carcinogenic risk of heavy metals exposure among adults and children in indoor home environments, and to investigate the significant risk factors that associated with concentration of heavy metals in the indoor household settled dust.

2 Methods

2.1 Study Area

The study was conducted in Kampar Town, the largest town in Kampar District, Perak state, Malaysia, between January 2023 – October 2023. Kampar is an ex-tin mining town that situated within the Kinta Valley (4° 18′ 0" N, 101° 9′ 0" E), which is surrounded with lakes. It experiences significant changes after the cessation of tin mining activities in the late 1980s. The rise of agriculture, commercial activities, and education institutions has transformed Kampar's economic landscape. Kampar has a tropical climate that experiences significant rainfall even during the drier months, with less rainfall occurring between June and August. The yearly average temperature and rainfall in Kampar are 24.8 °C (76.6 °F) and 3189 mm, respectively (Data Source 2022).

2.2 Study Population

The study population in this study was residents who were staying in Kampar town. Inclusion and exclusion criteria were set for households and respondents' selection to control potential confounding bias. For housing selection, this study included landed terrace houses, apartments, condominiums, or residential flats that located in Kampar Town, while the residential units above the shop lots, industrial buildings, schools, offices and homestays were excluded in this study.

A total of 51 households from 17 residential areas in Kampar were randomly approached. Then, the survey questionnaires were distributed to 200 Kampar residents who living in these 51 households through physical or online questionnaire. Respondents who were not living in Kampar, younger than 13 years old or older than 64 years old were excluded from this study.

In the questionnaire, the participants were asked to provide information about their household characteristics, daily activities, and habits as investigated in other previous published studies (Norbäck et al. 2019; Wang et al. 2019; Liu et al. 2022). The questions on household characteristics included as below "Do your current staying house is less than 200 m from the main road or highway?", "Is the house you currently staying has been renovated in the past 12 months?", and "Smoker occupant in house" (yes/no). One question consists of the presence frequency of pest in the house, followed by list of pest: cockroaches, mice/rats, houseflies/mosquitoes, each with possible responses of 'always', 'sometimes', 'rarely' and 'never'. Then one question regards the frequency of household members engage the following activities (switch on air conditioning, use of air purifier, spray insect repellent/aerosol, burning incense/light the candle/ burn mosquito coils, open burning (include nearby neighbourhood), cooking), given the possible responses 'always', 'often', 'sometimes', 'rarely' and 'never'. Then, the final part of the survey form requested their consent for the collection of indoor house dust samples. For participants who agreed to participate in dust sample collection, home visits were conducted one to two times to collect an adequate amount of dust sample (at least 0.5 g).

2.3 Indoor Settled Dust Sample Collection and Analysis

A total of 51 household settled dust samples were collected across Kampar Town between January 2023 and October 2023. The settled dust from each household was collected from accessible places (floors, windowsills, fans, and furniture) in the living rooms (Boisa and Odagwe 2019; Latif, et al. 2014) using a handheld vacuum cleaner (Brand: AmazeFan, Model: 338,000 rpm/min Wireless Vacuum Cleaner). The vacuumed settled dust was transferred into resealable plastic bags, and labelled accordingly (Bai et al. 2003). These dust samples were then stored in a laboratory freezer at -18 °C until further analysis. The samples were sieved (< 100 µm) to remove large particles such as stones, insect carcasses, hair (Wahab, et al. 2012), and pet fur. The remaining dust was dried in a drying oven at 105 °C for 24 h and transferred to desiccator to cool down prior sample digestion.

About 0.5–1.0 g of dust sample was weighed for each household dust sample and 30 mL *aqua regia* solution (65% HNO_3, 36% HCl, v/v, 3:1) were used to digest the sample (Harrison and Perry 1986; Hassan 2012). The mixture was digested on the hot plate for an hour under magnetic stirring, and the watch glass was placed on the beaker to monitor the brownish gas emitted. The watch glass was removed interval to release brownish gas emitted during the heating process. The halting of brownish gas emitted indicated the complete of digestion process. The digestate was cooled to 25 °C, followed with top up to 50 mL using Milli-Q water, before being filtered through 0.45 µm CA syringe filter. Each digestate dust sample was serially diluted, with all dilutions prepared in duplicate. The filtered solution samples were kept in centrifuge tubes and stored under -20 °C prior the Inductively Couple Plasma Optical Emission Spectrometry (ICP-OES) (PerkinElmer *Optima 7000 DV,* USA) analysis.

2.4 Quality Control and Assurance

The ICP-OES instrument was calibrated using blank and a standard curve of 50 ppb, 100 ppb, 200 ppb and 500 ppb was prepared from multi-element stock solution (Sigma-Aldrich, *Multielement Standard Solution 6 for ICP*, Switzerland). The detection limit of ICP-OES for each element were Al: 0.9 ppb, As: 3.6 ppb, Cd:0.07 ppb, Cr: 0.25 ppb, Cu: 0.9 ppb, Fe: 0.2 ppb, Mn: 0.03 ppb, Ni: 0.4 ppb, Pb: 1.4 ppb, and Zn: 0.2 ppb.

To minimise cross-contamination, the apparatus and head of vacuum cleaner were washed with laboratory detergent, followed by soaked in 1% HNO_3 for overnight and rinsed with distilled water (Wahab et al. 2012). Besides, the dust cup filter was replaced once dust sample collection of each household was completed, to prevent cross-contamination.

2.5 Enrichment Factor

The enrichment factor (EF) was used to evaluate the degree of contamination of indoor household dust samples compared to the background value. The formula used was as below (Li et al. 2019):

$$EF = \frac{\left[\frac{Cx}{Cref}\right] sample}{\left[\frac{Cx}{Cref}\right] background}$$

where, [Cx/Cref] sample represents the ratio of the concentration of the targeted element to the reference element (Al) in indoor house dust samples, while [Cx/Cref] background represents the ratio of the background concentration of the targeted element to the reference element (Al), using the provided background values. Basically, Al was used as a reference element for assessing the enrichment factor due to it is high abundance element and relatively stable compared to other selective elements in Malaysia (Shaari et al. 2018). The degree of heavy metals enrichment (Li et al. 2019) was classified as depicted in Table 1.

2.6 Health risk Assessment (HRA)

The non-carcinogenic risk of HM exposure for adults and children was assessed for Al, Zn, Fe, Pb, Cu, Cr, Mn, Cd, Ni, and As by computing the Hazard Quotient (HQ) for three exposure routes (oral intake, dermal absorption, inhalation)

Table 1 Enrichment factor (EF) classification

Enrichment range (EF)	Description
EF < 1	No enrichment
1 < EF < 2	Minor enrichment
2 < EF < 5	Moderate enrichment
5 < EF < 20	Significant enrichment
20 < EF < 40	Very significant
EF > 40	Extremely enrichment

as showed in Eqs. (1) – (4) (US EPA 2011). Then, the sum value of the HQ for three exposure routes was calculated as Hazard index (HI), as showed in Eq. (5). If HI value more than 1.0, it indicates a significant non-carcinogenic risk. The reference values and denotations of parameters used in this study were shown in Table 2. Table 3 shows the reference doses for HRA estimation, with every element has its respective reference dose value for different exposure pathways that used in current study (USEPA, 2002; USDOE, 2011; USEPA, 2011a; USEPA., 2011b).

$$\mathrm{ADDingestion} = \frac{(\mathrm{C} \times \mathrm{Ing} \times \mathrm{EF} \times \mathrm{ED})}{(\mathrm{BW} \times \mathrm{AT})} \times 10^{-6} \quad (1)$$

$$\mathrm{ADDskin} = \frac{(\mathrm{C} \times \mathrm{SA} \times \mathrm{SAF} \times \mathrm{ABS} \times \mathrm{EF})}{(\mathrm{BW} \times \mathrm{AT})} \times 10^{-6} \quad (2)$$

$$\mathrm{ADDinhalation} = \frac{(\mathrm{C} \times \mathrm{InhR} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{PEF})}{(\mathrm{BW} \times \mathrm{AT})} \quad (3)$$

$$\mathrm{HQ} = \mathrm{ADD} \times \mathrm{RfD} \quad (4)$$

$$\mathrm{HI} = \sum \mathrm{HQ} = \mathrm{HQingestin} + \mathrm{HQskin} + \mathrm{HQinhalation} \quad (5)$$

Certain elements in this study, for instance Ni, As, Cd, Cr, and Pb, that possibly pose carcinogenic risk (CR) to children and adults were estimated (Agency for Research on Cancer IACR, 2013). Carcinogenic risk of each element was calculated using Eq. (6) by adopting the cancer slope factor listed in Table 3. The Total Lifetime Carcinogenic Risk (TLCR) of each element was assessed by total-up the values of three exposure pathways (Eq. (7)). The TLCR value exceeds the threshold value 1×10^{-4} indicates significant carcinogenic risk posed to humans, if ranges between 1×10^{-4} and 1×10^{-6} indicates the TLCR is within the permissible limit, while lower than 1×10^{-6} indicates the carcinogenic risk posed to residents is negligible (USEPA, 2002).

$$\mathrm{CR} = \mathrm{ADD} \times \mathrm{CSF} \quad (6)$$

$$\mathrm{TLCR} = \sum \mathrm{CRingestion} + \mathrm{CRskin} + \mathrm{CRinhalation} \quad (7)$$

Table 3 Reference dose and cancer slope factor (mg/kg/day) for each heavy metal (USEPA, 2002; USDOE, 2011; USEPA 2011a; USEPA 2011b)

Element	RfD oral	RfD dermal	RfD inhalation	CSF
Al	1	1	4.00E-04	–
Fe	7.00E-01	7.00E-01	7.00E-01	–
Zn	3.00E-01	6.00E-02	3.00E-01	–
Cu	4.00E-02	1.20E-02	4.00E-02	–
Mn	2.40E-02	1.40E-02	1.40E-02	–
As	3.00E-04	1.23E-04	3.00E-04	1.51E+00
Cd	1.00E-03	1.00E-05	1.00E-03	6.30E-01
Cr	3.00E-03	6.00E-05	2.86E-05	4.20E-01
Pb	3.50E-03	5.52E-04	3.52E-02	4.20E-02
Ni	2E-02	5.40E-03	2.06E-02	8.40E-01

Table 2 The constant value for each parameter in health risk assessment equation (USEPA 2002; USEPA 2011a)

Parameter	Symbol	Value
Heavy metal concentration	C	From household dust
Ingestion rate	Ing (mg/day)	Children = 200 mg/kg
		Adult = 100 mg/kg
Exposure duration	ED (years)	Children = 6 years
		Adult = 20 years
Exposure frequency	EF (days/year)	350 days/year
Body weight	BW (kg)	Children = 32 kg
		Adult = 60 kg
Average time for non-carcinogenic	AT (years)	ED × 365 days
Average time for carcinogenic	AT (years)	70 (lifetime) x 365 days
Expose dermal area	SA	Children = 2800 cm^2
		Adult = 5700 cm^2
Dermal adherence factor	SAF	Children = 0.2 mg cm^{-2}
		Adult = 0.07 mg cm^{-2}
Dermal absorption factor	ABS	0.001
Particle emission factor	PEF	1.36×10^9 m^3/kg
Inhalation rate	InhR (m^3/day)	Children: 7.6 m^3/day
		Adult: 20 m^3/day

2.7 Statistical Analysis

Data analysis was performed using Statistical Package for the Social Sciences (SPSS) software version 26.0 and STATA 18.0. The data distribution, skewness and kurtosis values for concentrations of heavy metals in this study were found not normally distributed. Thus, the Mann–Whitney U test was employed to evaluate significant differences in heavy metal concentrations in house dust between exposed and unexposed groups. The exposed group was defined as individuals with frequent exposure to potential risk factors, whereas the unexposed group comprised those without such exposure. Correlation coefficients between the elements were assessed using Spearman's rank correlation test. The multilevel linear mixed effect model adjusted with covariates (200 m away from highway or main road and house with renovation work in past 12 months) was performed to analyse the association between household occupants' activities and habits with the attribution of heavy metals concentration in household settled dust. All statistical tests were two- tailed, and a significance level of $p < 0.05$ was considered indicative of statistical significance.

3 Results and Discussion

3.1 Socio-Demographic of Respondents and Daily Living Activities

A total of 200 respondents participated in this survey study, with 51% of them were female, while 49% were male. The mean age of the respondents was 30 years (± 14.4), and their mean body weight was 60 kg (± 12.25). The daily household activities and habits of study respondents are summarised in Table 4. Majority (66.7%) of the respondents in this study lived in terrace house and near to busy road or highway. Dampness issues of the households were highlighted in this research (Table 5), notably 58.8% of the households had damp stain on the ceiling/floor/wall. Most of the households (60.8%) used liquefied petroleum gas (LPG) as cooking fuel, and the remaining 39.2% of household using electric induction cooker for cooking.

Table 5 Household characteristics in Kampar Town (n = 51)

Parameter		n (%)
Buildings type	Terrace house	34(66.7)
	Apartment/condominium	8(15.7)
	Town house	7(13.7)
	Flat	2(3.9)
< 200 m to highway/ busy road		34(66.7)
Renovated in last 12 months		11(21.6)
LPG as cooking fuel		31(60.8)
Mold odour [a]	Sometimes	22(43.1)
	Weekly	2(3.9)
Visible mold spot [a]		22(43.1)
Water damage [a]		21(41.2)
Damp stain [a]		30(58.8)
Presence of smoker		12(23.5)
Raise furry pets indoor		17(33.3)

[a]dampness condition in last 12 months

3.2 Distribution of Heavy Metals Concentration in Household Settled Dust

The metal loading concentration in the household dust samples is represented in Table 6. The highest median concentration in the household settled dust was Al, followed by Zn > Fe > As > Pb > Ni > Cu > Mn > Cr. The relatively higher concentrations of Al, Zn, and Fe in house dust might be due to the abundant earth crustal values in Malaysia, as similar trends of heavy metal distribution have been found in previous local studies (Han et al. 2014;

Table 4 Household anthropogenic activities (n = 51)

Activities	Frequency, n (%)				
	Never	Rarely	Sometimes	Often	Always
Air conditioning	6(11.8)	2(3.9)	7(13.7)	10(19.6)	26(51.0)
Air purifier	38(74.5)	6(11.8)	2(3.9)	2(3.9)	3(5.9)
Spray insect repellent/aerosol	9(17.6)	20(39.2)	17(33.3)	4(7.8)	1(2.0)
Burning incense/mosquito coil	33(64.7)	4(7.8)	3(5.9)	3(5.9)	8(15.7)
Open burning	27(52.9)	16(31.4)	5(9.8)	1(2.0)	2(3.9)
Cooking activities	2(3.9)	9(17.6)	14(27.5)	13(25.5)	13(25.5)
Pan frying	8(15.7)	9(17.6)	9(17.6)	15(29.4)	10(19.6)
Deep frying	17(33.3)	19(37.3)	8(15.7)	6(11.8)	1(2.0)
Boiling/steaming	2(3.9)	6(11.8)	14(27.5)	14(27.5)	15(29.4)
Baking	32(62.7)	13(25.5)	6(11.8)	0(0)	0(0)
Roasting	38(74.5)	12(23.5)	1(2.0)	0(0)	0(0)

Table 6 The heavy metals concentration in household settled dust (n = 51)

Elements (mg/kg)	Mean ± SD	Median	Min	Max	25th	75th
As	63.93 ± 41.68	56.55	1.06	204.59	34.23	89.17
Zn	7515.84 ± 10,876.40	4223.25	18.64	63,469.97	2440.13	7759.39
Fe	2918.10 ± 3452.670	1609.46	6.79	15,688.96	782.25	3696.02
Ni	70.53 ± 49.14	56.24	30.14	367.82	46.053	75.73
Pb	60.31 ± 33.97	56.31	0.31	165.32	34.48	80.70
Al	37,992.65 ± 70,192.54	24,397.00	1676.76	518,440.82	11,148.59	34,614.80
Cd	6.07 ± 3.19	5.53	1.52	16.77	3.92	6.74
Cu	176.48 ± 615.00	43.23	11.84	4596.73	25.98	64.68
Cr	22.66 ± 32.19	13.14	0.19	175.53	5.98	27.29
Mn	46.44 ± 41.28	35.85	0.18	203.31	17.59	56.55

Tay, et al. 2021). The descriptive statistics of metal concentrations in indoor dust are presented in Table 6. Among all elements, Al exhibited the highest mean concentration (37,992.65 mg/kg), consistent with its natural abundance in soil-derived particulate matter. Zinc showed the second highest mean concentration (7515.84 mg/kg) with a notably wide range (18.64–63,469.97 mg/kg), indicating substantial variability likely driven by site-specific anthropogenic inputs. Arsenic presented a high mean value of 63.93 mg/kg, with concentrations ranging from 1.06 to 204.59 mg/kg, suggesting potential anthropogenic activities contamination. Copper and Cr also demonstrated elevated variability, with Cu ranging from 11.84 to 4596.73 mg/kg and Cr from 0.19 to 175.53 mg/kg. Cadmium, present at lower absolute concentrations (mean: 6.07 mg/kg), Mn, Ni, and Pb with mean values ranging from 46.44 to 70.53 mg/kg. Overall, the high standard deviations observed for most metals imply heterogeneous distribution patterns, reflecting differences in household characteristics, occupant activities, and surrounding environmental sources.

3.3 Enrichment Factor

The enrichment factor of each element in household dust was determined in Kampar Town, ranging from insignificant enriched to extremely enriched. The purpose of this analysis is to identify the heavy metals were enriched by anthropogenic activities or origin from natural resources. Zinc was found to be extremely enriched (EF = 203.52), which indicated the Zn concentration in house dust were mainly attributed by inhabitants' daily activities or other anthropogenic activities. High Zn loading in indoor household dust samples can be explained by the widespread application of Zn in building materials and daily use items such as paint, wood preservatives, batteries, alloy-coated materials, utensils used for culinary activities, and outdoor sources. Moreover, As and Cd were extremely enriched, while Pb was significantly enriched

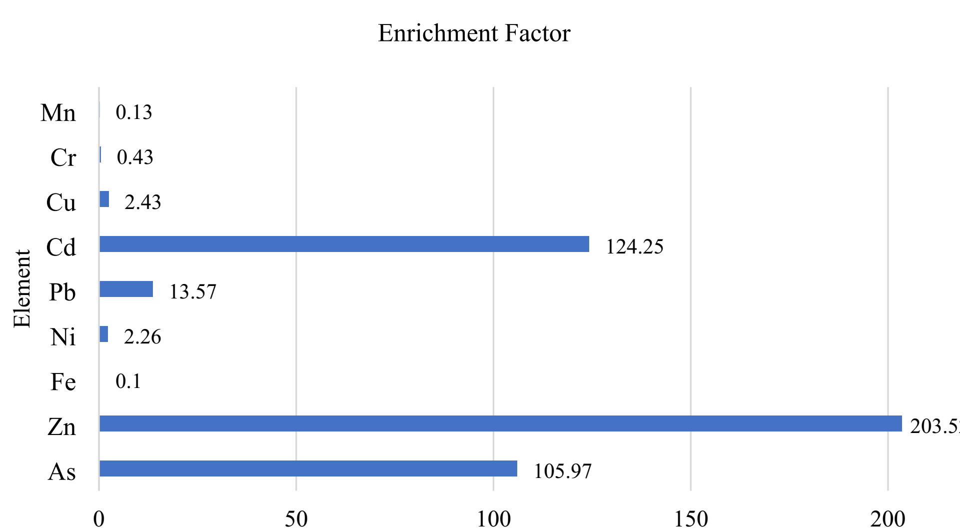


Fig. 1 Enrichment factor of heavy metals in household dust

(Fig. 1) due to anthropogenic activities by building occupants or from outdoor sources like automobile emissions, tire wear, road dust, construction, and factory emissions (Kurt-Karakus 2012; Rivero et al. 2023; Chattopadhyay et al. 2003). As Malaysian practice open window and door routinely for natural ventilation, the outdoor atmospheric metal-deposited grime can be transported into indoor dwellings via open windows and doors or entryways. Besides, a significant amount of heavy metals in house dust could be brought in by occupants' footwear from outside (Rivero et al. 2023). This is supported by the USEPA (2004) statement that up to 70% of indoor house dust originates from outdoor soil. Thus, the heavy metals in household settled dust in this study could be transported from the outdoor environment and indoor anthropogenic activities.

3.4 Correlation Matrices between Elements

The spearman ranking correlation test shows elements Mn-Fe-Zn-Al-Cu-Cr-Pb in the household settled dust were positively significant ($p < 0.05$) correlated with each other (Table 7). The Fe and Mn were strongly correlated ($p < 0.01$) with correlation coefficients of 0.903, suggesting they are from the natural background elements concentration (Jadoon et al. 2020). Most of the elements display a significant correlation with each other, which indicated they might originate from the same source. There were negative correlations between elements tabulated in Table 7, which suggested they might come from different sources of pollutants. Arsenic is significantly correlated with Cd, which could be originated from common anthropogenic sources, such as vehicular emissions, fossil fuel combustion, and household product usage. This indicates that indoor dust contamination is influenced by human activities rather than purely geogenic inputs.

3.5 Health Risk Assessment

Notably, the non-carcinogenic risk assessment indicates no significant non-carcinogenic risk was identified for children for other elements, except HI of 1.20 for As exposure in household dust among children in Kampar, which exceeds the acceptable threshold (HI > 1) that suggests a potential non-carcinogenic risk. As summarized in Table 8, the HI values for adults were below the critical limit (HI < 1) for all elements, which indicated minimal non-cancer risk for the adult population. For children, ingestion was the primary exposure route, with HQ of 1.12 for As exposure. According to a study by Diami and colleagues, the risk of arsenic exposure was found to be higher in former mining areas compared to active iron ore mining sites in Pahang, Malaysia, and suggested that the adverse effects of arsenic in the environment may persist long after mining activities have ceased (Diami et al. 2016). Besides, another study conducted at an inactive mining site in Thailand reported that 4.5% of the children's urine contained inorganic As level that exceeded the range set by Agency for Toxic Substances and Disease Registry (ATSRD) (Kunwittaya et al. 2022). Moreover, 16% of the drinking water in a former mining area located in Mexico was contaminated with As, above 0.025 mg/L, which is the standard limit of Mexican regulation (Wurl et al. 2018). Arsenic pollution in these areas was due to historical mining activities (Diami et al. 2016; Kunwittaya et al. 2022; Wurl et al. 2018). Chronic As exposure could lead to skin conditions such as hyperkeratosis and Bowen's disease (Li et al. 2016).

The carcinogenic health risk assessment for each carcinogenic element was assessed through calculation of Total Lifetime Cancer Risk (TLCR). The TLCR values in this study were within the tolerable range (1×10^{-4} to 1×10^{-6}), suggesting no significant cancer risk from exposure to heavy metals in household dust through ingestion, dermal contact, or inhalation for both children and adults in Kampar Town (Table 9). The TLCR values for elements were ranked in

Table 7 Correlation matrices of elements in house dust samples (n = 51)

	As	Zn	Fe	Ni	Pb	Al	Cd	Cu	Cr	Mn
As	1.000									
Zn	−0.353**	1.000								
Fe	−0.45**	0.766**	1.000							
Ni	0.129	0.248*	0.253*	1.000						
Pb	0.168	0.517**	0.288*	0.406**	1.000					
Al	−0.332**	0.634**	0.744**	0.094	0.265*	1.000				
Cd	0.274*	0.125	−0.156	0.356**	0.409**	−0.100	1.000			
Cu	−0.350**	0.518**	0.595**	0.545**	0.390**	0.380**	0.044	1.000		
Cr	−0.494**	0.574**	0.704**	0.439**	0.297*	0.557**	0.061	0.639**	1.000	
Mn	−0.482**	0.722**	0.903**	0.245	0.299*	0.823**	−0.0128	0.543**	0.691**	1.0000

*$p < 0.05$, **$p < 0.01$, n = sample size

Table 8 Non-carcinogenic risk associated with the heavy metals exposure in household dust among adults and children in Kampar, Perak

Adults	As	Zn	Fe	Ni	Pb	Al	Cd	Cu	Cr	Mn
ADI_oral	8.97E-05	6.70E-03	2.55E-03	8.92E-05	8.94E-05	3.87E-02	8.77E-06	6.86E-05	2.09E-05	5.69E-05
ADI_dermal	3.59E-06	2.68E-04	1.02E-04	3.57E-06	3.57E-06	1.55E-03	3.50E-07	2.74E-06	8.33E-07	2.27E-06
ADI_inh	1.32E-08	9.86E-07	3.76E-07	1.31E-08	1.31E-08	5.69E-06	1.29E-09	1.01E-08	3.07E-09	8.37E-09
HQ_oral	2.99E-01	2.23E-02	3.65E-03	4.46E-03	2.55E-02	3.87E-02	8.77E-03	1.71E-03	6.95E-03	4.06E-03
HQ_dermal	2.91E-02	4.46E-03	1.46E-04	6.60E-04	6.47E-03	1.55E-03	3.50E-02	2.28E-04	1.39E-02	5.98E-07
HQ_inh	4.40E-05	3.29E-06	5.37E-07	6.37E-07	3.73E-07	1.42E-02	1.29E-06	2.52E-07	1.07E-04	5.98E-07
HI = ∑HQ	3.28E-01	2.68E-02	3.79E-03	5.12E-03	3.20E-02	5.45E-02	4.38E-02	1.94E-03	2.09E-02	4.06E-03
Children										
ADI_oral	3.36E-04	2.51E-02	9.56E-03	3.34E-04	3.34E-04	1.45E-01	3.28E-05	2.57E-04	7.80E-05	2.13E-04
ADI_dermal	9.40E-06	7.02E-04	2.68E-04	9.35E-06	9.36E-06	4.06E-03	9.19E-07	7.19E-06	2.18E-06	5.96E-06
ADI_inh	9.38E-09	7.01E-07	2.67E-07	9.33E-09	9.34E-09	4.05E-06	9.17E-10	7.17E-09	2.18E-09	5.95E-09
HQ_oral	1.12E+00	8.36E-02	1.37E-02	1.67E-02	9.55E-02	1.45E-01	3.28E-02	6.42E-03	2.60E-02	1.52E-02
HQ_dermal	7.64E-02	1.17E-02	3.82E-04	1.73E-03	1.70E-02	4.06E-03	9.19E-02	5.99E-04	3.64E-02	4.25E-07
HQ_inh	3.13E-05	2.34E-06	3.81E-07	4.53E-07	2.65E-07	1.01E-02	9.17E-07	1.79E-07	7.62E-05	4.25E-07
HI = ∑HQ	1.20E+00	9.53E-02	1.40E-02	1.84E-02	1.12E-01	1.59E-01	1.25E-01	7.02E-03	6.25E-02	1.52E-02

Table 9 Carcinogenic risk associated with the exposure of heavy metals in household dust among adults and children in Kampar, Perak

Adults	As	Ni	Cr	Cd	Pb
ADI_oral	2.56E-05	2.55E-05	5.96E-06	2.50E-06	2.55E-05
ADI_dermal	1.02E-06	1.02E-06	2.38E-07	9.99E-08	1.02E-06
ADI_inh	3.77E-09	3.75E-09	8.76E-10	3.68E-10	3.75E-09
CR_oral	3.85E-05	2.14E-05	2.50E-06	1.58E-06	1.07E-06
CR_dermal	1.53E-06	8.55E-07	9.98E-08	6.30E-08	4.28E-08
CR_inh	5.65E-09	3.15E-09	3.68E-10	2.32E-10	1.58E-10
∑ TLCR	4.00E-05	2.23E-05	2.60E-06	1.64E-06	1.12E-06
Children					
ADI_oral	2.88E-05	2.86E-05	6.69E-06	2.81E-06	2.87E-05
ADI_dermal	8.06E-07	8.01E-07	1.87E-07	7.87E-08	8.02E-07
ADI_inh	8.04E-10	8.00E-10	1.87E-10	7.86E-11	8.01E-10
CR_oral	4.32E-05	2.40E-05	2.81E-06	1.77E-06	1.20E-06
CR_dermal	1.21E-06	6.73E-07	7.86E-08	4.96E-08	3.37E-08
CR_inh	1.21E-09	6.72E-10	7.85E-11	4.95E-11	3.36E-11
∑ TLCR	4.44E-05	2.47E-05	2.89E-06	1.82E-06	1.24E-06

descending order as follows: As, Ni, Cr, Cd, and Pb for both adults and children. Arsenic exhibited the highest TLCR, particularly among children (4.44×10^{-5}), with cancer risk (CR) values of 4.32×10^{-5} for ingestion, 1.21×10^{-6} for dermal contact, and 1.21×10^{-9} for inhalation.

Hazardous metalloids pollutions were mainly linked with the anthropogenic activities such as mining, urbanisation, wastewater discharge, and application of pesticides and fertilisers in agriculture practice. In developing countries, weak environmental regulatory enforcement and limited education on safe handling practices of hazardous chemicals contribute to HM exposure in workers, contamination and pollution to the environment. These heavy metals could accumulate in the food chain and pose a significant public health concern. Some previous research work reported high As content was found in rice (0.11–53 mg/kg), fish (0.01–50.34 mg/kg), meat (0.002–44.6 mg/kg), and vegetables (0.004–27.3 mg/kg) (Machate 2023).

The concentrations of indoor HM could be influenced by building occupants' activities such as cooking activities, the flaking building materials or transport from outdoor fine particles by wind or shoes, mining activities, use of pesticides and herbicides. Our research findings are in line with findings of other studies in which a health risk assessment of heavy metal study conducted in Hubei, China reported carcinogenic risk of Asc exposure posed to children aged 3–5 years old in urban residential indoor dust was around 4.00×10^{-5}, and the indoor As concentration was significantly ($p < 0.05$) higher compared to outdoor As concentration (Liu et al. 2016). In this study, we found that the TLCR values of As, Ni, Cr, Cd, and Pb were higher for children compared to adults, reflecting the greater vulnerability of children due to their lower body weight and higher inhalation rates in the exposure models.

The ingestion route was identified as the predominant exposure pathway for heavy metals in dust particles, followed by dermal contact and inhalation, which were consistent with previous findings (Shabanda et al. 2019; Tashakor et al. 2022; Jadoon et al. 2020). This pattern is particularly pronounced in children due to behaviours such as crawling on the floor and frequent hand-to-mouth activities, which increase the likelihood of ingesting dust particles containing heavy metals (Tashakor et al. 2022; Xu et al. 2021; Tan et al. 2018).

3.6 The Risk Factors Attributed to Heavy Metals in Indoor House Settled Dust

The results shown in Table 10 revealed the factors and daily activities engaged by occupants that significantly associated with the increase of heavy metals in household settled dust in Kampar Town using both bivariate (Mann–Whitney U test) and multivariate (Multilevel Linear Mixed Effect model) analysis.

3.6.1 Pest Presence

Mann–Whitney U identified a significant association between the presence of houseflies and mosquitoes and increased concentrations of Pb ($p < 0.001$, U-value = 283.00) and Zn (p = 0.003, U-value = 257.00), suggesting that pest presence is linked to higher heavy metal levels in house dust. Multilevel linear mixed model analysis, adjusted with < 200 m proximity to heavy road/ highway and underwent renovation in last 12 months, refined these findings, showing that only Cd (p = 0.041, OR: 1.182, 95% CI = 1.007–1.219) and Zn (p = 0.021, OR: 1.757, 95% CI: 1.089–2.834) remained significantly associated with more frequent pest presence. This highlights the potential role of confounding factors in the observed bivariate relationships and underscores the need for adjusted models to identify significant independent predictors. Poor hygiene and waste management practice create favorable conditions for the pest's infestation, especially in urban areas. The waste and garbage that is contaminated with hazardous substances attract houseflies and mosquitoes. Hence, mosquitoes and houseflies act as the vectors to contaminate the household environment (Gutberlet and Uddin 2018). Mosquitoes and houseflies' infestation may increase the usage of insecticides and mosquitoes' sprays by residents to kill the pest. These insecticides and mosquito sprays contain heavy metals such as Zn, Cd, Pb, Cu which may increase the concentration of heavy metals in the household settings (Alengebawy et al. 2021).

3.6.2 Furry Pets Ownership

Households with furry pets showed lower concentrations of several heavy metals, including Zn, Fe, Ni, Pb, Al and Cd, compared to those without pets. Bivariate analysis revealed a significant negative association between pet ownership and copper (Cu) levels (p = 0.040, U-value = 186.00), possibly reflecting more frequent cleaning practices by pet owners (Xu et al. 2021). However, this association was not significant in the multivariate analysis, suggesting that pet-related cleaning may interact with other household factors that influence heavy metal accumulation in the settled dust.

3.6.3 Burning Practices and Heavy Metal Exposure

The burning of incense sticks and mosquito coils was significantly associated with elevated Pb levels in both bivariate (p = 0.003, U-value = 348.00) and multivariate analyses ($p < 0.05$, OR: 1.202, 95% CI: 1.028–1.405). These findings are consistent with prior studies linking incense burning to increased indoor lead exposure (Lee et al. 2021). Burning mosquitoes' coil in spiral shape is usually used as insect repellents while incense for ritual purpose, both emitting smoke containing trace elements such as Cd, Zn, Pb (Liu et al. 1987; Lee et al. 2021). Conversely, open burning, which was significant in bivariate analysis ($p < 0.05$), did not remain significant in the multivariate model, indicating the influence of confounding variables such as outdoor air quality or ventilation practices.

3.6.4 Air Purifiers and Air Conditioning

The use of air purifiers significantly reduced Al levels in the bivariate analysis (p = 0.049, U-value = 53.00). Multivariate analysis confirmed these results, showing significant reductions in concentrations of Al (p = 0.034, OR: 0.763, 95% CI: 0.594–0.980) and Mn (p = 0.014, OR: 0.698, 95% CI: 0.525–0.929). These findings support the effectiveness of air purifiers equipped with high efficiency particulate air (HEPA) and electrostatic filters in mitigating indoor heavy metal pollution (Fazlzadeh et al. 2022). In contrast, frequent use of air conditioner was associated with higher Cu levels in the bivariate analysis (p = 0.043,

Table 10 Associations of indoor heavy metal dust concentration (log 10 transformed) between the daily household activities and habits of residents

Variables	Al OR, 95% CI		Cd OR, 95% CI		Cu OR, 95% CI		Cr OR, 95% CI		Mn OR, 95% CI		As OR, 95% CI		Zn OR, 95% CI		Fe OR, 95% CI		Ni OR, 95% CI		Pb OR, 95% CI	
Cockroaches	0.955		1.130		0.916		1.022		1.071		0.950		0.998		1.187		1.057		0.868	
	0.604	1.511	0.934	1.367	0.565	1.484	0.641	1.629	0.630	1.820	0.646	1.398	0.558	1.787	0.652	2.159	0.887	1.260	0.595	1.268
Rats presence	0.615		1.042		0.751		0.995		0.680		1.103		1.070		0.640		1.105		1.265	
	0.375	1.007	0.840	1.292	0.440	1.281	0.591	1.673	0.380	1.218	0.718	1.696	0.559	2.048	0.331	1.237	0.909	1.342	0.832	1.925
House-flies/mosquitoes presence	1.020		**1.182***		1.291		1.066		1.073		1.106		**1.757***		1.245		1.137		1.346	
	0.686	1.516	**1.007**	**1.388**	0.855	1.949	0.713	1.593	0.679	1.697	0.793	1.542	**1.089**	**2.834**	0.744	2.085	0.980	1.319	0.979	1.851
Visible mold spot	0.858		1.000		1.043		0.873		0.931		0.801		0.683		0.878		0.933		0.634	
	0.478	1.538	0.782	1.280	0.563	1.933	0.482	1.580	0.473	1.832	0.491	1.306	0.327	1.424	0.408	1.886	0.746	1.167	0.397	1.014
Mould odour	1.122		1.130		1.331		1.236		1.104		1.022		1.004		1.248		1.013		1.044	
	0.676	1.861	0.915	1.396	0.784	2.259	0.741	2.062	0.614	1.984	0.666	1.566	0.527	1.910	0.645	2.418	0.833	1.230	0.686	1.590
Water damage	0.881		1.047		0.718		0.954		0.799		1.108		0.524		0.815		0.902		0.788	
	0.490	1.584	0.818	1.341	0.389	1.325	0.525	1.733	0.406	1.573	0.676	1.817	0.254	1.081	0.379	1.757	0.721	1.129	0.486	1.277
Damp stain	0.934		0.965		0.811		0.721		0.920		1.110		0.799		1.161		0.863		0.777	
	0.518	1.686	0.753	1.238	0.437	1.507	0.399	1.305	0.465	1.822	0.676	1.823	0.379	1.686	0.537	2.512	0.691	1.079	0.478	1.261
Vacuum the floor	0.853		**0.899*****		0.928		0.909		0.863		0.997		0.880		0.894		0.971		0.909	
	0.724	1.004	**0.842**	**0.959**	0.777	1.108	0.767	1.077	0.713	1.046	0.864	1.149	0.712	1.087	0.718	1.113	0.911	1.036	0.792	1.044
Air purifier	**0.763***		1.106		0.882		1.080		**0.698***		1.148		0.794		0.731		1.045		1.065	
	0.594	**0.980**	0.994	1.231	0.671	1.160	0.829	1.407	**0.525**	**0.929**	0.924	1.426	0.573	1.099	0.525	1.018	0.946	1.155	0.858	1.322
Burning incense/mosquito coil/candle	1.062		1.082		0.921		1.026		0.984		1.143		1.213		1.026		1.004		**1.202***	
	0.871	1.293	0.998	1.173	0.749	1.133	0.840	1.255	0.782	1.237	0.971	1.344	0.949	1.550	0.792	1.329	0.931	1.084	**1.028**	**1.405**

Table 10 (continued)

Variables	Al OR, 95% CI		Cd OR, 95% CI		Cu OR, 95% CI		Cr OR, 95% CI		Mn OR, 95% CI		As OR, 95% CI		Zn OR, 95% CI		Fe OR, 95% CI		Ni OR, 95% CI		Pb OR, 95% CI	
Cooking fuel type	0.681		1.190		0.708		1.026		0.841		1.898		1.707		0.870		0.981		**1.804***	
	0.378	1.225	0.929	1.523	0.380	1.319	0.559	1.882	0.422	1.676	1.185	3.042	0.812	3.591	0.399	1.900	0.780	1.234	**1.129**	**2.882**
Pan frying	0.968		0.952		1.013		1.088		0.931		1.067		0.899		0.911		**1.100***		0.999	
	0.780	1.200	0.870	1.041	0.807	1.271	0.875	1.353	0.726	1.193	0.891	1.278	0.685	1.179	0.688	1.207	**1.017**	**1.190**	0.835	1.195
Deep frying	0.958		0.994		1.005		1.205		0.886		1.124		0.967		0.904		1.075		1.120	
	0.729	1.258	0.886	1.115	0.754	1.341	0.917	1.582	0.647	1.214	0.895	1.412	0.684	1.367	0.633	1.291	0.969	1.191	0.895	1.402
Smoker occupant	0.796		1.152		0.798		1.568		0.705		1.413		0.970		0.892		1.128		1.234	
	0.402	1.577	0.865	1.534	0.388	1.640	0.790	3.113	0.321	1.550	0.799	2.499	0.406	2.314	0.364	2.188	0.868	1.464	0.701	2.174
Smoking frequency	0.850		**1.173***		0.896		1.176		0.763		1.183		0.939		0.818		**1.124***		1.049	
	0.627	1.153	**1.027**	**1.340**	0.747	1.075	0.894	1.545	0.446	1.305	1.005	1.393	0.549	1.608	0.435	1.535	**1.027**	**1.231**	0.874	1.260

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Model adjusted with cofounders: < 200 m proximity to heavy road/ highway, underwent renovation in last 12 months

U-value = 172.00), and this finding aligned with the research done by Tashakor et al. (2022). Air-conditioner can act as air filter or sink for air pollutants if they are infrequent cleaned and maintenance (Zainal et al. 2019). This research finding emphasizes the importance of proper cleaning and maintenance of indoor air pollution control devices in mitigating potential air quality impacts.

3.6.5 Cleaning Practices and Heavy Metal Reduction

Multivariate analysis identified frequent vacuuming (≥ 4 times per week) as a significant predictor of reduced Cd concentrations (OR: 0.899, 95% CI: 0.842–0.959, $p < 0.001$) in the household settled dust. This finding corroborates previous research highlighting the effectiveness of vacuuming in removing heavy metal particles from indoor surfaces (Naimabadi et al. 2020).

3.6.6 Cooking Methods and Heavy Metal Emissions

Cooking with liquid petroleum gas (LPG) or natural gas was significantly associated with higher levels of As (p = 0.022, U-value = 429.00) and Pb (p = 0.027, U-value = 425.00) in bivariate analysis. Utilization of liquid petroleum gas as cooking fuel could increase the heavy metals concentration in house (Pal et al. 2023), heavy metals are contained in the combustion as by-products of the fuel and deposited in the particulate matter which may be emitted during the cooking process. Besides that, the metal surface of cooking appliances while contact with high temperature also could be the possible source of indoor heavy metals at household. Although the association between cooking using LPG and higher Pb concentrations in household settled dust remains significant (p = 0.014, OR: 1.804, 95% CI: 1.129–2.882) in the multilevel linear mixed model, there was no evident found using LPG for cooking activities associated to Pb and As contamination in house dust. These results may therefore be influenced by other factors like residential locations of the respondents in this study. Most of the respondents who were using LPG for cooking were living in Old Town residential areas. In this study, the Old Town areas revealed significantly higher concentrations of Pb (p = 0.007) and As (p = 0.006) in the household settled dust compared to New Town. This could be due to old aged residential buildings in Old Town. Besides that, pan-frying was significantly associated with higher nickel (Ni) concentrations in both bivariate (p = 0.028, U-value = 441.50) and multivariate analyses (p = 0.018, OR: 1.100, 95% CI: 1.017–1.190), likely due to the release of pollutants from heated cookware (Pal et al. 2023).

3.6.7 Smoking and Indoor Heavy Metals

Smoking was associated with significantly higher concentrations of Cd and Ni ($p < 0.05$) in multivariate analysis. These results are consistent with the known contribution of cigarette smoke, which contains heavy metals such as Cd, Pb, and Ni, to indoor dust contamination (Caruso et al. 2014). According to Willers et al. (2005), one tobacco cigarette containing 1–2 µg cadmium and blood lead concentration of children had increased because of parental smoking behaviour in that study. Hence, tobacco cigarette smoking is one of the risk factors that increase the heavy metals exposure of the building occupants. Thus, smokers are advised to smoke outside of the house to reduce the occupants exposed to second-hand smoke.

3.7 Strengths, Limitations and Recommendations

This study has several notable strengths. Researcher conducted indoor home environment inspections while settled dust sample collection which complemented the questionnaire survey and allowing verification of building characteristics data reported by the respondents. Potential information bias was minimised by follow-up with participants to address the missing information in the questionnaire. In addition, the quantitative measurements of HM concentrations provided objective evidence which reflected the indoor home HM exposure levels, thereby enhancing the study's validity.

There were some limitations in this study, including reliance on self-reported data for the daily activities of the respondents, which is subject to response bias, as respondents may underreport or overreport their activities. Another limitation is the lack of information on the use, characteristics and efficiency of range hoods used for cooking among the respondents. The dust sampling strategy in this study targeted long-term accumulated dust rather than short-term cooking emissions, in which the absence of ventilation-related data could introduce residual confounding in the observed HM concentrations. This study had defined its scope of study due to time and funding constraints, which may have excluded other potential variables that may influence the concentrations of heavy metals in the indoor residential environment. Lastly, another limitation of the study is cross-sectional study design can only identify possible risk factors and cannot establish cause-and-effect relationships.

For future research, it is recommended to have longitudinal study designs to establish causal relationships of the study variables, Detailed assessments of the household ventilation can be carried out to elucidate the roles of mechanical and natural ventilation in influencing the indoor HM exposure profile. Evaluating the effectiveness of specific interventions in the long term also recommended to evaluate their effectiveness in reducing the indoor air pollutants.

From a public health policy perspective, these findings highlight the importance of strengthening indoor air quality standards and enhancing community awareness about the indoor air quality issue and appropriate intervention measures. Regular vacuuming or cleaning are recommended to minimize the accumulation of dust and heavy metals. The use of air purifier and air-conditioning system can help filter the indoor air pollutants, provided that their filters are cleaned and maintained regularly. Maintaining household cleanliness is also crucial to prevent pest infestations and reduce the need for pesticide use that may contain heavy metals. Furthermore, it is advisable to avoid or minimise pollution-emitting household activities, such as indoor smoking and burning practices.

4 Conclusions

This study indicated no carcinogenic risk of heavy metals exposure in the household settled dust to the Kampar Town community. Arsenic posed a non-carcinogenic risk (hazard index [HI] = 1.20) for children, with oral intake identified as the predominant pathway of heavy metal exposure from household settled dust. The findings of this study highlight the complex interplay of household activities, environmental factors, and building characteristics in influencing heavy metal concentrations in household settled dust. Human activities, building occupants' habits, and household characteristics such as cooking fuel and methods, smoking, incense/mosquito coil burning practice and presence of houseflies/mosquitoes, were significantly ($p < 0.05$) influenced the concentrations of these elements in household settled dust. Interventions aimed at reducing indoor heavy metal concentrations should prioritize improving household hygiene, adopting cleaner energy sources, and reducing reliance on combustion-based activities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44408-025-00073-3.

Acknowledgements This research was supported by the Universiti Tunku Abdul Rahman (UTAR), Malaysia, under UTAR Research Fund (UTARRF) (IPSR/RMC/UTARRF/2021-C2/L10). The authors would like to express their gratitude to all the participants who generously volunteered their time and effort, particularly in assisting with the questionnaire study and collection of household dust samples, which were crucial to the success of this research.

Author Contributions Y.C.L: Conceptualization; Methodology; Data collection; Formal analysis; Writing – original draft preparation. X.G.: Supervision, Methodology and experiment guidance; Investigation; Visualization– review and editing. V.H.: Health risk assessment estimation; Validation; Writing – review and editing. S.H.W: Volunteer recruitment; Resources; Writing – review and editing. D.N.: Data Interpretation of findings; Writing – review and editing. F.L.L.: Conceptualization; Supervision; Funding acquisition; Writing – review and editing; Corresponding author.

Data availability The data are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical Approval Ethics approval was obtained from the Universiti Tunku Abdul Rahman Scientific and Ethical Review Committee (Ref: U/SERC/22/2023).

Consent to participate Written consent was obtained from the study participants. All personal information of the participants will be kept confidential and used solely for educational and research purposes.

Consent for Publication Not applicable.

References

Abdul Hamid NH, Mohd Hidzir N, Mohd Radzali NA, Mokhtar AK (2020) Radiological and heavy metals analysis in soil and water at the former tin mining site in the urban area (Danau Kota Lake Kuala Lumpur). IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/785/1/012011

Abdul Wahab NA, Darus FM, Isa N, Sumari SM, Muhamad Hanafi NF (2012) Heavy metal concentration of settled surface dust in residential building. Malays J Anal Sci 16(1):18–23

Abu Bakar AF, Yusoff I, Ng TF, Ashraf MA (2014) Cumulative impacts of dissolved ionic metals on the chemical characteristics of river water affected by alkaline mine drainage from the Kuala Lipis gold mine, Pahang, Malaysia. Chem Ecol 31(1):22–33. https://doi.org/10.1080/02757540.2014.950569

Alengebawy A, Abdelkhalek ST, Qureshi SR, Wang MQ (2021) Heavy metals and pesticides toxicity in agricultural soil and plants: ecological risks and human health implications. Toxics 9(3):42. https://doi.org/10.3390/toxics9030042

Ashraf MA, Maah MJ, Yusoff I (2010) Study of water quality and heavy metals in soil & water of ex-mining area Bestari Jaya, Peninsular Malaysia. Int J Basic Appl Sci 10(3):7–23

Ashraf MA, Maah MJ, Yusoff I (2011) Analysis of physio-chemical parameters and distribution of heavy metals in soil and water of ex-mining area of Bestari Jaya. Peninsular Malaysia. Asian J Chem 23(8):3493–3499

Bai Z, Yiin L-M, Rich DQ, Adgate JL, Ashley PJ (2003) Field evaluation and comparison of five methods of sampling lead dust on carpets. AIHAJ 64:528–532

Boisa N, Odagwe BU (2019) Indoor dust-based pollution status and risk assessment for a rural town, Ebedei in Nigeria hosting gas flare facility. J Environ Prot 10(2):208–220. https://doi.org/10.4236/jep.2019.102012

Cao S, Wen D, Chen X, Duan X, Zhang L, Wang B, Qin N, Wei F (2022) Source identification of pollution and health risks to metals in household indoor and outdoor dust: a cross-sectional study in a typical mining town, China. Environ Pollut 293:118551. https://doi.org/10.1016/j.envpol.2021.118551

Caruso RV, O'Connor RJ, Stephens WE, Cummings KM, Fong GT (2014) Toxic metal concentrations in cigarettes obtained from U.S. smokers in 2009: results from the International Tobacco Control (ITC) United States Survey Cohort. Int J Environ Res Public Health 11(1):202–217. https://doi.org/10.3390/ijerph110100202

Chattopadhyay G, Lin KCP, Feitz AJ (2003) Household dust metal levels in the Sydney metropolitan area. Environ Res 93:301–307

Data Source. (2022). Kampar Climate & Temperature. Climate-Data.org. https://en.climate-data.org/asia/malaysia/perak/kampar-25987/ [Accessed 8 August 2024]

Diami SM, Kusin FM, Madzin Z (2016) Potential ecological and human health risks of heavy metals in surface soils associated with iron ore mining in Pahang, Malaysia. Environ Sci Pollut Res Int 23(20):21086–21097. https://doi.org/10.1007/s11356-016-7314-9

Doyi INY, Isley CF, Soltani NS, Taylor MP (2019) Human exposure and risk associated with trace element concentrations in indoor dust from Australian homes. Environ Int 133:105–125. https://doi.org/10.1016/j.envint.2019.105125

Fazlzadeh M, Nabizadeh R, Salarifar M, Hassanvand MS, Shamsipour M, Naddafi K (2022) Health benefits of using air purifier to reduce exposure to PM-bound polycyclic aromatic hydrocarbons (PAHs), heavy metals, and ions 2.5. J Clean Prod 352:131570

Gutberlet J, Uddin SMN (2018) Household waste and health risks affecting waste pickers and the environment in low- and middle-income countries. Int J Occup Environ Health 23(4):299–310. https://doi.org/10.1080/10773525.2018.1484996

Han NMM, Latif MT, Othman M, Dominick D, Mohamad N, Juahir H, Tahir NM (2014) Composition of selected heavy metals in road dust from Kuala Lumpur city centre. Environ Earth Sci 72(3):849–859

Harrison RM, Perry R (1986) Handbook of air pollution analysis, 2nd ed. Chapman and Hall, London

Hassan SKM (2012) Metal concentrations and distribution in the household, stairs and entryway dust of some Egyptian homes. Atmos Environ 54:207–214

Hassan SK, El-Abssawy AA, Khoder MI (2015) Chemical composition, characterization and factors affecting household dust (<20 μm) in Greater Cairo, Egypt. Open J Air Pollut 4(4):81–96. https://doi.org/10.4236/ojap.2015.44008

IARC (2013) Agents classified by the IARC Monographs. IARC Monogr. Eval. Carcinog. Risks Hum. 1–108.

Iwegbue CMA, Oliseyenum EC, Martincigh BS (2017) Spatio-temporal distribution of metals in household dust from rural, semi-urban and urban environments in the Niger Delta, Nigeria. Environ Sci Pollut Res 24(4):3955–3966

Jadoon WAJ, Abedel-Dayem SMMA, Saqib Z, Takeda K, Sukugawa H, Hussain M (2020) Heavy metals in urban dusts from Alexandria and Kafr El-Sheikh, Egypt: implications for human health. Environ Sci Pollut Res 28:2007–2018

Kunwittaya S, Ruksee N, Khamnong T, Jiawiwatkul A, Kleebpung N, Chumchua V, Plitponkarnpim A, Nopparat C, Permpoonputtana K (2022) Inorganic arsenic contamination and the health of children living near an inactive mining site: northern Thailand. EXCLI J 21:1007–1014. https://doi.org/10.17179/excli2022-4922

Kurt-Karakus PB (2012) Determination of heavy metals in indoor dust from Istanbul, Turkey: estimation of the health risk. Environ Int 50:47–55. https://doi.org/10.1016/j.envint.2012.09.011

Latif MT et al (2011) Composition of heavy metals and airborne fibers in the indoor environment of a building during renovation. Environ Monit Assess 181:479–489

Latif MT, Yong SM, Saad A, Mohamad N, Baharudin NH, Mokhtar M, Tahir NM (2014) Composition of heavy metals in indoor dust and their possible exposure: a case study of preschool children in Malaysia. Air Qual Atmos Health 7(2):181–193

Lee CW, Vo TTT, Wee Y, Chiang Y-C, Chi MC, Chen ML, Hsu LF, Fang ML, Lee K-H, Guo S-E, Cheng H-C, Lee I-T (2021) The adverse impact of incense smoke on human health: from mechanisms to implications. J Inflamm Res 14:5451–5472. https://doi.org/10.2147/JIR.S332771

Li Y, Ye F, Wang A, Wang D, Yang B, Zheng Q, Sun G, Gao X (2016) Chronic arsenic poisoning probably caused by arsenic-based pesticides: findings from an investigation study of a household. Int J Environ Res Public Health 13(1):133. https://doi.org/10.3390/ijerph13010133

Li Y, Fang F, Lin Y, Wang Y, Kuang Y, Wu M (2019) Heavy metal contamination and health risks of indoor dust around Xinqiao Mining Area, Tongling, China. Hum Ecol Risk Assess 26(1):46–56. https://doi.org/10.1080/10807039.2018.1503930

Liu WK, Wong MH, Mui YL (1987) Toxic effects of mosquito coil (a mosquito repellent) smoke on rats: I. properties of the mosquito coil and its smoke. Toxicol Lett 39(2–3):223–230

Liu Y, Ma J, Yan H, Ren Y, Wang B, Lin C, Liu X (2016) Bioaccessibility and health risk assessment of arsenic in soil and indoor dust in rural and urban areas of Hubei Province, China. Ecotoxicol Environ Saf 126:14–22. https://doi.org/10.1016/j.ecoenv.2015.11.037

Liu Y, Ma H, Zhang N, Li Q (2022) A systematic literature review on indoor PM2.5 concentrations and personal exposure in urban residential buildings. Heliyon 8(8):e10174. https://doi.org/10.1016/j.heliyon.2022.e10174

Machate DJ (2023) Anthropogenic hyperactivity for natural resources increases heavy metals concentrations in the environment: toxicity of healthy food and cancer risks estimated. J Trace Elem Miner 4:100057. https://doi.org/10.1016/j.jtemin.2023.100057

Naimabadi A, Gholami A, Ramezani AM (2020) Determination of heavy metals and health risk assessment in indoor dust from different functional areas in Neyshabur, Iran. Indoor Built Environ 30(10):1781–1795. https://doi.org/10.1177/1420326X20963378

Norbäck D, Zhang X, Fan Q, Zhang Z, Zhang Y, Li B, Zhao Z, Huang C, Deng Q, Lu C, Qian H, Yang X, Sun Y, Sundell J (2019) Home environment and health: domestic risk factors for rhinitis, throat symptoms, and non-respiratory symptoms among adults across China. Sci Total Environ 681:320–330

Pal M, Gope M, Basu A, Laha T, Masto RE, Labar R, Kundu TK, Hoque RR, Khillare PS, Balachandran S (2023) Indoor quality of residential homes and schools of an industrial area in Asansol: characterization, bioaccessibility and health risk assessment of potentially toxic elements. Nat Environ Pollut Technol 22(2):123–134

Praveena SM, Abdul Mutalib NS, Aris AZ (2015) Determination of heavy metals in indoor dust from primary school (Sri Serdang, Malaysia): estimation of the health risks. Environ Forensic 16(3):257–263. https://doi.org/10.1080/15275922.2015.1059388

Rivero IDC, Fry KL, Gillings MM, Barlow CF, Aelion CM, Taylor MP (2023) Sources, pathways and concentrations of potentially toxic trace metals in home environments. Environ Res 220:115173

Shaari H, Sakinah N, Razak A, Afiq WM, Khalik WM, Azhar N, Shazili M, Bidai J (2018) Spatial distribution of heavy metals in tropical coastal sediment of the Northern Malacca Strait, Malaysia. Nat Environ Pollut Technol 17:1115–1123

Shabanda IS, Koki IB, Raof SFA, Lee YH, Mainal A, Abu Bakar NK, Khor SM (2019) Distribution of heavy metals in roadside dust of

Petaling Jaya, Malaysia with multivariate and correlation analyses for source identification. Int J Environ Anal Chem, 1–24.

Shafie AF, Mokhtar MAM (2021) Exposure concentration of heavy metals in indoor air of FELDA Bukit Goh's residential area. MAEH J Environ Health 3(2):7–11

Shi T, Wang Y (2021) Heavy metals in indoor dust: spatial distribution, influencing factors, and potential health risks. Sci Total Environ 755:142367

Sulaiman FR, Bakri NI, Nazmi N, Latif MT (2017) Assessment of heavy metals in indoor dust of a university in a tropical environment. Environ Forensic 18(1):74–82. https://doi.org/10.1080/15275922.2016.1263903

Tan S, Praveena S, Abidin E, Cheema M (2016) A review of heavy metals in indoor dust and its human health-risk implications. Rev Environ Health 31(4):447–456. https://doi.org/10.1515/reveh-2016-0026

Tan SY, Praveena SM, Emilia ZA, Manraj SC (2018) Heavy metal quantification of classroom dust in school environment and its impacts on children health from Rawang (Malaysia). Environ Sci Pollut Res 25:34623–34635

Tashakor M, Dahmardeh Behrooz R, Asvad SR, Kaskaoutis DG (2022) Tracing of heavy metals embedded in indoor dust particles from the industrial city of Asaluyeh, South of Iran. Int J Environ Res Public Health 19(13):7905. https://doi.org/10.3390/ijerph19137905

Tay JH, Azmi SA, Zul Kornain MII (2021) Heavy metal in different size fractions of household dust collected from rural residential area of Simpang Renggam, Johor. Malays J Anal Sci 25(6):911–920

United States Department of Energy (USDOE). (2011). The Risk Assessment Information System (RAIS). U.S. Department of Energy, Oak Ridge Operations Office (ORO).

United States Environmental Protection Agency (USEPA). (2002). Supplemental Guidance for Developing Soil Screening Levels for Superfund Sites. U.S. Environmental Protection Agency, Washington, DC.

United States Environmental Protection Agency (USEPA). (2004). Child-Specific Exposure Factors Handbook. National Center for Environmental Assessment, U.S. Environmental Protection Agency, Washington, DC.

United States Environmental Protection Agency (USEPA). (2011). Exposure Factors Handbook. National Center for Environmental Assessment, Washington, DC. EPA/600/R-09/052F.

United States Environmental Protection Agency (USEPA). (2011). Integrated Risk Information System (IRIS). U.S. Environmental Protection Agency, Washington, DC. Available at: http://www.epa.gov/IRIS/

Wahab NAA, Darus FM, Isa N, Sumari SM, Fatihah N, Hanafi M (2012) Heavy metal concentration of settled surface dust in residential building. Malays J Anal Sci 16(1):18–23

Wang J, Pindus M, Janson C, Sigsgaard T, Kim J-L, Holm M, Sommar J, Orru H, Gislason T, Johannessen A, Bertelsen RJ, Norbäck D (2019) Dampness, mould, onset and remission of adult respiratory symptoms, asthma, and rhinitis. Eur Respir J 53:1801921. https://doi.org/10.1183/13993003.01921-2018

Willers S, Gerhardsson L, Lundh T (2005) Environmental tobacco smoke (ETS) exposure in children with asthma—relation between lead and cadmium, and nicotine concentrations in urine. Respir Med 99:1521–1527

Wurl J, Imaz Lamadrid M, Mendez-Rodriguez L, Acosta Vargas B (2018) Arsenic concentration in the surface water of a former mining area: the La Junta Creek, Baja California Sur, Mexico. Int J Environ Res Public Health 15(3):437. https://doi.org/10.3390/ijerph15030437

Xu R, Zheng X, Lin Y, Lin C, Guo Y, Huo X (2021) Assessment of dust trace elements in an e-waste recycling area and related children's health risks. Sci Total Environ 791:148154

Yap CK, Krishnan T, Chew W (2011) Heavy metal concentrations in ceiling fan dusts sampled at schools around Serdang area, Selangor. Sains Malays 40(6):569–575

Zainal ZA, Hashim Z, Jalaludin J, Lee LF, Hashim JH (2019) Sick building syndrome among office workers in relation to office environment and indoor air pollutant at an academic institution, Malaysia. Malays J Med Health Sci 15(3):126–134

Zeng X, Xu X, Boezen HM, Huo X (2016) Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148:408–415. https://doi.org/10.1016/j.chemosphere.2015.10.078