

Health Risk Assessment of Workers Exposed to Particulate Matter and Heavy Metal in Industrial Waste Treatment

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Abstract

The occupational hazards on workers in two industrial waste treatment plants were investigated, involving waste management, recycling, and disposal activities. The workers have been exposed to various pollutants, for instance, Particulate Matter, PM (PM_{2.5}, PM_{10-2.5}) and heavy metals contaminating during the waste treatment process. The health risks of workers exposed to particulate matter and heavy metals were studied. Particulate matter samples were collected using a Personal Modular Impactor (PMI) in the working area and personal sampling. The urine samples were collected from volunteer workers following the national guideline method. PM concentrations were analyzed by the gravimetric method. Heavy metals; As, Pb, Cr, Cd, and Hg associated with PM, and in the urine samples were analyzed by Inductively Coupled Plasma Spectrometry. The average PM concentrations of PM_{2.5}; area samples (30.33 ± 2.51 and 41.21 ± 1.12 µg/m³), person samples (45.86 ± 9.85 and 144.99 ± 119.11 µg/m³) and PM_{10-2.5}; area samples (14.77 ± 0.29 and 15.09 ± 0.35 µg/m³), person samples (27.73 ± 8.63 and 48.04 ± 43.49 µg/m³) in Plant 1 and 2, respectively. Heavy metal in the particulate samples; As, Cd, and Pb concentrations in plant 1; area samples were 1.19 ± 0.09, 0.55 ± 0.05 and 0.78 ± 0.14 µg/m³, personal sample were 1.22 ± 0.08, 0.55 ± 0.08, and 0.87 ± 0.12 µg/m³, respectively. In-Plant 2; As, Cd and Pb concentrations in area samples were 0.52 ± 0.21, 0.55 ± 0.05 and 0.38 ± 0.05 µg/m³, personal samples were 0.58 ± 0.13, 0.53 ± 0.06 and 0.41 ± 0.05 µg/m³, respectively. The values of As, Cd, and Pb in the dust were within the limit level prescribed by the Occupational Health National Standard. Cr and Hg were not detected in the particulate samples. The average levels of total-As, Cr, Cd, Pb, and Hg that were found in the urine were total-As (91.67 ± 98.63 and 59.29 ± 32.03 µg/L), Cr (0.82 ± 0.51 and 1.03 ± 1.02 µg/L), Cd (1.46 ± 1.14 and 0.62 ± 0.46 µg/g.creatinine), Pb (8.83 ± 12.70 and 0.31 ± 0.52 µg/g.creatinine), and Hg (7.80 ± 15.62 and 0.66 ± 1.50 µg/g.creatinine) in plant 1 and 2, respectively. As, Cd and Pb in urine samples of plant 1 were higher than in plant 2. This could be because the waste loading in plant 1 was higher in electronic waste than in plant 2, where the majority of waste was plastic waste. The non-carcinogenic risk assessment, Hazard Quotient, and Hazard Index of As and Cd in oral/ingestion route exposure were more than 1. Cancer risk of As, Cd, and Pb in oral/ingestion exposure and As in dermal exposure were >10⁻⁶ in both plants. To reduce risk, the control of food/drink intake in the workplace, an annual health check program, and providing of personal protective equipment for employees were recommended.

Keywords: Particulate matter; Heavy metal; Worker exposure; Health risk, Industrial Wastes

1. Introduction

Thailand's industrial waste treatment plants are starting to grow. Therefore, the government has to implement a strategy to have systematic management of industrial waste as a result of economic and industrial expansion. The workers at industrial waste disposal plants and the public's health in the vicinity of the facility are the major concern for the government (DIW, 2011). In 2018, Thailand accumulated 22 million tons of industrial waste, 1.2 million tons of hazardous waste, and 20.82 million tons of non-hazardous garbage, with the central area having the largest industrial waste disposal plants. The waste treatment industry has 954 factories in the Middle region, 733 in the Eastern region, 112 in the Northeastern region, 63 in the Western region, 59 in the Southern region, and 46 in the Northern region, respectively (PCD, 2019).

The high amount of industrial waste in Thailand (Office of the National Economic and Social Development Council, 2016), has caused environmental damage and remains a serious problem, (PCD, 2019). All industrial waste disposal plants codes 101, 105, and 106 in Thailand have waste management issues and community complaints, including reports of metal contamination in nearby communities (Ministry of Industry, 2018). Heavy metals are normally found in the workplace of industrial waste disposal operations (Omrane *et al.*, 2018). The workers in industrial waste treatment plants are exposed to physical, chemical, biological, ergonomic, and psychological risks. Particularly matter (PM), both PM₁₀ and PM_{2.5} (Fang *et al.*, 2013). Environmental Criteria and Assessment Office, 1993), that might be encountered in the workplace as a result of sorting processes. Heavy metal pollutants were discovered in the dust after dissection, cutting/tearing, melting, and other procedures (Fang *et al.*, 2013). Heavy metals are harmful and toxic substances to the body. Contamination can be found in a variety of industrial waste streams. Heavy metal pollutants, such as arsenic, lead, cadmium, chromium, mercury, and others, are most commonly found in industrial waste, such as electrical or electronic equipment, metals, plastics, and other materials (Singh

et al., 2018). Waste management in the industrial sector (Mousavian *et al.*, 2017);(Singh *et al.*, 2018) and effects of dust exposure in the workplace can affect health in the short term, namely irritating the eyes, nose, and throat, increasing the manifestation of asthma and chronic bronchitis. And in the long term, it will reduce lung function, induce cardiovascular disease and other chronic respiratory diseases (Koenig, 2000).

Exposure to heavy metals can be toxic to the body by intake on three pathways include ingestion, inhalation, and skin absorption (Yohannessen *et al.*, 2019). The acute effect of heavy metal exposure to the body in workers can lead to lung inflammation, hepatic cell destruction, kidney damage, and nervous system damage and damage. neurological damage or it can be fatal (Omrane *et al.*, 2018), and chronic exposure to heavy metals such as Arsenic (As) can cause diseases such as skin lesions, cancer, cardiovascular diseases (CVD), and other chronic diseases such as diabetes and respiratory dysfunctions (World Bank, 2019). In addition, the US. Agency for Toxic Substances and Disease Registry (ATSDR), heavy metals are classified as hazardous to health in 2019. The ranking is as follow; the arsenic (As) the first, (As), Lead (Pb) the second, (Pb), Mercury (Hg) the third, and Cadmium (Cd) the seventh (ATSDR, 2019);(Omrane *et al.*, 2018). The health effect and toxicity of these heavy metals were reported in these examples as followed: Lead (Pb) in the case of short-term exposure there will be symptoms: fatigue, muscle pain, anemia, and peripheral neuropathy, and if chronic lead poisoning often has hypertension, renal failure, and encephalitis (Nouioui *et al.*, 2019).

Mercury (Hg), most often the effect is from inhalation of mercury vapor 80%, thus affecting the lungs the most and has a permeability of the bloodstream into the kidney, causing renal impairment/ renal failure, affecting the nervous system, such as hand tremors, increased memory disturbances, affecting the thyroid and immune system, and other systems (Phanpravit *et al.*, 2019);(Correia *et al.*, 2020); GUL *et al.*, 2020).

Cadmium (Cd), acute poisoning has caused nausea, vomiting, abdominal cramps, and abdominal cramps and diarrhea, chills, and muscle aches. Long-term exposure to cadmium can cause respiratory symptoms such as Bronchial and pulmonary irritation, pneumonitis, emphysema, renal effects: increased urinary excretion of low-molecular-weight proteins, affect the glomerular function and bone effects: osteoporosis and osteomalacia (Goyal *et al.*, 2020);(Sovičová *et al.*, 2019).

Chromium (Cr), which is the most toxic often Chromium-hexavalent; Cr-VI and upon entering the body can cause lung cancer, nasal ulcer, hypersensitivity reactions, and contact dermatitis (Lacerda *et al.*, 2019).

The main objective of this study was to assess the health risks of factory workers in industrial waste treatment plants. The findings may be useful in addressing the health impacts and risk management of employees who may be exposed to heavy metals in the workplace, as well as improving the health of those who work in industrial waste treatment plants in the years ahead.

2. Materials and Methods

All samples were collected during October-November 2021 including three parts, (1) Particulate matter (PM) in the workplace (2) Personal PM sampling, and (3). Workers’ urine samples.

2.1 Site Criteria

Two selected industrial waste treatment plants registered with the Department of Industrial Works and located in Chonburi province (Factory 1) and Suphanburi province (Factory 2). These two factories were categorized as industrial waste disposal plants in Group101 and 105 (Ministry of Industry 2018). The activities included waste sorting,

waste recycling, and disposal of waste. These two factories operated more than 10 years. There are approximately 10-20 employees in each factory, working five days a week, from 8.00 am-5.00 pm. The average amount of industrial waste that is disposed of is more than 1 ton per year (Table 1).

2.2 Particulate matter sampling

The PM in the workplace, both area sampling and personal sampling in waste separation, sorting sector, part dissection, and waste melting sector, were measured for 8 working hours in 5 working days. Air samples were collected by using a personal low flow pump attached to a collector device (Personal Modular Impactor; PMI) with a PVC filter for PM_{10-2.5} and a PTFE filter for PM_{2.5} at a flow rate of 3 L/min.(SKC, 2013);(Wang *et al.*, 2016);(Liu *et al.*, 2014). The PM_{10-2.5} and PM_{2.5} mass concentrations were obtained by weighing the filters before and after the sampling, after a storage period (24 hr) in a temperature- and humidity-controlled desiccator (ambient temperature, 25 ± 0.2 °C; relative humidity, 50% ± 1%), using an ultra-microbalance (UMX-2; Mettler-Toledo).

The difference between pre and post-sampling weight was used in the PM concentration calculation according to the guidelines of the National Institute for Occupational Safety and Health (NIOSH) No.0600 (NIOSH, 2003), Equation 1.

$$C \text{ (mg/m}^3\text{)} = \frac{(W_2 - W_1) - (B_2 - B_1)}{V \text{ (m}^3\text{)}} \times 10^3 \text{ (Eq.1)}$$

Where W₁ is the weight of filter before sampling (mg), W₂ is the post-sampling weight of sample-containing filter (mg), B₁ is the mean tare weight of blank filters (mg), B₂ is the mean post-sampling weight of blank filters (mg) and V is air volume sampled (L)

Table 1. The amount of industrial waste treated in each plant.

Factory	Waste treatment (Tons/Years)		
	2019	2020	2021*
Factory 1, Chonburi	1.52	1.88	1.36
Factory 2, Suphanburi	1.32	1.61	1.03

Note: *Data until 31 October 2021

2.3 Urine sampling

The workers' urine sampling was conducted following a standard method of ACGIH (2021). The samples were collected on the last day of the workweek for 10 ml and kept in a temperature-controlled tank at 4°C before delivering for Urine-creatinine analysis within 24 hours at the Division of Occupational and Environmental Disease laboratory.

2.4 Data analysis and statistic

Data were statistically analyzed by using SPSS software for Windows, version 28. Descriptive statistics were applied to determine the association of heavy metals; As, Pb, Cd, Cr and Hg and particulate matter (PM).

2.5 Chemical analysis

2.5.1 Heavy metal in dust

The samples were digested with 10% nitric acid (HNO₃) 10 ml by microwave digestion using USEPA 3051 method (US. EPA., 2007) at 175°C for 30 min, then filtered with a No.42 Whatman filter paper and adjusted volume to 50 ml. The samples were analyzed for heavy metals As, Pb, Cd, Cr, and Hg by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (US.EPA., 2018) and calculated heavy metal in the sample by using Equation 2. (NIOSH *et al.*, 2003)

$$C = \frac{C_s V_s - C_b V_b}{L}, \text{ mg/m}^3 = \mu\text{g/L} \quad (\text{Eq.2})$$

Where, the solution sample concentrations, Cs (µg/mL), and the average media blank, Cb (µg/mL), the solution sample volume, Vs (mL), and the blank volume, Vb (mL), calculate the concentration, C (mg/m³), of each element in the air volume sampled, V (L).

2.5.2 Heavy metal in Urine

Urine samples were centrifuged with a 15,000 rpm, for 5 min, and 1 ml of the clear sample was extracted with 9 ml of 2% concentration of pure (99%) nitric acid (HNO₃) (1:9) according to the CDC: Urine. Multi-

Element ICP-DRC-MS method No.3018.6-02 (15 element panel) and 3018A.4-02 (Total arsenic)(Caldwell, 2015). Heavy metal As, Pb, Cd, Cr, and Hg samples were analyzed using an Inductively Coupled Apparatus Plasma-Mass Spectrometer (ICP-QMS).

2.6 Risk assessment

Workers in industrial waste treatment plants can expose to heavy metals through three routes: inhalation, ingestion, and skin absorption. The risk of heavy metal exposure from the workplace, both Non-carcinogenic and Carcinogenic were assessed following the USEPA method (Fang *et al.*, 2013).

The non-carcinogenic risk was calculated from Equations 3 - 5 and for Carcinogenic risk from Equation 6, details are given in Table 2.

$$\text{ADD}_{\text{ing}} = \frac{C \times \text{Ingr} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (\text{Eq.3})$$

$$\text{ADD}_{\text{inh}} = \frac{C \times \text{InhR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT} \times \text{PEF}} \quad (\text{Eq.4})$$

$$\text{ADD}_{\text{derm}} = \frac{C \times \text{SA} \times \text{SL} \times \text{ABS} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (\text{Eq.5})$$

$$\text{CDI} = \frac{C \times \text{CF} \times \text{IR} \times \text{ET} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (\text{Eq.6})$$

Non-carcinogenic risk parameter, hazard Quotient (HQ) was calculated from the ratio of the average daily intake and the Reference dose (RfD) of each heavy metal, and Hazard Index (HI) is a summation of HQ, as shown in Equation 7 and 8. If HQ and HI value has less than one, it is suggested to be unlikely adverse health effects. HQ and HI more than 1 indicated the probability of adverse health effects, and HQ and HI more than 10, it would be suggested as a high chronic risk.

$$\text{HQ} = \frac{\text{ADD}}{\text{RfD}} \quad (\text{Eq.7})$$

$$\text{HI} = \sum \text{HQ} \quad (\text{Eq.8})$$

Cancer Risk (CR) was calculated for the cancer risk characterization, multiplying the chronic daily intake and the cancer slope factor (CSF) as shown in Equation 9. If CR value is CR < 1x10⁻⁶ suggested to be unlikely adverse health effects and CR >1x10⁻⁶ indicated the probability of adverse health effects.

$$\text{CR} = \text{CDI} \times \text{CSF} \quad (\text{Eq.9})$$

Table 2. Description and value of each parameter used in the formulas.

Parameter	Description	Unit	Value	Reference
ADD _{inh}	the average daily dose of inhalation	mg/Kg.day	-	-
ADD _{ing}	the average daily dose of ingestion	mg/Kg.day	-	-
ADD _{derm}	the average daily dose of dermal absorption	mg/Kg.day	-	-
CDI	The Chronic Daily Intake	mg/Kg.day	-	-
C	Heavy metal concentration in dust PM ₁₀ or PM _{2.5}	µg/m ³	-	Sampling in this study
IngR	The intake rate	mg/day	100	Pollution Control Department
PEF	Particle emission factor	m ³ /Kg	1.36x10 ⁹	(PCD), 2020
SA	The exposure skin area	cm ²	2,253	
SL	The skin adherence factor	mg/cm ² .day	0.2	
ABS	Dermal absorption factor	-	0.001	
EF	Exposure frequency	Day/year	250	
ED	- Exposure duration for non-carcinogen - Exposure duration for carcinogen	Years Years	10 30	
AT	- Average time for non-carcinogen - Average time for carcinogen (70 years x 365 days)	Days Days	3,650 25,550	
CF	Conversion factor (1Years/8,760 hr.)	Year/hr.	1.14x10 ⁻⁴	
InhR / IR	Inhalation rate	m ³ /day	20	Černá et al., 1997
BW	Average bodyweight	Kg	62.45	From questionnaire
ET	Exposure Time	hr./days	8	From questionnaire

3. Results and Discussion

3.1 Respirable particulate matter (RPM) concentrations in workplace

The particulate matter size 10-2.5 micron (PM_{10-2.5}) and the particulate matter size 2.5 micron and less (PM_{2.5}) collected by area sampling and personal sampling from different sections in two factories were conducted following the process of waste management, shown in Figure 1.

The average concentration (\pm SD) of RPM (PM_{10-2.5} and PM_{2.5}) in factory 1 at section 1; area sample as PM_{10-2.5} were 14.97 ± 4.86 µg/m³, PM_{2.5} was 28.56 ± 12.29 µg/m³ and personal sample as PM_{10-2.5} were 33.83 ± 14.98 µg/m³, PM_{2.5} was 52.82 ± 15.80 µg/m³ and at section 2; area sample as PM_{10-2.5} were 14.56 ± 3.85 µg/m³, PM_{2.5} was 32.11 ± 5.76 µg/m³ and personal sample as PM_{10-2.5} were 21.63 ± 9.51 µg/m³, PM_{2.5} was 38.90 ± 15.09 µg/m³ and in the factory 2 at section 1; area sample as PM_{10-2.5} were 14.85 ± 4.30 µg/m³, PM_{2.5} was 42.00 ± 15.18 µg/m³ and personal sample as

PM_{10-2.5} were 78.80 ± 46.81 µg/m³, PM_{2.5} was 229.21 ± 182.13 µg/m³ and at section 2; area sample as PM_{10-2.5} were 15.35 ± 2.75 µg/m³, PM_{2.5} was 40.42 ± 5.96 µg/m³ and personal sample as PM_{10-2.5} were 17.29 ± 2.79 µg/m³, PM_{2.5} were 60.77 ± 12.55 µg/m³, respectively. The average concentration of PM_{2.5} was greater than PM_{10-2.5} as all sampling in these studies. (Figure 2) In this regard, the concentration of PM_{2.5} in personal samples of section 1 sorting activity at factory 2 was more concentrated than all samples because the section had more industrial waste than factory 1.

The activity process of industrial waste treatment in factory 2 was more than that of factory 1. The mass of waste in factory 2 was also higher than that of factory 1 (Table 1.). In comparison to previous studies, (Fang *et al.*, 2013) the concentration of PM_{2.5} in the workplace was similar to this study. There was a typical factory for cathode ray tube television recycling in China having the same range of PM_{2.5} in this study. The concentration of PM₁₀ was found to be higher than the concentration of PM_{2.5} in the workplace of an e-waste recycling area in Accra, Ghana (Kwarteng *et al.*, 2022). Similar findings were obtained in a Brazilian indoor workplace (Wikuats *et al.*, 2020).

However, the results were within the criteria specified by the Occupational Health National Standard (Ministry of Interior Thailand, 1977) and the Occupational Safety and Health Administration (Occupational Safety and Health Administration (OSHA), 2021) of Inhalable dust was 15,000 µg/m³ and Respirable dust was 5,000 µg/m³. Although, the PM concentrations in the workplace don't exceed the standard but it should be monitored

to control the level in the workplace and to arrange the protective equipment for the potential risk workers.

3.2 The heavy metal concentration in workplace

The heavy metal average concentration of As, Cd, Pb, Cr, and Hg at the workplace in this study, found in factory 1; the area was 1.19 + 0.09, 0.55 + 0.06, and 0.78 + 0.14 µg/m³, personal sample were 1.22 ± 0.08, 0.55 ± 0.08, and 0.87 ± 0.12 µg/m³, respectively. In the factory 2, there were only As, Cd and Pb; area samples were 0.55 ± 0.13, 0.51 ± 0.06 and 0.38 ± 0.05 µg/m³, personal samples were 0.58 ± 0.13, 0.53 ± 0.06 and 0.42 ± 0.05 µg/m³, respectively, (Figure 3).

In this study, Cr and Hg were not found in the workplace, it could be below the detection limit of ICP-OES analysis. As, Cd and Pb in factory 1 were higher than in factory 2, this could be the difference in waste type. The major waste in factory 1 was disposal of electronic industrial waste but the waste in factory 2 was disposal of plastic waste.

The values of As, Cd, and Pb in the particulate matter were within the limit level prescribed by the Occupational Health National Standard (Department of Labour Protection and Welfare (DLPW) Thailand, 2017) at As-inorganic was 10 µg/m³, Cd was 5 µg/m³, and Pb was 50 µg/m³ and was within the limit level prescribed by the OSHA (Occupational Safety and Health Administration (OSHA), 2021b) and the American Conference of Governmental Industrial Hygienists too(American conference of governmental industrial hygienist (ACGIH), 2021).

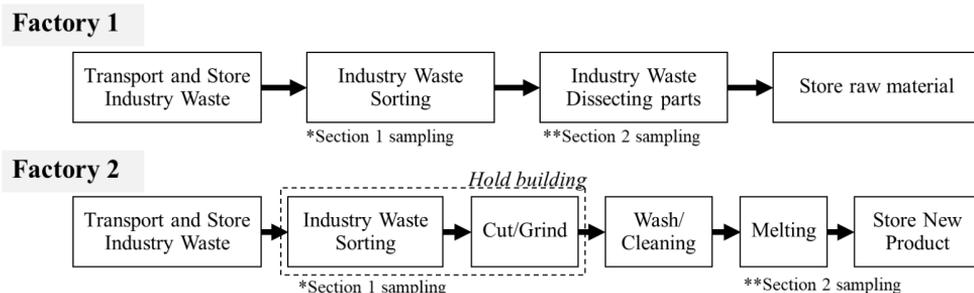


Figure1. Process of Industry waste management in two factories.

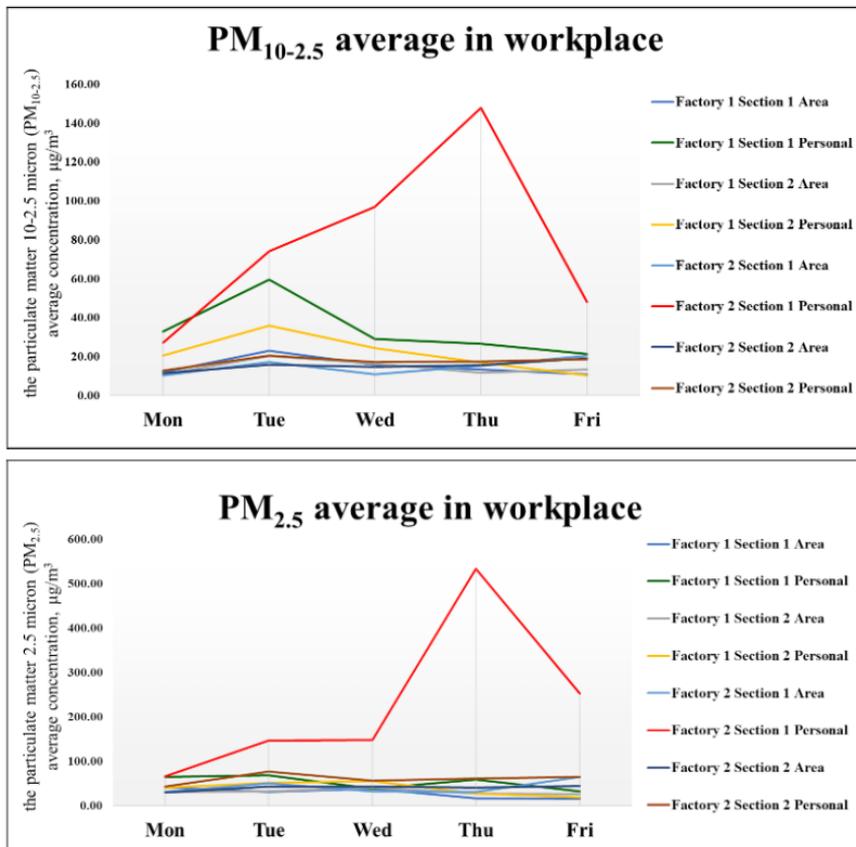


Figure 2. The concentration of PM_{10-2.5} and PM_{2.5} in the workplace of each factory.

3.3 Worker exposed to heavy metal in urine sample

The urine samples were collected from 31 volunteers working in the heavy metal industry at the end of the workweek. The worker had worked for 4 days before collecting of the urine sample including no seafood in their meals for 3 days, no using pesticides for 7 days, and no alcohol drinking.

The overall of factory has average levels of total-As, Cr, Cd, Pb, and Hg that were found in the urine were $71.82 \pm 66.63 \mu\text{g/L}$, $0.95 \pm 0.85 \mu\text{g/L}$, $0.95 \pm 0.88 \mu\text{g/g.creatinine}$, $3.42 \pm 10.16 \mu\text{g/g.creatinine}$, and $3.61 \pm 8.78 \mu\text{g/g.creatinine}$, respectively. In the factory 1 and factory 2 has average levels of total-As, Cr, Cd, Pb, and Hg in the urine were total-As, (91.67 ± 98.63 and $59.29 \pm 32.03 \mu\text{g/L}$), Cr (0.82 ± 0.51 and $1.03 \pm 1.02 \mu\text{g/L}$), Cd (1.46 ± 1.14 and $0.62 \pm 0.46 \mu\text{g/g.creatinine}$),

Pb (8.83 ± 12.70 and $0.31 \pm 0.52 \mu\text{g/g.creatinine}$), and Hg (7.80 ± 15.62 and $0.66 \pm 1.50 \mu\text{g/g.creatinine}$), respectively (Table 3).

3.4 Health risk assessment of worker exposed to heavy metal

Heavy metal exposure can occur through three routes: ingestion/oral route, inhalation route, and dermal absorption route. This study's health risk assessment is based on the US.EPA. The health risk assessment for non-carcinogenic used reference dose value (RfD) and carcinogenic used cancer slope factor (CSF) from the database of the United States Environmental Protection Agency (US. EPA.), The Agency for Toxic Substances and Disease Registry (ATSDR), Office of Environmental Health Hazard Assessment (OEHHA), other organizations, and research studies used is presented in Table 4.

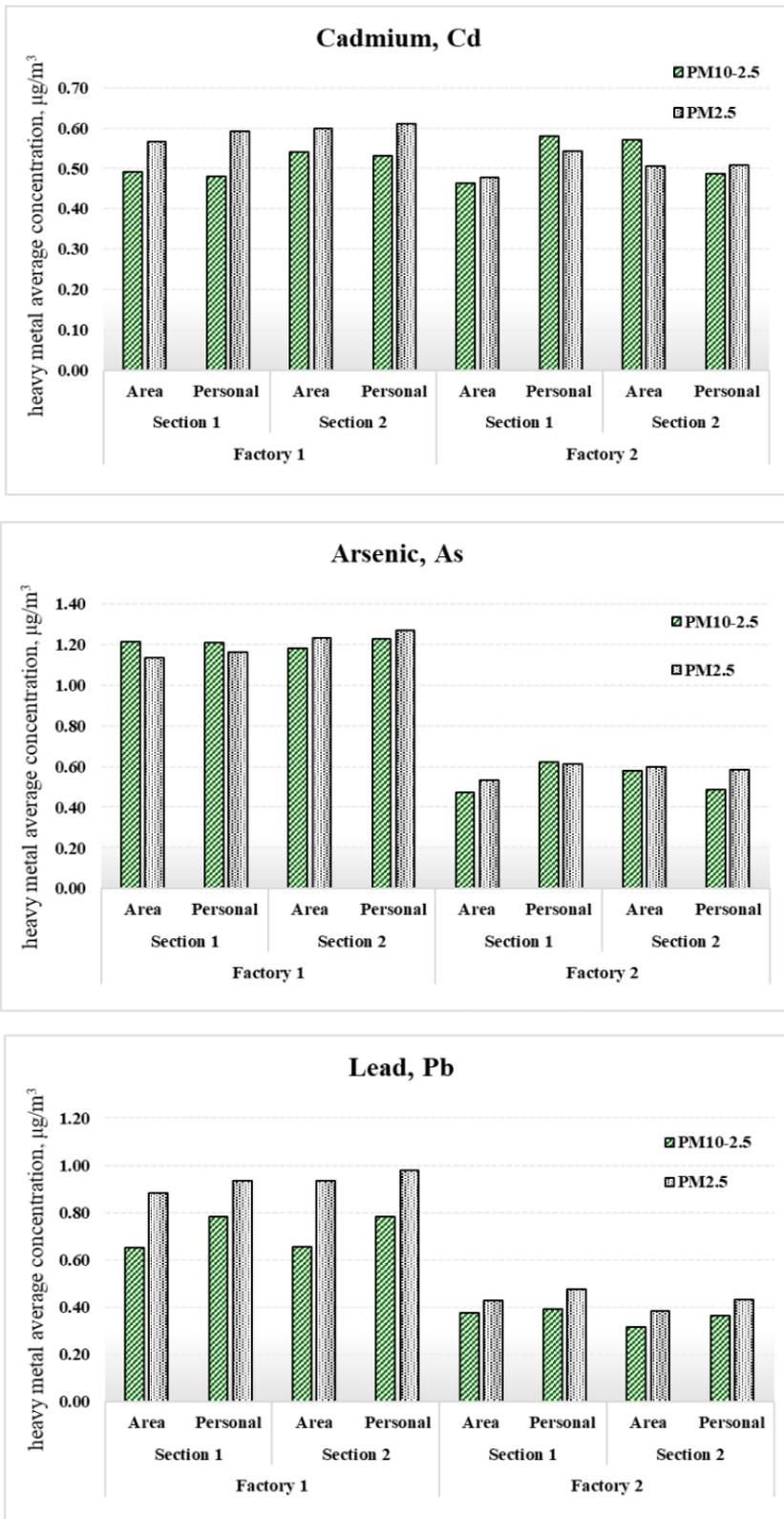


Figure 3. the concentration of heavy metal (As, Cd, and Pb) in the workplace.

Table 3. Worker exposure to concentration of heavy metal (As, Cd, Pb, Cr, and Hg) in urine

Heavy metal	BEI in Urine		Factory 1			Factory 2			Average (±SD)
	Thai-BEI 2014	ACGIH 2021	Min	Max	Average (± SD)	Min	Max	Average (± SD)	
As ^(a)	35 µg/L ^(b)	35 µg/L ^(b)	11.7 3	348.09	91.67 ± 98.63	11.57	121.3 6	59.29 ± 32.03	71.82 ± 66.63
Cr	25 µg/L	0.7 µg/L	0.09	1.91	0.82 ± 0.51	0.23	4.89	1.03 ± 1.02	0.95 ± 0.85
Cd	5 µg/g.cre	5 µg/g.cre	0.35	4.37	1.46 ± 1.14	0.19	1.72	0.62 ± 0.46	0.95 ± 0.88
Hg	20 µg/g.cre	20 µg/g.cre	ND	48.84	7.80 ± 15.62	ND	6.73	0.66 ± 1.50	3.61 ± 8.78
Pb ^(c)	NA	NA	0.95	47.80	8.83 ± 12.70	0.01	2.02	0.31 ± 0.52	3.42 ± 10.16

Note: NA= Not Available, ND=Not Detected, BEI= Biological Exposure Indices, Thai-BEI=Thailand of Biological Exposure Indices (Department of Disease Control(DDC), 2014), ACGIH= the American Conference of Governmental Industrial Hygienists (American conference of governmental industrial hygienist (ACGIH), 2021), (a) = Arsenic reported in “total-arsenic (As-total)” and used BEI was 100 µg/L of urine (sum of all metabolites) from WorkSafe New Zealand.(WorkSafe New Zealand, 2018), (b) = Arsenic for Inorganic in urine, (c) = used BEI for Lead (Pb) was 150 µg/g.creatinine of urine from Guidelines on Medical Surveillance Malaysia.(Ministry of Human Resources, 2001)

Table 4. The reference dose (RfD) /Reference concentration (RfC) and cancer slope factor (CSF) of heavy metal for health risk assessment

Heavy metal	Reference dose (RfD)/ Reference concentration (RfC)			Cancer slope factor (CSF)		
	RfD _{Inges/Oral} (mg/Kg.day)	RfD _{Inha} (mg/Kg.day)	RfD _{Dermal} (mg/Kg.day)	CSF _{Inges/Oral} (mg/Kg.day)	CSF _{Inha} (mg/Kg.day)	CSF _{Dermal} (mg/Kg.day)
As	3 x 10 ⁻⁴ (a)	NA	8 x 10 ⁻⁴ (h)	1.5 (a)	12 (f)	1.5 (j)
Cd	5 x 10 ⁻⁴ (b)	NA	5 x 10 ⁻⁶ (e)	0.38 (k)	6.1 (e)	0.38 (k)
Pb	3.5 x 10 ⁻³ (i)	NA	5.25 x 10 ⁻⁴ (l)	8.5 x 10 ⁻³ (f)	4.2 x 10 ⁻² (f)	NA
Cr	3 x 10 ⁻³ (c)	1 x 10 ⁻⁴ (e)	NA	0.42 (f)	510 (f)	NA
Hg	NA	3 x 10 ⁻⁴ (d)	NA	NA	NA	NA

Note: (a) U.S. Environmental Protection Agency, 1988 , (b) U.S. Environmental Protection Agency, 1987 , (c) U.S. Environmental Protection Agency, 1998 , (d) U.S. Environmental Protection Agency, 2020 , (e) University of Tennessee, 1991 , (f) Office of Environmental Health Hazard Assessment(OEHHA), 2020 , (g) University of Tennessee, 1998 , (h) The Agency for Toxic Substances and Disease Registry(ATSDR), 1997 , (i) Anyanwu & Onyele, 2018 , (j) Rockafellow-Baldoni et al., 2018 , (k) Nduka et al., 2019 , (l) Mowla et al., 2021 and NA= Not Available

The risk characterization of non-carcinogenic risk; calculated worker exposure by the average daily dose (ADD) in three pathways of exposure; ingestion/oral route, inhalation route, and dermal absorption route, and which calculated the hazard quotient (HQ) and the hazard indices (HI). (Table 5.) The results found As and Cd was HQ and HI > 1 in oral/ingestion route exposure and other exposure route were less than 1. The HQ_{Ing/Oral} of As and were more than 1 in factory 1 and factory 2 in PM_{10-2.5}; area samples were

4.376 and 1.921, personal sample were 4.458 and 2.021, and in PM_{2.5}; area samples were 4.324 and 2.064, personal samples were 4.445 and 2.188, respectively. The HQ_{Ing/Oral} of Cd was more than 1 in factory 1 and factory 2 in PM_{10-2.5}; area samples were 1.132 and 1.135, personal samples were 1.108 and 1.171, and in PM_{2.5}; area samples were 1.276 and 1.080, personal sample were 1.319 and 1.150, respectively. The HI of As and Cd were more than 1 same of the HQ_{Ing/Oral} pathway exposure and in the ΣHI_{Total} when arranged high to low,

found that $\Sigma HI_{Total} (PM_{2.5} \text{ person}) > \Sigma HI_{Total} (PM_{2.5} \text{ area}) > \Sigma HI_{Total} (PM_{10-2.5} \text{ person}) > \Sigma HI_{Total} (PM_{10-2.5} \text{ area})$ presented in Table 5.

In the risk characterization of carcinogenic risk; calculated worker exposure by the chronic daily intake (CDI) in three pathways of exposure same of the non-carcinogenic risk and which calculated the cancer risk (CR) as shown in Table 6. the results showed the cancer risk (CR) of As, Cd, and Pb in oral/ingestion route exposure and As in dermal absorption exposure route were $CR > 10^{-6}$ in both factories, it means to suggest the probability of adverse health effects to cancer (U.S. Environmental Protection Agency, 2019) and the $CR_{Average}$ for all of the sample sites were more than 10^{-6} when arranged high to low, found that $CR_{Average} (PM_{2.5} \text{ person}) > CR_{Average} (PM_{2.5} \text{ area}) > CR_{Average} (PM_{10-2.5} \text{ person}) > CR_{Average} (PM_{10-2.5} \text{ area})$ presented in Table 6. The CR level in this study was 10^{-4} which was within the considered acceptable or tolerable threshold limit value for cancer risk is ranged from 10^{-6} to 10^{-4} (U.S. Environmental Protection Agency, 2004); (Ahmed *et al.*, 2020).

4. Conclusion

The PM and associated heavy metal concentrations in the workplace were at an acceptable level within the criteria specified by the Occupational Health National Standard. As, Cd and Pb in urine samples of plant 1 were higher than in plant 2. This could be due to the waste loading in plant 1 being more electronic wastes than in plant 2 where a majority of wastes were plastic and organic wastes. Health risks of workers exposed to particulate matter and heavy metals were evaluated. The non-carcinogenic risk assessment, Hazard Quotient (HQ), and Hazard Index (HI) of As and Cd in oral/ingestion route exposure were more than 1. Cancer risk (CR) of As, Cd, and Pb in oral/ingestion exposure and As in dermal exposure were in the range of 10^{-4} to 10^{-5} in plant 1 and plant 2. CR values were more than 10^{-6} , indicating potential risk but this was still in the acceptable range. To reduce the risk, personal protective equipment

was recommended for the potential risk workers and the good practice of workplace management, pollutants monitoring, and health surveillance were suggested. Results from this study could be applied in sustainable industrial development as a tool to protect the workers from acute or chronic adverse effects in the waste treatment industry.

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Ethic Reference

This study was certified research ethics by the Research Ethics Review Committee for Research Involving Human Research Participant, Group 1 of Chulalongkorn University. Reference COA.No.041/2021, Protocol no.227-1/63.

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Table.5 The risk characterization of Non-carcinogenic to HQ and HI

Factory	Sample site	Heavy metal	The Average Daily Dose (ADD)			The Hazard Quotient (HQ)			HI	ΣHI Total	HI mean	
			ADD _{Ing/Oral}	ADD _{Inhal}	ADD _{Dermal}	HQ _{Ing/Oral}	HQ _{Inhal}	HQ _{Dermal}				
Factory 1	PM _{10-2.5} of Area sample	As	1.31 x 10 ⁻³	1.93 x 10 ⁻¹³	5.92 x 10 ⁻⁶	4.376	NC	0.007	4.384	6.237	2.119	
		Cd	5.66 x 10 ⁻⁴	8.32 x 10 ⁻¹⁴	2.55 x 10 ⁻⁶	1.132	NC	0.510	1.642			
		Pb	7.16 x 10 ⁻⁴	1.05 x 10 ⁻¹³	3.23 x 10 ⁻⁶	0.205	NC	0.006	0.211			
		Cr	NC	NC	NC	NC	NC	NC	NC			NC
		Hg	NC	NC	NC	NC	NC	NC	NC			NC
PM _{2.5} of Area sample	As	1.30 x 10 ⁻³	1.91 x 10 ⁻¹³	5.85 x 10 ⁻⁶	4.324	NC	0.007	4.332	6.475	2.119		
	Cd	6.38 x 10 ⁻⁴	9.38 x 10 ⁻¹⁴	2.87 x 10 ⁻⁶	1.276	NC	0.575	1.850				
	Pb	1.00 x 10 ⁻³	1.47 x 10 ⁻¹³	4.49 x 10 ⁻⁶	0.285	NC	0.009	0.293				
	Cr	NC	NC	NC	NC	NC	NC	NC			NC	
	Hg	NC	NC	NC	NC	NC	NC	NC			NC	
PM _{10-2.5} of Personal sample	As	1.34 x 10 ⁻³	1.97 x 10 ⁻¹³	6.03 x 10 ⁻⁶	4.458	NC	0.008	4.465	6.325	2.167		
	Cd	5.54 x 10 ⁻⁴	8.15 x 10 ⁻¹⁴	2.50 x 10 ⁻⁶	1.108	NC	0.499	1.607				
	Pb	8.59 x 10 ⁻⁴	1.26 x 10 ⁻¹³	3.87 x 10 ⁻⁶	0.245	NC	0.007	0.253				
	Cr	NC	NC	NC	NC	NC	NC	NC			NC	
	Hg	NC	NC	NC	NC	NC	NC	NC			NC	
PM _{2.5} of Personal sample	As	1.33 x 10 ⁻³	1.96 x 10 ⁻¹³	6.01 x 10 ⁻⁶	4.445	NC	0.008	4.453	6.674	2.167		
	Cd	6.59 x 10 ⁻⁴	9.69 x 10 ⁻¹⁴	2.97 x 10 ⁻⁶	1.319	NC	0.594	1.913				
	Pb	1.05 x 10 ⁻³	1.54 x 10 ⁻¹³	4.73 x 10 ⁻⁶	0.300	NC	0.009	0.309				
	Cr	NC	NC	NC	NC	NC	NC	NC			NC	
	Hg	NC	NC	NC	NC	NC	NC	NC			NC	
Factory 2	PM _{10-2.5} of Area sample	As	5.76 x 10 ⁻⁴	8.48 x 10 ⁻¹⁴	2.60 x 10 ⁻⁶	1.921	NC	0.003	1.925	3.682	1.241	
		Cd	5.67 x 10 ⁻⁴	8.34 x 10 ⁻¹⁴	2.56 x 10 ⁻⁶	1.135	NC	0.511	1.646			
		Pb	3.79 x 10 ⁻⁴	5.57 x 10 ⁻¹⁴	1.71 x 10 ⁻⁶	0.108	NC	0.003	0.112			
		Cr	NC	NC	NC	NC	NC	NC	NC			NC
		Hg	NC	NC	NC	NC	NC	NC	NC			NC
PM _{2.5} of Area sample	As	6.19 x 10 ⁻⁴	9.10 x 10 ⁻¹⁴	2.79 x 10 ⁻⁶	2.064	NC	0.003	2.067	3.765	1.241		
	Cd	5.40 x 10 ⁻⁴	7.94 x 10 ⁻¹⁴	2.43 x 10 ⁻⁶	1.080	NC	0.486	1.566				
	Pb	4.46 x 10 ⁻⁴	6.55 x 10 ⁻¹⁴	2.01 x 10 ⁻⁶	0.127	NC	0.004	0.131				
	Cr	NC	NC	NC	NC	NC	NC	NC			NC	
	Hg	NC	NC	NC	NC	NC	NC	NC			NC	

Note: NC= Not calculated because not detected heavy metal in sample and reference dose value not available.

Table.5 The risk characterization of Non-carcinogenic to HQ and HI (Cont.)

Factory	Sample site	Heavy metal	The Average Daily Dose (ADD)			The Hazard Quotient (HQ)			ΣHI Total	HI _{mean}	
			ADD _{ing/oral}	ADD _{inha}	ADD _{dermal}	HQ _{ing/oral}	HQ _{inha}	HQ _{dermal}			
Factory 2 (Cont.)	PM _{10-2.5} of Personal sample	As	6.06 x 10 ⁻⁴	8.91 x 10 ⁻¹⁴	2.73 x 10 ⁻⁶	2.021	NC	0.003	2.024		
		Cd	5.85 x 10 ⁻⁴	8.61 x 10 ⁻¹⁴	2.64 x 10 ⁻⁶	1.171	NC	0.528	1.698		
		Pb	4.14 x 10 ⁻⁴	6.09 x 10 ⁻¹⁴	1.87 x 10 ⁻⁶	0.118	NC	0.004	0.122	3.844	
		Cr	NC	NC	NC	NC	NC	NC	NC	NC	
		Hg	NC	NC	NC	NC	NC	NC	NC	NC	1.308
PM _{2.5} of Personal sample	Personal sample	As	6.56 x 10 ⁻⁴	9.65 x 10 ⁻¹⁴	2.96 x 10 ⁻⁶	2.188	NC	0.004	2.191		
		Cd	5.75 x 10 ⁻⁴	8.46 x 10 ⁻¹⁴	2.59 x 10 ⁻⁶	1.150	NC	0.518	1.669		
		Pb	4.95 x 10 ⁻⁴	7.28 x 10 ⁻¹⁴	2.23 x 10 ⁻⁶	0.142	NC	0.004	0.146	4.006	
		Cr	NC	NC	NC	NC	NC	NC	NC	NC	
		Hg	NC	NC	NC	NC	NC	NC	NC	NC	

Note: NC= Not calculated because not detected heavy metal in sample and reference dose value not available.

Table.6 The risk characterization of Carcinogenic to CR

Factory	Sample site	Heavy metal	The Chronic Daily Intake (CDI)			The Cancer Risk (CR)			CR _{mean}	
			CDI _{ing/oral}	CDI _{inha}	CDI _{dermal}	CR _{ing/oral}	CR _{inha}	CR _{dermal}		
Factory 1	PM _{10-2.5} of Area sample	As	5.63 x 10 ⁻⁴	8.27 x 10 ⁻¹¹	2.54 x 10 ⁻⁶	8.44 x 10 ⁻⁴	9.93 x 10 ⁻¹⁰	3.80 x 10 ⁻⁶		
		Cd	2.43 x 10 ⁻⁴	3.57 x 10 ⁻¹¹	1.09 x 10 ⁻⁶	9.22 x 10 ⁻⁵	2.18 x 10 ⁻¹⁰	4.15 x 10 ⁻⁷		
		Pb	3.07 x 10 ⁻⁴	4.51 x 10 ⁻¹¹	1.38 x 10 ⁻⁶	2.61 x 10 ⁻⁶	1.90 x 10 ⁻¹²	NC	1.18 x 10 ⁻⁴	
		Cr	NC	NC	NC	NC	NC	NC	NC	
		Hg	NC	NC	NC	NC	NC	NC	NC	
PM _{2.5} of Area sample	Area sample	As	5.56 x 10 ⁻⁴	8.18 x 10 ⁻¹¹	2.51 x 10 ⁻⁶	8.34 x 10 ⁻⁴	9.81 x 10 ⁻¹⁰	3.76 x 10 ⁻⁶	1.45 x 10 ⁻⁴	
		Cd	2.73 x 10 ⁻⁴	4.02 x 10 ⁻¹¹	1.23 x 10 ⁻⁶	1.04 x 10 ⁻⁴	2.45 x 10 ⁻¹⁰	4.68 x 10 ⁻⁷		
		Pb	4.27 x 10 ⁻⁴	6.28 x 10 ⁻¹¹	1.93 x 10 ⁻⁶	3.63 x 10 ⁻⁶	2.64 x 10 ⁻¹²	NC	1.18 x 10 ⁻⁴	
		Cr	NC	NC	NC	NC	NC	NC	NC	
		Hg	NC	NC	NC	NC	NC	NC	NC	

Note: NC= Not calculated because not detected heavy metal in sample and reference dose value not available.

Table.6 The risk characterization of Carcinogenic to CR. (Cont.)

Factory	Sample site	Heavy metal	The Chronic Daily Intake (CDI)			The Cancer Risk (CR)				
			CDI _{ing/oral}	CDI _{inha}	CDI _{dermal}	CR _{ing/oral}	CR _{inha}	CR _{dermal}	CR _{mean}	CR _{mean}
Factory 1 (Cont.)	PM _{10-2.5} of Personal sample	As	5.73 x 10 ⁻⁴	8.43 x 10 ⁻¹¹	2.58 x 10 ⁻⁶	8.60 x 10 ⁻⁴	1.01 x 10 ⁻⁹	3.87 x 10 ⁻⁶		
		Cd	2.73 x 10 ⁻⁴	3.49 x 10 ⁻¹¹	1.07 x 10 ⁻⁷	9.02 x 10 ⁻⁵	2.13 x 10 ⁻¹⁰	4.07 x 10 ⁻⁷		
		Pb	3.68 x 10 ⁻⁴	5.41 x 10 ⁻¹¹	1.66 x 10 ⁻⁶	3.13 x 10 ⁻⁶	2.27 x 10 ⁻¹²	NC	1.20 x 10 ⁻⁴	
	Cr	NC	NC	NC	NC	NC	NC	NC		
	Hg	NC	NC	NC	NC	NC	NC	NC		
	PM _{2.5} of Personal sample	As	5.72 x 10 ⁻⁴	8.40 x 10 ⁻¹¹	2.58 x 10 ⁻⁶	8.57 x 10 ⁻⁴	1.01 x 10 ⁻⁹	3.86 x 10 ⁻⁶		1.48 x 10 ⁻⁴
		Cd	2.83 x 10 ⁻⁴	4.15 x 10 ⁻¹¹	1.27 x 10 ⁻⁶	1.07 x 10 ⁻⁴	2.53 x 10 ⁻¹⁰	4.84 x 10 ⁻⁷		
		Pb	4.50 x 10 ⁻⁴	6.61 x 10 ⁻¹¹	2.03 x 10 ⁻⁶	3.82 x 10 ⁻⁶	2.78 x 10 ⁻¹²	NC	1.22 x 10 ⁻⁴	
	Cr	NC	NC	NC	NC	NC	NC	NC		
	Hg	NC	NC	NC	NC	NC	NC	NC		
Factory 2	PM _{10-2.5} of Area sample	As	2.47 x 10 ⁻⁴	3.63 x 10 ⁻¹¹	1.11 x 10 ⁻⁶	3.71 x 10 ⁻⁴	4.36 x 10 ⁻¹⁰	1.67 x 10 ⁻⁶		
		Cd	2.43 x 10 ⁻⁴	3.58 x 10 ⁻¹¹	1.10 x 10 ⁻⁶	9.24 x 10 ⁻⁵	2.18 x 10 ⁻¹⁰	4.16 x 10 ⁻⁷		
		Pb	1.62 x 10 ⁻⁴	2.39 x 10 ⁻¹¹	7.32 x 10 ⁻⁷	1.38 x 10 ⁻⁶	1.00 x 10 ⁻¹²	NC	5.83 x 10 ⁻⁵	
	Cr	NC	NC	NC	NC	NC	NC	NC		
	Hg	NC	NC	NC	NC	NC	NC	NC		
	PM _{2.5} of Area sample	As	2.65 x 10 ⁻⁴	3.90 x 10 ⁻¹¹	1.20 x 10 ⁻⁶	3.98 x 10 ⁻⁴	4.68 x 10 ⁻¹⁰	1.79 x 10 ⁻⁶		7.34 x 10 ⁻⁵
		Cd	2.31 x 10 ⁻⁴	3.40 x 10 ⁻¹¹	1.04 x 10 ⁻⁶	8.79 x 10 ⁻⁵	2.08 x 10 ⁻¹⁰	3.96 x 10 ⁻⁷		
		Pb	1.91 x 10 ⁻⁴	2.81 x 10 ⁻¹¹	8.61 x 10 ⁻⁷	1.62 x 10 ⁻⁶	1.18 x 10 ⁻¹²	NC	6.12 x 10 ⁻⁵	
	Cr	NC	NC	NC	NC	NC	NC	NC		
	Hg	NC	NC	NC	NC	NC	NC	NC		
PM _{10-2.5} of Personal sample	As	2.60 x 10 ⁻⁴	3.82 x 10 ⁻¹¹	1.17 x 10 ⁻⁶	3.90 x 10 ⁻⁴	4.58 x 10 ⁻¹⁰	1.76 x 10 ⁻⁶			
	Cd	2.51 x 10 ⁻⁴	3.69 x 10 ⁻¹¹	1.13 x 10 ⁻⁶	9.53 x 10 ⁻⁵	2.25 x 10 ⁻¹⁰	4.30 x 10 ⁻⁷			
	Pb	1.77 x 10 ⁻⁴	2.61 x 10 ⁻¹¹	8.00 x 10 ⁻⁷	1.51 x 10 ⁻⁶	1.10 x 10 ⁻¹²	NC	6.11 x 10 ⁻⁵		
Cr	NC	NC	NC	NC	NC	NC	NC			
Hg	NC	NC	NC	NC	NC	NC	NC			
PM _{2.5} of Personal sample	As	2.81 x 10 ⁻⁴	4.14 x 10 ⁻¹¹	1.27 x 10 ⁻⁶	4.22 x 10 ⁻⁴	4.96 x 10 ⁻¹⁰	1.90 x 10 ⁻⁶		7.74 x 10 ⁻⁵	
	Cd	2.46 x 10 ⁻⁴	3.62 x 10 ⁻¹¹	1.11 x 10 ⁻⁶	9.37 x 10 ⁻⁵	2.21 x 10 ⁻¹⁰	4.22 x 10 ⁻⁷			
	Pb	2.12 x 10 ⁻⁴	3.12 x 10 ⁻¹¹	9.57 x 10 ⁻⁷	1.80 x 10 ⁻⁶	1.31 x 10 ⁻¹²	NC	6.50 x 10 ⁻⁵		
Cr	NC	NC	NC	NC	NC	NC	NC			
Hg	NC	NC	NC	NC	NC	NC	NC			

Note: NC= Not calculated because not detected heavy metal in sample and reference dose value not available.