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Research article

Size Distributions of Inhalable Particulate Matter and Particle-bound Heavy Metals and Their Potential Occupational Health Risk Related to Informal E-waste Recycling in Thailand

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Abstract

Keywords

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inhalable particles;
heavy metals;
risk assessment;
size distributions

Concentrations and size distributions of atmospheric particulates and particulate-bound heavy metals in different inhalable fractions were studied in working areas during manual dismantling, thermal cutting and cable sheath burning activities. The particulate samples were collected on quartz fiber filters using an eight-stage cascade impactor with flow rate of 28.3 l min^{-1}. Mass concentrations of the particles were measured in each size fraction. Heavy metals bound on the particles were extracted with acid digestion and then analyzed using Atomic Absorption Spectrophotometer. Risk assessment of worker exposure to the particles was determined. The results indicated that the concentrations of ultrafine (d_{ae} < 0.43 µm), fine (0.43 < d_{ae} < 2.1 µm) and coarse (2.1 < d_{ae} < 10 µm) particles were in the ranges of 14.49-62.04, 57.51-120.26 and 153.26–646.99 µg m^{-3} during manual dismantling, 363.41-1,011.95, 2,105.40-4,899.11 and 1,698.54-7,075.61 µg m^{-3} during thermal cutting and 364.73-1,694.72, 1,953.33-4,431.41 and 1,385.97-6,126.13 µg m^{-3} during cable sheath burning, respectively. The concentrations of $PM_{2.1}$ and PM_{10} released from these activities did not exceed the OSHA PEL threshold limits. Heavy metals adsorbed on the particles (Fe, Cr, Zn, Cu, Pb, Mn) detected during manual dismantling did not exceed the TWA standard. Concentrations of Cr and Pb during cable sheath burning highly exceeded the standards whereas Pb concentrations during thermal cutting slightly exceeded the standard. The heavy metals released from these recycling activities were more enriched on coarse mode than fine mode. Inhalation exposure to Cr, Pb and Mn posed a potential health risk to the workers.

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1. Introduction

Electronic waste (e-waste), defined as discarded or damaged electrical and electronic appliances, is commonly known as one of the fastest growing waste streams in the world. It has increased substantially because the global market of electrical and electronic equipment continues to grow quickly, whereas the life span of these products becomes shorter owing to fast technological change. The amount of e-waste generated worldwide was about 53.6 million metric tonnes in 2019, up 21% over five years according to the Global E-waste Monitor 2020. It is predicted to rise to 74 million metric tonnes by 2030 [1]. E-waste contains a lot of potentially harmful substances including heavy metals, polyvinyl chloride (PVC), brominated flame retardants (BFRs) and other toxic organic pollutants as well as valuable materials such as gold (Au), silver (Ag), palladium (Pd), platinum (Pt), copper (Cu), aluminum (Al) [2]. Even though it contains many valuable components, the current recycling rate of e-waste is relatively low. Only 17.4% (9.3 million metric tonnes) of e-waste produced was properly collected and recycled in 2019 [1]. Most e-waste still ends up in improper recycling and uncontrolled disposal methods. This inappropriate disposal can result in adverse health effects and environmental problems.

Nowadays, Thailand has become one of the world's dumping grounds for e-waste due to its low labor costs and weak environmental laws on waste management [3-5]. Huge amounts of e-waste have been smuggled into the country via trading in second-hand goods or plastic waste since the Chinese government enacted a ban on the import of scrap and waste products [6]. Moreover, quantities of e-waste generated are substantially increased by the residential, commercial, institutional and industrial sectors due to a rise in local consumption of electrical and electronic devices. It was estimated that Thailand generated 421,335 tonnes of e-waste in 2019 (65% of total generation of municipal hazardous waste) but only 104,526 tonnes (16.12% of the production) was appropriately managed [7]. Most e-waste is burnt in unapproved incinerators or in the open air, dumped unsafely in landfills, or improperly recycled through primitive techniques.

Crude recycling methods of e-waste introduce massive amounts of toxic pollutants into the surroundings [8]. Large quantities of e-waste in Thailand are recycled in the small-scale informal private sector where poor and low educated people are regularly involved in the operations without personal protective equipment. With little awareness of the impact on their occupational health and safety, workers are likely exposed to atmospheric particulate matter and particle-bound toxic substances in the workplace. Exposure to these substances through the air can cause various respiratory diseases. These health effects depend on the toxicity, exposure concentration and duration [9-12]. It was also found that small household e-waste recycling workshops can cause more severe heavy metal pollution than large-scale e-waste recycling plants [13]. Previous work indicated that manual dismantling emitted atmospheric particulate-bound heavy metals such as chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn) and zinc (Zn), into the environment [10-12, 14]. It was reported that size distribution of particles obtained from thermal cutting of metals was associated with cutting parameters such as cutting materials, cutting methods, cutting conditions [15, 16]. Many studies revealed that open burning of insulated copper wire and electronic waste released small particles, PAHs and heavy metals into the atmosphere [17-19]. Several findings reported that concentrations of atmospheric particle-bound heavy metals in e-waste recycling areas were significantly higher than those in uncontaminated areas [11, 12, 20-22]. Although there are several reports concerning environmental effects and potential health risks of toxic substances released from e-waste recycling sites [11, 23], there are few studies on emissions of toxic pollutants in working areas during unregulated recycling activities and on the health risks derived from the exposure to these contaminants.

The objectives of this study were to investigate concentrations and size distributions of inhalable particles and particulate-bound heavy metals released during different recycling activities

at small-scale, informal e-waste recycling workshops. Emissions of airborne particles from manual dismantling, thermal cutting and burning of cable sheath were examined. An estimate of the potential health risk to the workers through inhalation exposure was also evaluated.

2. Material and Methods

2.1 Air sampling

In this study, air samples were collected during manual dismantling of e-waste from an e-waste recycling workshop located in Chatuchak District, Bangkok (latitude 14°49′24.0″ N and longitude 100°35′09.8″ E). The samplings were conducted on April 6, 2015; April 8-10, 2015 and April 20-21, 2015 (n = 6). The samples were taken at the height of 1 m above ground level, which was about the same height as the inhalation level of workers while sitting on the floor. This dismantling activity was conducted outside the workshop under a roof. Each sample was taken over a 6 h period, starting from 9.00 a.m. to 4.00 p.m. The samples were collected under uncontrolled operating (such as amounts and types of e-waste, disassembling tools) and environmental conditions. A control was taken from the same site during non-recycling activity on April 7, 2015.

Air samples were taken during thermal cutting from an e-waste recycling workshop located in Mueng Samutprakan District, Samutprakan Province, Thailand (latitude 13°39′18.3″ N and longitude 100°36′27.8″ E). E-waste containing valuable metals was cut with a gas cutting torch. These cutting operations were performed under uncontrolled amounts and types of e-waste used as well as environmental conditions. This activity was operated for a short period, and meanwhile other recycling activities were still running in the workshop. Samples were collected during cutting operation for 30 min on April 29, 2015; August 27, 2015 and December 18, 2015 (n = 3) from the worker's breathing zone, which was 1 m above ground level. The thermal cutting activity was done outside the workshop, under a roof. Control air samples were taken at the same site during non-thermal cutting for 30 min on April 20, 2015. The locations of the sampling sites are shown in Figure 1.

As open burning of cable sheathing to recover copper wire is illegal, this recycling activity was always operated at night to avoid being arrested. In this work, 1 kg of insulated cable was burnt in the open air at Faculty of Science, King Mongkut's Institute of Technology Ladkrabang. Air samples were taken in the downwind direction around 1.50 m from the burning site. They were collected for 30 min on May 1, 2015 and May 11, 2015 (n = 3) at 1.5 m above ground level. Ambient air was also sampled at the same site as a control.

The atmospheric particle samples were collected on 81-mm diameter quartz fiber filters (Toyo Roshi Kaisha, Japan) using an Eight-Stage Non-Viable Andersen Cascade Impactor (Thermo Scientific, USA) at a flow rate of 28.3 l min^{-1}. The particle fractions were classified based on aerodynamic particle diameters into the following size ranges: 10.0-9.0, 9.0-5.8, 5.8-4.7, 4.7-3.3, 3.3-2.1, 2.1-1.1, 1.1-0.65, 0.65-0.43, and <0.43 µm. The inhalable fractions of atmospheric particles were grouped into three size ranges based on their formation mechanism: ultrafine particles (d_{ae} < 0.43 µm), fine particles (0.43 µm < d_{ae} < 2.1 µm), and coarse particles (2.1 µm < d_{ae} < 10 µm). In this study, the sum of the concentrations of ultrafine, fine and coarse fractions (<0.43 µm < d_{ae} < 10 µm) was defined as PM_{10} concentration while those of the ultrafine and fine fractions (<0.43 µm < d_{ae} < 2.1 µm) were determined as $PM_{2.1}$ concentration. The sampling procedures were conducted following the US EPA method [24]. The sampling details were described in Phoothiwut and Junyapoon [25].

Figure 1. Sampling locations at a small-scale family-run workshop located in Chatuchak District and a junk shop located in Mueang Samut Prakan District, Samut Prakan Thailand (adapted from Wikipedia [26])

2.2 Gravimetric analysis

In order to determine particle concentrations, the exposed filters were equilibrated after sampling in a desiccator for at least 24 h under controlled conditions (relative humidity 30-40 % and temperature 15-30°C) and were then weighed on the five-digit electronic microbalance (Sartorius BA 210, France). Particle concentrations were calculated as the weight change of the exposed filter divided by the volume of air sample corrected to standard ambient temperature and pressure (25°C, 1 atm). Meteorological data were obtained from the monitoring station of the Meteorological Department of Thailand, located near the sampling site as listed in Table 1 [27]. After weighing, the exposed filters were stored in the same containers and kept in a desiccator. Each sample was analyzed within 1 week of sampling to minimize sample losses.

2.3 Extraction and analysis of heavy metals

This study focused on the investigation of six enriched heavy metals (iron (Fe), chromium (Cr), zinc (Zn), copper (Cu), lead (Pb), manganese (Mn)) found in e-waste recycling areas [12]. These heavy metals were digested and analyzed according to Compendium U.S. EPA Method IO-3.2 modification [28]. Each sampled filter was cut into small pieces and placed in a 50 ml beaker. The filter was digested with 10 ml of a mixture of conc. HCl: HNO_3 (3:1) (Carlo Erba, Italy) using a hot plate for at least 30 min until the digested solution was clear. After cooling down, the digested solution was transferred to a 10 ml volumetric flask and then adjusted to the level with deionized water. Finally, the digested solution was filtered with 0.45 µm pore size nylon filter (ANPL Scientific Instrument, China) before being analyzed with a 200-AA Atomic Absorption Spectrometer (Perkin Elmer, USA). An international standard reference material of Fe (Panreac, EU), Pb, Zn (Ajax Finechem, New Zealand), Cu (Scharlab S.L., Spain), Mn (Fisher Scientific, UK),

Cr (Merck, Germany) was used for standard calibration. The linear correlation coefficients of the standard calibration curves were in the range of 0.9931-0.9989. The determined concentrations of target metals were in the dynamic linear range of the standard curve. Recovery efficiencies of heavy metals were determined in triplicate using a spike method. The average recoveries of Fe, Pb, Zn, Cu, Mn, and Cr from the standard reference materials were 91.94%, 94.35%, 95.02%, 94.51%, 94.01%, and 96.66%, respectively. Solvent and field blank samples were measured using the same method as the samples. All sample measurements were subtracted from the blanks but they were not corrected for the recoveries of target metals.

2.4 Assessment of human health risk through inhalation exposure

Inhalation exposure of workers to particle-bound heavy metals released from three e-waste recycling activities (manual dismantling, thermal cutting and burning of cable sheath) was observed. In this study, the risk assessment of workers was evaluated through inhalation pathway. The average daily dose exposure to metals through inhalation contact (ADD_{inh}) (mg kg^{-1} d^{-1}) can be calculated by equation (1) [29].

$$ADD_{inh}\ (mg\ kg^{-1}d^{-1}) = \frac{C\ x\ InhR\ x\ ET\ x\ EF\ x\ ED}{BW\ x\ AT} \quad (1)$$

Where C is the concentration of heavy metals bound on particles in air (mg m^{-3}). The average inhalation rate (InhR) for ambient air is 0.67 m^3 h^{-1} for a worker of an average age of 43 years old, according to the Exposure Factors Handbook [30]. ET is the exposure time (8 h d^{-1}). EF is the exposure frequency (365 d yr^{-1}). ED is the exposure duration (10 years). The average body weights (BW) of adult Thai males and females were 71.01 kg and 59.79 kg, respectively, according to the study of NSTDA [31]. AT is the average time (d; ED x 365 d).

The non-carcinogenic risk of each heavy metal through inhalation was estimated using the Hazard Quotient (HQ) as shown in equation (2). The Reference Dose for inhalation exposure (RfD_{inh}) is the reference dose of an individual heavy metal through inhalation exposure (mg kg^{-1} day^{-1}). The RfD_{inh} values of analyzed metals are presented in Table 2 [32-34]. A hazard quotient less than or equal to 1 ($HQ \leq 1$) indicates no adverse health effects, whereas a hazard quotient greater than 1 ($HQ > 1$) suggests that adverse health effects are likely to occur because the estimated exposure exceeds the reference dose. A hazard quotient greater than 10 ($HQ > 10$) indicates high chronic risk [35].

$$HQ = \frac{ADD_{inh}}{RfD_{inh}} \quad (2)$$

2.5 Statistical analysis

Analyses were performed at a significance level of 0.05 using Minitab. Two-way ANOVA with Fisher's Least Significant Difference (LSD) post hoc test was applied to assess the mean differences. Hypothesis test for difference of means was conducted. The effect of e-waste recycling activity on the particle size fractions as well as the effect of e-waste recycling activity on the heavy metal levels were analyzed. A 95% confidence interval (CI) was used to assess the range for health risks.

Table 1. Meteorological data during sampling periods obtained from the monitoring station of Pollution Control Department located near the sampling sites [a] [27]

Activity	Sample date	Meteorological data				
		Temp. (°C)	Atmospheric pressure (mbar)	Relative humidity (%)	Avg. wind speed [b] (km h^{-1})	Wind direction (measured at 10.00 am, 1.00 pm, 4.00 pm)
Manual dismantling						
Manual dismantling	Apr 6, 2015	31.0±3.2	1,007.81±1.52	71±13.6	7±1.5 (Light breeze)	SSW, S, SSW
	Apr 8, 2015	27.1±2.0	1,010.56±1.60	81±7.2	6±4.4 (Light breeze)	SW, NW, SE
	Apr 9, 2015	28.8±3.8	1,010.75±1.29	75±16.0	4±2.7 (Light air)	SSE, SE, S
	Apr 10, 2015	30.7±3.1	1,010.35±1.58	70±16.4	6±2.1 (Light breeze)	S, S, S
	Apr 20, 2015	31.7±3.4	1,008.64±1.78	69±15.9	7±2.4 (Light breeze)	SSW, SW, W
	Apr 21, 2015	32.8±3.4	1,007.59±2.03	60±21.4	7±1.5 (Light breeze)	WSW, SW, W
No recycling activity	Apr 7, 2015	31.6±3.2	1,007.93±1.75	69±12.1	7±2.3 (Light breeze)	S, SSW, SSW
Thermal cutting						
Thermal cutting	Apr 29, 2015	31.2±2.8	1,009.65±1.61	78±9.3	3±2.8 (Light air)	S, S, SE
	Aug 27, 2015	29.4±2.7	1,009.74±1.35	75±12.7	2±2.3 (Light air)	WSW, SW, SW
	Dec 18, 2015	24.9±2.2	1015.80±1.48	61±7.9	3±2.3 (Light air)	ENE, NE, NE
No thermal cutting activity	Aug 20, 2015	30.8±3.4	1,007.46±1.39	66±7.7	4±1.9 (Light air)	WNW, WSW, S
Burning of cable sheath						
Burning of cable sheath	May 1, 2015	32.1±2.5	1,008.32±1.62	62±13.3	6±3.5 (Light breeze)	SSW, S, S
	May 11, 2015	31.2±2.4	1,008.03±1.34	66±13.4	7±2.7 (Light breeze)	S, SSW, SSW
No burning activity	May 12, 2015	32.2±2.2	1008.06±1.71	64±9.1	8±2.6 (Light breeze)	S, SSW, S

Note: [a] Meteorological data obtained from the Meteorological Department of Thailand at Don Muang Airport station for manual dismantling, Bangna station for thermal cutting and Suvarnabhumi Airport station for burning of cable sheath.

[b] Meteorological data were measured every 3 h from 10.00 am - 4.00 pm. Wind speed < 1 km h^{-1} = calm; wind speed 1-5 km h^{-1} = light air; wind speed 6-11 km h^{-1} = light breeze

Table 2. The reference RfD_{inh} of heavy metals

Heavy metals	RfD_{inh} (mg kg^{-1} d^{-1})	References
Fe	7.00E-01	[32]
Cr	2.86E-05	[33, 34]
Cu	4.02E-02	[33, 34]
Pb	3.52E-03	[33, 34]
Zn	3.00E-01	[33, 34]
Mn	1.43E-05	[34]

3. Results and Discussion

3.1 Concentrations and size distributions of inhalable particles emitted from e-waste recycling activities

In this study, the emissions of inhalable particles from three e-waste recycling activities (manual dismantling, thermal cutting and burning of cable sheath) were investigated. These particles were classified into three groups: ultrafine particles (d_{ae} < 0.43 µm), fine particles (0.43 < d_{ae} < 2.1 µm), and coarse particles (2.1 < d_{ae} < 10 µm). The sum of concentrations of ultrafine, fine and coarse fractions (<0.43 µm < d_{ae} < 10 µm) was defined as PM_{10} concentration while those of the ultrafine and fine fractions (<0.43 µm < d_{ae} < 2.1 µm) were considered as $PM_{2.1}$ concentration. Their mean, median values and concentration ranges are listed in Table 3.

Measurements of inhalable particles produced during manual dismantling indicated the dominance of coarse fraction (72.05% of total mass) followed by the fine (20.08% of total mass) and ultrafine fractions (7.87% of total mass). The average concentrations of coarse and fine particles released during manual dismantling were about 3.1 and 2.2 times higher than those during no recycling activity whereas there were no significant differences in concentrations of ultrafine particles. Coarse and fine particles likely resulted from the fragments of e-waste during disassembly which is consistent with the results of previous studies [8, 14]. It was reported that particle size distribution was influenced by types of dismantling tools and material compositions of e-waste. The average concentrations of PM_{10} and $PM_{2.1}$ in the air during manual dismantling were around 2.5 and 1.6 times higher than those during no recycling activity (Table 3). Large amounts of airborne particles were produced from the thermal cutting activity. The mass concentrations of coarse, fine and ultrafine particle fractions emitted during thermal cutting contributed 43.73%, 48.05% and 8.22% of total mass, respectively, while those during no thermal cutting activity were 80.09%, 16.82% and 3.09% of total mass, respectively (Table 3). These results correspond with the work of Ebadian *et al*. [36], who reported that the cutting of metals with plasma torch produced large numbers of fine and coarse particle fractions. Ultrafine particles may have originated from condensation of vaporized materials and then rapid formation of aggregates. Coarse particles likely arose from the emission of melted materials or fragments. The concentration levels of ultrafine, fine, and coarse particles released during thermal cutting were approximately 8.3, 8.9, and 1.7 times higher than those emitted during no thermal cutting activity, respectively. The emissions of PM_{10} and $PM_{2.1}$ during thermal cutting activity were about 3.1 and 8.8 times higher than those during no thermal cutting activity, respectively. During the period of no thermal cutting, high levels of coarse particles were observed because other recycling activities were carried out when the air samples were collected. Our previous work revealed the large concentrations of inhalable particles were emitted from open burning of electric cable sheath [17].

Table 3. Concentrations of inhalable particles emitted during manual dismantling, thermal cutting and burning of cable sheath activities

Samples		Concentration (μg m^{-3}) at 25 °C, 1 atm				
		Ultrafine particles (<0.43 μm)	Fine particles ($0.43<d_{ae}<2.1$ μm)	Coarse particles ($2.1<d_{ae}<10$ μm)	PM_{10}	$PM_{2.1}$
Manual dismantling						
Manual dismantling	Mean ± SD	33.99±17.86 [b]	86.73±25.42 [b]	311.17±175.85 [b]	431.89±162.46	120.72±31.61
	Median	34.69	82.53	289.91	391.81	126.34
	Range	14.49-62.04	57.51-120.26	153.26-646.99	279.66-741.34	74.37-161.44
	Ratio	(7.87%)	(20.08%)	(72.05%)		
No recycling activity		36.35 (20.65%)	39.71 (22.56%)	99.94 (56.79%)	176.00	76.06
Thermal cutting						
Thermal cutting	Mean ± SD	667.57±326.14 [b]	3,901.89±1,558.95 [a]	3,550.74±3,053.94 [a]	8,120.20±4,480.08	4,569.46±1,842.38
	Median	627.35	4,701.16	1,878.08	7,206.59	5,328.51
	Range	363.41-1,011.95	2,105.40-4,899.11	1,698.54-7,075.61	4,167.35-12,986.67	2,468.82-5,911.06
	Ratio	(8.22%)	(48.05%)	(43.73%)		
No thermal cutting activity		80.47 (3.09%)	438.54 (16.82%)	2,088.10 (80.09%)	2,607.11	519.01
Burning of cable sheath *						
Burning of cable sheath	Mean ± SD	1,045.82±665.58 [b]	3,557.50±1,391.11 [a]	4,529.03±2722.09 [a]	9,132.35±4,718.55	4,603.32±2,015.28
	Median	1,078.02	4,287.76	6,075.00	11,440.78	5,365.78
	Range	364.73-1,694.72	1,953.33-4,431.41	1,385.97-6,126.13	3,704.03-12,252.26	2,318.06-6,126.14
	Ratio	(11.45%)	(38.96%)	(49.59%)		
No burning activity		4.08 (2.70%)	69.32 (45.95%)	77.47 (51.35%)	150.87	73.40

Note: * Cable sheath burning data is derived from our previous work [17].
Means with different superscript letters are significant different.

During the burning of cable sheath, the fractions of coarse particles, fine and ultrafine particles were 49.59%, 38.96% and 11.45% of total mass, respectively. Whereas those during no burning activity were 51.35%, 45.95% and 2.70% of total mass, respectively (Table 3). Cable insulation burning emitted fine and coarse particle fractions into the atmosphere, a result that correlated with the works of Bungadaeng *et al*. [37]. The coarse particles may be produced from incomplete combustion of plastic insulation while fine particles may be transformed from the agglomeration of ultrafine particles and condensation of volatile species. The ultrafine particles may be emitted directly during burning of cable sheath or formed by gas-to-particle conversion process [38]. The concentration levels of coarse, fine, and ultrafine particles emitted during burning of cable sheath were approximately 58.5, 51.3, and 256.3 times higher than those during no burning activity, respectively. The emissions of PM_{10} and $PM_{2.1}$ during burning of cable sheath were about 60.5 and 62.7 times higher than those during no burning activity, respectively. In this study, the concentrations of $PM_{2.1}$ and PM_{10} were calculated based on their sampling period. It was found that the atmospheric concentrations of $PM_{2.1}$ and PM_{10} released from manual dismantling, thermal cutting and burning of cable sheath did not exceed the average 8-h permissible exposure limits of the Occupational Safety and Health Administration (OSHA-PEL) of 5,000 and 15,000 μg m^{-3}, respectively [39]. This may be because these e-waste recycling activities were managed in the open air. However, concentrations of $PM_{2.1}$ released from thermal cutting and burning of cable sheath activities were slightly below the standard level.

A wide range of particle concentrations in each size fraction obtained from manual dismantling, thermal cutting and burning of cable sheath activities was observed as shown in Figure 2. This may be because these activities were managed under uncontrolled operating conditions such as material components and quantities of e-waste including environmental conditions.

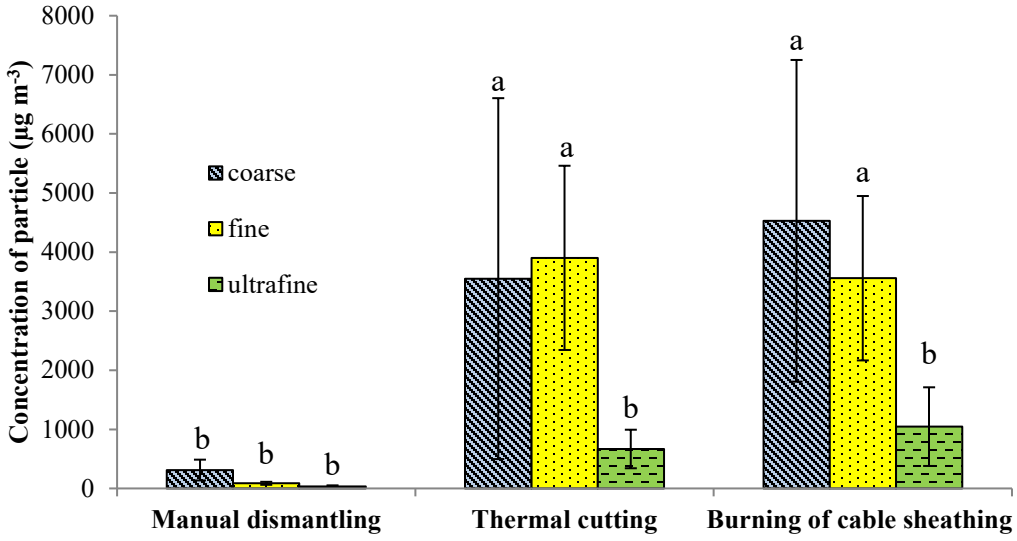

Figure 2. Concentrations of ultrafine, fine and coarse particles released during manual dismantling, thermal cutting and burning of cable sheathing activities
Remark: Cable sheathing burning data is derived from our previous work [17] and a, b denote significant differences of the sample means.

These results were evaluated statistically based on significant difference between mean values among particle size fraction, recycling activity and interaction of size fraction and recycling activity using Two-way ANOVA with Fisher's Least Significant Difference (LSD) post hoc test. There was a significant difference for interaction of particle size fraction and recycling activity ($F_{4,27}$ = 2.75, p-value 0.049). The mean concentrations of coarse and fine particles released from thermal cutting and burning of cable sheath were not significantly different but they were markedly higher than those of the ultrafine particles. There were no significant differences among concentrations of ultrafine, fine and coarse particles from manual dismantling. The mean concentrations of coarse and fine particles released during thermal cutting and burning of cable sheath were higher than those during manual dismantling (Figure 2).

In this study, the particle-size distribution was characterized into three modes: nucleation (d_{ae} < 0.43 µm), accumulation (0.43 < d_{ae} < 2.1 µm) and coarse modes (2.1 < d_{ae} < 10 µm). The size distribution plots of particle mass in the atmospheric aerosols during manual dismantling, thermal cutting and burning of cable sheath are presented in Figure 3. The particle size distribution during manual dismantling was bimodal, which had a major peak in the coarse mode (9.0-5.8 µm) and a minor peak in the accumulation mode (1.1-0.65 µm), as shown in Figure 3(a). These results showed that the manual dismantling activity largely generated coarse and fine particles, which is consistent with the work of Ruan *et al*. [8]. Meanwhile, the particle size distribution during no recycling activity was bimodal with a dominant coarse mode in the size range of 5.8-4.7 µm and a less abundant mode in the accumulation mode (1.1-0.65 µm). The particle size distribution during thermal cutting was bimodal with a predominant peak in the coarse mode in the size range of 5.8-4.7 µm and a minor peak in the accumulation mode in the size range of 1.1-0.65 µm. This was in agreement with the findings of Novick *et al*. [40] who presented the bimodal size distributions of aerosols from plasma torch cuts on stainless steel, with one mode at about 0.2 µm and the other at about 10 µm. The particle size distribution during no thermal cutting activity was trimodal with a dominant peak (5.8-4.7 µm), a less abundant peak (3.3-2.1 µm) in coarse mode, and another minor peak in the accumulation mode (1.1-0.65 µm), as shown in Figure 3(b). Our previous work [17] indicated that the particle size distribution in atmospheric aerosols during burning of insulated wire was bimodal with a dominant coarse mode in the size range of 5.8-4.7 µm and a minor peak in accumulation mode in the size range of 1.1-0.65 µm (Figure 3(c)). Burning of cable insulation produced a large amount of coarse and fine particles in the atmosphere, which was in good agreement with the work of Bungadaeng *et al*. [37]. A trimodal particle size distribution with the presence of a major peak in the coarse mode (5.8-4.7 µm) and two minor peaks in accumulation mode in the size range of 2.1-1.1 µm and 0.65-0.43 µm was observed during no burning activity. Rovelli *et al*. [41] indicated that a trimodal size distribution of atmospheric particles was found in an urban environment. These results revealed that bimodal particle size distribution with a main peak in coarse mode and a minor peak in accumulation mode was detected in all recycling activities.

3. 2 Concentrations and size distributions of particle-bound heavy metals in air emitted from e-waste recycling activities

The concentrations of heavy metals bound on inhalable particles emitted during manual dismantling, thermal cutting and burning of cable sheath activities are listed in Table 4. In this study, the sum of the amounts of the six heavy metals, Fe, Zn, Cu, Mn, Pb, Cr, was reported as total heavy metal concentration. It was found that e-waste recycling activities released larger amounts of heavy metals into the surroundings than no recycling activity which was consistent with the work of Huang *et al*. [10]. The concentrations of total heavy metals emitted during manual dismantling, thermal cutting and burning of cable sheath were 1.5, 2.1 and 32.1 times higher than those found during no recycling activity, respectively. The average concentrations of heavy metals released during manual

dismantling, thermal cutting and cable sheath burning were 1.5, 2.1 and 32.3 times higher for Fe, 1.8, 2.5 and 69.8 times higher for Cr, 0.5, 2.1 and 14.8 times higher for Zn, 1.6, 0.8 and 5.3 times higher for Cu, 1.7, 2.3 and 21.3 times higher for Pb, and n.d., 4.1, 9.7 times higher for Mn than those observed during no recycling activity, respectively. Types and amounts of heavy metals vary depending on recycling processes and e-waste materials [42]. It was found that the concentrations of total Cr and Pb released from the burning of cable sheath greatly exceeded the TLV levels of 500 and 50 μg m^{-3}, respectively [39] whereas the concentrations of Pb emitted from thermal cutting slightly exceeded the TLV level.

Significant differences were observed in the mean values among interaction of size fraction and recycling activity as shown in Figure 4 (a). Cable insulation burning released larger amounts of heavy metals into the environment than thermal cutting and manual dismantling activities. The average concentrations of total heavy metals bound on coarse and fine particles released from burning of cable sheath were not significantly different but they were higher than those adsorbed on ultrafine particles. There were no significant differences among concentrations of total heavy metals adsorbed on ultrafine, fine and coarse particles emitted during manual dismantling and thermal cutting activities. Figure 4 (b) shows significant differences of the mean values between recycling activities and types of heavy metals. There were no significant differences among the mean concentrations of Zn, Cu and Mn in these three activities. The mean concentrations of Fe, Cr and Pb emitted from burning of cable sheath were higher than those found during thermal cutting and manual dismantling. This is because cable insulation is composed of additives (e.g. TiO_2, ZnO, Cr_2O_3, Fe_2O_3), flame retardants (e.g. brominated organics combined with Sb_2O_3), and stabilizers or plasticizers (e.g. compounds of Ba, Cd, Pb, Sn, Zn) [43]. When cable insulation is burnt, their heavy metal components are released into the atmosphere. However, only small amounts of Zn were detected because it could be vaporized in flame due to its high vapor pressure [44].

It was found that Cr and Pb were the main toxic heavy metals released from manual dismantling, thermal cutting and burning of cable sheath activities. In this study, the Cr/Pb ratio was used as a source apportionment of heavy metals originated from e-waste recycling processes. The average ratios of Cr/Pb obtained for the PM_{10} and $PM_{2.1}$ fractions were 0.633 and 0.742 during manual dismantling, 1.057 and 1.185 during thermal cutting, 1.209 and 1.350 during cable sheath burning, respectively, while those were 0.595 and 0.427 during no manual dismantling, 0.980 and 0.366 during no thermal cutting, 0.369 and 0.453 during no cable sheath burning, respectively. The Cr/Pb ratios obtained for the PM_{10} and $PM_{2.1}$ fractions during thermal cutting and burning of cable sheath were significantly higher than those of no recycling activities. Whereas, similar Cr/Pb ratios obtained for the PM_{10} and $PM_{2.1}$ fractions were found during with and without manual dismantling activities. These results implied that burning of cable sheath generated the highest levels of toxic heavy metals into the atmosphere followed by thermal cutting and manual dismantling, respectively. The Cu/Zn ratio is used as a source apportionment of heavy metals produced from automobile components. Cadle *et al*. [45] reported that the Cu/Zn ratios of 0.21±0.15 and 0.01±0.003 are characteristic of gasoline- and diesel-powered vehicles, respectively. In this study, the average ratios of Cu/Zn obtained for the PM_{10} and $PM_{2.1}$ fractions were 0.340 and n.d. during manual dismantling, 0.065 and 0.063 during thermal cutting, and 0.058 and 0.151 during cable sheath burning, respectively. The Cu/Zn ratios obtained for the PM_{10} and $PM_{2.1}$ fractions were 0.101 and n.d. during no manual dismantling, and 0.166 and 0.038 during no thermal cutting, respectively. Cu was not detected during no burning of cable sheath. The Cu/Zn ratios obtained for the PM_{10} and $PM_{2.1}$ fractions during thermal cutting and burning of cable sheath activities were unlikely to be generated from vehicular emissions. While Cu/Zn ratios in air during manual dismantling indicated that vehicular emissions may contribute to heavy metals found in the working area.

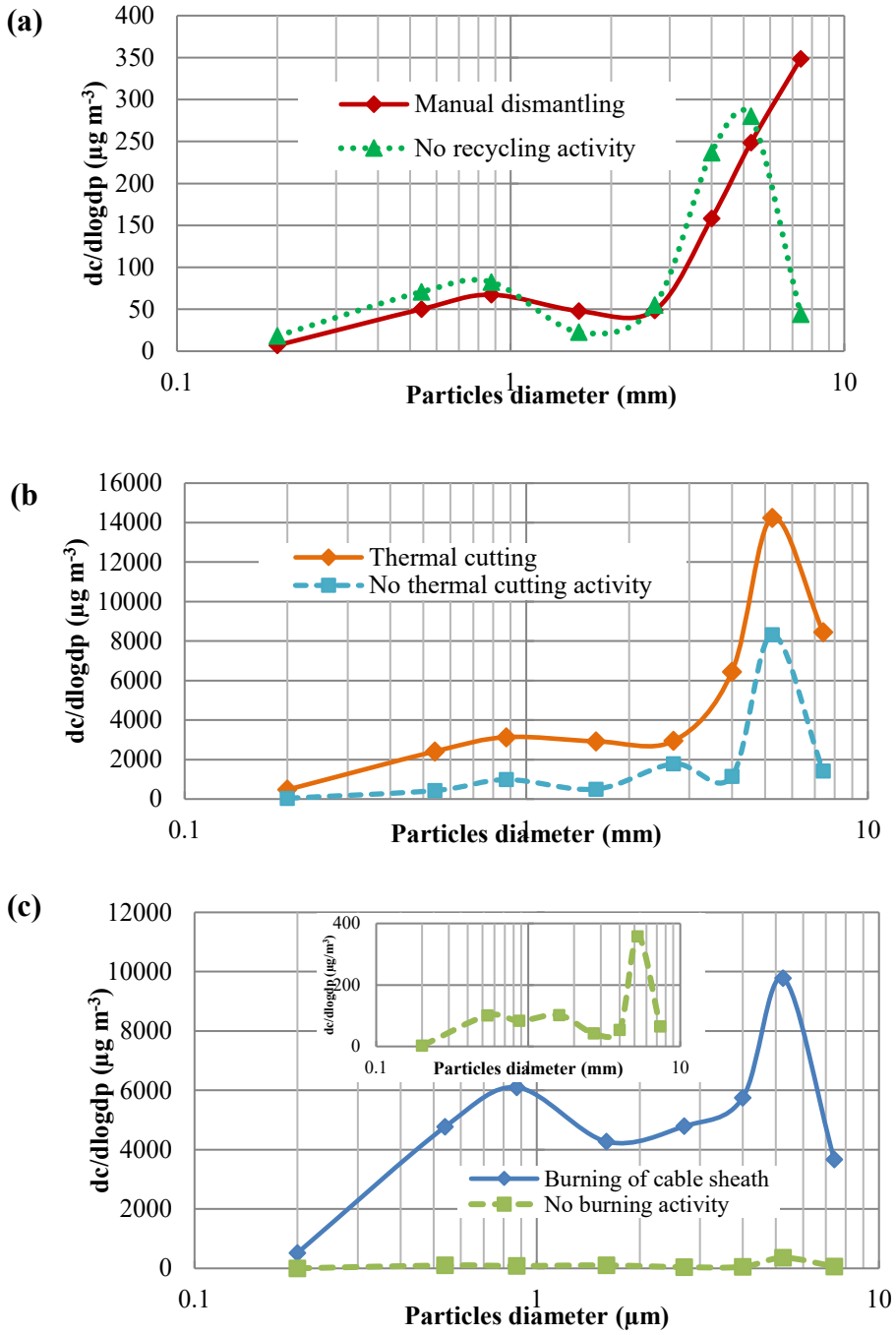

Figure 3. Size distributions of particles emitted during manual dismantling (a), thermal cutting (b), and burning of cable sheath activities (c)
Remark: Cable sheath burning data is derived from our previous work [17].

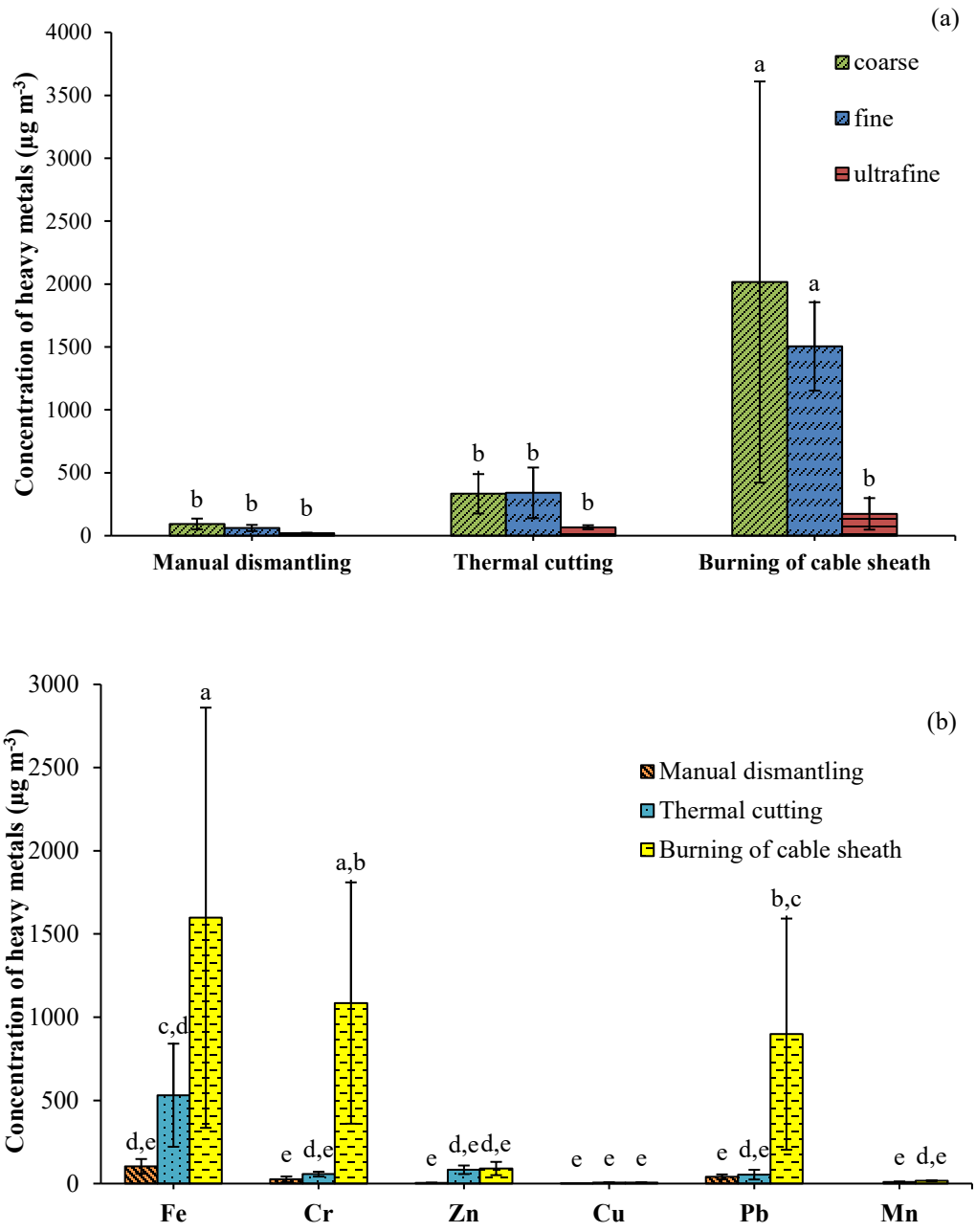

Figure 4. Concentration of total heavy metals adsorbed on ultrafine, fine and coarse particles (a), and individual heavy metals adsorbed on particles released during recycling activities (b)
Remark: a, b, c, d, e denote significant differences of the sample means.

Table 4. Heavy metals concentrations emitted from e-waste recycling activities

Heavy metal	Particle size	Concentration (μg m^{-3})											
		Manual dismantling				Thermal cutting				Open burning of cable sheath			
		Sample			No activity	Sample			No activity	Sample			No activity
		Mean±SD	Median	Range		Mean±SD	Median	Range		Mean±SD	Median	Range	
Fe	Ultrafine	11.68±4.35	12.59	5.52-16.50	8.35	46.64±5.52	43.60	43.31-53.01	14.73	23.55±11.46	18.91	15.13-36.60	0.82
	Fine	36.92±17.05	37.77	13.38-61.97	25.98	248.78±186.07	141.67	141.04-463.63	52.08	735.16±536.65	966.57	121.63-1,117.29	7.36
	Coarse	54.64±29.72	57.71	13.38-87.62	32.77	235.67±119.24	188.06	147.59-371.35	191.61	838.94±958.91	307.12	263.79-1,945.91	41.28
	Total	**103.24±44.39**			**67.10**	**531.09±309.76**			**258.42**	**1,597.65±1262.82**			**49.46**
Cr	Ultrafine	3.22±1.30	3.45	0.88-4.71	1.26	9.37±7.59	5.04	4.943-18.13	5.13	89.54±74.23	132.01	3.83-132.78	1.23
(8 hr-TWA	Fine	9.86±7.09	11.85	1.08-18.67	6.21	25.28±2.77	26.50	22.10-27.23	1.27	411.32±181.70	515.71	201.51-516.72	6.54
0.5 $mg.m^{-3}$)*	Coarse	12.40±9.95	13.70	1.34-22.40	6.57	22.21±5.44	23.53	16.24-26.87	16.72	584.23±469.36	848.98	42.31-861.40	7.77
	Total	**25.48±17.38**			**14.04**	**56.86±14.52**			**23.12**	**1,085.09±725.27**			**15.54**
Zn	Ultrafine	0.33±0.19	0.26	0.13-0.66	0.64	5.34±1.44	5.78	3.733-6.505	2.90	2.78±2.24	1.77	1.23-5.34	nd
	Fine	1.18±0.82	0.95	0.67-2.83	3.53	34.59±11.30	39.79	21.63-42.35	16.77	32.10±11.31	29.79	22.13-44.40	nd
	Coarse	2.34±1.20	2.33	0.91-4.38	4.13	43.05±16.26	34.48	32.88-61.80	20.51	55.63±38.04	42.57	25.84-98.48	6.13
	Total	**3.85±2.09**			**8.30**	**82.98±25.71**			**40.18**	**90.51±39.92**			**6.13**
Cu	Ultrafine	nd	nd	nd	nd	0.36±0.21	0.42	0.12-0.53	0.32	2.21±1.37	2.16	0.86-3.60	nd
(8 hr-TWA	Fine	nd	nd	nd	nd	2.16±1.41	2.79	0.54-3.16	0.42	3.04±1.69	3.343	1.22-4.56	nd
1 $mg.m^{-3}$)*	Coarse	1.31±0.93	1.16	0.46-2.77	0.84	2.87±0.57	2.74	2.37-3.49	5.91	nd	nd	nd	nd
	Total	**1.31±0.93**			**0.84**	**5.39±1.11**			**6.65**	**5.25±3.05**			**nd**
Pb	Ultrafine	4.15±1.95	4.61	0.551-5.82	2.19	4.13±2.39	3.40	2.19-6.81	2.19	54.68±42.35	71.15	6.58-86.33	0.82
(8 hr-TWA	Fine	13.47±4.97	14.36	4.74-18.13	15.32	25.12/±9.74	25.31	15.29-34.76	15.32	316.30±246.69	375.69	45.35-527.88	16.35
0.05 $mg.m^{-3}$)*	Coarse	22.64±7.97	24.92	7.86-29.79	6.07	24.55±17.31	19.60	10.25-43.79	6.07	526.90±406.93	677.81	66.08-836.82	24.93
	Total	**40.26±14.80**			**23.58**	**53.80±29.20**			**23.58**	**897.88±694.84**			**42.10**
Mn	Ultrafine	nd	nd	nd	nd	1.10±0.23	1.21	0.83-1.25	0.12	0.84±0.09	0.86	0.74-0.91	0.08
(8 hr-TWA	Fine	nd	nd	nd	nd	4.73±0.96	4.80	3.74-5.66	0.54	6.20±1.11	5.65	5.47-7.48	0.86
0.1 $mg.m^{-3}$-	Coarse	nd	nd	nd	nd	4.66±1.30	4.11	3.73-6.14	1.87	10.11±1.78	10.58	8.15-11.62	0.82
IHL)*	**Total**	**nd**			**nd**	**10.49±0.98**			**2.53**	**17.15±2.80**			**1.76**
Total heavy metals		**174.14**			**113.86**	**740.61**			**354.48**	**3,693.53**			**114.99**

Notes: TWA = Time Weight Average, IHL = inhalable
*OSHA Annotated Table Z-1 [39]

Figure 5 illustrates the contributions of particle-bound heavy metals released from the e-waste recycling activities. The concentrations of particle-bound heavy metals during manual dismantling decreased in the order of Fe (59.29 % of the total mass) > Pb (23.12 % of the total mass) > Cr (14.63 % of the total mass) > Zn (2.21 % of the total mass) > Cu (0.75 % of the total mass), while that during no recycling activity was ranked in the order of Fe (58.93 % of the total mass) > Pb (20.71 % of the total mass) > Cr (12.33 % of the total mass) > Zn (7.29 % of the total mass) > Cu 0.74 % of the total mass). Mn was not detected in the manual dismantling site. The ratios of Cr and Pb emitted during manual dismantling were slightly higher than those during no recycling activity. The relative order of the mean metal concentrations released during thermal cutting was Fe (71.71 % of the total mass) > Zn (11.20 % of the total mass) > Cr (7.68 % of the total mass) ~Pb (7.26 % of the total mass) > Mn (1.42 % of the total mass) > Cu (0.73 % of the total mass) whereas the order during no thermal cutting was Fe (72.91 % of the total mass) > Zn (11.33 % of the total mass) > Pb (6.65 % of the total mass) ~ Cr (6.52 % of the total mass) > Cu (1.87 % of the total mass) > Mn (0.72 % of the total mass). The ratios of each heavy metal emitted during thermal cutting were closely related to those of no thermal cutting activity. This may be because other recycling activities still operated in the workplace during no thermal cutting activity. The composition profile of particle-bound heavy metals during burning of cable sheath decreased in the order of Fe (43.26 % of the total mass) > Cr (29.38 % of the total mass) > Pb (24.31 % of the total mass) > Zn (2.45 % of the total mass) > Mn (0.46 % of the total mass) > Cu (0.14 % of the total mass) while that of during no burning activity was ranked in the order Fe (43.02 % of the total mass) > Pb (36.62 % of the total mass) > Cr (13.51 % of the total mass) > Zn (5.33 % of the total mass) > Mn (1.53 % of the total mass). Cu was not detected during no burning. The ratios of each heavy metal released during burning of cable sheath were different from those during no burning activity. The composition profiles of particle-bound heavy metals during these three recycling activities were significantly different. These findings indicated that the emission ratios of heavy metals could provide the source identification of e-waste recycling activity even though there were several uncontrollable recycling parameters and environmental conditions.

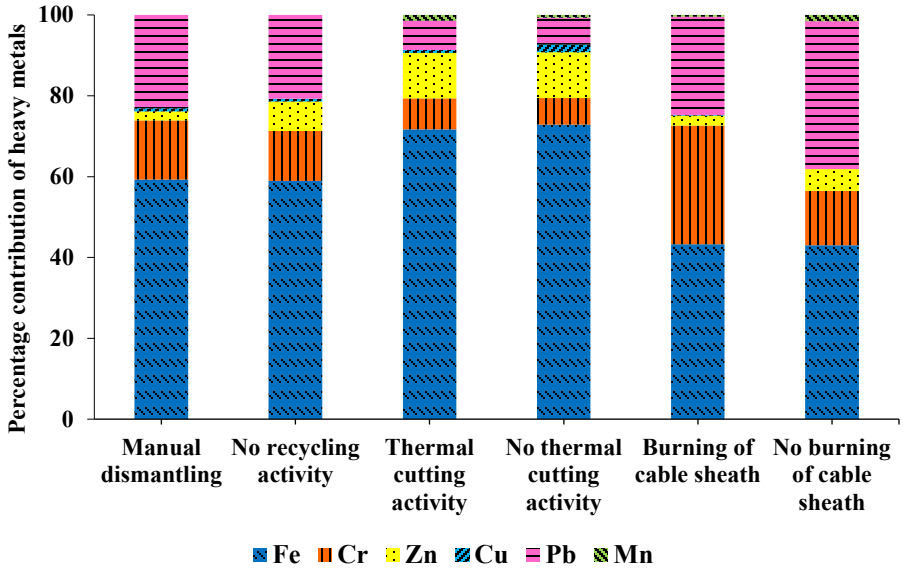

Figure 5. Percentage of heavy metals concentration during different e-waste recycling activities

Figure 6 (a) shows the size distribution plots of heavy metals bound on particles during manual dismantling. The size distributions of Fe, Cr, Zn and Pb were trimodal with a major peak (5.8 to 4.7 μm) and a minor peak in coarse mode (3.3 to 2.1 μm) as well as a minor peak in accumulation mode (1.1-0.65 μm for Fe and Cr; 0.65-0.43 μm for Zn and Pb). The size distribution of Cu was unimodal with a main peak in coarse mode (5.8-4.7 μm). The size distribution of these heavy metals shifted to large particle during manual dismantling. During no dismantling activity, the size distributions of Fe, Cr, Zn and Pb were trimodal but their distributions were different from manual dismantling. The distribution of Cu was unimodal and shifted to larger particle size (Figure 6 (b)). Figure 6 (c) shows the size distribution plots of heavy metals bound on particles during thermal cutting. The size distributions of Fe, Cr and Zn exhibited as trimodal patterns. The distribution of Fe had a major peak in accumulation mode (0.65-0.43 μm) and two minor peaks in coarse mode (3.3-2.1 μm and 5.8-4.7 μm) while those of Zn had a dominant coarse mode in the size range of 3.3-2.1 μm and two slightly less abundant peaks in coarse mode (5.8-4.7 μm) and accumulation mode (0.65-0.43 μm). The size distribution of Cr had two peaks (3.3-2.1 μm and 5.8-4.7 μm) in coarse mode and a peak in accumulation mode (1.1-0.65 μm). The size distributions of Pb, Mn and Cu were bimodal with a dominant coarse mode in the size range of 5.8-4.7 μm and a slightly less abundant peak in accumulation mode (0.65-0.43 μm). During no thermal cutting activity, the size distributions of Fe, Pb, Cr and Mn were trimodal whereas that of Zn was bimodal, respectively (Figure 6 (d)). Figure 6 (e) shows the size distribution plots of heavy metals bound on particles during burning of cable sheath. The size distributions of Pb, Cr, Zn and Mn were bimodal with a major peak in coarse mode (5.8-4.7 μm) and a minor peak in accumulation mode (0.65-0.43 μm for Pb, Cr and Zn; 1.1-0.65 μm for Mn). The size distribution of Fe was trimodal with a main peak in coarse mode (5.8-4.7 μm) and two minor peaks in accumulation mode (2.1-1.1 μm and 0.65-0.43 μm) whereas that of Cu was unimodal with a main peak in accumulation mode (0.65-0.43 μm). During no burning activity, the size distributions of Cr, Zn and Pb were bimodal whereas those of Mn and Fe were trimodal (Figure 6 (f)). The distributions of heavy metals during recycling activities were significantly different from those during no recycling activities. Fe was the main contributor in these recycling activities which was in agreement with the work of Huang *et al*. [10]. The distributions of particle-bound heavy metals indicated that the heavy metals were at higher level in coarse mode than in fine mode in e-waste recycling areas. These results were not consistent with the work of Huang *et al*. [10]. This is because the distributions of particle-bound heavy metals depend on several factors such as recycling activities, types of e-waste, atmospheric conditions and so on. Additionally, these results implied that the majority of airborne particle-bound heavy metals emitted from manual dismantling, thermal cutting and cable sheath burning could penetrate through the respiratory tract and deposit in the pharynx followed by the alveolar regions.

3.3 Potential health risk through inhalation exposure

Inhalation exposures of heavy metals bound on ultrafine, fine, coarse particles and PM_{10} from e-waste recycling activities were assessed by a model of health risk assessment of EPA (US) [35]. The ranges of human health risks were evaluated in term of the hazard quotients (HQ) with 95% confidence intervals (CI) for the element components of PM_{10}. The risk assessment of heavy metals to human health both males and females was presented by the average daily dose exposure to heavy metals through inhalation contact (ADD_{inh}) and the hazard quotients (HQ) as shown in Table 5.

The mean amounts of heavy metals bound on PM_{10} during burning of cable sheath indicated that the highest exposure doses were Fe (1.21E-01 mg kg^{-1} d^{-1} for males and 1.43E-01 mg kg^{-1} d^{-1} for females), followed by Cr (8.19E-02 mg kg^{-1} d^{-1} for males and 9.73E-02 mg kg^{-1} d^{-1} for females), Pb (6.78E-02 mg kg^{-1} d^{-1} for males and 8.05E-02 mg kg^{-1} d^{-1} for females), Zn (6.83E-03 mg kg^{-1} d^{-1} for males and 8.11E-03 mg kg^{-1} d^{-1} for females) and Mn (1.29E-03 mg kg^{-1} d^{-1} for males and 1.54E-

03 mg kg^{-1} d^{-1} for females), respectively. The lowest exposure amounts were 3.96E-04 and 4.71E-04 mg $kg^{-1}d^{-1}$ of Cu for males and females, respectively. During thermal cutting activity, the exposure levels of these heavy metals were ordered as follows: Fe (4.01E-02 mg kg^{-1} d^{-1} for males and 4.76E-02 mg kg^{-1} d^{-1}) > Zn (6.26E-03 mg kg^{-1} d^{-1} for males and 7.44E-03 mg kg^{-1} d^{-1} for females) > Cr (4.29E-03 mg kg^{-1} d^{-1} for males and 5.10E-03 mg kg^{-1} d^{-1} for females) > Pb (4.06E-03 mg kg^{-1} d^{-1} for males and 4.82E-03 mg kg^{-1} d^{-1} for females) > Mn (7.92E-04 mg kg^{-1} d^{-1} for males and 9.40E-04 mg kg^{-1} d^{-1} for females) > Cu (4.07E-04 mg kg^{-1} d^{-1} for males and 4.83E-04 mg kg^{-1} d^{-1} for females). During manual dismantling activity, the exposure levels of Fe (7.79E-03 mg kg^{-1} d^{-1} for males and 9.26E-03 mg kg^{-1} d^{-1} for females), Pb (3.04E-03 mg kg^{-1} d^{-1} for males and 3.61E-03 mg kg^{-1} d^{-1} for females) and Cr (1.92E-03 mg kg^{-1} d^{-1} for males and 2.28E-03 mg kg^{-1} d^{-1} for females) were in the same order of magnitude which was one order of magnitude higher than Zn (2.90E-04 mg kg^{-1} d^{-1} for males and 3.44E-04 mg kg^{-1} d^{-1} for females). The lowest exposure levels were 9.89E-05 mg kg^{-1} d^{-1} and 1.17E-04 mg kg^{-1} d^{-1} of Cu for males and females, respectively. Mn was not detected during the manual dismantling activity. The exposure levels of heavy metals bound on coarse and fine particles were higher than ultrafine particles in all recycling activities.

These results displayed that the HQ values of Fe, Zn and Cu bound on all particle size ranges for both males and females from all activities were less than 1, which indicated no adverse health effects. The HQ values of Pb (except bound on PM_{10} for female) and Mn for both males and females from manual dismantling activity also indicated no adverse health effects. The HQ levels of Cr adsorbed on PM_{10} for both males and females were 6.72E+01 (95% CI 3.05E+01–1.04E+02) and 7.99E+01 (95% CI 3.63E+01–1.23E+02) for manual dismantling, 1.50E+02 (95% CI 1.07E+02–1.93E+02) and 1.78E+02 (95% CI 1.27E+02–2.30E+02) for thermal cutting and 2.86E+03 (95% CI 6.98E+02–5.03E+03) and 3.40E+03 (95% CI 8.29E+02–5.97E+03) for burning of cable sheath. Inhalation of Cr from these recycling activities may cause high chronic risk. It was found that the HQ values of Pb bound on PM_{10} both males and females from burning of cable sheath were 1.93E+01 (95% CI 2.39E+00–3.61E+01) and 2.29E+01 (95% CI 2.84E+00–4.29E+01), which indicated high chronic risk whereas those bound on ultrafine and fine particles were higher than 1. The HQ levels of Pb attached on PM_{10} for both males and females from thermal cutting were 1.15E+00 (95% CI 4.45E-01–1.86E+00) and 1.37E+00 (95% CI 5.29E-01–2.21E+00), respectively. The HQ values of Mn bound on fine, coarse particles and PM_{10} for both males and females from thermal cutting and burning of cable sheath activities were higher than 10, which points to high chronic risk whereas those attached on ultrafine particles were higher than 1. In this study, the HQ values of Pb and Mn from manual dismantling were similar to the results of Papaoikonomou *et al*. [14]. whereas that of Cr was about 4,000 times higher than the previous work [14]. The results implied that worker exposure to heavy metals through inhalation during burning of cable sheath activity carried higher risk than thermal cutting and manual dismantling activities. It was found that women working in e-waste recycling workshops had a higher risk through inhalation exposure than men. Therefore, proper e-waste recycling methods are required to reduce the occupational health hazard and environmental pollution.

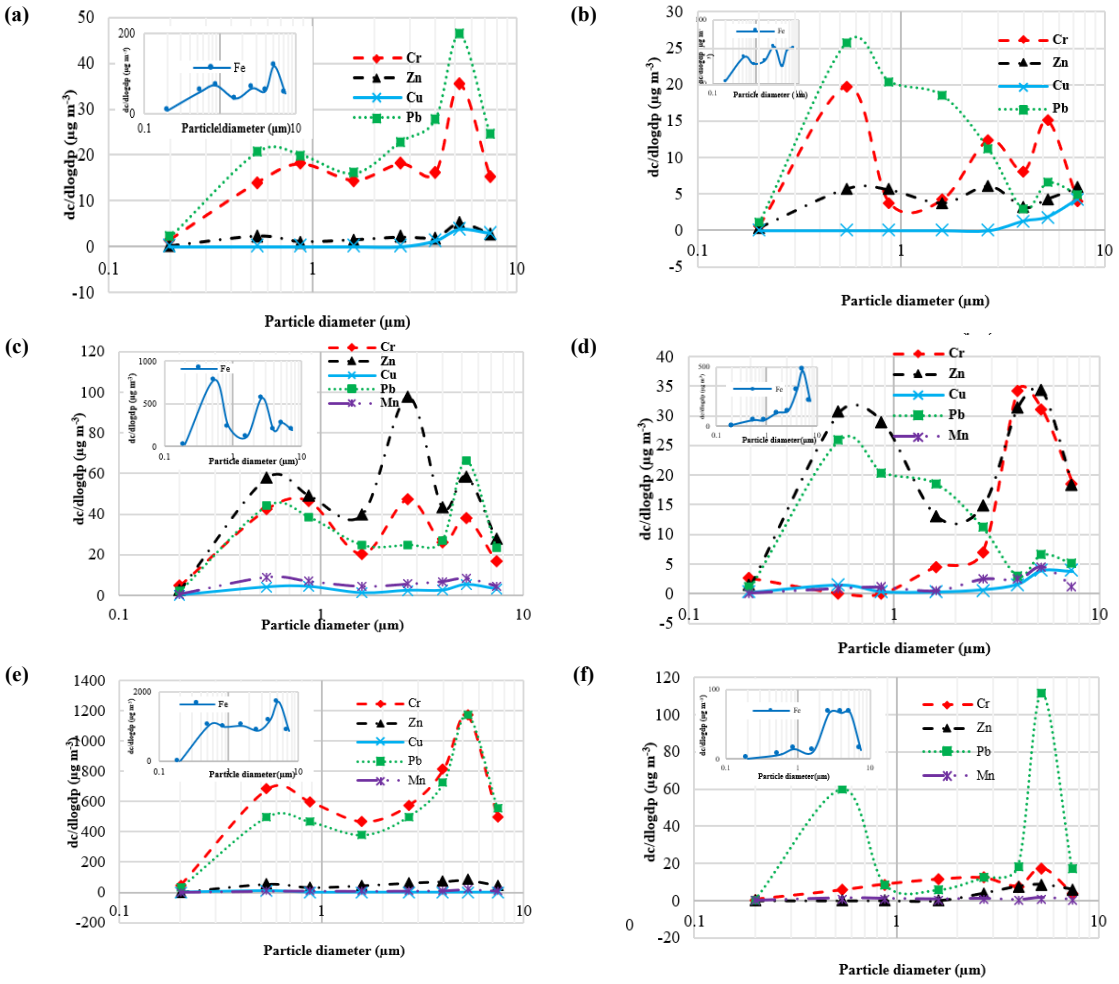

Figure 6. Size distributions of heavy metal during manual dismantling (a), no recycling activity (b), thermal cutting (c), no thermal cutting activity (d), burning of cable sheath (e), and no burning activity (f)

Table 5. The average daily dose exposure to metals through inhalation contact (ADD_{inh}) and hazard quotient (HQ) for inhalation of heavy metals exposed in air during e-waste recycling activities

Heavy metals	Particle sizes		Manual dismantling				Thermal cutting				Open burning of cable sheath			
			ADDinh (mg kg^{-1} d^{-1})		HQ		ADDinh (mg kg^{-1} d^{-1})		HQ		ADDinh (mg kg^{-1} d^{-1})		HQ	
			Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Fe	Ultrafine	Mean	8.82E-04	1.05E-03	1.26E-03	1.50E-03	3.52E-03	4.18E-03	5.03E-03	5.97E-03	1.78E-03	2.11E-03	2.54E-03	3.02E-03
	Fine	Mean	2.79E-03	3.31E-03	3.98E-03	4.73E-03	1.88E-02	2.23E-02	2.68E-02	3.19E-02	5.55E-02	6.59E-02	7.93E-02	9.41E-02
	Coarse	Mean	4.12E-03	4.90E-03	5.89E-03	7.00E-03	1.78E-02	2.11E-02	2.54E-02	3.02E-02	6.33E-02	7.52E-02	9.05E-02	1.07E-01
	PM_{10}	Mean	7.79E-03	9.26E-03	1.11E-02	1.32E-02	4.01E-02	4.76E-02	5.73E-02	6.80E-02	1.21E-01	1.43E-01	1.72E-01	2.05E-01
		95 CI			7.30E-03 - 1.50E-02	8.67E-03 - 1.78E-02			1.95E-02 - 9.51E-02	2.31E-02 - 1.13E-01			1.82E-02 - 3.26E-01	2.16E-02 - 3.88E-01
Cr	Ultrafine	Mean	2.43E-04	2.89E-04	8.50E+00	1.01E+01	7.07E-04	8.40E-04	2.47E+01	2.94E+01	6.76E-03	8.03E-03	2.36E+02	2.81E+02
	Fine	Mean	7.44E-04	8.84E-04	2.60E+01	3.09E+01	1.91E-03	2.27E-03	6.67E+01	7.92E+01	3.10E-02	3.69E-02	1.09E+03	1.29E+03
	Coarse	Mean	9.36E-04	1.11E-03	3.27E+01	3.89E+01	1.68E-03	1.99E-03	5.86E+01	6.96E+01	4.41E-02	5.24E-02	1.54E+03	1.83E+03
	PM_{10}	Mean	1.92E-03	2.28E-03	**6.72E+01**	**7.99E+01**	4.29E-03	5.10E-03	**1.50E+02**	**1.78E+02**	8.19E-02	9.73E-02	**2.86E+03**	**3.40E+03**
		95 CI			**3.05E+01 - 1.04E+02**	**3.63E+01 - 1.23E+02**			**1.07E+02 - 1.93E+02**	**1.27E+02 - 2.30E+02**			**6.98E+02 - 5.03E+03**	**8.29E+02 - 5.97E+03**
Zn	Ultrafine	Mean	2.49E-05	2.96E-05	8.30E-05	9.86E-05	4.03E-04	4.79E-04	1.34E-03	1.60E-03	2.10E-04	2.49E-04	6.99E-04	8.31E-04
	Fine	Mean	8.91E-05	1.06E-04	2.97E-04	3.53E-04	2.61E-03	3.10E-03	8.70E-03	1.03E-02	2.42E-03	2.88E-03	8.08E-03	9.59E-03
	Coarse	Mean	1.77E-04	2.10E-04	5.89E-04	6.99E-04	3.25E-03	3.86E-03	1.08E-02	1.29E-02	4.20E-03	4.99E-03	1.40E-02	1.66E-02
	PM_{10}	Mean	2.90E-04	3.44E-04	9.66E-04	1.15E-03	6.26E-03	7.44E-03	2.09E-02	2.48E-02	6.83E-03	8.11E-03	2.28E-02	2.70E-02
		95 CI			5.45E-04 - 1.39E-03	6.48E-04 - 1.65E-03			1.36E-02 - 2.82E-02	1.61E-02 - 3.35E-02			1.14E-02 - 3.41E-02	1.35E-02 - 4.05E-02

Table 5. The average daily dose exposure to metals through inhalation contact (ADD_{inh}) and hazard quotient (HQ) for inhalation of heavy metals exposed in air during e-waste recycling activities (continued)

Heavy metals	Particle sizes		Manual dismantling				Thermal cutting				Open burning of cable sheath			
			ADDinh (mg kg^{-1} d^{-1})		HQ		ADDinh (mg kg^{-1} d^{-1})		HQ		ADDinh (mg kg^{-1} d^{-1})		HQ	
			Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
Cu	Ultrafine	Mean	-	-	-	-	2.72E-05	3.23E-05	6.76E-04	8.03E-04	1.67E-04	1.98E-04	4.15E-03	4.93E-03
	Fine	Mean	-	-	-	-	1.63E-04	1.94E-04	4.06E-03	4.82E-03	2.29E-04	2.73E-04	5.71E-03	6.78E-03
	Coarse	Mean	9.89E-05	1.17E-04	2.46E-03	2.92E-03	2.17E-04	2.57E-04	5.39E-03	6.40E-03	-	-	-	-
	PM_{10}	Mean	9.89E-05	1.17E-04	2.46E-03	2.92E-03	4.07E-04	4.83E-04	1.01E-02	1.20E-02	3.96E-04	4.71E-04	9.86E-03	1.17E-02
		95 CI			1.06E-03 - 3.86E-03	1.26E-03 - 4.58E-03			7.76E-03 - 1.25E-02	9.22E-03 - 1.48E-02			3.38E-03 - 1.63E-02	4.01E-03 - 1.94E-02
Pb	Ultrafine	Mean	3.13E-04	3.72E-04	8.90E-02	1.06E-01	3.12E-04	3.70E-04	8.86E-02	1.05E-01	4.13E-03	4.90E-03	1.17E+00	1.39E+00
	Fine	Mean	1.02E-03	1.21E-03	2.89E-01	3.43E-01	1.90E-03	2.25E-03	5.39E-01	6.40E-01	2.39E-02	2.84E-02	6.78E+00	8.06E+00
	Coarse	Mean	1.71E-03	2.03E-03	4.85E-01	5.77E-01	1.85E-03	2.20E-03	5.26E-01	6.25E-01	3.98E-02	4.72E-02	1.13E+01	1.34E+01
	PM_{10}	Mean	3.04E-03	3.61E-03	8.63E-01	**1.03E+00**	4.06E-03	4.82E-03	**1.15E+00**	**1.37E+00**	6.78E-02	8.05E-02	**1.93E+01**	**2.29E+01**
		95 CI			6.09E-01 - 1.12E+00	**7.24E-01 - 1.33E+00**			**4.45E-01 - 1.86E+00**	**5.29E-01 - 2.21E+00**			**2.39E+00 - 3.61E+01**	**2.84E+00 - 4.29E+01**
Mn	Ultrafine	Mean	-	-	-	-	8.30E-05	9.86E-05	5.81E+00	6.90E+00	6.34E-05	7.53E-05	4.43E+00	5.27E+00
	Fine	Mean	-	-	-	-	3.57E-04	4.24E-04	2.50E+01	2.97E+01	4.68E-04	5.56E-04	3.27E+01	3.89E+01
	Coarse	Mean	-	-	-	-	3.52E-04	4.18E-04	2.46E+01	2.92E+01	7.63E-04	9.06E-04	5.34E+01	6.34E+01
	PM_{10}	Mean	-	-	-	-	7.92E-04	9.40E-04	**5.54E+01**	**6.58E+01**	1.29E-03	1.54E-03	**9.05E+01**	**1.08E+02**
		95 CI							**4.95E+01 - 6.12E+01**	**5.88E+01 - 7.27E+01**			**7.38E+01 - 1.07E+02**	**8.77E+01 - 1.27E+02**

4. Conclusions

Manual dismantling predominantly produced coarse particle fraction whereas thermal cutting and cable sheath burning mainly generated fine and coarse particle fractions. The concentrations of $PM_{2.1}$ and PM_{10} emitted from these recycling activities did not exceed the OSHA PEL threshold limit values. The particle size distributions from these recycling activities were bimodal with one major peak in coarse mode and another minor peak in accumulation mode. Cable sheath burning emitted significantly higher concentrations of heavy metals (Fe, Cr, Zn, Cu, Pb, Mn) than thermal cutting and manual dismantling, respectively. Concentrations of Cr and Pb bound on particles released from burning of cable sheath greatly exceeded the 8 hr-TWA standards of 500 and 50 μg m^{-3}, respectively. Concentrations of Pb attached on particles emitted from thermal cutting slightly exceeded the TWA standard. The size distributions of heavy metals bound on particles emitted from manual dismantling, thermal cutting and cable sheath burning activities were different. The emission of inhalable particles and heavy metals bound on these particles during e-waste recycling activities were significantly higher than no recycling activity. The worker exposure to Cr, Pb and Mn during cable sheath burning, Cr and Mn during thermal cutting, and Cr during manual dismantling posed a high chronic risk (HQ>10). There was no relevant health risk caused by occupational exposure to Fe, Zn, Cu elements from these activities.

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