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$PM_{2.5}$-Bound Trace Metals within Vicinity of a Coal-Fired Power Plant: Source Apportionment and Health Risk Assessment

(Logam Surih Terikat $PM_{2.5}$ dalam Persekitaran Loji Janakuasa Arang Batu: Pembahagian Sumber dan Penilaian Risiko Kesihatan)

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ABSTRACT

A coal-fired power plant is an industry known for its environmental health effects due to emissions containing pollutants like $PM_{2.5}$. Studies show $PM_{2.5}$ contains multiple hazardous pollutants, including metals. This study was conducted in Klang, Malaysia, to assess the concentration of trace metals in $PM_{2.5}$ near a coal-fired power plant, identify their sources, and evaluate human health risks. The average $PM_{2.5}$ concentration was 14.42 ± 8.7 µg/m³, with maximum levels (43.15 µg/m³) exceeding the Malaysian Ambient Air Quality Standard. $PM_{2.5}$ samples were collected from June to November 2018 and extracted using sonication in ultrapure water. Eighteen trace metals were analysed using ICP-MS, and the results were used for Principal Component Analysis (PCA) for source identification. PCA showed that the trace metals originated from sea salt and biomass burning (37%), coal combustion and vehicular emissions (34%), oil combustion (17%), and soil dust (12%). A health risk assessment (HRA) for selected metals indicated that carcinogenic and non-carcinogenic risks were generally within acceptable limits. However, the Hazard Quotient (HQ) for nickel exceeded the acceptable limit at one point (HQ_{max} = 2.24). A limitation of this study is that its sampling period was confined to the southwest monsoon and intermonsoon seasons, so the findings may not be representative of the entire year. The findings highlight the importance of managing industrial emissions to improve air quality, aligning with UN Sustainable Development Goals for Affordable and Clean Energy (SDG 7) and Climate Action (SDG 13).

Keywords: HRA; power plant; $PM_{2.5}$; source apportionment

ABSTRAK

Stesen jana kuasa arang batu adalah industri yang dikenali dengan kesan terhadap kesihatan persekitaran akibat pelepasan yang mengandungi bahan pencemar seperti $PM_{2.5}$. Kajian menunjukkan $PM_{2.5}$ mengandungi pelbagai bahan pencemar berbahaya, termasuk logam. Kajian ini dijalankan di Klang, Malaysia, untuk menilai kepekatan logam surih dalam $PM_{2.5}$ berhampiran stesen jana kuasa arang batu, mengenal pasti puncanya dan menilai risiko kesihatan manusia. Purata kepekatan $PM_{2.5}$ adalah 14.42 ± 8.7 µg/m³, dengan tahap maksimum (43.15 µg/m³) melebihi Piawai Kualiti Udara Ambien Malaysia. Sampel $PM_{2.5}$ dikumpulkan dari Jun hingga November 2018 dan diekstrak menggunakan kaedah sonikasi dalam air ultratulen. Lapan belas logam surih dianalisis menggunakan ICP-MS dan hasilnya digunakan untuk Analisis Komponen Utama (PCA) bagi mengenal pasti punca. PCA menunjukkan bahawa logam surih berpunca daripada garam laut dan pembakaran biojisim (37%), pembakaran arang batu dan pelepasan kenderaan (34%), pembakaran minyak (17%) dan habuk tanih (12%). Penilaian risiko kesihatan (HRA) untuk logam terpilih menunjukkan bahawa risiko karsinogenik dan bukan karsinogenik secara amnya berada dalam had yang boleh diterima. Walau bagaimanapun, Darjah Bahaya (HQ) untuk nikel melebihi had yang boleh diterima pada satu ketika (HQmaks = 2.24). Satu batasan kajian ini ialah tempoh pensampelannya terhad kepada musim monsun barat daya dan antara monsun, justeru keputusan ini mungkin tidak mewakili keseluruhan tahun. Keputusan kajian ini juga menekankan kepentingan pengurusan pelepasan industri untuk meningkatkan kualiti udara, selari dengan Matlamat Pembangunan Mampan PBB, terutamanya bagi Tenaga Mampu Milik dan Bersih (SDG 7) dan Tindakan terhadap Iklim (SDG 13).

Kata kunci: HRA; pembahagian sumber; $PM_{2.5}$; stesen janakuasa

INTRODUCTION

Coal-fired power plants are environmentally taxing industries that pollutes local areas (Du et al. 2020; Ebenstein et al. 2017). Coal combustion introduces various pollutants into the air, such as sulphur dioxide (SO_2), nitrogen oxide (NOx), carbon dioxide (CO_2), trace metals and $PM_{2.5}$ (Asif et al. 2022; EIA 2020). Coal-fired power plants are a common source of $PM_{2.5}$ in ambient air (Chio et al. 2019; Duan et al. 2021; Tao et al. 2014). A study on Hengshui City reported that the operation of coal-fired powered plants increases the average monthly $PM_{2.5}$ concentration by roughly 5% (Chen et al. 2020). Another study also stated that the national average contribution of industrial coal burning to $PM_{2.5}$ concentration in China is 10 μgm^{-3}, which is 17% of the total ambient $PM_{2.5}$ (Ma et al. 2017). The high contribution of coal-fired power plants to $PM_{2.5}$ concentration can potentially increase the mortality rate. Chio et al. (2019) estimated that $PM_{2.5}$ from a planned power plant will cause six deaths per 10,000 people. Another study in India also predicted that the operation of proposed coal-fired power plants will increase the ambient $PM_{2.5}$ by 13% and potentially cause over 844,000 premature deaths throughout the power plant lifetime (Cropper et al. 2021). Therefore, coal-fired power plants are potentially harmful to human health.

$PM_{2.5}$ from coal-fired power plants contain various trace metals, and some of which are hazardous to humans. Several studies have linked lead (Pb), arsenic (As), antimony (Sb), cadmium (Cd) and zinc (Zn) to coal combustion (Duan et al. 2021; Hao et al. 2018; Liu et al. 2018; Tao et al. 2014). International Agency for Research on Cancer (IARC) has classified As and Cd as Group 1 (carcinogenic to humans) and Pb and Sb as Group 2A (probably carcinogenic to humans) (IARC 2022), thereby indicating that coal-fired power plant emissions are potentially cancerous to human beings. Furthermore, the mixture of these metals can potentially induce harmful effects to human health. Some active metals, specifically non redox active metals, such as Cd and Zn, can cause cellular damage via oxidative stress (Mahey et al. 2020) by overwhelming the cellular antioxidant defences (Nuran Ercal, Hande Gurer-Orhan & Nukhet Aykin-Burns 2001). Free radicals induced from metals can cause unwanted modifications to deoxyribonucleic acid (DNA) bases. Fenton reaction involving Fe, Cu, Cr, V, and Co can generate superoxide and hydroxyl radical which further disrupt the reactive oxygen species and antioxidant equilibrium within cells (Valko, Morris & Cronin 2005). To summarise, the combination of metals in $PM_{2.5}$ can promote the increase of ROS thus resulting in oxidative stress.

Hence, this study was conducted in Klang, an urban-industrial city in the central region of Peninsular Malaysia, to analyse the effect of a coal-fired power plant on the air quality of its surrounding area and its health risk towards local human population. This study aims to identify the coal-fired power plant's contribution to $PM_{2.5}$ concentrations, average $PM_{2.5}$ concentration, source apportionment of ambient $PM_{2.5}$ within the vicinity, trace metal concentrations within ambient $PM_{2.5}$ and health risks of nearby residents from their exposure to ambient $PM_{2.5}$. The results of this work can provide guidance to policy makers in improving existing policies on ambient air quality to enhance the quality of life or ushering in new types of energy that is more environmental and health friendly, aiming towards sustainable development goals (SDG) number 7 (affordable and clean energy) and 13 (climate action) (United Nations n.d.).

MATERIALS AND METHODS

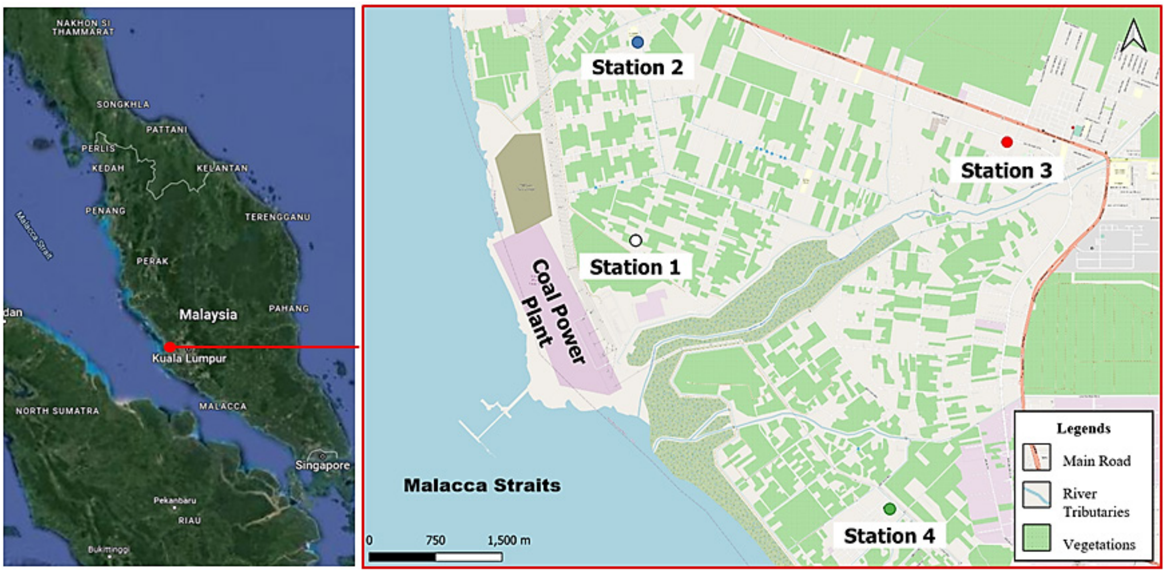
SAMPLING SITE

Study was conducted in Klang, Malaysia to determine the concentration of $PM_{2.5}$, its metal composition and emission sources. The sampling was conducted from June to November 2018 which was during the southwest monsoon from June to September and intermonsoon from October to November. Large southwest movement of air was observed during the sampling period. The sampling site is abundant in vegetation, especially palm oil plantations, based on observations. Notable industries in the sampling site include thermal power plant, palm oil mill and various manufacturing industries. Four sampling stations with varying distance from the thermal power plant were selected to investigate the influence of distance from the power plant on $PM_{2.5}$ concentrations. Station 1 (1.24 km) is nearest to the power plant, followed by Stations 4 (3.84 km), 2 (4.01 km) and 3 (5.72 km). Figure 1 shows the map of the sampling site and location of sampling stations.

SAMPLING PROTOCOL AND METAL ANALYSIS

Samples were collected from June to November 2018. The sampling protocol was designed to capture pollutant variations. One station was targeted each week for sample collection. Two 24-h samples were gathered from that site. The sampling days were varied weekly to capture daily changes. A high-volume sampler with quartz filters collected the particles. Each sample was gathered over a 24-h period. The sampler's flow rate was a constant 1.13 m^3/min. A total of 28 samples were successfully obtained. Equipment malfunctions reduced the sampling frequency. This issue mainly occurred in October and November. This prevented a continuous weekly collection schedule. Field blanks were also collected for quality assurance.

A portion of filter samples (1/16) was cut into small pieces and then placed into 50 mL centrifuge tubes containing ultrapure water for extraction. The extraction process involves sonication, centrifugation and mechanical shaking, as described by Khan et al. (2016). Samples and ultrapure water mixture were separated using a microfibre glass filter to obtain the metal extracts. Extracts were refrigerated at 4 °C until further analysis. Eighteen elements (Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, Rb, Sr, V, and Zn) were analysed through inductively coupled



Source: Google Maps 2022; Openstreet Map, 2018

FIGURE 1. Map of study location and sampling stations in Klang

plasma mass spectroscopy (ICP-MS). Data obtained from ICP-MS were in pbb and converted into ngm^{-3} using the equation below (US EPA 1999):

$$C = \frac{(M \times V(S) - B)}{V_{std}}$$

where C is the concentration of metal in ngm^{-3}; M is the concentration of metal in ppb; V is the total sample extraction volume (50 mL); S is the cut size factor of the filter strip and equal to 16 in this work; B is the average concentration of field blank filter in ppb; and Vstd is the standard air volume pulled through the filter in m^3.

The analysis focused on the water-soluble fraction of trace metals to specifically quantify the bioaccessible portion, which is more directly relevant to human health risk assessment than total metal content that can overstate toxicity by including inert, non-absorbable forms (Roper et al. 2019; Vidal et al. 2017). This approach is an 'operationally defined' procedure, a concept recognized by the International Union of Pure and Applied Chemistry (IUPAC 2016), where the methodology itself defines the quantity being measured. Consequently, the use of water as an extraction solvent is a deliberate choice to isolate this specific fraction, and the resulting concentrations are expected to be different from, and not directly comparable to, methods designed for total elemental analysis (ASTM International 2021). For this reason, a traditional recovery test using a Certified Reference Material for total concentration is scientifically inappropriate, as it would incorrectly evaluate a selective extraction against a total-digestion standard. Method performance was instead ensured through established quality assurance protocols, including multi-point instrument calibration with certified standards and the routine analysis of field and laboratory blanks, which align with general method validation principles (U.S. EPA 2016). Thus, the observed concentrations are an expected and intentional outcome of this targeted analytical strategy, and values below the method detection limit (MDL), calculated as three times the standard deviation of field blanks, were replaced with half the MDL value.

HEALTH RISK ASSESSMENT

Health risk of trace metal exposure was estimated through the inhalation pathway. Assessment was only conducted for Al, As, Cd, Co, Cr, Mn, Ni, and V given the lack of available inhalation risk data for other trace metals. As, Cd, and Cr were investigated for lifetime cancer risk (LCR), whilst Al, Cd, Co, Cr, Mn, Ni, and V were explored for hazard quotient (HQ). Health risk assessments (HRAs) were determined according to the standardized methodology described by US EPA (2009). Exposure concentration (EC) for non-cancer and cancer risks is expressed herewith:
Non-cancer risks:

$$EC\ (\mu gm^{-3}) = \frac{CA\ (\mu gm^{-3}) \times ET\ (h/day) \times EF\ (days/year) \times ED\ (years)}{ED\ (years) \times 365\ (days) \times 24 (h/day)}$$

$$HQ = \frac{EC\ (\mu gm^{-3})}{Toxicity\ (\mu gm^{-3}) \times 1{,}000}$$

Cancer risks:

$$\mathrm{EC}\ (\mu gm^{-3}) = \frac{\mathrm{CA}\ (\mu\mathrm{gm}^{-3}) \times \mathrm{ET(h/day)} \times \mathrm{EF\ (days/year)} \times \mathrm{ED\ (years)}}{\mathrm{Lifetime\ (years)} \times 365\mathrm{(days)} \times 24\mathrm{(h/day)}}$$

$$\mathrm{LCR} = \mathrm{EC}\ (\mu gm^{-3}) \times IUR\ (\mu gm^{-3})^{-1}$$

where CA is the trace metal concentration in air (μgm^{-3}); ET is the exposure time (h/day), EF is the exposure frequency (day year^{-1}); ED is the exposure duration (years), AT is the averaging time (days), toxicity value is the inhalation reference dose (RfC) (mgm^{-3}) or chronic MRL (mgm^{-3}) (Minimal Risk Level) and IUR is the inhalation unit risk (μgm^{-3}). AT is equal to ED for HQ, whilst ED is equal to 70 years for LCR (US EPA 1989). EF of 350 days per year was used for EC calculations under the assumption that all receptors in the exposure scenario are exposed to the inhalation exposure pathway for 350 days per year. This assumption is based on the estimation that receptors are away from the study location for a maximum of 2 weeks per year (Jamhari et al. 2014). LCR and HQ were calculated according to respective sampling stations.

Both maximum and average concentrations of Al, As, Cd, Co, Cr, Mn, Ni, and V were used in this study to calculate the exposure concentration (EC). Non-carcinogenic risks were estimated through the hazard quotient for specified trace metals (Al, Cd, Co, Cr, Mn, Ni, and V), and the cancer risk was approximated through LCR for As, Cd, and Cr. Cr typically exists in two forms (Cr(III) and Cr(VI)), due the latter being more dangerous, Cr was assessed as Cr(VI) since for health risk assessment, overestimation offers more protective assessment. Hazard quotient is the ratio of potential exposure to a substance to the level at which no adverse effects are expected. If the calculated hazard quotient is less than 1, then, no adverse health effects are expected from the exposure. If the hazard quotient is greater than 1, then, adverse health effects are possible. Cancer risk values greater than 1×10^{-4} are considered high, whilst values below 1×10^{-6} are considered minimal risk to humans; notably, the acceptable range is between 1×10^{-4} and 1×10^{-6} (National Research Council et al. 2004). Respective ECs were compared with toxicity values specific to the assessed metals obtained from various credible sources which can be found in Table 1. Toxicity values in this study were referred to three different sources which are from US EPA's Integrated Risk Information System (IRIS), US EPA's Peer-Reviewed Toxicity Values (PPRTV), and Minimal Risk Level (MRL) from Agency for Toxic Substances and Disease Registry (ATSDR). Both HQ and LCR was calculated for general population as per recommendations of the latest US EPA guideline (US EPA 2009, 1989).

The health risk assessment (HRA) results are presented as point estimates, but it is acknowledged that these values are subject to inherent uncertainties. Uncertainty arises from the exposure parameters, which are based on standardized assumptions for an average population (exposure frequency) and may not reflect the variability in individual behaviours or exposure patterns. Significant uncertainty is also associated with the toxicity values (RfC and IUR), which are derived from toxicological studies and can vary between different health agencies, as noted in the values adopted for this study. Therefore, the calculated risk values should be interpreted not as precise predictions of individual risk, but as a conservative, screening-level assessment intended to be protective of public health, in line with standard US EPA guidance (US EPA 1989).

TABLE 1.Toxicity values of metals used for health risk assessment

Metals	Toxicity values				Sources
	RfC (mgm^{-3})	Critical effect	IUR (μgm^{-3})$^{-1}$	Critical effect	
Al	5.0×10^{-3}	Psychomotor and cognitive impairment	NA	NA	PPRTV
As	NA	NA	4.3×10^{-3}	Lung cancer	IRIS
Cd	*1.0×10^{-5}	Proteinuria	1.8×10^{-3}	Lung, trachea, bronchus cancer deaths	ATSDR, IRIS
Co	6.0×10^{-6}	Decreased pulmonary function and respiratory tract irritation	NA	NA	PPRTV
Cr(VI)	8.0×10^{-6}	Nasal septum atrophy	1.2×10^{-2}	Lung cancer	IRIS
Mn	5.0×10^{-5}	Impairment of neurobehavioral function	NA	NA	IRIS
Ni	*1.0×10^{-5}	Chronic lung inflammation, fibrosis, alveolar proteinosis	NA	NA	ATSDR
V	*1.0×10^{-4}	Degeneration of respiratory epithelium of the epiglottis	NA	NA	ATSDR

*Indicates the use of chronic MRL as toxicity values. An MRL is an estimate of the daily human exposure to a hazardous substance that is likely to be without appreciable risk of adverse non-cancer health effects over a specified duration of exposure (ATSDR 2018)

STATISTICAL ANALYSIS

PRINCIPAL COMPONENT ANALYSIS (PCA)

The statistical analysis for source apportionment was conducted using Principal Component Analysis (PCA) in SPSS version 25. Prior to analysis, the dataset was normalized using z-scores to achieve a mean of zero and a standard deviation of one. The successful application of PCA is predicated on key statistical assumptions, including linearity in the relationships between variables and a suitable underlying correlation structure. Therefore, the dataset's suitability was verified using two tests. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy yielded a value of 0.722, indicating a meritorious dataset for factor analysis. Concurrently, Bartlett's Test of Sphericity was highly significant ($p<0.001$), confirming that the correlations between trace metals were sufficient for analysis. Following this validation, principal components with eigenvalues greater than 1 were extracted and subjected to a varimax rotation to simplify factor interpretation. The percentage contribution of each identified source was then calculated using Multiple Linear Regression (MLR).

In interpreting the results, the inherent limitations of source apportionment, such as potential confounding variables, were considered. The primary confounder in this context is source co-linearity, where different emission sources may share similar chemical tracers, making them difficult to distinguish statistically (Song et al. 2006). This inherent limitation is reflected directly in the PCA output, which identified the primary factor as a 'Mixture of coal combustion and vehicular emissions'. This demonstrates that the model accounted for this confounding effect by grouping these co-located and chemically similar sources. Therefore, when interpreting the impact of this factor, it is treated as a combined industrial-traffic source profile, acknowledging that its effects cannot be uniquely attributed to either source alone.

RESULTS AND DISCUSSION

$PM_{2.5}$ AND TRACE METAL CONCENTRATIONS

The $PM_{2.5}$ and trace metal concentrations measured in this study are detailed in Table 2. The average $PM_{2.5}$ concentration was 14.42 ± 8.7 µg/m³, a level comparable to

TABLE 2. $PM_{2.5}$ and trace metal concentrations comparison with previous studies

Element	MDL	Klang (Khan et al. 2016, UPW)	Bangi (Khan et al. 2016, UPW)	Changzhi (Duan et al. 2021, Acid)	Chengdu (Tao et al. 2014, Acid)
$PM_{2.5}$	-	14.40	18.30	56.10	119.00
Al	1.18	15.10	11.90	868.00	560.00
As	0.04	2.20	3.30	4.90	20.00
Ca	108.01	141.00	-	867.00	402.00
Cd	0.06	0.50	0.20	0.70	3.50
Co	0.00	0.10	0.00	0.20	-
Cr	1.12	1.20	-	14.30	9.20
Cu	1.73	12.70	2.50	7.80	23.00
Fe	0.51	9.30	5.70	864.00	693.00
K	55.24	513.00	120.00	584.00	1576.00
Mg	85.64	87.90	8.50	843.00	196.00
Mn	0.47	4.50	1.20	21.50	66.00
Na	411.87	939.00	-	331.00	837.00
Ni	0.12	2.60	0.70	4.20	2.50
Pb	0.08	7.40	4.50	30.80	172.00
Rb	0.13	2.50	1.10	-	7.60
Sr	1.78	1.50	-	3.00	5.70
V	0.18	4.40	1.30	2.10	1.70
Zn	4.25	89.30	15.80	82.30	350

*Units are in ng m^{-3} except for $PM_{2.5}$, which is in µg m^{-3}

the 18.3 μg/m³ reported in a study in Bangi which used the same water-based extraction method. While this average was within the annual Malaysian Air Quality Standard, the study's maximum 24-h concentration of 43.15 μg/m³ exceeded the national limit of 35 μg/m³. Within the study area, a clear concentration gradient was observed across the sampling sites, increasing in the order of Station 1 (7.95 μg/m³), Station 4 (13.0 μg/m³), Station 2 (17.0 μg/m³), and Station 3 (20.0 μg/m³).

The observed $PM_{2.5}$ gradient is not dictated by simple proximity to the power plant; instead, it reflects a complex interplay of hyperlocal emission sources, regional atmospheric conditions, and the specific analytical methodology employed. The lack of a proximity-based trend is clear, as Station 1, nearest to the plant at 1.24 km, had the lowest concentration, while Station 3, the most distant at 5.72 km, had the highest. A comparison with the inland Bangi study further highlights the unique pollution profile of the coastal Klang site, which showed exceptionally high sodium (Na), a sea salt tracer, at 939.0 ngm^{-3}. Furthermore, substantially higher concentrations of traffic and biomass burning markers like zinc (Zn) and potassium (K) in Klang suggest a stronger influence from these local and transboundary sources. While these factors explain regional differences, the analytical method explains the contrast with international studies. Both this study and the Bangi study, using water extraction, report significantly lower concentrations of crustal metals like Aluminium (15.1 ngm^{-3}) compared to studies using acid digestion, such as in Changzhi (868.0 ngm^{-3}) and Chengdu (560.0 ngm^{-3}). Overall, this study shows that getting a true picture of air quality means looking beyond a single big source like a power plant. It is also necessary to consider pollution from local traffic, the effects of the surrounding area like the coastline, and the specific portion of pollutants being measured.

PRINCIPAL COMPONENT ANALYSIS (PCA)

The four factors identified from PCA account for 84.5% of the total variance. Additional details are presented in Table 3 and Figure 2 for varimax rotated loading factor and regression analysis on factor scores, respectively. Factor 1 explained 58.24% of the total variance and was associated with high loading to As, Ca, Cd, Co, K, Mn, Pb, Rb, Sr, and Zn. This factor was attributed to a mixture of coal combustion and traffic emissions and contributed to 34% of the total metal concentration of $PM_{2.5}$. Very strong correlations ($r_s>0.8$, $p<0.05$) were observed between these metals. As, Pb, and Se are common predictors of coal combustion in various industries, including thermal power plants (Duan et al. 2012; González et al. 2017; Mohammadi et al. 2018; Zhong et al. 2016). As, Zn, Pb, and Cd are major elements of coal combustion in China that originate from power stations (Hao et al. 2018), whilst As, Pb, K, and Cd are associated with coal combustion in Korea (Kim et al. 2018). Furthermore, Cd emissions were attributed to high-temperature coal (Uberoi & Shadman 1991). Although Ca, Co, and Mn are rarely observed in coal combustion, some studies have reported their slight contribution to coal combustion emissions (Liu et al. 2018; Peng et al. 2017). Factor 1 can also be influenced by vehicular emissions given that the contribution of coal combustion to Co, Mn, and Sr is weak. Tailpipe emissions, tank fuel vapours, brake wear, clutch and tyre wear are generally referred to as vehicular emissions. Some of the widely accepted markers for vehicular emissions include Zn and Mn (Jain et al. 2017; Singh et al. 2017). Zn comes from tyre wear (Khan, Hirano & Masunaga 2010) because Zn is usually used as an oxidising agent in the rubber vulcanisation process (Fomba et al. 2018; Hao et al. 2018). Mn and Co can also be from tyre and break wears, whilst Sr is related to road abrasions (Juda-Rezler et al. 2020). Sr and Mn were also observed in break particles due to multiple variations of brake materials (Jeong et al. 2019). Although Pb is also related to traffic where it comes from pre-existing road dust resuspension instead of directly originating from vehicles (Jain et al. 2017).

Factor 2 explained 11.84% of the total variance and was associated with high loading to Al, Cr, and Fe. Strong correlations ($0.6<r_s<0.8$, $p<0.05$) were observed between these metals. This factor was attributed to soil sources and contributed to 12% of the total metal concentration of $PM_{2.5}$. Factor 2 presents the minimum percentage contribution to the total metal concentration of $PM_{2.5}$. These elements are typical soil components. Al and Fe are abundant crustal elements in resuspended dust or soil sources (Kim et al. 2018). Ledoux et al. (2017) highlighted Al and Fe as typical soil components. A study in Seoul, Korea also reported that Al, Fe, and Cr are common components for soil sources of $PM_{2.5}$ (Park et al. 2018). Peng et al. (2017) associated Al, Fe, and Cr with soil dust and added that Cr and Co are common tracers for soil.

Factor 3 explained 7.94% of the total variance and was associated with high loading to Ni and V. Very strong correlation ($r_s=0.82$, $p<0.05$) was observed between Ni and V. This factor was attributed to oil combustion and contributed to 17% of the total metal concentration of $PM_{2.5}$. Ni and V are typical indicators for oil combustion (Kim et al. 2018; Li et al. 2017; Motesaddi Zarandi et al. 2019; Park et al. 2018) and common elements in petroleum (Hao et al. 2018). A study suggested that V and Ni are emitted from transport sources, especially diesel engines (Liu et al. 2018). Heavy transports that use diesel engines are common in the study location and can contribute to Ni and V composition in the ambient air because one of the sampling stations was located beside the main road in a mixed commercial–industrial area. Another study also suggested that V and Ni come from oil combustion from marine traffic. Emissions from ships can contribute to Ni and V composition in ambient air in the study location given that Malacca Straits are the busiest waterways in the

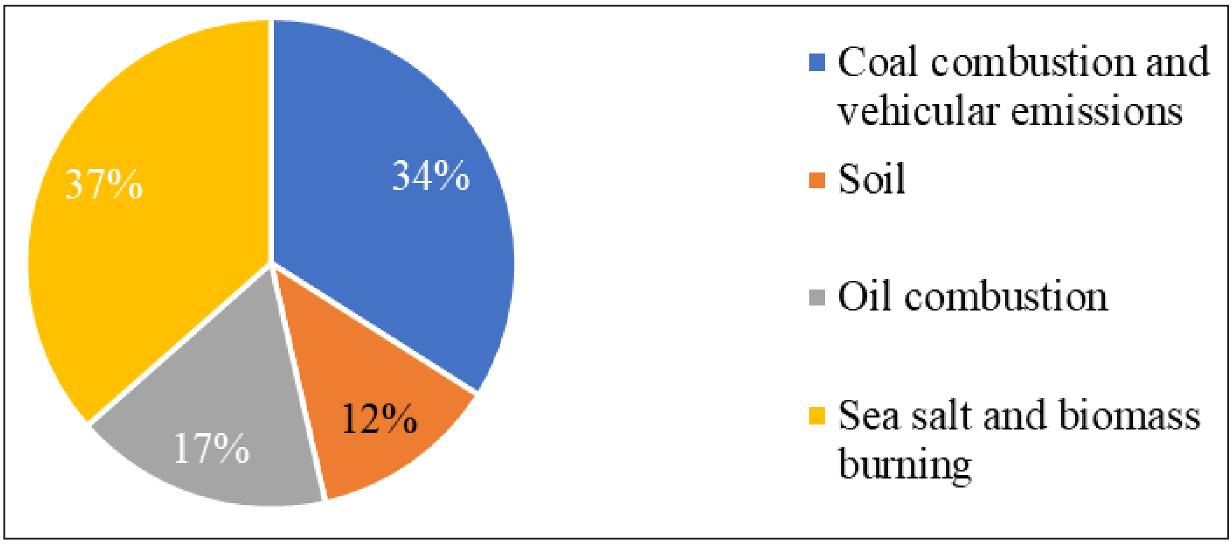


FIGURE 2. Percent contribution of water-soluble trace metals sources of $PM_{2.5}$ in Klang

TABLE 3. Varimax rotated factor loading at Klang

Components	Factor 1	Factor 2	Factor 3	Factor 4
Al	0.277	**0.765**	0.180	0.183
As	**0.558**	0.456	0.229	0.298
Ca	**0.642**	0.374	0.032	**0.648**
Cd	**0.869**	0.381	0.102	0.169
Co	**0.720**	0.224	0.544	0.276
Cr	0.183	**0.851**	0.223	-0.108
Cu	0.511	0.505	0.556	-0.166
Fe	0.096	**0.875**	0.007	0.081
K	**0.737**	0.269	0.518	0.391
Mg	0.507	0.490	0.281	**0.611**
Mn	**0.900**	0.328	0.244	0.185
Na	0.130	-0.042	0.030	**0.923**
Ni	0.240	-0.053	**0.834**	0.409
Pb	**0.794**	-0.014	-0.052	0.099
Rb	**0.737**	0.298	0.539	0.279
Sr	**0.632**	-0.035	0.454	0.571
V	0.033	0.374	**0.847**	-0.125
Zn	**0.941**	0.203	0.238	0.122
% total variance	58.236	11.842	7.939	6.501
eigen value	10.982	2.233	1.497	1.226
Attributed source	Mixture of coal combustion and vehicular emissions	Soil	Oil combustion	Mixture of sea salt and biomass burning

Bolded values highlight the significant PCA factor loadings world, with nearly 80,000 ships served annually (MIMA 2021). V and Ni can also come from the power plant itself because it contains three generating facilities, and one of which uses gas and oil as fuel whilst the two other facilities utilise coal, gas and oil as fuel (Kapar Energy 2022).

Factor 4 explained 6.50% of the total variance and was associated with high loading to Ca, Mg, and Na. Strong correlations ($0.6<r_s<0.8$, $p<0.05$) was observed between Mg, Ca, and Na. This factor was attributed to the mixture of sea sprays and biomass burning that contributed to 37% of the total metal concentration of $PM_{2.5}$. HYSPLIT modelling in Figure 3 illustrated that winds come from Sumatra from June to September due to the southwest monsoon season. The wind coming from Sumatra clearly brought biomass burning elements to the study location because Sumatra was experiencing forest fires in July (Bernama 2018). Na is a key component in combusted biomass particles (Hao et al. 2018). High factor loadings of Si, Fe, Ca, Mg, and K are typical elements related to biomass burning (Tang, Chen & Tian 2017). The contribution of sea salt to Factor 4 is assumed because this factor presents the maximum percentage contribution of the total metal concentration of $PM_{2.5}$, which is slightly higher by 3% compared with that of Factor 1. Sea sprays from the Indian Ocean and South China Sea can be carried by the wind towards the sampling site. Kim et al. (2018) reported that Na, Mg, and K can originate from aged sea salt.

HEALTH RISK ASSESSMENT

EC was used to calculate the noncarcinogenic risks of Al, As, Cd, Co, Cr, Mn, Ni, and V from the inhalation exposure route. HQ is the ratio of the dose of a pollutant of interest compared with a toxicological endpoint (Bleam 2017). Which means if the dose exceeded the endpoint (HQ>1), adverse health effect is expected to occur. The results for hazard quotient (HQ) of trace metals in $PM_{2.5}$ are listed in Table 4. Risk assessments were conducted for each sampling station. Max and average concentration of metals was used for HRA. The non-carcinogenic risk of exposure to metals in $PM_{2.5}$ were within the acceptable range of HQ<1 for Al, Cd, Co, Cr, Mn, and V in all sampling stations. HQ of Ni however exceed the acceptable range of HQ<1 (HQ = 2.24) at Station 3. This shows that at one point, concentration of Ni in air was very high. Station 3 was near the main road in Kapar. High Ni might be coming from the traffic emission of diesel engines. However, the extreme risk from Ni is not on a day-to-day basis. Ni concentration varies every day. Average HQ for Ni is only 0.47 at Station 3, which is the highest HQ when compared to other stations.

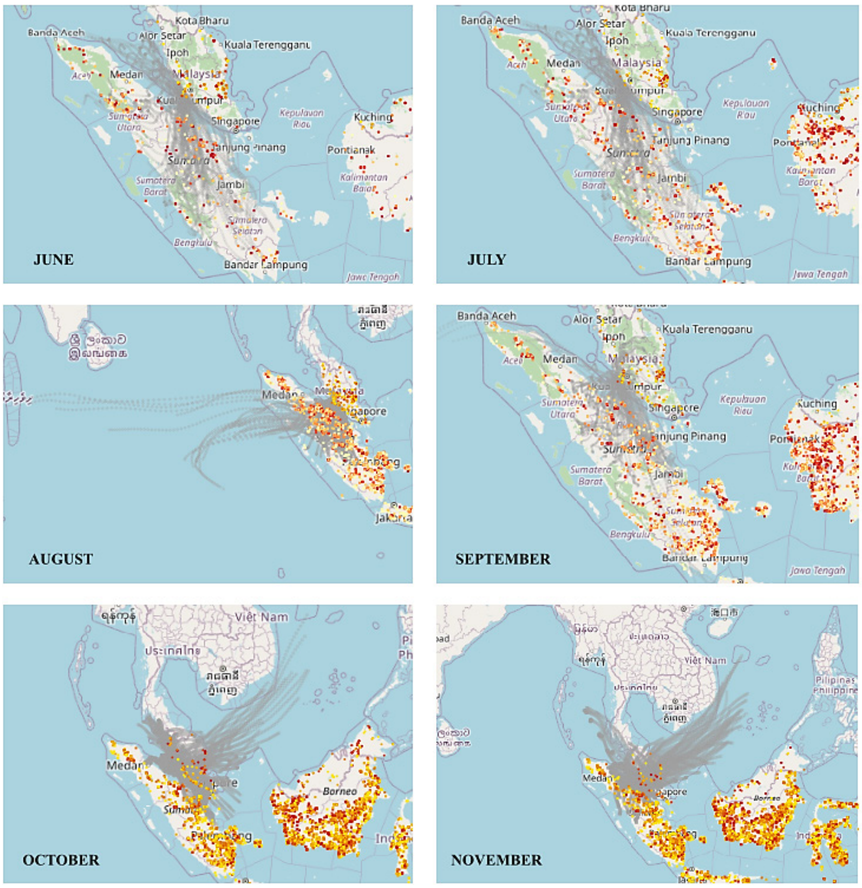


FIGURE 3. Monthly backward trajectory analysis in Klang from June to November 2018

TABLE 4. Average and max HQ for $PM_{2.5}$-bound metals in four sampling stations in Kapar, Klang

Metals	Station 1		Station 2		Station 3		Station 4	
	Average	Max	Average	Max	Average	Max	Average	Max
Al	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
Cd	0.03	0.12	0.05	0.12	0.08	0.15	0.04	0.12
Co	0.00	0.01	0.01	0.01	0.01	0.03	0.01	0.02
Cr	0.11	0.23	0.13	0.19	0.14	0.17	0.18	0.29
Mn	0.06	0.18	0.07	0.13	0.13	0.29	0.09	0.18
Ni	0.10	0.27	0.14	0.23	0.47	**2.24**	0.25	0.49
V	0.04	0.08	0.03	0.05	0.04	0.09	0.07	0.18

Bolded text indicates HQ higher than 1

TABLE 6. Average and max LCR for $PM_{2.5}$-bound metals in four sampling station in Kapar, Klang

Metals	Station 1		Station 2		Station 3		Station 4	
	Average	Max	Average	Max	Average	Max	Average	Max
As	**4.0E-06**	**1.7E-05**	**5.3E-06**	**9.9E-06**	**5.7E-06**	**1.1E-05**	**6.5E-06**	**1.5E-05**
Cd	2.8E-07	**1.2E-06**	4.8E-07	**1.3E-06**	8.7E-07	**1.6E-06**	4.4E-07	**1.2E-06**
Cr	**5.8E-06**	**1.3E-05**	**7.2E-06**	**1.0E-05**	**7.9E-06**	**9.1E-06**	**9.7E-06**	**1.6E-05**

Bold text indicates LCR within 1×10^{-4} and 1×10^{-6}

Lifetime cancer risk (LCR) is the risk of getting cancer from exposure to a carcinogen. LCR is generally acceptable within the range between 1×10^{-4} and 1×10^{-6} which translate to 1 cancer case in a population of 10,000 to 1 cancer case in a population of 1,000,000. The results of LCR for trace elements of $PM_{2.5}$ for every sampling station are listed in Table 5. Cancer risks from exposure to $PM_{2.5}$-bound As, Cd and Cr are within the acceptable range of 1×10^{-4} to 1×10^{-6}. Cd had the lowest average LCR among the other metals in all stations. As had the highest max LCR at Station 1, indicating that Station 1 were exposed to the highest As concentration. This is probably due to the proximity of Station 1 to the coal-fired power plant. During low air movement, As emission from the power plant might not travel far and dispersed well resulting in high As concentration in $PM_{2.5}$. Despite that, LCR of As was still within the acceptable limit and there is low chance that the population will develop cancer from exposure to ambient $PM_{2.5}$.

The interpretation of the calculated health risks is subject to several key uncertainties. These uncertainties stem from standardized exposure assumptions that do not capture individual behaviours, the inherent variability of the toxicity values used, and daily fluctuations in pollutant concentrations. The effect of concentration variance, for instance, is clear in the case of nickel (Ni), which only posed an unacceptable risk at its maximum measured concentration (HQ = 2.24), not its average (HQ = 0.47). Most significantly, the calculated risk represents an underestimation because several measured metals, like zinc (Zn), copper (Cu), and lead (Pb), could not be assessed due to a lack of official inhalation toxicity data. Therefore, this health risk assessment should be viewed as a conservative, screening-level assessment of a subset of known hazards rather than a complete prediction of all health risks.

CONCLUSION

The findings of this study on $PM_{2.5}$ in Klang, Malaysia, showed an average concentration of 14.42 µg/m³. This level was found to be slightly below the Malaysian Ambient Air Quality Standard (MAAQS) of 15 µg/m³ for annual exposure. However, daily peak $PM_{2.5}$ levels, reaching 43.15 µg/m³, exceeded the 24-h MAAQS of 35 µg/m³, indicating periods of elevated concern. A comparison with more stringent international benchmarks showed that Klang's average $PM_{2.5}$ surpassed the World Health Organization (WHO) annual guideline of 5 µg/m³, the European Union's proposed annual limit value of 10 µg/m³, and the US Environmental Protection Agency (EPA) primary annual standard of 9.0 µg/m³. The exceedance of these widely recognized international standards highlights potential public health risks and underscores the critical need for more ambitious pollution control strategies in the region, even if local annual standards are met. Source apportionment identified coal combustion and vehicular emissions as contributing 34% of $PM_{2.5}$, while sea salt and biomass burning, influenced by transboundary haze from

Sumatra, accounted for 37%. These results emphasize the importance of continued policy interventions, including enhanced emission controls for industrial sources like coal power plants, and measures to promote cleaner transportation. Addressing transboundary haze also necessitates sustained regional cooperation, including robust enforcement of the ASEAN Agreement on Transboundary Haze Pollution (AATHP). Furthermore, the elevated health risk associated with nickel (Ni) from diesel emissions at one sampling station highlights the relevance of regulating specific toxic metal emissions. For instance, the European Union's Ambient Air Quality Directives explicitly set objectives and limit values for nickel, requiring abatement measures where standards are not met. Therefore, comprehensive policies addressing both local emission sources and regional transboundary pollution are essential to improve public health outcomes in the study area.

This study, however, has several limitations that warrant consideration for future research. Firstly, the analysis focused on the water-soluble fraction of trace metals. While this approach is valuable for assessing bioaccessible components, which are more indicative of actual health risks, it means the results are not directly comparable to studies that measure total metal content. Secondly, the sampling period was confined to the southwest monsoon and intermonsoon seasons, potentially limiting the representativeness of the findings for the entire year, as seasonal variations, particularly during the northeast monsoon, can significantly influence air quality and pollutant sources. Lastly, the health risk assessment could not include all measured metals, such as zinc (Zn), copper (Cu), and lead (Pb), due to a lack of universally accepted inhalation toxicity data, which may have led to an underestimation of the overall health risks.

To build upon these findings and address the identified limitations, future research should pursue several specific directions. Investigating the health risks by directly comparing water-soluble versus total metal concentrations in $PM_{2.5}$ would provide a more comprehensive understanding of their respective contributions to overall toxicity and help refine risk assessment methodologies. Expanding the sampling to cover all seasons, including the northeast monsoon, is essential to capture the full seasonal variability of $PM_{2.5}$ sources and concentrations, especially considering its impact on transboundary pollution. Furthermore, future health risk assessments should aim to incorporate unregulated or unassessed trace metals like Zn, Cu, and Pb, by either developing new toxicity data or utilizing emerging research on their inhalation health effects. Investigating the synergistic effects of heavy metal mixtures in $PM_{2.5}$ inhalation, particularly for combinations like Zn, Cu, and Pb, would also provide a more accurate picture of the complex health impacts of air pollution.

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