ATMOSPHERIC $PM_{2.5}$ AND PARTICLE NUMBER CONCENTRATION IN SEMI-URBAN INDUSTRIAL-RESIDENTIAL AIRSHED

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DEDICATION

This thesis is dedicated to my supportive husband, Mohd Shahrul Azrie bin Ruslan, and most importantly to my beloved mother, Assoc. Prof. Dr. Faizah binti Mohamad Nor, and my beloved father, Hj. Dahari bin Derani, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Air pollution is one of the crucial factors that cause premature death and health problems. Fine particulate matter ($PM_{2.5}$) has a high association with adverse health effects due to its capability to penetrate deep into the human respiratory system. The deterioration of air quality in Malaysia, especially Johor Bahru city, is worrying due to the swift industrial, transportation as well as housing expansion. Air pollution has a closer relationship with the particle number concentration (PNC) rather than the particle mass concentration. However, measurement of the $PM_{2.5}$ is normally reported in particle mass concentration. Due to the light-weighted small particle sizes that dominate the PNC, they are accounted for only a few percent of the total particle mass concentration. Thus, these small particles could be neglected if the toxicological effects are determined primarily by the mass concentration rather than the PNC. This study aims to investigate the 24 h mean $PM_{2.5}$ mass concentrations, meteorological parameters and PNC, besides determining the concentrations of the trace metals and water-soluble inorganic ions of the $PM_{2.5}$ pollutant collected at the industrial-residential airshed of Skudai, Johor Bahru. This research analysed the source apportionment of the $PM_{2.5}$ composition and the relationship of the $PM_{2.5}$ mass concentrations with PNC. The meteorological variables, PNC data and $PM_{2.5}$ samples were collected from August 2017 until January 2018. The source apportionment of the $PM_{2.5}$ composition were determined using Positive Matrix Factorisation (PMF). This study found that the highest 24 h $PM_{2.5}$ mass concentration is 44.6 μgm^{-3}, with a mean value of 21.85 μgm^{-3} throughout the SW through the NE monsoon. 43.33% of the daily $PM_{2.5}$ mass exceeded the 24 h World Health Organization Guideline, while 8.33% of the concentration exceeded the 24 h Malaysia Ambient Air Quality Standard. The ambient temperature throughout the monsoon seasons shows a significant positive correlation ($p < 0.05$) with $PM_{2.5}$ mass ($r^2 = 0.43$ to $r^2 = 0.54$), while the wind speed ($r^2 = -0.23$ to $r^2 = -0.01$) and the relative humidity ($r^2 = -0.47$ to $r^2 = -0.27$) show negative correlations. The rainfall on the other hand shows weak correlation towards $PM_{2.5}$ mass. The accumulation mode particles (0.27 μm < Dp < 1.0 μm) corresponded to 94~98% of the total particle number concentration, with highest hourly mean of 372.20 $\#cm^{-3}$ during the SW monsoon. The accumulation mode has the highest correlation value of $r^2 = 0.8701$ among the other particle size bins. The major trace elements identified were Fe (279.2 $\pm$ 69.2 ngm^{-3}), Ba (200.1 $\pm$ 57.2 ngm^{-3}), Zn (133.2 $\pm$ 67.6 ngm^{-3}), Mg (116.3 $\pm$ 43.8 ngm^{-3}) and Al (104.1 $\pm$ 30.6 ngm^{-3}). For inorganic ions, the secondary inorganic aerosols (SIA) were highly contributed by NO_3^- (639.9 $\pm$ 138.1 ngm^{-3}), SO_4^{2-} (556.9 $\pm$ 203.0 ngm^{-3}) and NH_4^+ (424.1 $\pm$ 106.1 ngm^{-3}). Despite the anthropogenic activities as the sources of particulates, a minor fraction of pollutants may also due to the regional transboundary transport. The PMF analysis shows that non-combustion traffic source is the main contributor to the ambient $PM_{2.5}$ (25.4 %). The six predominant sources identified were (1) mineral dust pollution (4.2 %), (2) source of mixed road dust and biomass burning (18.1%), (3) mixed secondary inorganic aerosol and road dust emission (18.1%), (4) emission of the non-combustion traffic source (25.4%), (5) industrial emission (18.1 %) and (6) undefined (16.1 %). The comprehensive findings of this study may support the need to control the $PM_{2.5}$ sources.

ABSTRAK

Pencemaran udara adalah salah satu faktor penting yang menyebabkan kematian awal dan masalah kesihatan. Bahan zarahan halus ($PM_{2.5}$) mempunyai hubungan yang tinggi dengan kesan kesihatan yang buruk kerana keupayaannya yang dapat menembusi jauh ke dalam sistem pernafasan manusia. Kemerosotan kualiti udara di Malaysia, terutamanya bandaraya Johor Bahru, adalah membimbangkan disebabkan oleh industri, pengangkutan serta perkembangan perumahan yang pantas. Pencemaran udara mempunyai hubungan yang lebih dekat dengan kepekatan bilangan zarah dan bukan kepekatan jisim zarah. Walau bagaimanapun, pengukuran $PM_{2.5}$ biasanya dilaporkan dalam kepekatan jisim zarah bukan dalam kepekatan bilangan zarah. Zarah kecil dan ringan yang mendominasi kepekatan bilangan zarah menyumbang hanya beberapa peratus daripada jumlah kepekatan jisim zarah. Oleh itu, zarah-zarah kecil ini boleh diabaikan jika kesan toksikologi hanya ditentukan oleh kepekatan jisim dan bukannya kepekatan bilangan zarah. Kajian ini bertujuan untuk menyiasat purata 24 jam kepekatan jisim $PM_{2.5}$, parameter meteorologi dan kepekatan bilangan zarah, selain menentukan kepekatan logam dan ion bukan organik yang larut dalam air dari pencemar $PM_{2.5}$ yang dikumpul di kawasan perumahan dan perindustrian di Skudai, Johor Bahru. Kajian ini menganalisis pembahagian sumber komposisi $PM_{2.5}$ dan hubungan kepekatan jisim $PM_{2.5}$ dengan kepekatan bilangan zarah. Data meteorologi, kepekatan bilangan zarah dan sampel $PM_{2.5}$ dikumpulkan dari Ogos 2017 hingga Januari 2018. Pengagihan sumber komposisi $PM_{2.5}$ ditentukan dengan menggunakan Pemfaktoran Matriks Positif (PMF). Kajian ini mendapati bahawa 24 jam kepekatan jisim $PM_{2.5}$ yang tertinggi adalah 44.6 μgm^{-3}, dengan nilai purata 21.85 μgm^{-3} semasa monsun barat daya hingga timur laut. 43.33% daripada kepekatan jisim $PM_{2.5}$ harian melebihi 24 jam Garis Panduan Organisasi Kesihatan Dunia, manakala 8.33% kepekatan jisim melebihi nilai 24 jam Garis Panduan Kualiti Udara Ambien Malaysia. Suhu ambien sepanjang musim monsun menunjukkan korelasi positif yang ketara ($p < 0.05$) dengan $PM_{2.5}$ (r^2 = 0.43 hingga r^2 = 0.54), manakala kelajuan angin (r^2 = -0.23 hingga r^2 = -0.01) kelembapan (r^2 = -0.47 hingga r^2 = -0.27) menunjukkan korelasi negatif. Hujan pula menunjukkan korelasi lemah yang signifikan terhadap jisim $PM_{2.5}$. Partikel mod pengumpulan (0.27 µm < Dp < 1.0 µm) bersamaan dengan 94 ~ 98% daripada jumlah kepekatan jumlah zarah, dengan purata jam tertinggi sebanyak 372.20 $\#cm^{-3}$ semasa monsun barat daya. Mod pengumpulan mempunyai nilai korelasi tertinggi iaitu r^2 = 0.8701. Unsur-unsur jejak utama yang dikenal pasti ialah Fe (279.2 ± 69.2 ngm^{-3}), Ba (200.1 ± 57.2 ngm^{-3}), Zn (133.2 ± 67.6 ngm^{-3}), Mg (116.3 ± 43.8 ngm^{-3}) dan Al (104.1 ± 30.6 ngm^{-3}). Kepekatan ion disumbangkan oleh NO_3^- (639.9 ± 138.1 ngm^{-3}), SO_4^{2-} (556.9 ± 203.0 ngm^{-3}) dan NH_4^+ (424.1 ± 106.1 ngm^{-3}). Analisis PMF menunjukkan bahawa sumber trafik bukan pembakar adalah penyumbang utama kepada $PM_{2.5}$ (25.4%). Enam sumber utama yang dikenal pasti ialah (1) pencemaran habuk mineral (4.2%), (2) sumber habuk campuran dan pembakaran biomas (18.1%), (3) campuran aerosol anorganik sekunder dan pelepasan habuk jalan (18.1%), 4) pelepasan sumber trafik bukan pembakaran (25.4 %), (5) pelepasan perindustrian (18.1%) dan (6) tidak ditentukan (16.1%). Penemuan komprehensif kajian ini boleh membantu mengawal sumber $PM_{2.5}$.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BC	-	Black Carbon
EC	-	Elemental Carbon
OC	-	Organic Carbon
PAH	-	Polycyclic Aromatic Hydrocarbons
UPW	-	Ultrapure Water
TM	-	Trace Metal
WSII	-	Water-Soluble Inorganic Ions
PM	-	Particulate Matter
IC	-	Ion Chromatography
MDL	-	Method Detection Limit
NAAQG	-	National Ambient Air Quality Standard
ICP-MS	-	Inductively Coupled Plasma–Mass Spectrometry
CMB	-	Chemical Mass Balance
PMF	-	Positive Matrix Factorization
SW	-	Southwest
IM	-	Inter-Monsoon
NE	-	Northeast
PNC	-	Particle Number Concentration
SIA	-	Secondary Inorganic Ions
SEA	-	Southeast Asia
WHO	-	World Health Organization
DOE	-	Department of Environment
API	-	Air Pollutant Index

LIST OF SYMBOLS

Dp	-	Particle Diameter
x_{ij}		Concentration of j_{th} species
S_{ij}	-	Measure of the uncertainty in the measured value
u_{if}	-	Uncertainty
f_{kj}	-	Factor Profile
e_{ij}	-	Residual matrix
p	-	Number of factors
σ_{ij}	-	Estimated measurement error
X_{ij}	-	Observed concentration
X_j	-	Mean value
C_{PM}	-	Concentration of $PM_{2.5}$ mass, μgm^{-3}
W_m	-	Net mass of filter paper, g
W_b	-	Weight of filter blank, g
Q	-	Average air flow rate, L min^{-1}
T	-	Sampling time, min
C	-	Concentration of element in atmosphere, ngm^{-3}
C_1	-	Concentration of element in sample solution, μgL^{-1}
C_b	-	Concentration of element in filter blank solution, μgL^{-1}
V	-	Volume of extraction, L

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Clean air is essential in order for human beings to live healthily in carrying out daily activities and ensuring the quality of life. However, natural and anthropogenic activities have caused tremendous air pollution in urban and suburban region as well (Environment Board of the Province of West Java, 2009). Air pollution issue has resulted to 537,000 premature human deaths annually (WHO, 2002). According to World Health Organization (WHO), the increasing number of population in developing countries leads to atmospheric pollution (WHO, 2005). One of the main pollutants which contributes to the negative impact of the global climate is airborne particulate matter (PM) (Mallet et al., 2016). The World Health Organization (WHO) reported that 1/8 of premature deaths are caused by airborne pollution. Every year, more than 3 million premature deaths is caused by the exposure to the pollution of ambient air (WHO, 2014).

$PM_{2.5}$ is particulate matter that has an aerodynamic diameter of less than 2.5 micrometers and is known to be hazardous to mankind. These particles have the ability to deteriorate local and regional air quality, as well as atmospheric visibility (Cascio et al., 2009). $PM_{2.5}$ can reside for a longer period of time in the atmosphere. The excessive exposure to $PM_{2.5}$ can pose severe health problems due to its capability of penetrating deep into the alveolar region of human respiratory system. This causes various diseases including heart attack, acute bronchitis, asthma, cardiopulmonary mortality and lung cancer (Hu and Jiang, 2014; Gao et al., 2015; Tao et al., 2012; Cisternas et al., 2014; WHO, 2013; Oberdorster et al., 2005; Elser et al., 2016; Thevenotetal., 2013).

Malaysia, apart from other neighbouring countries in Southeast Asia (SEA) has also made an effort recently to improve the quality of the ambient air through the implementation of clean air acts. This acts cover the emission air control measures and strict continuous air quality monitoring in every major cities including Johor Bahru. Under the supervision of Department of Environment (DOE), which reports the performance of air quality based on Air Pollutant Index (API), Johor Bahru station is equipped with the automatic monitoring Continuous Air Quality Monitoring (CAQM). These stations are designed to collect data continuously (24 h).

Recent epidemiological and toxicological studies on $PM_{2.5}$ pollution present evidence of a closer correlation with particle number concentration (PNC) rather than particle mass concentration. The particle mass concentration is mostly dominated by the mass of the larger particles while the number of particle concentration is usually conquered by the smaller-sized particles of $PM_{2.5}$ (particle diameter, Dp < 100 nm) (Donaldson et al., 2002). These smaller particles have more proficiency to reach and deposit deep in the alveoli region of the lungs (Jaques and Kim, 2000). Hence, this suggests that the particle number concentration is a better indicator to the adverse health effects of the $PM_{2.5}$ (Seaton et al., 1995).

1.2 Problem Statement

In this globalization era, metropolitan city of Johor Bahru is evolving into an economic city. The deterioration of air quality in SEA especially Malaysia, and specifically Johor Bahru city, has reached to a worrying stage due to the rapid industrial, transportation as well as housing development. Major economic activities are normally concentrated within the existing city boundaries. However, once the city is packed with the human population, transportations, buildings and traffic activities, the urban sprawl trend is implemented to introduce the new developments in the semi-urban areas. Due to the lower living cost in the semi-urban area of Skudai and expensive housing prices in Johor Bahru city centre, more population decides to reside in this perisphery area rather than in the city. Therefore, the trip distance that increases tremendously suggests the needs to promote sustainable transportation.

Although many advanced innovations of fuel technologies in reducing vehicle emissions and fuel usage had been introduced, the increasing number of car ownerships counterbalances these inventions. Therefore, this issue would aggravate the pollution of the local ambient air.

Among other main pollutants in Malaysia, $PM_{2.5}$ gives the biggest adverse impact to the human body due to its capability to penetrate deep into the alveoli of our respiratory system. Previous toxicological studies reported that there have been consistent reports on high positive correlations between $PM_{2.5}$ mass concentrations and adverse health effects (Chen et al., 2012). However, only recently DOE decided to implement the ambient $PM_{2.5}$ threshold guideline, after years of practicing PM_{10} standard and monitoring the ambient PM_{10} pollution in Malaysia. Previously, major studies of air pollution in Malaysia were mainly focused on the PM_{10} pollutant and its chemical composition.

Donaldson et al. (2002) stated that the air pollution presented proofs of a closer relationship with the particle number concentration (PNC) rather than the particle mass concentration. However, the measurement of the harmful $PM_{2.5}$ in the ambient air is usually reported in particle mass concentration instead of PNC (McMurry, 2000; Dominick et al., 2015). PNC is based on the number of particles of different size ranges (Cheung et al., 2015). According to Liu et al. (2017a), studies regarding PNC affecting human health deserves equal or greater attention than particulate mass concentration as only limited previous studies concerned the aerosol number concentration. Ultrafine particles dominate the PNC and carry large concentrations of toxic pollutants. However, due to their small sizes, they hardly account for more than a few percent of the total particle mass concentration. The smaller particles are too small to build up aerosol mass even in high PNC. Hence, if the toxicological effects are determined primarily by the mass concentration rather than the particle number concentration, these small particles could be neglected. Although the measurements of PNC and size distributions have been conducted in diverse environments around the world in recent years, only a few measurements were conducted in developing countries, such as India, China and Malaysia. Most of the studies in these countries usually focused on the characteristics of particulate mass concentrations and optical properties (Zhang et al., 2010).

It is important to study the correlation of PNC and size distribution as there is limited number of PNC studies related to $PM_{2.5}$ mass concentration, especially in Malaysia (Amil et al., 2014; Dominick et al., 2015, Khan et al., 2015a). The previous studies only studied on the trends of PNC, and not the correlations of $PM_{2.5}$ and PNC, size distribution and size modes. The new outcome of this relationship may represent a better indicator to the adverse health effects, in comparison with the $PM_{2.5}$ mass concentration. Hence, discovering much sensitive and newer indicator associated to air pollution issues.

In order to also improve the knowledge on the particulate matter of air pollution in the semi-urban industrial-residential region of Malaysia and to address the needs for a comprehensive characterization of the $PM_{2.5}$ and their effects, it is necessary to determine the detailed chemical compositions of the emitted particulates in order to apportion the source origins of the particulates through receptor modelling approach and backward trajectory analysis. The assessment of the $PM_{2.5}$ samples and the source origins may contribute to the knowledge of existing information on the $PM_{2.5}$ pollution in similar semi-urban residential-industrial settings, besides assisting in suggesting the appropriate mitigation measures.

1.3 Research Objectives

The objectives of the research are:

(RO1) To evaluate the seasonal trends and the correlations of the ambient fine particulate concentrations ($PM_{2.5}$) and meteorological variations in industrial-residential semi-urban environment of Skudai, Johor Bahru.

(RO2) To investigate the relationships of $PM_{2.5}$ mass concentration and number concentration.

(RO3) To characterize the seasonal chemical components of segregated $PM_{2.5}$ including trace metals and water-soluble inorganic ions.

(RO4) To classify the possible source origins of the particulate emissions via source apportionment method.

1.4 Scope of the Study

The study was conducted in a semi-urban industrial-residential airshed of Skudai, Johor Bahru during half-year period of three seasonal cycles of southwest (August to September 2017), intermonsoon (October to November 2017) and northeast monsoons (December 2017 to January 2018). The parameter of interest in this study is the particle number concentration and the size segregated particle mass concentration of fine particulate matters ($PM_{2.5}$), the chemical species of trace metals and water-soluble inorganic ions and the source origins of the particulate emissions.

The scope of the study covered the analysis on the trends of the ambient fine particulate concentrations ($PM_{2.5}$) and the meteorological parameters collected in the study area to solicit the inter-relationship among the fine particles and the influence of meteorological factors on $PM_{2.5}$. In addition, this research characterizes the chemical species of $PM_{2.5}$ samples which are limited to the concentrations of trace metals and water-soluble inorganic ions.

The elements were further subjected to a receptor modelling of positive matrix factorization to assess for possible source origins of the particulates in study area. The particulate number concentration data was investigated in order to study its relationships with the $PM_{2.5}$ mass concentration.

1.5 Significance of the Study

The semi-urban industrial-residential area of Skudai is developing steadily into an almost urban area due to the high population in Universiti Teknologi Malaysia (UTM), the education centre with great intensity of human activities and transportation rate, besides being located next to the Skudai and Senai Highway that have heavy traffic volume, as well as being located nearby to Johor Bahru city centre, Nusajaya and heavy industrial area of Pasir Gudang. Thus, a greater consideration has to be given since the continuous development deteriorates the ambient air of the environment due to the local anthropogenic activities in the study area where the population is high. Although the local authorities are also making efforts by monitoring the air pollution of the southern part of Peninsular Malaysia of Johor Bahru city, which are located in Larkin (urban area) and Pasir Gudang (industrial area) stations, however there is no nearby station located in the Skudai region, and also no available data and information to study the nature of this study area as the use of nationally-averaged findings may not represent the $PM_{2.5}$ problems within a given region. The main objective of conducting a study at this area is due to the needs to investigate the effects of local and transboundary (air issues which are long-range transported from the urban city of Johor Bahru, the polluted industrial areas of Pasir Gudang and Senai, or from the neighbouring countries) pollution towards the semi-urban of mixed commercial-industrial-residential airshed in Skudai-Iskandar Puteri developing region. Since the area has less population density and is located far from the industrial activities, city centre and commercial areas, the site is perceived to having significantly clear days throughout the years.

Hence, this work is essential to provide the information on the state of the air scenarios and facilitate the future development within the study area. There is also limited number of studies that focus on the temporal variation of $PM_{2.5}$ in this expanding semi-urban region. The aim of this study is also to determine and analyze the variation and correlations of $PM_{2.5}$ mass concentration and meteorological influence in this southern region of Peninsular Malaysia, over a 6-month period to cover the southwest, inter-monsoon and northeast monsoons of Malaysia.

Moreover, the measurement of $PM_{2.5}$ fractions stipulates auxiliary knowledge of the secondary inorganic aerosol (SIA) since SIA is predominantly found in the fine fraction. The findings on the $PM_{2.5}$ concentration in this study could provide as an important knowledge and result validation rather than a duplicative information. Hence, the seasonal variation findings may suggest insights on the possible improvements in the local air quality development as well as assisting in examining the significant health implications that are related to the $PM_{2.5}$ pollutant and origins of the developing semi-urban area of mixed industrial-residential airshed. The findings will efficiently assist the need to manage and control the $PM_{2.5}$ sources.

This investigation analyzes and compares the dual mode parameters of particle number concentration and particle mass concentrations of $PM_{2.5}$. The reported chemical elements characterization provides valuable findings in providing information of the source origins of the particulate emissions. The reported elemental concentrations and PNC would be a good source of knowledge that can assist DOE in improving the air quality monitoring. The determination of the particle size distribution and PNC are important as they might represent a better indicator to the adverse health effects. The outcome of this study will discover a sensitive indicator related to air pollution issues.

1.6 Overview of the Thesis

The thesis consists of six chapters where Chapter 1 briefly imparts the introduction of the study. It explains the study in general while the detailed descriptions are presented in the incoming particular chapters. The objectives and the significance of the study are also presented in this chapter. Next, Chapter 2 presents the literature study and background of the research. This chapter presents the description of the fundamental theory revolving atmospheric pollution including $PM_{2.5}$ particle size fraction, particle number concentration, and the source apportionment approach. Meanwhile, Chapter 3 presents the methodology of the whole study involving from the step of sample collection up to data analysis, besides describing the location of the sampling sites, and also the introductory to the the sampler and analytical tools used in the study including a short explanation on the receptor modelling technique which is PMF. Chapter 4 displays the results and discussions including the overall trends and seasonal variations of the air pollutants concentrations ($PM_{2.5}$), particle number concentration (PNC), meteorological parameters of relative humidity (RH), wind speed (WS), wind direction (WD), temperature (T), rainfall (RF) and also the results of its pearson correlation. The concentrations were also discussed and compared among other studies in SEA. The severity of the mass concentration was based on the threshold limits recommended by the 24-h Malaysian Ambient Air Quality Standard (DOE, 2013), World Health Organization (WHO, 2016) and US National Ambient Air Quality Standard (US EPA, 2017). This chapter also determines the chemical elemental characteristics of the segregated size particulate matter of $PM_{2.5}$ samples collected over half-year of three seasonal cycles. A total of thirty-two (32) constituents had been determined and reported involving the trace metal and water-soluble inorganic ions components. In addition, Chapter 4 also reported the approach of identifying and quantifying the origin of pollutant emissions at the sampling site through a form of receptor modelling. In this chapter, the analysis of the particle number concentration and its relationship with $PM_{2.5}$ size segregated particles is also presented. Finally, Chapter 5 of the thesis concludes the overall summary of the research besides recommending possible research work in the future.

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Appendix A Flow to Operate Low Volume Minivol™ Portable Air Sampler

Flow to Operate low volume MiniVol™ portable air sampler

↓

Multiple impactor adapter with the PM_{10} impactor (silver) was installed on top of the preseparator assembly, while the $PM_{2.5}$ impactor (gold) was installed in the preseparator assembly.

↓

- Greasing and cleaning of the impactor's target disk was performed initially and after every seventh sample.

↓

- Sampler was calibrated and flow rate adjustment was set in accordance with Operation Manual.

↓

Filter paper was loaded in filter holder assembly.

↓

Button was pressed to start the pump to obtain the initial flow rate.

↓

A single-point flow rate was checked using a soap-bubble meter or other flow measuring device of known accuracy and compared to the curve established during calibration.

↓

All tubing for were checked for crimps, cracks or breaks.

↓

Any malfunctions was investigated and corrected before proceeding.

↓

Select a filter and remove cover from petri slide and place the filter cassette in the filter holder.

↓

Battery pack was inserted into the battery slot and PROG button was pressed.

↓

CLOCK button was held down to set the desired power-off time

↓

PROG button was pressed again to indicate that the power-on time is ready to be programmed.

Appendix B PMF Results (C = 0.4, Factor, *p* = 5)

Appendix B (a) Regression diagnostics on 5-factor solution

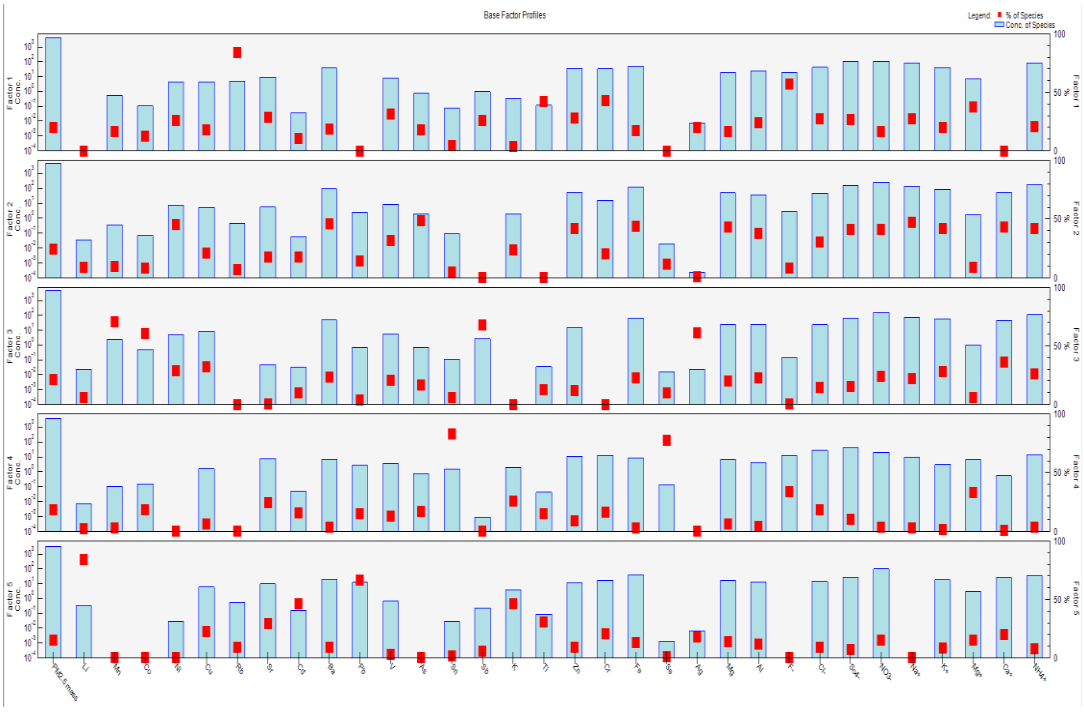
Species	Intercept	Slope	SE	r^2	Stat	P Value
PM2.5 mass	4193.62	0.73	4320.49	0.73	0.07	0.90
Li	0.27	0.15	0.23	**0.36**	0.10	0.58
Mn	1.80	0.32	1.59	**0.25**	0.09	0.70
Co	0.64	0.10	0.43	**0.14**	0.12	0.35
Ni	10.17	0.32	3.62	**0.59**	0.14	0.17
Cu	16.89	0.27	8.07	**0.14**	0.06	0.97
Rb	-0.10	0.86	2.87	0.74	0.07	0.93
Sr	8.42	0.60	13.49	**0.43**	0.07	0.94
Cd	0.24	0.09	0.14	**0.31**	0.10	0.64
Ba	2.04	0.97	28.58	0.79	0.06	0.98
Pb	7.28	0.42	9.09	**0.36**	0.08	0.80
V	9.39	0.54	5.28	0.76	0.09	0.71
As	1.75	0.42	0.98	0.71	0.14	0.19
Sn	0.10	0.86	0.66	0.90	0.06	0.99
Sb	0.69	0.71	1.46	**0.58**	0.10	0.63
K	1.72	0.63	3.27	**0.44**	0.09	0.75
Ti	0.09	0.48	0.12	**0.52**	0.08	0.82
Zn	31.83	0.68	21.98	0.82	0.08	0.87
Cr	7.20	0.80	25.06	0.70	0.09	0.67
Fe	-25.92	1.08	35.83	0.82	0.07	0.93
Se	0.03	0.45	0.15	**0.35**	0.16	0.11
Ag	0.01	0.55	0.02	**0.38**	0.10	0.58
Mg	26.35	0.73	16.22	0.80	0.07	0.92
Al	7.18	0.90	18.38	0.69	0.08	0.86a
F^-	4.10	0.70	17.47	**0.59**	0.10	0.58
Cl^-	38.54	0.69	40.15	0.64	0.13	0.24
So_4^{2-}	85.79	0.73	45.19	0.92	0.12	0.34

NO_3^-	-137.40	1.20	79.97	0.81	0.10	0.58
Na^+	11.67	0.94	34.53	0.92	0.11	0.45
K^+	39.57	0.77	35.63	0.65	0.10	0.64
Mg^{2+}	5.30	0.53	7.61	0.62	0.10	0.53
Ca^+	61.89	0.46	31.80	**0.11**	0.11	0.50
NH_4^+	-38.81	1.07	54.26	0.82	0.06	0.99

Appendix B (b) Bootstrapping results on 5-factor solution

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Unmapped
Boot Factor 1	71	12	4	1	9	3
Boot Factor 2	4	86	2	5	3	0
Boot Factor 3	0	0	86	4	9	1
Boot Factor 4	1	2	0	90	5	2
Boot Factor 5	2	2	1	0	94	1

Appendix B (c) Five-Factor Source profiles of $PM_{2.5}$ predicted by PMF version 5.0



Appendix C PMF Results (C = 0.4, Factor, *p* = 7)

Appendix C (a) Regression diagnostics on 7-factor solution

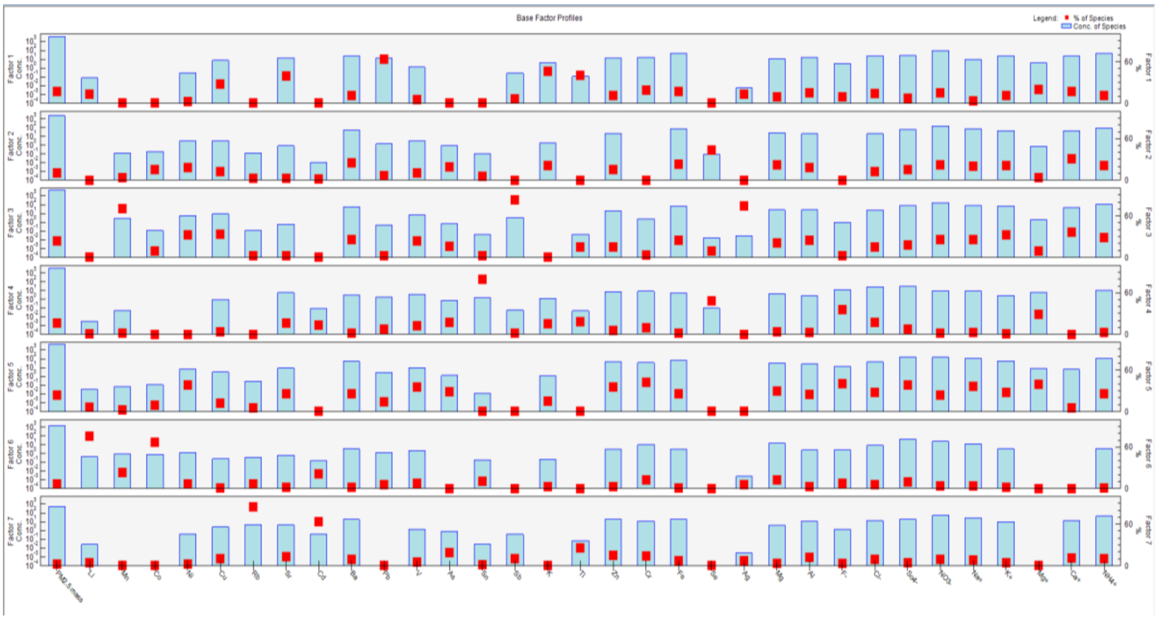
Species	Intercept	Slope	SE	r^2	Stat	P Value
PM2.5 mass	3561.21	0.77	4218.73	0.76	0.09	0.66
Li	0.26	0.37	0.41	**0.51**	0.18	0.04
Mn	1.68	0.40	1.76	**0.29**	0.08	0.88
Co	0.58	0.33	0.89	**0.29**	0.12	0.40
Ni	8.44	0.44	4.09	0.68	0.11	0.50
Cu	17.56	0.27	7.39	**0.16**	0.06	0.99
Rb	0.79	0.71	3.47	**0.58**	0.19	0.02
Sr	6.43	0.71	12.00	**0.58**	0.09	0.74
Cd	0.23	0.46	0.34	0.63	0.12	0.40
Ba	20.06	0.88	25.85	0.79	0.06	0.99
Pb	5.51	0.61	7.91	0.61	0.06	0.97
V	7.16	0.65	5.55	0.80	0.12	0.38
As	1.80	0.43	1.31	0.60	0.14	0.16
Sn	0.02	0.95	0.62	0.93	0.11	0.41
Sb	0.42	0.82	1.07	0.78	0.07	0.95
K	2.05	0.65	2.76	**0.54**	0.11	0.43
Ti	0.09	0.44	0.11	**0.52**	0.11	0.46
Zn	33.22	0.68	28.63	0.72	0.08	0.86
Cr	-1.70	0.96	21.93	0.81	0.08	0.83
Fe	-6.19	1.01	30.55	0.84	0.09	0.66
Se	0.05	0.53	0.11	**0.58**	0.13	0.27
Ag	0.01	0.64	0.01	**0.51**	0.11	0.41
Mg	16.75	0.82	17.15	0.82	0.09	0.73
Al	11.69	0.85	16.45	0.72	0.09	0.68
F^-	6.79	0.61	16.08	**0.57**	0.11	0.45
Cl^-	31.02	0.74	38.35	0.70	0.11	0.42
So_4^{2-}	41.63	0.87	51.65	0.92	0.06	0.99

NO_3^-	-70.36	1.10	79.13	0.79	0.15	0.15
Na^+	-6.65	1.00	37.79	0.91	0.07	0.91
K^+	30.11	0.82	31.57	0.73	0.10	0.62
Mg^{2+}	5.95	0.56	6.74	0.70	0.10	0.62
Ca^+	67.43	0.44	28.02	**0.13**	0.09	0.67
NH_4^+	-17.53	1.02	52.23	0.81	0.13	0.26

Appendix C (b) Bootstrapping results on 7-factor solution

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7	Unmap
Boot Factor 1	85	3	5	0	2	2	2	1
Boot Factor 2	3	81	5	2	0	0	2	7
Boot Factor 3	1	0	98	0	0	0	0	1
Boot Factor 4	3	0	3	91	2	0	0	1
Boot Factor 5	2	1	2	1	94	0	0	0
Boot Factor 6	2	0	5	1	1	88	1	2
Boot Factor 7	6	3	10	0	7	2	68	4

Appendix C (c) Seven-Factor Source profiles of $PM_{2.5}$ predicted by PMF version 5.0



LIST OF PUBLICATIONS

Dahari, N., Muda, K., Latif, M. T. and Hussein, N. (2020) 'Influence of Meteorological Variables on Suburban Atmospheric $PM_{2.5}$ of Southern Region of Peninsular Malaysia', *Aerosol and Air Quality Research*. doi: 10.4209/aaqr.2019.06.0313 **(Q1)**

Dahari, N., Muda, K., Latif, M. T. and Hussein, N. (2019) 'Studies of Atmospheric $PM_{2.5}$ and its Inorganic Water Soluble Ions and Trace Elements around Southeast Asia: a Review', *Asia-Pacific Journal of Atmospheric Sciences*. doi: 10.1007/s13143-019-00132-x **(Q2)**

Dahari, N., Muda, K., Hussein, N. Latif, M. T., Khan, M. F. and Mohamad Khir, M.S. (2019) 'Long-Range Transport and Local Emission of Atmospheric $PM_{2.5}$ in Southern Region of Peninsular Malaysia', *IOP Conference Series: Materials Science and Engineering***.** **(SCOPUS)**

Dahari, N., Khan, M. F., Muda, K., Latif, M. T. and Hussein, N. (2019) 'Chemical Characterization and Source apportionment of $PM_{2.5}$ Near Residential-Industrial Areas', *Aerosol and Air Quality Research*. (**Q1 -submitted)**

Dahari, N., Doreena, D., Muda, K., Latif, M. T., Khan, M. F. and Hussein, N. (2019) 'The Seasonal Variations of Particle Number Concentration and its Relationship with $PM_{2.5}$ Mass Concentration in Industrial-Residential Airshed', *Aerosol and Air Quality Research.* (**Q1 -submitted)**

Dahari, N., Muda, K., Latif, M. T., Hussein, N. and Mohamad Khir, M.S. (2018) 'Suburban Atmospheric $PM_{2.5}$ Distribution In Southern Region Of Peninsular Malaysia', *Proceedings of 162ND THE IIER INTERNATIONAL CONFERENCE.* 162: 75-80 **(International Proceedings)**

Mohamad Khir, M.S., Muda, K., Hussein, N., Abdul Khanan, M.F., Othman, M.N., Hashim, N. and Dahari, N. (2018) 'Spatio-Temporal Analysis of PM_{10} in Southern Peninsular Malaysia', *IOP Conference Series Special Issue* 9 (7): 3.9 **(SCOPUS)**