ROADSIDE $PM_{2.5}$, PM_{10} AND HEAVY METAL COMPOSITION RELATED TO OVERCROWDED TRAFFIC AND ROAD CONSTRUCTION ACTIVITIES IN BANGKOK

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Hazardous Substance and Environmental Management
Inter-Department of Environmental Management
Graduate School
Chulalongkorn University
Academic Year 2019

พีเอ็ม 2.5, พีเอ็ม 10 และ องค์ประกอบของโลหะหนักในอนุภาคฝุ่นริมถนนที่มีความสัมพันธ์กับความหนาแน่นของการจราจร และ กิจกรรมก่อสร้างในกรุงเทพมหานคร

นายปภินวิทย์ ธรรมสาโรช

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาการจัดการสารอันตรายและสิ่งแวดล้อม สหสาขาวิชาการจัดการสิ่งแวดล้อม
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ปีการศึกษา 2562

Thesis Title	ROADSIDE $PM_{2.5}$, PM_{10} AND HEAVY METAL COMPOSITION RELATED TO OVERCROWDED TRAFFIC AND ROAD CONSTRUCTION ACTIVITIES IN BANGKOK
By	Mr. Paphinwit Thammasaroj
Field of Study	Hazardous Substance and Environmental Management
Thesis Advisor	Professor Wanida Jinsart, Ph.D.

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Science

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ปกินวิทย์ ธรรมสาโรช : พีเอ็ม 2.5, พีเอ็ม 10 และ องค์ประกอบของโลหะหนักในอนุภาคฝุ่นริมถนนที่มีความสัมพันธ์กับความหนาแน่นของการจราจร และ กิจกรรมก่อสร้างในกรุงเทพมหานคร. (ROADSIDE $PM_{2.5}$, PM_{10} AND HEAVY METAL COMPOSITION RELATED TO OVERCROWDED TRAFFIC AND ROAD CONSTRUCTION ACTIVITIES IN BANGKOK) อ.ที่ปรึกษาหลัก : ศ. ดร.วนิดา จีนศาสตร์

ปัญหาประชากรหนาแน่นและสภาพการจราจรที่ติดขัดในประเทศไทยโดยเฉพาะเมืองหลวงอย่างกรุงเทพมหานครฯ ทำให้เกิดปัญหาด้านมลพิษทางอากาศ ทั้งอนุภาคฝุ่นละอองขนาดเล็กพีเอ็ม2.5 (อนุภาคฝุ่นละอองขนาดเล็กที่มีขนาดเล็กที่มีเส้นผ่านศูนย์กลางน้อยกว่า 2.5 ไมโครเมตร) และ อนุภาคฝุ่นขนาดเล็กพีเอ็ม10 (อนุภาคฝุ่นละอองขนาดเล็กที่มีขนาดเส้นผ่านศูนย์กลางน้อยกว่า 10 ไมโครเมตร) ได้รับการตรวจวัดเพื่อหาปริมาณที่บริเวณริมถนนซึ่งกำลังมีการก่อสร้างและบริเวณริมถนนซึ่งการจราจรมีความหนาแน่นสูง แล้วนำไปเปรียบเทียบกับบริเวณที่ไม่มีการก่อสร้างและการจราจรที่หนาแน่นเข้ามาเกี่ยวข้อง งานวิจัยนี้ได้เลือกถนนพัฒนาการและถนนศรีนครินทร์ที่เป็นถนนทางฝั่งตะวันออกและถนนทั้งสองสายตัดกันที่สี่แยกดังกล่าวให้เป็นบริเวณเก็บตัวอย่าง โดยใช้ชุดเก็บตัวอย่างฝุ่นละอองในบรรยากาศ (MiniVolume Air Sampler) ในการเก็บอนุภาคฝุ่นละอองขนาดเล็กพีเอ็ม2.5 ในขณะที่เครื่องเก็บอากาศขนาดพกพา(Cyclone Air Sampler) ได้ถูกนำมาใช้เพื่อเก็บตัวอย่างฝุ่นละอองขนาดเล็กพีเอ็ม10 ช่วงเวลาการดำเนินงานวิจัยครั้งนี้ได้ทำการศึกษาในเดือนพฤศจิกายนไปจนถึงเดือนธันวาคมปีพ.ศ.2561 และ ได้เก็บตัวอย่างเป็นเวลา 12 ชั่วโมงต่อวัน ต่อเนื่อง 5 วันในแต่ละพื้นที่ที่ทำการศึกษา หลังจากนั้นนำตัวอย่างฝุ่นละอองข้างต้นที่เก็บมาไปสกัดด้วยเครื่องย่อยสลายตัวอย่างด้วยระบบไมโครเวฟ เพื่อหาธาตุโลหะหนักเหล่านี้ได้แก่ เหล็ก ทองแดง สังกะสี แคดเมียม และ ตะกั่ว หลังจากนั้นนำตัวอย่างที่ได้ทำการย่อยแล้วไปวิเคราะห์ต่อด้วยเครื่องมือวัดการดูดกลืนแสงของอะตอม (Graphite Furnace Atomic Absorption Spectrometer - GFAAS) เพื่อหาปริมาณความเข้มข้นของสารตัวอย่าง นอกจากนี้ตามบริเวณที่เก็บตัวอย่างแต่ละจุด ได้มีการติดตั้งกล้องบันทึกภาพแบบเคลื่อนไหวเพื่อบันทึกสภาพการจราจรในช่วงเวลาดังกล่าว โดยพบว่าสภาพการจราจรในบริเวณที่มีการก่อสร้างบนท้องถนนมีความหนาแน่นมากกว่า นอกเหนือจากนี้ความเข้มข้นเฉลี่ยของอนุภาคฝุ่นละอองขนาดเล็กทั้งพีเอ็ม2.5และพี่เอ็ม10 ในบริเวณที่มีการก่อสร้างยังแสดงค่าที่มากกว่าบริเวณอื่นๆ ในทางตรงกันข้าม บริเวณที่ไม่มีได้รับผลกระทบจากการจราจรและการก่อสร้างแสดงค่าที่ต่ำที่สุดจากทุกๆบริเวณเก็บตัวอย่างอื่นๆ ปัญหาสิ่งแวดล้อมที่กล่าวมาข้างต้นนี้ควรได้รับการตระหนักและความสำคัญในการพิจารณาแม้ว่าการก่อสร้างต่างๆในเมืองจะมีความสำคัญต่อการพัฒนาและการอำนวยความสะดวกต่างๆจากสิ่งก่อสร้าง เพราะฉะนั้นงานวิจัยนี้จึงมีความคุ้มค่าที่จะทำการตรวจวัดถึงผลกระทบที่ซึ่งเป็นมลภาวะทางอากาศต่อๆไปในอนาคต

สาขาวิชา	การจัดการสารอันตรายและสิ่งแวดล้อม	ลายมือชื่อนิสิต .....
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6087544120 : MAJOR HAZARDOUS SUBSTANCE AND ENVIRONMENTAL MANAGEMENT
KEYWORD: PM2.5, PM10, Heavy metals, Road traffic, Construction, Graphite Furnace Atomic Absorption Spectrometry (GFAAS)

Paphinwit Thammasaroj : ROADSIDE $PM_{2.5}$, PM_{10} AND HEAVY METAL COMPOSITION RELATED TO OVERCROWDED TRAFFIC AND ROAD CONSTRUCTION ACTIVITIES IN BANGKOK. Advisor: Prof. Wanida Jinsart, Ph.D.

The capital city of Thailand, Bangkok, is facing a serious problem caused by overpopulation and traffic congestion. In the this work, particulate matter, both $PM_{2.5}$ (diameter < 2.5 μm) and PM_{10} (diameter < 10 μm) were quantified at the road nears construction areas and road with high traffic; compared with a control area. The sampling area comprised of Pattanakarn Road and Srinagarindra Road located on the eastern route, located between the inbound and outbound junction. Mini-volume air sampler was used to collect $PM_{2.5}$, while cyclone air samplers were used to collect PM_{10}. The samples were collected from November to December 2018, for 12 hours per day for 5 days at each sites. The collected samples were then digested by using microwave digestion for heavy metal components like Fe, Cu, Zn, Cd and Pb. Then, they were analyzed by Graphite Furnace Atomic Absorption Spectrometry (GFAAS) to quantify the heavy metal concentrations. Video recorders were installed at each sampling areas to monitor the traffic flow and it was found that construction areas were the most crowded. The average $PM_{2.5}$ and PM_{10} concentrations in the construction areas were higher than those in traffic areas with no construction and the background site (a park), which had no impacts from construction and traffic. Heavy metals associated with particulate matter emitted during construction activities is an emerging environmental issue; however, construction activities are required for convenience and development. This study provides important data required to monitor the future trends of air pollution sources.

Field of Study:	Hazardous Substance and Environmental Management	Student's Signature .....
Academic Year:	2019	Advisor's Signature .....

ACKNOWLEDGEMENTS

First and foremost, I would like to offer my sincere thanks to Prof. Wanida Jinsart for all her kind support, encouragement, and advice during my thesis work. Moreover, I am deeply grateful to the International Postgraduate Program in Hazardous Substance and Environmental Management (IP-HSM), under the Graduated School, of Chulalongkorn University, for the education I received, and also for providing the laboratory instruments and equipment required for the present study.

I would like to express my appreciation to the chairman, Associate Professor Ekawan Luepromchai, Ph.D., and the committee members, Assistant Professor Chantra Tongcumpou, Ph.D.; Chidsanuphong Chart-asa, Ph.D.; and external examiner Assistant Professor Panwadee Suwattiga, Ph.D., of my thesis defense for their helpful comments, discussions, and suggestions to improve and help complete in this thesis.

I am also thankful for the financial support I received, covering every year of my studies, from the International Postgraduate Program in Hazardous Substance and Environmental Management (IP-HSM).

I would like to offer my special thanks to laboratory staff members, Mrs. Ketsaraporn Kaenkaew, Mr. Pathompong Vibhatabandhu, at Department of Environmental Science, Faculty of Science, Chulalongkorn University and also Mrs. Chantana Intim at the Center of Excellence on Hazardous Substance and Environmental Management (HSM) for guiding me on how to use laboratory instruments and equipment.

I owe my sincere thanks to the Department of Environmental Science, Faculty of Science, Chulalongkorn University, for providing use of their laboratory for my experiment.

I owe my deepest gratitude to Miss Akiko Uyeda for perfectly thesis writing editing, and Mr. Tin Thongtummachart and Miss. Pradub Mesawat for their help and suggestions during the experimental phase of my thesis.

I wish to thank the Suanluang District Office, Suanluang Rama IX Park, Thai Meteorological Department, Pollution Control Department, for their permission in the experiment areas and access to useful data.

My deepest appreciation goes to my family and my friends for their support, encouragement, and suggestions throughout my course work and thesis. Thank you.

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CHAPTER I
INTRODUCTION

1.1 Introduction

Bangkok, the capital city of Thailand, has a population around 9 million, with a population density of approximately 5258.6 per km^2. It is a city that attracts a large number of diverse tourists (Latlong, 2018). The roads are the main means of transportation in Bangkok, comprising of 53% private vehicles and 47% of public transport. Owing to overpopulation, including the influx of immigrant workers, and increases in the population growth rate, the public transport systems of the city are becoming inadequate. In addition, this urban area was not designed for building further road transport paths, and the Bangkok population tends to use their own vehicles rather than public transport; thus, Bangkok has faced serious traffic problems for decades (BMA Data Center, 2018). Consequently, traffic emissions from high levels of traffic are causing serious air pollution issues, especially the high prevalence of particulate matter (Jinsart, Tamura et al., 2002).

Air pollution is the pollutants releasing into the air that is harmful to both human health and the planet (NRDC, 2018). Two main types of air pollution are indoor air pollution and outdoor air pollution. Indoor air pollution occurs in poor countries with low quality of life; people use solid fuel and kerosene in open fires and have insufficient kitchen equipment. These activities produce high levels of household air pollutants, including smoke that can penetrate deep into the lungs. The indoor smoke can be 100 times higher than acceptable levels for fine particles in poorly ventilated residents. However, outdoor air pollution, which include particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), is also a major environmental health problem. The key sources of outdoor air pollutants are from the industrial energy, transportation, power generation, municipal and agricultural waste management sectors (World Health Organization, 2018).

Particulate matter (PM), which is called particulate pollution, is a mixture of solid particles and liquid droplets suspended in the air. The main components of PM are sulfate, nitrate, ammonia, sodium chloride, black carbon, mineral dust, and water (World Health Organization, 2018). Moreover, near the roadside, mineral dust is also the main component of PM (Green Facts, 2018). Other inorganic ions such as sodium, potassium, calcium,

magnesium and chloride ions and metals such as cadmium, copper, nickel, vanadium, and zinc are present in PM. Some particles are large or dark enough and visible; however, other small particles can only be detected with high resolution microscope. PM that is well-known includes $PM_{2.5}$ (in which the diameter of a particle is smaller than 2.5 μm) and PM_{10} (in which the diameter of a particle is smaller than 10 μm) (United States Environmental Protection Agency, 2017).

Particulate matter causes adverse health effects to humans. The particles less than 10 μm in diameter are more hazardous because of their ability to penetrate deep into the lungs or blood circulation system. There is evidence showing that fine particles ($PM_{2.5}$) are more dangerous than coarse particles (PM_{10}) in causing cardiovascular and respiratory diseases. In toxicological study, several physical, biological, and chemical characteristic found that the toxic produced from metal content, polycyclic aromatic hydrocarbons (PAHs), other organic components , $PM_{2.5}$ and PM_{10} (Chen, Hu et al., 2016; Green Facts, 2018). Many studies have informed that exposure to these particualte pollutants can lead to variety of health impacts such as premature death in people with heart or lung disease, non-fatal heart attacks, irregular heartbeats, aggravated asthma, decreased lung function, and respiratory symptoms (United States Environmental Protection Agency, 2017). Moreover, the World Health Organization's International Agency for Research on Cancer (IARC) classified PM as a lung carcinogen (World Health Organization, 2018). Although PM standards have been set, Bangkok sometimes faces the problem of $PM_{2.5}$ values exceeding the air quality limit. Thus, this issue needs effective mitigation strategies and policies to assist Bangkok air quality in being below the WHO PM limit. Furthermore, people in the areas that break the WHO limit need to be cognizant of the effects of particulate matter to raise their awareness on this issue.

Particulate matter can have a variety of adverse effects from impairing visibility to causing damage to materials. The reduction of visibility is mainly caused by fine particles ($PM_{2.5}$). Since particles can be transported over long distances by wind, they can damage the ground water where they settle, depending on their chemical compositions. Example of what they can cause are as follows: acid lakes and acid streams, nutrient changes in large water or coastal water, decreased soil nutrients, damage to forests and farms, impacts on ecosystems, and occurrence of acid rain. Acid rain can lead to staining of stone and other materials, like statues and monuments.

The emitted particulate matter can be of various shapes, sizes and chemical compositions. The possible sources that tend to generate PM are

construction sites, unpaved roads, fields, smokestacks and fires. The chemicals emitted from power plants, industries, and automobiles such as sulfur dioxides and nitrogen oxides create particles that are formed by complex reactions (Environmental Protection Authority Victoria, 2018). Moreover, the PM sources also include combustion engines (both diesel and petrol), solid-fuel (coal, lignite, heavy oil and biomass), and combustion for energy production in household and industries, as well as other industrial activities (building, mining, manufacture of cement, ceramics and bricks, and smelting) (World Health Organization, 2018). $PM_{2.5}$ emitted from road transportation is generated from two main sources: exhaust and non-exhaust emissions. Exhaust emissions are emitted from fuel combustion, which are petrol exhaust and diesel exhaust. In case of non-exhaust emissions, they are emitted from brake wear, re-suspension, and road surface wear (Lawrence, Sokhi et al., 2013; Jandacka, Durcanska et al., 2017). With regard to Bangkok transportation, although there are many choices for commuters, public transportation options are insufficient to support everyone including immigrant workers. Bangkok citizens prefer using their own private vehicles over public transportation, leading to an increase in the number of cars; as a result, Bangkok suffers from traffic congestion (BMA Data Center, 2018). These reasons also confirm that automobiles in traffic areas are the main source of PM emissions.

An increasing demand for modern conveniences and improving quality of life has resulted in higher exposure to air pollutants from industrial activities, traffic, and energy production. Thus, these problems require agencies and organizations to set standards, levels, and goals that provide public to have safe air to breath. These standards also include sensitive population subgroups (e.g., children, asthmatic, and elderly people). It is difficult to assess the risk from metals because organisms have always been exposed to metals and organisms and respond to metals in different ways. Metals may only bio-transform into another form, but they cannot be destroyed by either biological or chemical processes. Exposure to metals in the air can cause adverse human health effects such as cardiovascular disease, pulmonary inflammation, damage to vital organs, and cancer. Cotemporary research has revealed that metal components of particulate matter (PM) potentially contribute to adverse health effects, even though the total metal concentration in the ambient air is low. Moreover, emerging research reveals evidence that metallic particles are more dangerous than other PM components and it can be concluded that using only the PM mass concentration is not enough to assess the health effects from exposure to PM. Generally, metals are emitted from combustion processes such as fossil fuel burning and waste burning. These metals occur in small particles or fine fractions, which are

characterized as $PM_{2.5}$. On the other hand, the larger particles are generated from mechanical disruption, construction, agriculture operations and the like. Consequently, metals from coarse sized particles like Al, Zn, and Fe can be released into the atmosphere. However, studies on the metal size distribution of $PM_{2.5}$ in 2010 showed that most of toxic metals accumulate in small sized particles ($PM_{2.5}$ or less). Other related results show that fine metal particles in contact with lung tissues are involved with the release of metal ions into the biological system with higher sorption and penetration. They have the longest resident time in the atmosphere, which allows them to be distributed in the environment more than usual. Recent studies have also shown that metal contents from fine particles are the primary contributors to negative human health, and they significantly cause global climate change(Andrea Geiger and John Cooper, 2010).

Major and trace inorganic elements within $PM_{2.5}$ can be differentiated in natural (e.g., Na, Mg, K, Ca, Si, Al) and anthropogenic (e.g., V, Cr, Mn, Ni, Cu, Zn, Cd, Pb) emissions. The anthropogenic emission sources include: fossil fuel combustion as a main emission source, coal combustion, oil combustion, industrial processing, traffic emission, and road dust (Contini, Belosi et al., 2012). For heavy metals emitted from non-exhaust vehicles, it was found that Ti, Cu, and Cr are key trace elements generated from brake wear and brake lining and tire wear are significantly contributed to the contamination in road dust (Adamiec, Jarosz-Krzeminska et al., 2016). At a road construction area, Cu, V, Ni, Cr, As, and Cr concentrations were about two times higher than those at the residential area (Abah, 2014). According to these studies, major heavy metal species detected from construction activities and traffic congestion related dust was Cd, Cu, Fe, Pb, and Zn.

Construction, especially earth works, causes five major impacts: global warming, acidification, eutrophication, photochemical oxidation, and human toxics (Li and Wang, 2016; Sandanayake, Zhang et al., 2018). In this study, many people in these areas are impacted by decreased air quality due to on-road construction. Roadside monitoring, which does not cover the whole area in Bangkok, should be conducted to measure PM levels to categorize the air quality using $PM_{2.5}$ and PM_{10} as indicators. Demolition and construction activities like road construction, road pavement construction and construction of buildings need to measure the emission of $PM_{2.5}$ and PM_{10} for air quality maintenance (Aeroqual, 2018), and the further investigation about the characterization and quantification of heavy metals in PM is also required.

1.2 Objectives

1.1) The quantification of $PM_{2.5}$ and PM_{10} air pollution at roadsides that is associated with on-road construction activity and traffic volume.

1.2) The quantification of the amounts of heavy metals in $PM_{2.5}$ and PM_{10} at emitted at roadsides due to different on-road construction activites and traffic volume.

1.3) Identifying the association of heavy metal composition between on-road construction activity and traffic volume

1.3 Hypothesis

On-road construction activities and traffic flow elevate $PM_{2.5}$ and PM_{10} levels in the sampling area over those in the background site. Consequently, the amount of characterized heavy metals (Cd, Cu, Fe, Pb, and Zn) in $PM_{2.5}$ and PM_{10} from on-road construction areas are higher than those from the other sites.

1.4 Scope of the study

1.4.1 Study site

The sampling areas lie in Suanluang district at the Pattanakarn Road and Srinagarindra Road junction. Pattanakarn Road consisted of two sampling points: Pattanakarn roadside 1 (PRS 1) and Pattanakarn roadside 2 (PRS 2). Along Srinagarindra Road, crossing with Pattanakarn Road, there were two sampling points, which were construction site at Srinagarindra roadside (SRS), while Suanluang Rama IX Park (SL 9) as a background sampling point. These sampling sites were chosen to monitor the actual roadside exposure data and provide data on the sampling areas.

1.4.2 Pollutants

1) $PM_{2.5}$ and PM_{10} concentrations at four sampling areas and data recorded by the Pollution Control Department (PCD)

2) Heavy metal concentrations extracted from $PM_{2.5}$ and PM_{10}, including iron (Fe), copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb)

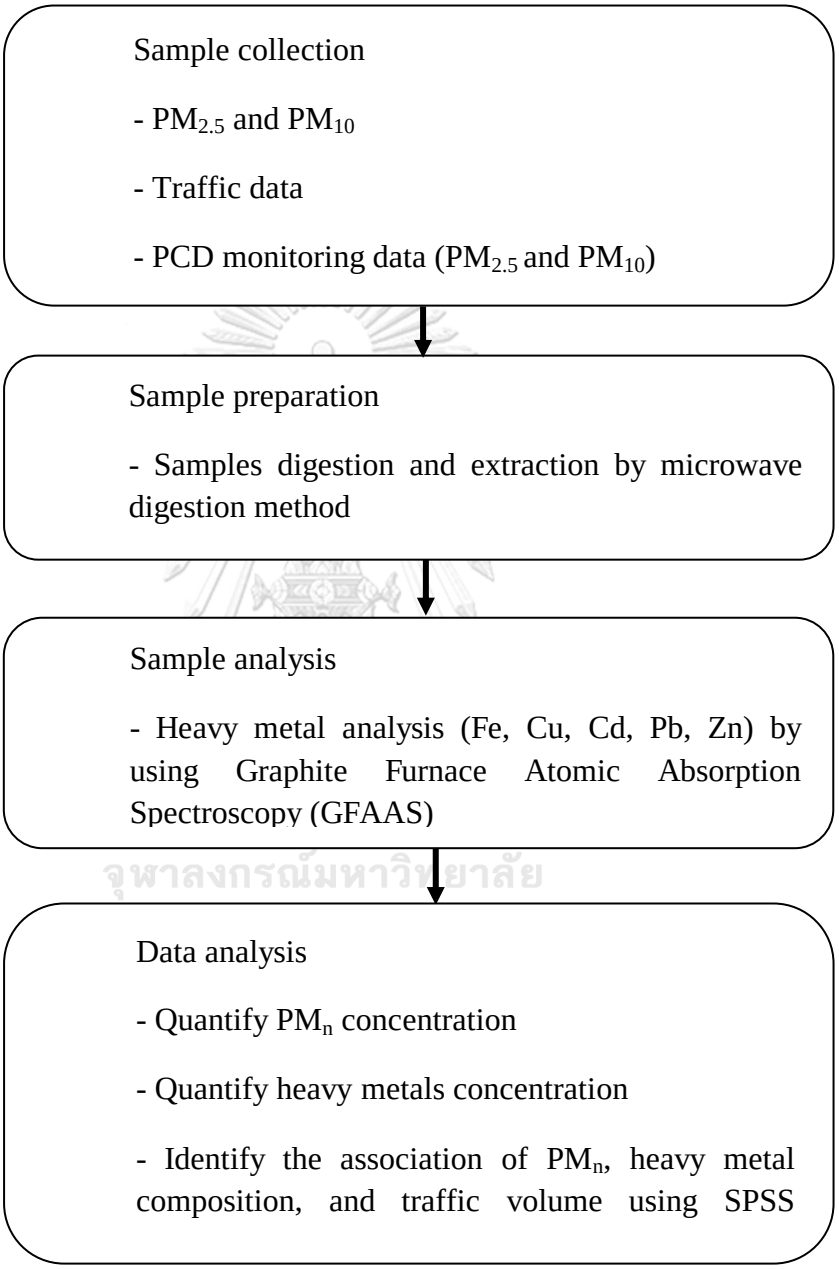
1.4.3 Study duration

The study was carried out in winter (dry season), from November to December 2018. According to the objectives, this sampling period related to the duration of an on-road construction project in the sampling area.

1.5 Expected benefits

Roadside $PM_{2.5}$ and PM_{10} were sampled to analyze their heavy metal compositions because of the PM crisis in Bangkok. The expected outcomes from this research are, first, to use the data from the selected sampling areas as additional monitoring information for further construction planning. The construction near the residential areas or public area should be managed thoroughly and the health of people should be prioritized. Secondly, this research intends to raise awareness among people about the effects from construction activities. Thus, they will be able to properly protect themselves and prevent pollution exposure. Next, an expected benefit from this research is to reveal the actual air conditions in the impacted areas. This research will provide monitoring data for the study areas which are not covered by , PCD monitoring station.

1.6 Conceptual framework



1.7 Thesis outline

This research is divided in six parts:

Chapter 1: Introduction

This part includes the introduction, objectives, hypothesis, scope of study, and expected benefits.

Chapter 2: Theories and Literature reviews

This part includes the theories reviewed from other reference sources and journals related to this study

Chapter 3: Methodology

This part of thesis describes the method and sampling details including the sampling duration, sampling collection and plans, and equipment. This part also covers sample extraction and sample analysis procedures.

Chapter 4: Results and Discussions

The analyzed samples are reported within tables and graph profiles. The reported data are analyzed statistically and the results are discussed.

Chapter 5: Conclusion

The discussed results are concluded to check how the objectives and hypothesis relate according to the scope of this study. Additional further work related to this study is suggested to address and improve upon any information.

CHAPTER II
THEORIES AND LITERATURE REVIEW

2.1 Description of study area

2.1.1 Site topography

Bangkok, the capital city, is located in the middle part of Thailand (13.7563, 100.5017) (Latlong, 2018). The area of Bangkok city in (Fig. 2.1) covers about 1568.7 km^2. Around 9 million people live in this city, and the population density is 5258.6/km^2 (New World Encyclopedia, 2018). People in Bangkok mainly commute by land transport, of which 53% are private vehicles and the remaining 47% are public vehicles (BMA Data Center, 2018).

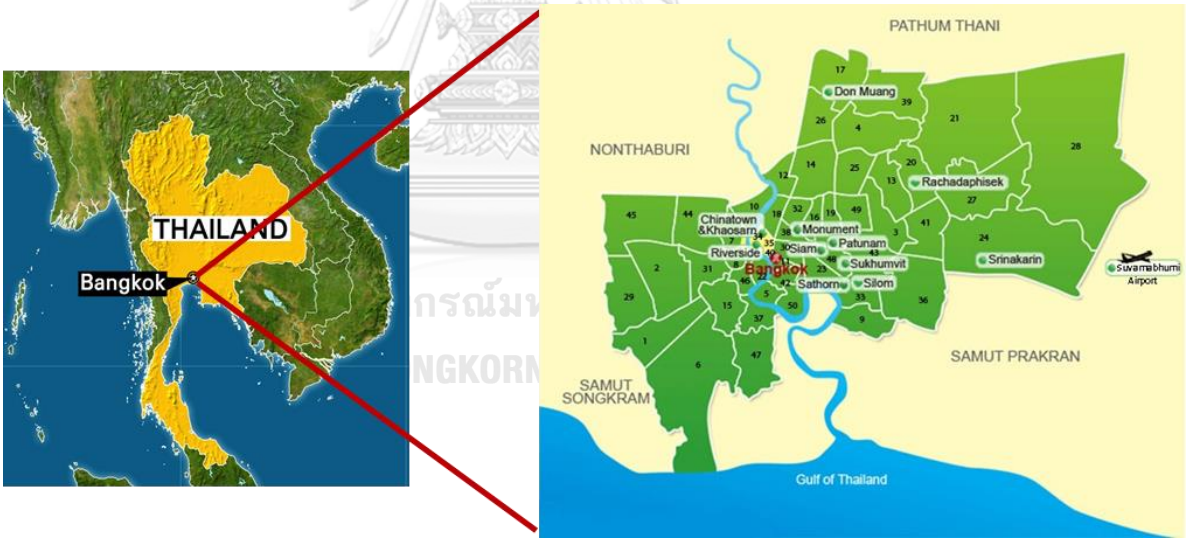


Figure 2.1 Location and districts of Bangkok, Thailand
(Ref: http://bangkokwow.blogspot.com/2008/12/bangkok-map-50-districts.html)

Pattanakarn is another district on the eastern side of Bangkok city that is located at Khlongtan junction and parallel to On Nut Road and Rama IX Road. This area has been developed for decades, expanding from developed areas such as renovated malls, London Street, Maxvalu, and Airport Rail-link (Cultured Creatures, 2015). However, since 21st April 2016, the Pattanakarn-Ramkamhaeng Tunnel project has been under construction by the Department of Public Work. It has tooken a long time for a construction, and its opening has been postponed several times (the deadline was in October 2018). This project has also made the traffic worse, by cutting off lanes of the road leading to a bottleneck because there are only 2 lanes remaining for transportation. Due to the traffic jam together with construction in this area, air pollution in this area has increased significantly. (Font, Baker et al., 2014) found that the level of air pollution at post-road widening was higher than pre-road widening construction. These impacts mostly affect venders and people who lived near to the road.

Srinagarindra Road was built to glorify the queen of King Rama IX. This road, cross Pattanakarn Road, starts from Ladprao Road and ends at Sukumvit Road. There are many famous places along this road such as Seacon Square, Paradise Park, Suanluang Rama IX Park, Thanya Park (Wikiwand, 2018). The emerging construction project is MRT yellow line (Ladpraw-Samrong), which starts from Ladprao Road and continues to Srinagarindra Road. This construction site is located along the road from Pattanakarn conjunction to Udomduk conjunction. Similar to the Pattanakarn construction site, one adjacent lane from the traffic isle of the road is cut off, in each direction. Consequently, the traffic is congested granting the vehicles on the road to emit more air pollutants. Additionally, these construction areas are located near two famous shopping plazas where many people go for shopping, dining, doing their business, and so forth.

2.2 $PM_{2.5}$ and PM_{10}

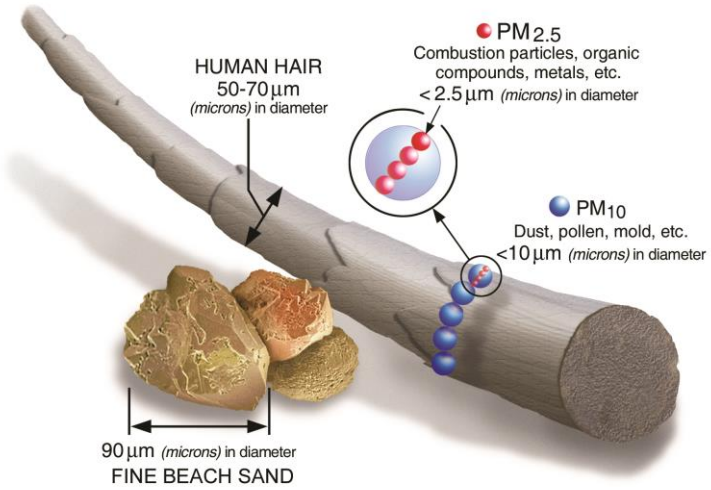


Figure 2.2 $PM_{2.5}$ and PM_{10} size comparison
(https://www.epa.gov/pm-pollution/particulate-matter-pm-basics)

Particulate matter (PM), which is called particulate pollution, is a mixture of solid particles and liquid droplets suspended in the air (Fig. 2.2). Some particles are large or dark enough and visible; however, other small particles can only be detected with high resolution microscope. PM that is well-known includes $PM_{2.5}$ (the diameter of the particle is smaller than 2.5 micrometer) and PM_{10} (the diameter of the particle is smaller than 10 micrometer)(Environmental Protection Authority Victoria, 2018).

Particulate matter 2.5 ($PM_{2.5}$) are termed as fine particle that are less than 2.5 micron in diameter, and it refers to tiny sized particles or droplets suspended in the air. This particle also called fine inhalable particle and it is one kind of many air pollutants that causes adverse effects to both environment and human's health (Department of Health, 2018).

Particulate matter 10 (PM_{10}), which are less than 10 micron in diameter, is a coarser particle compared to $PM_{2.5}$. Like $PM_{2.5}$, it is catalogued as floating dust and known as gaseous pollutants in the atmosphere (Department of Health, 2018).

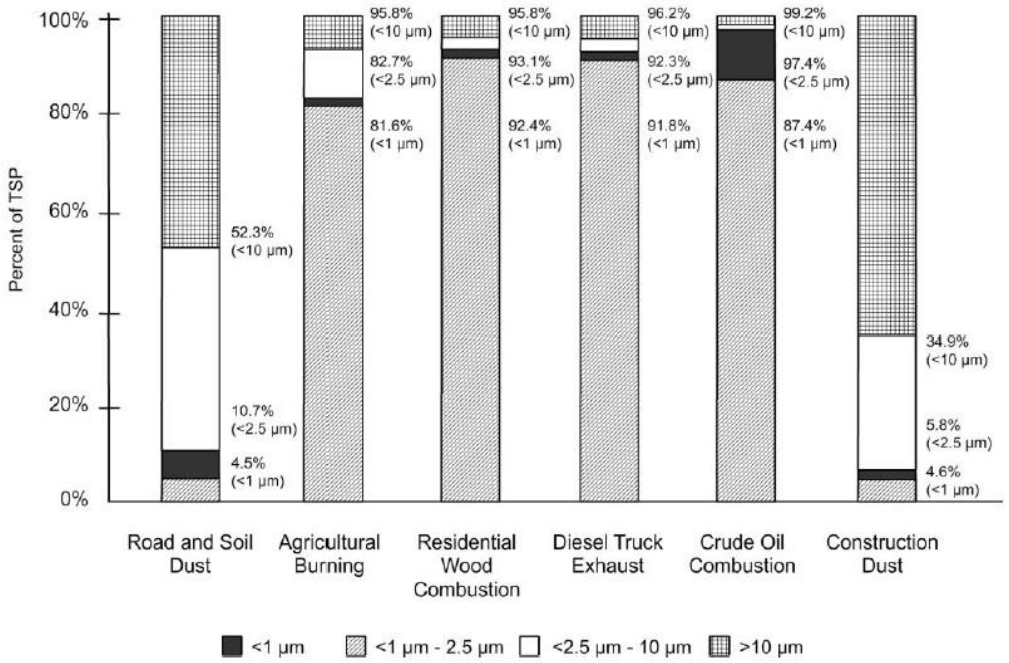


Figure 2.3 Size distributions and emission sources of particulate matter. (source: U.S. EPA)

Particulate matter may be emitted from outdoor sources and indoor sources. The main outdoor sources are cars, trucks and off-road vehicles (e.g., construction equipment, locomotive, snow mobile) exhausts, burning fuel operation, heating oil, coal burning, natural sources(e.g., forest fires) (Fig. 2.3). At the roadside and nearby area, automobiles are the main source of $PM_{2.5}$ and PM_{10} (Jinsart, Tamura et al., 2002),and roadside pollution and traffic volume are significantly associated (Huong Giang and Kim Oanh, 2014). The fine particle also forms from the secondary reaction of gases or droplets suspended in the atmosphere from the emission sources. These chemical reactions may occur miles away from the emission sources due to the influenced by wind speed and wind direction (Department of Health, 2018). Because the coarse particle size is bigger, it tends to be taken down by gravity and washed out by rain. Thus, this coarse particle can be transported over shorter distances and has lower chance in alteration of composition or change of characteristics of the particles through physiochemical processes. In fact, PM diffuses and spreads in to the atmosphere approximately 1-10 kilometer for PM_{10} and 100 to 1000 for $PM_{2.5.}$ $PM_{2.5}$ can be suspended in the air for weeks, while PM_{10} takes a minute to an hour (Pollution Control Department, 2018).

As ambient particulate matter accumulates in ultrafine size, it can penetrate the respiratory system, lungs, and bloodstream through inhalation. By exposure to PM, it causes many diseases such as cardiovascular, cerebrovascular, respiratory impacts. Moreover, World Health Organization's International Agency for Research on Cancer (IARC) classified PM as a lung carcinogen (Karita, Yano et al., 2001; Jinsart, Tamura et al., 2002; World Health Organization, 2018).

Cotemporary research has revealed that metal components of particulate matter (PM) potentially contribute to adverse health effects, even though the total metal concentration in the ambient air is low. Moreover, emerging research reveals the evidences that the metallic particles are more dangerous than other PM components and can be concluded that using only PM mass concentration is not enough to assess the health effects from exposure to PM. Generally, metals are emitted from combustion processes such as fossil fuel burning, waste burning, etc. These metals occur in small particles or fine fraction, which is characterized as $PM_{2.5}$. On the other hand, the larger particles are generated from mechanical disruption, suspension of construction materials, agriculture operations, for example. Consequently, metals from coarse sized particles include Al, Zn, and Fe. However, many studies of metal size distribution in $PM_{2.5}$ in the year 2010 showed that most of toxic metals accumulate in small size particles ($PM_{2.5}$ or less). Other related results showed that fine metal particles in contact with lung tissues lead to the release of metal ions in to biological system with higher sorption and penetration. They have the longest resident time in the atmosphere which allows them to distribute in the environment more than usual. Recent studies have also showed that metal contents from fine particles are the primary contributors to negative human health, and they are significantly adding to global climate change (Environmental Protection Agency, 2010).

2.3 $PM_{2.5}$ and PM_{10} standard

The airborne particulate matter (PM) is the cause of adverse health impacts which occurs within urban population in both developed and developing countries. Although the health effects are of a wide range, the respiratory and cardiovascular systems are the main diseases caused by PM. Most of the population is affected according to their susceptibility to PM, which depends on their age and health. The WHO has conducted several long-term and short-term epidemiological study on PM, and eventually created guidelines for $PM_{2.5}$ and PM_{10}. The $PM_{2.5}$ annual mean concentration was set

at 10 µg/m^3 and the 24-hour mean concentration was at 25 µg/m^3. The PM_{10} annual mean concentration was set at 20 µg/m^3 and the 24-hour mean concentration was at 50 µg/m^3 (World Health Organization, 2005).

Air quality category	24-hr $PM_{2.5}$ µg/m3	One-hour $PM_{2.5}$ µg/m3
Very good	0–8.2	0–13.1
Good	8.3–16.4	13.2–26.3
Fair	16.5–25.0	26.4–39.9
Poor	25.1–37.4	40–59.9
Very poor	37.5 or greater	60 or greater

Figure 2.4 $PM_{2.5}$ air quality categories in 24-hr averaged and 1-hr averaged (source:https://www.epa.vic.gov.au/your-environment/air/air-pollution/pm25-particles-in-air#AQcats)

Environment Protection Agency (EPA) also promulgated the National Ambient Air Quality Standard (NAAQS) for particulate matter under section 109 of the Clean Air Act. The PM standard has been revised for several times since 1997, 2006, and 2012. The revised version is to increase the protection against health effects due to both long-term and short-term exposure. Furthermore, the secondary $PM_{2.5}$ standard can provide sufficient protection against visibility impairment and non-visibility effects. In addition, EPA classified the area as nonattainment or unclassifiable/attainment in December 2014. Accordingly, the annual primary $PM_{2.5}$ concentration standard is 12 µg/m^3 and the secondary is 15 µg/m^3, while the $PM_{2.5}$ 24-hour standard is 35 µg/m^3. PM_{10} annual standard is 25 µg/m^3 and the 24-hour standard is 50 µg/m^3 (EPA, 2019). These standards may be variously set in each area. $PM_{2.5}$ air quality is categorized in one-hour average on EPA AirWatch as Very good (0 - 13.1 µg/m^3), Good (13.2 – 26.3 µg/m^3), Fair (26.4 – 39.9 µg/m^3), Poor (40 – 59.9 µg/m^3), and Very poor (60 µg/m^3 or greater) (Fig. 2.4). Similar to $PM_{2.5}$, the one-hour averaged PM_{10} air quality is categorized as Very good (0 – 26.3 µg/m^3), Good (26.4 -52.7 µg/m^3), Fair (52.8 – 79.9 µg/m^3), Poor (80.0 – 119.9 µg/m^3), and Very poor (120 µg/m^3 or greater) (EPA Victoria, 2016) (Fig. 2.5).

Air quality category	24-hr PM_{10} µg/m3	One-hour PM_{10} µg/m3
Very good	0–16.4	0–26.3
Good	16.5–32.9	26.4–52.7
Fair	33–49.9	52.8–79.9
Poor	50–74.9	80–119.9
Very poor	75 or greater	120 or greater

Figure 2.5 PM_{10} air quality categories in 24-hr averaged and 1-hr averaged (source: https://www.epa.vic.gov.au/your-environment/air/air-pollution/pm10-particles-in-air)

Thailand has the $PM_{2.5}$ and PM_{10} standard get by the Pollution Control Department (PCD). The annual PM_{10} standard concentration is 50 µg/m^3 (2.5 times higher than WHO standard) and the 24-hour standard is 120 µg/m^3 (2.4 times higher than WHO standard). Meanwhile, the annual $PM_{2.5}$ standard concentration is 25 µg/m^3 (2.5 times greater than WHO standard) and the 24-hour standard concentration is 50 µg/m^3 (2 times greater than WHO standard). Even though Thailand has higher standard value than WHO standard limit, both $PM_{2.5}$ and PM_{10} concentration in Bangkok still exceed the PCD periodically (Thai PCD, 2019).

2.4 Traffic congestion in Bangkok

At present, the traffic condition in Bangkok seems to get worse every year. Every road is full of vehicles during rush hours, i.e., when people commute towards their workplace in the morning and when they commute toward their home after work. According to INRIX Global Traffic Scorecard (INRIX, 2019) the traffic was measured daily for 1,360 cities worldwide. The analyzed data in (Fig. 2.6) reported that the most traffic congestion in the world was in Thailand where Thai people waste around 56 hour/year and the average INRIX congestion index was recorded at 11.

RANK	COUNTRY	AVERAGE PEAK HOURS SPENT IN CONGESTION	AVERAGE INRIX CONGESTION INDEX
1	Thailand	56	11
2	Indonesia	51	11.1
3	Colombia	49	10.2
4	Venezuela	42	8.2
5	Russia	41	9.2
5	USA	41	7.3
7	Brazil	36	7.3
8	South Africa	36	5.9
9	Turkey	32	6.7
10	UK	31	5.6
10	Puerto Rico	31	5.7
12	Germany	30	5.5
13	Poland	29	5.5
13	Slovakia	29	5.2
15	Luxembourg	28	4.2
16	Canada	27	5.1
16	Switzerland	27	4.5
18	Norway	26	4.3

Figure 2.6 Peak hour spent in congestion for each country and average INRIX congestion index (source: INRIX Global Traffic Scorecard, 2019)

The individual surveys, refer to each city, reported that the traffic in Los Angeles of U.S. is the worst, while the traffic in Bangkok ranks 16th worldwide, 1st in Asia and Thailand. The Thai government plans to resolve this crisis by setting up eight new sky train projects covering the whole areas of Bangkok (Best Living Test, 2018).

Table 2.1 shows the number of cars registered in Bangkok over five years indicating the trend of increase in Bangkok's total number of vehicles. In the future, the number of almost all types of vehicles are likely to increases (Department of Land and Transport, 2019).

Table 2.1 The car registration in Bangkok 5 years backward (2014- 2018)

Type	Year				
	2014	**2015**	**2016**	**2017**	**2018**
Passenger car	390,330	355,416	369,903	417,068	444,562
Motorcycle	405,649	408,520	455,830	479,586	472,808
Truck	187	254	292	388	549
Others	36,345	32,577	32,445	36,844	40,117
Total	832,511	796,767	858,470	933,886	958,036

(source: https://web.dlt.go.th/statistics/)

This recorded data can imply that Bangkok is facing a challenge of traffic congestion and traffic air pollution because of high population, unorganized urban planning, and increasing number of vehicles. Moreover, the road construction or maintenance such as the construction of a road tunnel, the MRT yellow line and BTS extensions along with the worsening of Bangkok's traffic conditions generates dust particles and its re-suspension. Consequently, the congested traffic leads to air pollution issues in the city, which is emitted mainly from diesel exhaust combustions.

2.5 $PM_{2.5}$ and PM_{10} situation in Bangkok

Because of the congested traffic in Bangkok, the air quality continues to decrease. Table 2 shows the average annual $PM_{2.5}$ and PM_{10} concentration in the previous five years and the annual standard of Pollution Control Department (PCD) (PCD, 2019). PCD set the annual $PM_{2.5}$ standard at 25 $\mu g/m^3$ and PM_{10} standard at 50 $\mu g/m^3$. Since 2014, both $PM_{2.5}$ and PM_{10} were in critical level, and exceeded the PCD annual standard. Besides the exceeded standard limit in each year, $PM_{2.5}$ and PM_{10} levels are expected to increase every year.

Table 2.2 The annual concentration of $PM_{2.5}$ and PM_{10} in 5 years (2014- 2018)

	Annual concentration ($\mu g/m^3$)	
Year	**$PM_{2.5}$**	**PM_{10}**
2014	36	49
2015	36	44
2016	36	51
2017	25	53
2018	32	59
standard	25	50

$PM_{2.5}$ has continued to increase since 2014 and reached the peak in the year 2018. Bangkok faced the $PM_{2.5}$ crisis from November 2018 to January 2019, where $PM_{2.5}$ at almost all monitoring stations was at the highest concentration. It covered the entire Bangkok leading to the poor visibility in the city. People had to find their own Personal Protective Equipment (PPE) such as N95 mask, disposable mask to protect them. Moreover, Thai

government promulgated the $PM_{2.5}$ mitigation policies such as anti-smog gun, promoted public transportation, and banned high emission vehicle. Although the $PM_{2.5}$ level decreased, some monitoring stations still recorded levels that exceeded the standard limit.

2.6 Heavy metal

Heavy metals refer to metallic chemical element that have a relatively high density, and is toxic at low concentration. Heavy metals are natural composition of Earth's crust. They are persistent since they cannot be degraded or destroyed. In addition, when exposed to heavy metals, they enter our body via food ingestion, drinking of water, and inhalation of air. Human body needs heavy metal (e.g. Zinc, Copper, Selenium) for maintaining the metabolism; however, exposure to high level of heavy metal can cause poisoning. The potential sources of poisonous heavy metals entering the body are drinking contaminated water contamination (e.g., lead pipe lines), high ambient air concentration near emission sources, and via the food chain through the consumption of contaminated food.

Accordingly, heavy metals are hazardous because of their bioaccumulation, which means an increase of a chemical in biological organism overtime compared to the chemical concentration in the environment. Furthermore, the metabolism or excretion of heavy metals is slower than taken up or accumulation in organisms, which means they are persistent in the living organisms (Lenntech, 2018). The major heavy metal species that were studied in this study include Iron (Fe), Cadmium (Cd), Copper (Cu), Zinc (Zn), and Lead (Pb).

2.6.1 Cadmium (Cd)

Cadmium, an element with 112.4 g/mol atomic mass and 8.7 g/cm^3 density at 20 ^oC, is a lustrous, silver-white, ductile and a very malleable metal. The melting point of Cd is 321 ^oC, while the boiling point is 767 ^oC. Its surface has a bluish tinge and the metal is soft enough to be cut with knife, but it tarnishes in air. Cadmium is soluble in acids and forms many complex compounds.

Most of Cadmium is used as Ni-Cd batteries and the rest are used in pigments, coatings, plating, and stabilizer in plastics. By coating a film of Cadmium on electroplate steel, it completely protects the steel against the sea. Cadmium can absorb neutrons making it to be a barrier to control nuclear fission. Cadmium can be mainly found in combination with Zinc in the earth's crust. It is also found in industries of inevitable by-product of Zinc, Lead, and Copper extraction. Cadmium enters the environment mainly via ground because it is used as manures and pesticides. Naturally, Cadmium is released into the environment in large amounts throughout the year. The former is released from rocks weathering into rivers; the latter is released from volcano and forest fire to the air. The rest is released through anthropogenic activities as manufacturing process. No cadmium mining for the metal because it is a by-product of Zinc smelting.

Human uptakes Cadmium through food for instance livers, mushrooms, shellfish, mussels, cocoa powder, and dried seaweed. People are exposed to high levels of Cadmium from smoking, where tobacco smoke transports Cadmium into lungs. After that, it transports in the human body via blood system increasing the levels of Cadmium intake from the food. Other high Cadmium level accumulation may occur in people who live near hazardous waste sites, or workers who work in the metal refinery industries where Cadmium is released into the atmosphere. With these emissions, people breathe in Cadmium that severely damage lungs, and may even cause death. When Cadmium enters in the human body, it first transports to the liver via blood system. Then it bonds with proteins to form complexes that are transported to the kidneys damaging filtering mechanisms. The essential proteins and sugars in the body are excreted and eventually damage the kidneys. However, Cadmium is persistent and takes a long time to excrete from the human body.

Cadmium from the industrial activities such as Zinc production, phosphate ore implication, and bio-manure industry are released to soils. The waste from these activities may transport to the air through waste combustion and fossil fuel burning. Cadmium strongly absorb to organic matter in soils, which is dangerous as it can enter the food chains. With higher acidity, the ability of absorption in plant is higher. Animals which rely on plants are affected from plant consumption; as a result, Cadmium accumulates in their bodies. Cadmium poisoning, even in low concentration, can kill earthworms and other essential soil organisms. Consequently, it damages the soil structure, soil processes, and soil ecosystem. In aquatic system, cadmium can bio-accumulate in mussels, oysters, shrimps, lobsters, and fish. In contrast, ocean organisms are more resistant to cadmium poisoning than freshwater

organisms. Consumption of Cadmium elevates, blood-pressure, liver disease, and nerve and brain damage.

2.6.2 Copper (Cu)

Copper, which has an atomic mass of 63.546 g/mol and density of 8.9 g/cm^3 at 20^oC, is a reddish metal with a face-centered cubic crystalline structure. The melting point of Copper is 1083 ^oC, while the boiling point is 2595 ^oC. It is ductile, malleable, and act as an excellent heat conductor and electrical conductor. It is in the same group of gold and silver in periodic table. Copper has low chemical reactivity, so it is used to coat metals for corrosion in moist conditions.

Copper are used for many applications: electrical equipment, construction, (e.g. roofing and plumbing), industrial machinery (e.g. exchangers and alloys). Alloys with well-known applications are bronze, brass (Copper-Zinc), Copper-Tin-Zinc, Copper-Nickel, which are used to make guns, cannons, gun metals, and coins. Electrical wires are made of copper due to its ideal properties, which can be drawn into fine line wire and have a high electrical conductivity. Copper is a common substance that transports naturally in the environment through natural phenomena. Because human widely uses Copper for many applications such as in industries and agricultures, copper production increases and the amount of copper in the environment increases respectively. Consequently, more and more Copper are left in the environment. They contaminate the river, depositing on the sludge in the form of Copper contaminated wastewater. In the air, it is contaminated by fossil fuel combustion, which will remain for some time before it was washed down by rain. Accordingly, soil is the last media and contains a large amount of copper compound. Copper can be released mainly from anthropogenic activities and natural activities. Natural activities are wind-blown dust, decaying vegetation, forest fire, and sea spray. On the other hand, human activities include mining, metal production, wood production, and phosphate fertilizer production. Moreover, Copper is usually found near mines, industrial settings, landfills, and waste disposals. Copper compounds are mainly found in water sediments and soil particles. They affect human health, especially for the soluble compounds, which are generally released by agricultural activities.

People are exposed to copper compounds from food and air, because we daily absorb them via the main exposure pathways, which are breathing, drinking and eating. Even though humans can contain high amount of Copper concentration because it is an essential element for humans, too much of it can cause adverse health effects. Normally, copper concentration in the air is low and can be neglected, but the area near copper smelting processes is not safe for the people living there. In the water media, people are more exposed to copper, since it is corroded from the pipes to the drinking water. Furthermore, metal fever that is flu-like condition is found in workers that are exposed to copper. Being exposed to copper for a long time also causes following chronic effects: nose irritation, mouth irritation, eyes irritation, headache, stomachache, dizziness, vomiting, and diarrhea. Likewise, with higher level of exposure, it causes liver damage and death. Industrial exposure to copper fume, dusts, or mists may cause fume fever and changes in nasal mucous membrane. For the chronic effects of this type of exposure it can cause Wilson's disease, brain damage, demyelization, renal disease, and copper deposition in cornea.

Copper cannot transport well in soil because it is strongly attached to the organic matter and minerals in the soil. In contrast, it travels for a long distance in surface waters in the form of suspended sludge and particles as free ions. Because Copper does not breakdown naturally in the environment, plants and animals accumulate it in their bodies by uptake from the soils. Most species of plants cannot survive in the Copper-rich soils, so it is a serious problem in farmland productions. However, Copper-containing manures are still used. Another issue about Copper is it interrupts soil activity by disturbing microorganisms and earthworms. Thus, organic matters are persistent and cannot be decomposed regularly.

2.6.3 Zinc (Zn)

Zinc has an aomic mass of 65.37 g/mol and density of 7.11 g/cm^3 at 20 ^{o}C. It is a lustrous bluish-white metal, brittle and crystalline at room temperature. The melting point of Zinc is 420 ^{o}C, while the boiling point is 907 ^{o}C. It is a fairly reactive metal that can combine with oxygen and other non-metals, and will react with dilute acid to release oxygen.

People use Zinc in iron galvanization, and some metal alloy preparation. It is also used as negative plates in electric batteries, parts of automobile, roofing, or even as a gutter in building construction. In the form

of zinc oxide, it is used as a pigment in water color or paints such as using in plastics, cosmetics, photocopier paper, wallpaper, printing inks. Furthermore, zinc oxide is used in rubber processing process as an activator or catalyst. Zinc metal is made as a tablet for dietary product because of the anti-oxidant properties which protect skin and muscles of the body from premature aging.

Zinc is a common substance that naturally occurs in the air, water and soil, and many foods contain certain amount of zinc. Zinc is present in drinking water and may be present in higher concentration if stored in metal tanks. In contrast, industrial sources or toxic waste sites may contaminate the drinking water with the excess amount of zinc, which causes health problems. Human activities such as industrial activities, mining, coal and waste combustion, steel processing are the sources that unnaturally add zinc to the environment; resulting in, soil contamination from mining area, or sewage sludge from the fertilizer industries. The main zinc mining areas are Canada, Russia, Australia, USA, and Peru. According to the world production, commercially exploited of zinc exceed 100 million tons a year.

Zinc is an essential element for human health, which zinc deficiency can cause loss of appetite, decrease sense of taste and smell, slow wound healing, skin sores, or the worst is birth defects. On the other side, exposure to the excess amount of zinc can cause health problems such as stomach cramps, skin irritation, vomiting, nausea, and anemia. With very high levels of zinc can damage pancreas, protein metabolism disturbance, and arteriosclerosis. In addition, respiratory disorders are caused by zinc chloride, and can be a danger to unborn or newborn child via milk and blood of their mothers.

World zinc's production is still increasing, which means that more zinc will be stored in the environment. The large amount of waste water from industrial plants pollutes the water with zinc because it is not purified well before the emission. Consequently, the water acidity is increased due to the zinc-polluted sludge. These problems also relate to the accumulation of zinc in fishes that live in the zinc contaminated water. They can bio-magnify zinc up the food chain. The soil media contains large amount of zinc if the farmland is polluted with zinc. The animals in that area will then absorb zinc leading to bad health effects, while water-soluble zinc in the soils can contaminate further to the groundwater. Plants, accumulate zinc from soils, in the polluted areas cannot handle their systems. Moreover, zinc-polluted soil can interrupt the activity of microorganisms and earthworms and affects their capability to biodegrade to the organic matters in soil.

2.6.4 Lead (Pb)

Lead, which has atomic mass of 207.2 g/mol and density of 11.34 g/cm^3 at 20^oC, is a bluish-white lustrous metal. The melting point of Lead is 327 ^oC, while the boiling point is 1755 ^oC. It has poor electrical conductivity, but very resistant to corrosion. It can be tarnish, if exposed to air.

In the past, it was used as an emblem for Roman emperor, in bath's drain, and alloys. Some grades of petrol (gasoline) still use Tetraethyl lead ($PbEt_4$) for fuel; however, it is being abolished. Lead is also used in car batteries, ceramic glazes coloring, candles. Moreover, it is traditionally used as electrodes in process in, radiation prevention in computer and television screen, sheeting, cables, solders, glassware, ammunitions or even weights in sport equipment. Lead, which is rare in nature, is usually found in ore with Zinc, Silver, and Copper. It is mined from cerrussite and anglesite in the form of lead compound (PbS). Australia is responsible for 19% of the world's lead production, followed by the USA, China, Peru and Canada. The world's new lead production is around 6 million tons a year and usable reserves are around 85 million tons, which is not sufficient for the next 15 years.

Human activities increase most of the Lead concentration in the environment, even though it is naturally occurring. As it is applied in gasoline, unnatural Lead-cycle has begun. Lead in car engines is burned and lead salts (chlorines, bromine, oxides) are generated. These salts are emitted to the environment from the exhaust of cars. While the larger particles drop to the ground and pollute the surface waters and soils, the smaller pollute the environment through air medium for a long distance and remain in the atmosphere. Then, the smaller particles settle back to the earth by rain. This lead-cycle from anthropogenic sources takes longer duration than natural lead-cycle, so lead pollution has been a worldwide issue.

Not only cables, pipelines, and metal production that uses lead as materials, but also paints and pesticides. It is one of the most toxic metals, which can damage human health. It enters human body via ingestion of food (65%), water (20%), and inhalation of air (15%); for instance, vegetables, meat, grains, seafood, soft drinks, wines are potential sources of dietary lead. Cigarette only emit small amount of lead to the air, while lead enter drinking water through corrosion of pipes when the pH of water decreases (higher acidity). Lead is not an essential element for human body and only causes harmful effects, like disruption of hemoglobin biosynthesis, anemia, increase in blood pressure, kidney damage, miscarriages, damage of nervous system,

brain damage, sperm damage, decrease in children ability, behavior disruption of children.

Leaded gasoline increases lead concentration in the environment, like other human activities such as fuel combustion, industrial processes and solid waste combustion. Lead that transport to water through pipe corrosion cannot be broken down since it only changes its form. When it pollutes the water medium, it causes bioaccumulation in aquatic organisms and it also accumulates in soil. This lead poisoning effects directly to phytoplankton, which is an important oxygen source. Due to their oxygen production in seas is disturbed, these affect the global balance and animals. Moreover, in soils and related organisms, their functions are interfered and it is more serious in highways and farmlands, where the concentration of lead is probably high. Due to the mentioned reasons, lead is considered as hazardous chemical. Moreover, it bio-accumulates and biomagnifies in the food chain.

2.6.5 Iron (Fe)

Iron, an element with atomic mass of 55.85 g/mol and density of 7.8 g/cm^3 at 20^oC, is a lustrous, ductile, malleable, silver-grey metal (group VIII in periodic table) with four different crystalline forms. The melting point of Lead is 1536 ^oC, while the boiling point is 2861 ^oC. Iron only rusts in humid air and dilute easily even in dilute acid. It is an active chemical that exists as two major forms, ferrous (bivalent iron (II)) and ferric (trivalent iron(III)).

Iron is produced worldwide and it is used the most compared to other metals. When combined to other metals, it provides high strength with low cost. As a result, world iron production is over 500 million tons a year, where the main iron mining areas locate in China, Brazil, Australia, Ukraine, USA, Canada, Venezuela, Sweden, and India. The most common application of iron is in food containers, vehicles, mechanical tools, staples, cargo ships, etc. We can also classify the forms of iron in to seven forms: pig iron, cast iron, carbon steel, wrought iron, alloy steels, and iron oxides. Iron is the most abundant element of each layers of the earth, which contributes around 34.6%. The earth's core consists of large amounts of iron-nickel alloy. Iron is usually found in the form of oxides such as minerals, hematite, magnetite, and taconite. This element is essential for living things, ranging from micro-organisms to humans.

In daily life, iron is found in meat, meal products, potatoes, and vegetables. In addition, the human body absorbs iron from animal products more than plant products. Hemoglobin or the red coloring agent of the blood needs iron as an essential part of it to regularly transport oxygen through our body. On the other hand, iron may cause conjunctivitis, choroiditis, and retinitis if it contacts and remains in tissues. Chronically, excessive inhalation of iron fume or dust can cause pneumoconiosis (siderosis), which is detectable by x-ray changes. However, no physical impairment of lung function has been associated with siderosis. It is found that excess inhalation of iron oxide may increase the risk of lung cancer in workers who are exposed to pulmonary carcinogens. Commonly, the only problem of iron for human is iron deficiency, which leads to anemia; however, a normal diet will generally provide all that is needed. Average daily intake is 7 mg and 11 mg for men and women respectively. In case of hemochromatosis patient, organs such as pancreas, spleen, heart and liver are damaged because of iron overdose (higher than 200 ppm). Water binary soluble compounds have toxic effects at concentrations above 200 mg and are lethal for adult humans concentrations of 10-50g.

Iron is an essential element for every organism and many natural processes in binary and tertiary form; however, oxidized tertiary form cannot be used by organisms freely, if it is at high pH value. Iron is normally present in water in an insoluble form. For adding soluble iron, productivity in oceanic surface layers is increased because of its role in carboncycle. Iron is also essential for nitrogen binding, nitrate reduction, and it is a limiting factor for phytoplankton growth. Still, iron is not likely to dissolve in saline water. Plants can be harmed at feed concentration ranging from 5 to 200 ppm, provided by microorganisms and water saturated soil. Iron compounds are much more dangerous than elemental iron. In terms of LD_{50} value for oral intake of rats: iron(III) acetonate has a value of 1872 mg/kg, iron(II) chloride has a value of 984 mg/kg, and iron pentacarbonyl has a value of 25 mg/kg. The most hazardous form of iron to the environment is Iron (III)-O-arsenite that specially affects plants, contaminates air and water. As per the above mentioned reason, it is strictly recommended to prevent iron from eating the environment as it persistence.

2.7 Heavy metal standards

Atmospheric pollution due to PM has currently become a serious environmental issue. PM also contains several kinds of hazardous substances especially heavy metals, which human can be exposed through inhalation as a major pathway. These toxic substances cause a wide range of harmful health effects and diseases particularly cardiovascular and respiratory diseases. According to these hazardous chemicals pollution, some organizations are taking actions in chemical exposure level regulation and standards for safety.

In general, regulations or guidelines for chemical substances including heavy metal levels have been set in different standards depending on organizations. Occupational Safety and Health Administration (OSHA), a part of the United States Department of Labor, was established to guarantee better health and safety of working men and women. This standard was set and enforced from training, education, outreach, and assistance (United States Department of Labor, 2019). Likely, The National Institute for Occupational Safety and Health (NIOSH) cooperated with OSHA, intends to promote industrial hygiene information to workers, employers and occupational health professionals with recommended health and safety standards which help users recognize and control occupational chemical hazards. NIOSH documents recommend workplace exposure limits and appropriate preventive measures to prevent and reduce the adverse health effects and accidental injuries (Centers of Disease Control and Prevention, 2019). Another organization involved with the chemical substances standards is American Conference of Governmental Industrial Hygienists (ACGIH®) that is a well-respected organization for a decade in industrial hygiene and occupational and environmental health and safety industry (ACGIH, 2019). OSHA has reported the regulatory limits in OSHA Permissible Exposure Limits (PELs) which are 8-hour time weighted averages (TWAs) and California Division of Occupational Safety and Health Permissible Exposure Limits (Cal/OSHA PELs) that covers for California jurisdiction. Similar to OSHA, ACGIH® Threshold Limit Values (TLVs®) listed up to 8-hour time weighted averages (TWAs) including STEL (Short-term Exposure Limit) and C (Ceiling) values. While the NIOSH recommended limits were set in Recommended Exposure Limit (RELs) from the NIOSH Pocket Guide to Chemical Hazards that are for 10-hour time weighted averages (TWAs) during a 40-hour work per week.

Table 2.3 Heavy metal standards of OSHA, NIOSH, and ACGIH

Heavy metal	CAS No.	Regulatory Limits		Recommended Limits	
		OSHA (PEL)	Cal/OSHA (PEL) 8-hour TWA	NIOSH (REL) 10-hour TWA	ACGIH (TLV) 8-hour TWA
Cd	7440-43-9	-	0.005 mg/m^3	-	0.01 mg/m^3 (tot.) 0.002 mg/m^3 (resp.)
Cu	7440-50-8	0.1 mg/m^3 (fume)	0.1 mg/m^3	0.1 mg/m^3	0.2 mg/m^3
		1 mg/m^3 (dust, mist)	1 mg/m^3	1 mg/m^3	1 mg/m^3
Fe	1309-37-1	10 mg/m^3 (fume)	5 mg/m^3 (fume)	5 mg/m^3 (dust, fume)	5 mg/m^3 (resp.)
Pb	7439-92-1	-	0.05 mg/m^3	0.05 mg/m^3	0.05 mg/m^3
Zn	1314-13-2	-	5 mg/m^3 10 mg/m^3 (ST)	5 mg/m^3 10 mg/m^3 (ST)	2 mg/m^3 (resp.) 10 mg/m^3 (resp.) (ST)

ST = Short-term Exposure Limits (STEL)

2.8 Literature review

Jinsart *et al.* (2011) studied the particle air pollution, namely $PM_{2.5}$ and $PM_{10,}$ at roadside areas in Bangkok. By focusing in high polluted areas (busy intersection and average 70,000 vehicles/day) and low polluted areas (suburban area and average 40,000 vehicles/day), they found that most high polluted areas exceeded the National Ambient Air Quality Standards (NAAQS). Moreover, the correlation coefficient of $PM_{2.5}$ and PM_{10} in high polluted areas were related to automobile sources. With their measurements it can be concluded automobile exhaust was the main source of particulate air pollution. They recommended that the existing monitoring procedures and standards need to be revised to include specific measurements of fine particles such as $PM_{2.5}$.

Tran Huong Giang and Thi Kim Oanh (2014) characterized roadside levels of $PM_{2.5}$ and BTEX in Ho Chi Minh City, Vietnam. Residential areas and business activities are found along the heavy traffic roads, and air pollutants are emitted more when there are traffic jams. Samples were collected during both weekends and weekdays including 284 hourly BTEX samples, twenty-four 8-hr samples $PM_{2.5}$ and forty-two 24-hr $PM_{2.5}$ samples using Mini-volume air sampler. There were eight sampling points on both side of the street that has average traffic flow. The results showed that 24-hr $PM_{2.5}$ on weekdays was higher than weekends. By using Principal component analysis, the association between roadside pollution levels and traffic were confirmed. At roadside, urban background, other sources than traffic in the street, was removed by calculation algorithm. The main urban background pollutants were $PM_{2.5}$ (90- 98%) and BTEX (67- 97%) influenced by upwind side of the street and at late evening hours when less traffic was observed. Monitoring at different times also required in this study to get significant variations in the street traffic composition.

Lawrence, Sokhi, and Ravindra (2016) research was quantification of vehicle fleet PM_{10} particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques. High Volume, Dichotomous Stacked Filter Unit, and Partisol Air Sampler were used to sample, and it was found out that their volumes were not significantly different (p = 95%). The research revealed that $PM_{2.5}$ contributed 66% of PM_{10} proportion and was significantly related to traffic and meteorological

condition. Furthermore, PM_{10} mass emission factors responsible for Motorcycle (0.0003-0.001 mg/vkm), Cars (26.1-33.4 mg/vkm), LDVs (2.4-3.0 mg/vkm), HDVs (2.2-2.8 mg/vkm), and Buses (0.1 mg/vkm). According to (Lawrence *et al*., 2013), sources apportionment modeling in PM_{10} was brake wears (3.8-4.4 mg/vkm), petrol exhaust (3.9-4.5 mg/vkm), diesel exhaust (7.2-8.3 mg/vkm), re-suspension (9-10.4 mg/vkm), road surface wear (3.9-4.5 mg/vkm), and unexplained (7.2 mg/vkm). This could be concluded that the major emission was diesel exhaust and re-suspension; however, combined exhaust emission factor (11.1-12.8 mg/vkm) was lower than combined non-exhaust emission factor (16.7-19.3 mg/vkm). This research suggested that non-exhaust source was a significant emission sources compared to exhaust emission.

Qi-Li Dai *et al.*(2015) studied in the topic of characterization and source identification of heavy metals in ambient PM_{10} and $PM_{2.5}$ in an integrated iron and steel industry zone compared with a background site. $PM_{2.5}$ and PM_{10} were collected at iron and steel industry zone and back ground site. Then the twelve heavy metals (As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Ti, V, and Zn) were characterized using ICP-MS and it was found out that the dominant element was Fe followed by Zn and Pb. All species of the heavy metal showed higher concentration at industry zone than background site. Many heavy metal showed high correlation coefficient particularly in Fe-Zn. This research also concluded from the results of principle component analysis that main source of heavy metal was steel dust emission from coal combustion, coal-fired power plant, coke making, and steel making emission. Vehicle emission, road emission and soil dust emission are also significant sources of heavy metals. The steel dust possibly influenced the background site according to the heavy metal concentration.

Lawrence *et al*. (2013) identified the source apportionment of traffic emissions of particulate matter using tunnel method measurements to quantify exhaust and non-exhaust emissions at Hatfield Tunnel in United Kingdom. The tunnel provided adequate distance to for sampling and acted as an ideal location for sampling road traffic emissions since the dispersion in the tunnel was limited. Samples were collected, using high volume (HiVol) and Partisol air sampler for PM_{10} and Dichotomous stacked filter for $PM_{2.5}$, at the entrance and the exit of the tunnel for five weeks, November to December. ICP-AES was used to analyze heavy metals composition, while GC-MS was used to analyze organic compositions of PM_{10}. The results showed good correlation

between Fe, Cu, Mn, Ni, Pb, and Sb. In addition, polycyclic aromatic hydrocarbon and other organics significantly found at the entrance and the exit of the tunnel. PM_{10} mass was identified the emission source using Principal Component Analysis and Multiple Linear Regression Analysis that contributed to re-suspension (27%), diesel exhaust emission (21%), petrol exhaust emission (12%), brake wears emissions (11%), and road surface wears (11%) concluding that harmful chemical components originated from non-exhaust sources.

Santoso, et al. (2012) researched on Characterization of airborne particulate matter collected at Jakarta roadside of an arterial road. Gent stacked filter unit sampler was used to collect airborne particulate matter samples. The annual particulate matter (PM) both fine particles with diameter less than 2.5 um ($PM_{2.5}$) and diameter ranging between 2.5 to 10 μm (PM_{10}). In addition, mass concentration, black carbon and elemental concentration were also investigated to assess air quality in these roadside areas. By using source apportionment and proton induced X-ray emission (PIXE), the significant factors from the sources and elemental analysis were determined respectively. These factors consisted of soil (9.2 %), construction mixed with road dust (20.9 %), biomass burning mixed with seasalt (30.9 %), industry (7.5%), and motor vehicles (31.5 %), which are the main sources of PM. For the first factor, it had high concentrations in Al, Si, Ca, Ti, and Fe which were the main components in soil and were regarded as soil dust. The second factor was contributed with high concentration of Ca, Mg, K, and Pb that were generated by construction dust and contained high S from diesel vehicles used in road construction. Next factor was motor vehicles which includes high S and black carbon caused by low fuel quality. Biomass burning emission generated high carbonaceous and K, while the last factor generates high Zn from non-ferrous metal industry. With these emission issues, there should be attempts to reduce anthropogenic sources to successfully improve the air quality.

Shaojie *et al.* (2012) characterized chemicals of size-resolved $PM_{2.5}$ at roadside environment in Beijing, China. The size-resolved were in three ranges (0.2-0.5 μm, 0.5-1.0 μm, 1.0-2.5 μm) and they were collected at the roadside site during Olympic game 2008. The data determined PM mass, 14 elements (Ca, Mg, Al, Si, Ti, Fe, Mn, Na, K, Br, Cl, Cu, Z, Pb), 3 major inorganic ions (NH_4^+, NO_3^-, and SO_4^{2-}), and carbonaceous species. This study suggested that PM mass and chemical species were influenced by emission sources and meteorological data. The main contributors of $PM_{2.5}$ were crustal

sources, vehicle emissions, secondary aerosol formation together with coal combustion, biomass burning, and industrial processes, with vehicle emissions affecting more at roadside than urban areas. Particulate matter in the range of 0.5-1.0 μm was mostly resulted from secondary aerosol formation, while particulate matter in the range of 0.2-0.5 μm and some elements (Br, Cl, Pb, and Zn) were resulted from combustion heating sources. Moreover, the temporary heavy-duty truck control measures during the Olympic showed different results on different emission sources and chemical species. For construction dust, Ca decreased the most (80.9 %), and the chemical species related to vehicle emissions and re-suspended road dust (Al, Si, Mg, Cu, Zn, NO_3^-) decreased by 60-70 %.

Ondracek *et al*. (2011) studied the contribution of the road traffic to air pollution at busy speedways and suburban crossroads in Prague, which differed in traffic intensity. They found that, from size distribution, the ultrafine particles (diameter < 0.1 μm) were generated from traffic area. These traffic particles were divided in 2 types, one at 25-30 nm emitted from direct exhaust emissions and the nucleation of low volatility vapors and the other one at 0.06-0.07 μm from the coagulation of fine particles. The accumulation mode particles (0.1-1.0 μm) were mainly from background aerosol origin, and the coarse particles (> 1 μm) were also mainly from background aerosol including the construction works at the crossroad. Moreover, particles with 2.5 um diameters were termed as traffic related, which corresponded to brake and tire abrasion, abrasion of road surface and tire, and re-suspension of aerosol particles from road surface and tire abrasion. For elemental composition, most of the major elements were coarse particles. They included Fe, Cu, Mn, and Zn, which were emitted mainly from brake abrasion or mechanical abrasion of engine parts. The re-suspended particles included Si, Al, K, and Ca. K particles were emitted mainly from long range transport and Ca particles were emitted mainly from construction work taking place at crossroad. In conclusion, the $PM_{2.5}$ concentrations of total carbon concentration (TC) decreases with decreasing traffic intensity, which is mainly caused by decreasing of elemental concentration (EC) and proved with the comparison of EC/OC (organic carbon concentration) value.

Daniele *et al.* (2012) studied the comparison of PM_{10} concentration and metal content in three different sites of Venice Lagoon that focuses on analysis of possible aerosol sources. In the selected sites, mobile dams that connected the lagoon were being constructed and this construction work can

represent additional sources of pollutants. The composition of major and trace inorganic elements in particulate matter was divided into natural and anthropogenic emissions. The natural emission included Na, Mg, K, Ca, Si and Al, while anthropogenic emissions included V, Cr, Mn, Ni, Cu, Zn, Cd and Pb. For anthropogenic emissions, fossil fuel combustion was a main source of particulate matter (PM). Cu-Zn would have originated from traffic emission from diesel (Cu) and tire wear (Zn), or from road dust.

Vijayanand et al. (2008) assessed heavy metal contents in the ambient air of the city of Coimbatore in India. By collecting suspended particulate matter (SPM), they found that industrialization and urbanization are the two major causes of the decreasing ambient air quality. Their samples were analyzed for their heavy metal content, including the concentrations of seven heavy metals, which were Zn, Fe, Cu, Pb, Ni, Cr and Cd. They are particulate inorganic pollutants released to the atmosphere and transported through wind-blown dust. Heavy metals were considered to be released from metallurgical process, garbage incineration, combustion of fossil fuels, weathering of rocks, mining activities, etc. Furthermore, many studies in occupation and community setting have reported that accumulation of heavy metals via exposure through inhalation or ingestion can cause various adverse health effects; for example, cancer, neurotoxicity, immunotoxicity, and cardiotoxicity. In conclusion, they found that urban area had high levels of SPM and detected 6 heavy metals, excluding Cd. This study also requires further action that implements the monitoring of air quality to control air pollution, educating the industrialist to adapt their pollution control, and bring awareness among the common public to support strategies of air pollution abatement.

Abah *et al.* (2014) surveyed the levels of heavy metals from roadside dust along Katima Mulio Urban road construction in Namibia. Most significant environmental problems that release heavy metals are caused by anthropogenic activities such as urban road construction, quarrying, agriculture, waste incineration, sewage disposal, automobile workshop and bush burning. The presence of heavy metals also indicated the contamination of soil, sediments and dust in environment. Their accumulations were attributed by vehicle exhausts, industrial discharge, automobile parts, atmospheric deposition, particulate emission, etc. Another significant source of heavy metal contamination is gravels import because of different kinds of gravels that are imported from different quarry sites that are enriched with

various heavy metals. The results of this study revealed the significant presence of As, Pb, Cr, Cd, Co, Cu, Ni, Mn, V, Fe and Sn in the roadside dust along with contribution by construction. Although heavy metal contamination levels are not high, people who traverse along the roadside or are living near this area are exposed to potentially contaminant-bearing dust through inhalation, dermal contact, and ingestion. Because children have higher absorption rate of heavy metals intake, they are more vulnerable than adults. These heavy metals are human carcinogens and they are related to anthropogenic activities. Thus, this study suggested that environmental impact assessments should be carried out on road construction and mitigation strategies like water spraying should be implemented to reduce the heavy metal contamination of roadside dust.

CHAPTER III
METHODOLOGY

3.1 Site description

3.1.1 Study area and sampling sites

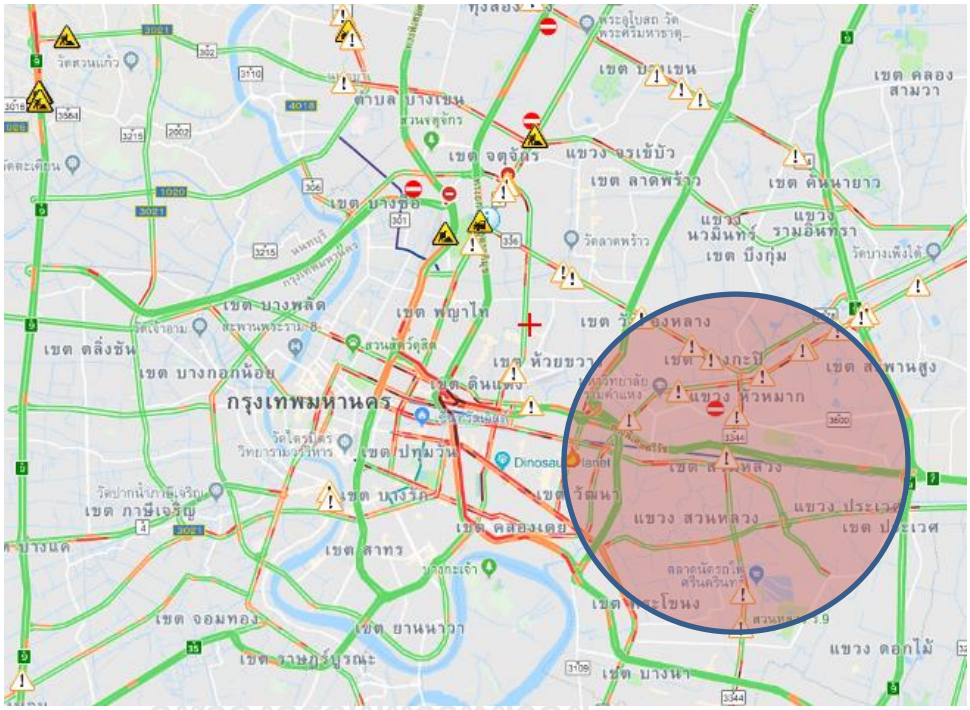


Figure 3.1 Location of study area including construction sites and events (https://map.longdo.com/)

The study area is located in Bangkok, covering an area of 1568.7 km^2 of the city in the middle part of Thailand. It lies in the areas of Suanluang district and Bangkapi district, where Pattanakarn Road intersects with Srinagarindra Road (Fig. 3.1). Both Pattanakarn Road and Srinagarindra Road have high traffic volumes and are crowded with commuters, especially during rush hour. The Pattanakarn-Ramkamhaeng Tunnel construction project of the Department of Public Work was initiated on 21 April 2016. Construction took a long time, and has been postponed several times (the deadline was October 2018). This project also worsened traffic by cutting off lanes of the road, creating a bottleneck with only two lanes available to traffic. Traffic jams coupled with construction in the area caused air pollution in the area to

increase significantly. This primarily impact affects venders and people who live near the road. In case of Srinagarindra Road, the construction project is the MRT yellow line (Ladpraw-Samrong), and a part of which pass through Srinagarindra Road. This under construction site is located along the road that runs from the Pattanakarn junction to Udomsuk junction.

Figure 3.2 The on-road construction sites at (left) Srinagarindra road and (right) Pattanakarn

Similar to the Pattanakarn construction site, one lane between traffic in both directions of Srinagarindra Road is cut off (Fig. 3.2). Consequently, the traffic is congested and therefore the vehicles on the road emit more air pollutants. Additionally, these construction areas are located near two famous shopping plazas, where many people go for shopping, dining, business activities, and so forth.

Pattanakarn Road and Srinagarindra Road (RS) were selected as sampling sites. Both sites are located in areas with overcrowded traffic and on-road construction sites along the traffic isle of these roads. At Pattanakarn Road, there is an ongoing underground road tunnel construction site that starts working at 7 am until 7 pm. When construction at this site is taking place, the two lanes are cut off from 4 lanes of the road. The traffic flow is slower (high traffic congestion) with the two lanes of the road available to traffic, thereby exacerbating vehicular emissions. Furthermore, emission from construction sites, including combustion of engines, machine for construction, drilling and

reconstruction of road pavement, generate dust over the roadside and nearby residential areas. Like Pattanakarn Road, Srinagarindra Road is another sampling site with ongoing construction along this road. Thus, high levels of air pollutants emitted due to overcrowded traffic and the Srinagarindra Road construction project are considered to be a source of air pollution.

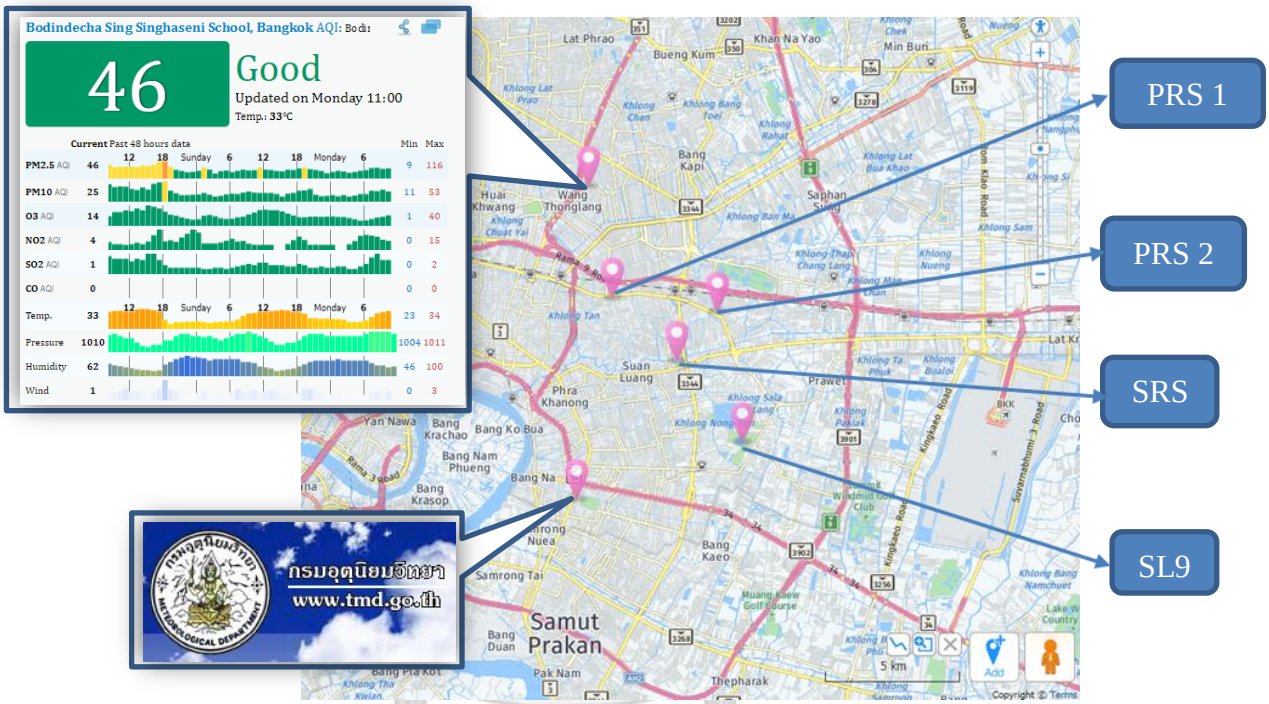


Figure 3.3 Location of sampling sites, Pollution Control Department, and Thai Meteorological Department (https://map.longdo.com/?locale=en)

In this study, the $PM_{2.5}$ and PM_{10} data from the Pollution Control Department's ambient air monitoring station were compared with three roadside $PM_{2.5}$ and PM_{10} data. The PCD monitoring station shown in Fig. 3.3 is located on Soi Ramkamhang 43/1, near Bodindecha (Sing Singhaseni) School (13.7694, 100.6147). Likewise, meteorological data was obtained from Bangna Agromet monitoring station (13.6678, 100.6052) of Thai Meteorological Department (TMD) due to the shortest distance between the weather monitoring station and the sampling sites. According to the map shown in Fig. 3.3, it is located to the south of the sampling sites.

3.1.1.1) Pattanakarn Road

The Pattanakarn sampling point 1 (PRS 1) is located along Pattanakarn Road at the footpath of Pattanakarn 30 (13.736250, 100.618339), and Pattanakarn sampling point 2 (PRS 2) is located along the same road divided with the Pattanakarn junction (13.731724, 100.650801) (Fig. 3.4). The lanes were closed with a row of bunkers because of construction activities at PRS 1, causing traffic congestion (Fig. 3.5). The construction activities in this area were part of road surface demolitions and tunnel drilling (up to 3-4 m). In contrast, PRS 2 sampling area had no road construction activity and was only influenced by crowded traffic (Fig. 3.6). Sampling points PRS 1 and PRS 2 are 3.78 km and 5.66 km, respectively, away from the nearest PCD monitoring station (61t). PRS 1 and PRS 2 were 3.46 km apart from each other. Thus, PRS 1 was characterized as roadside construction and traffic congestion site with the buildings in this area act as an semi-covered area. While, PRS 2 represented the only traffic congestion site in the same road condition.

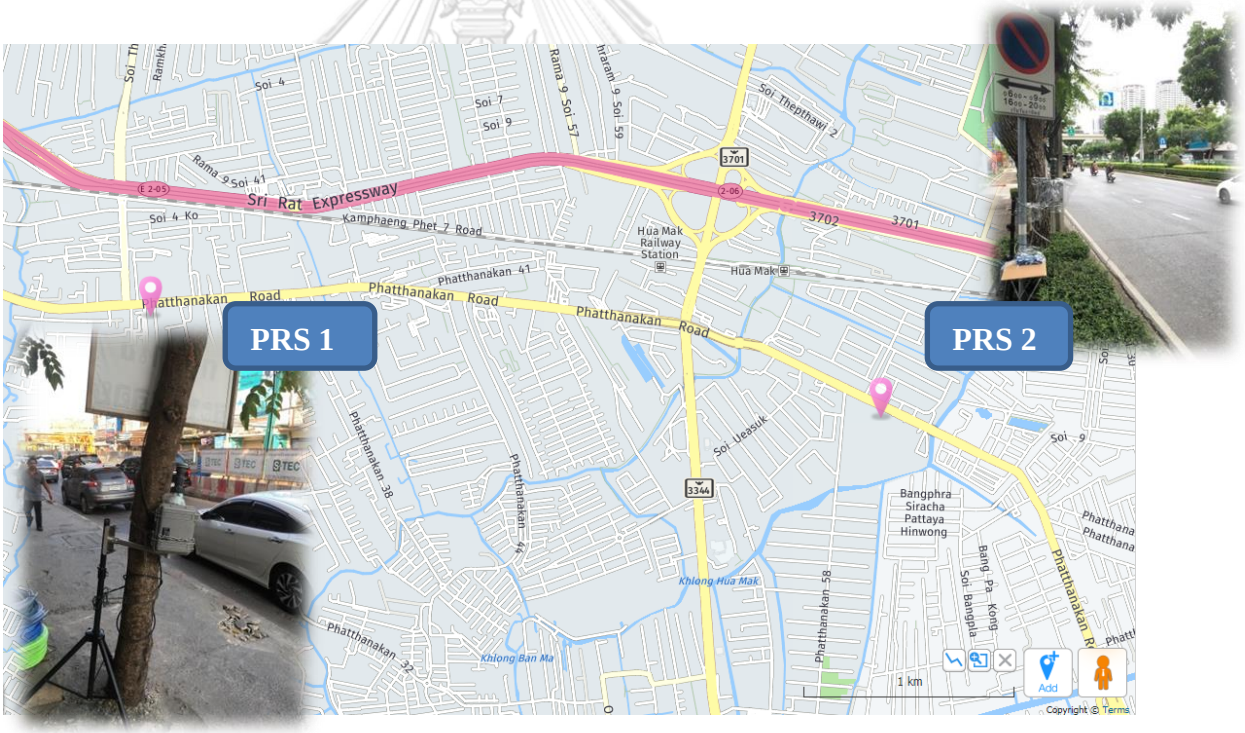


Figure 3.4 Sampling point of Pattanakarn road side 1 (PRS 1), and Pattanakarn road side 2 (PRS 2)

Figure 3.5 Pattanakarn road side sampling area at PRS 1 (source:https://www.google.com/maps/@13.7364232,100.6179208,3a,75y,281.91h,83.38t/data=!3m6!1e1!3m4!1s_-xjEbIQYCEK_O0rZXGeEw!2e0!7i13312!8i6656)

Figure 3.6 Pattanakarn road side sampling area at PRS 2 (source:https://www.google.com/maps/@13.7313621,100.6514042,3a,75y,131.45h,84.19t/data=!3m6!1e1!3m4!1svsJKAjOLmoiDIV6NQVr4yA!2e0!7i13312!8i6656)

3.1.1.2) Srinagarindra Road (Srinuch conjunction)

The Srinagarindra Road (SRS) sampling site is located at Srinuch junction, next to the police station on the corner of the road junction (13.712989, 100.643315) (Fig. 3.7). The sampling point was at the road junction near a market, with many pedestrians commuting during rush hour. The major road consists of eight lanes road crossed with another road. When construction activities (road pavement demolition) for the MRT project started, two lanes of this major road were cut off (Fig. 3.8). This sampling point is 6.95 km away from the PCD monitoring station. To be concluded, this site represented as the road construction and traffic congestion area with a wider road.

Figure 3.7 Sampling point of Srinagarindra road side (SRS)

Figure 3.8 Srinagarindra sampling area at SRS
(source:https://www.google.com/maps/@13.7127965,100.6436425,3a,75y,7.07h,84.28t/data=!3m6!1e1!3m4!1sYJ6sHHbt53P0JSksgPjULw!2e0!7i13312!8i6656)

3.1.1.3) Suanluang Rama IX Park (background site)

Suanluang Rama IX Park (13.688555, 100.664088), a large green space within the city, has many types of gardens and many kinds of canopies (Fig. 3.9). A lot of people visit this park, especially during the weekends, for its clean air and because it is a suitable place for exercising and working out. It was selected as a background site as the sampling point is located in the middle of the park measuring 800,000 m^2. This park has only a small car parking zone and with no pollution impacts from road traffic. This sampling site is around 3-5 km away from the other sampling sites and 10.29 km away from the PCD monitoring station (Fig. 3.10). Accordingly, this site was not affected by road construction and traffic congestion.

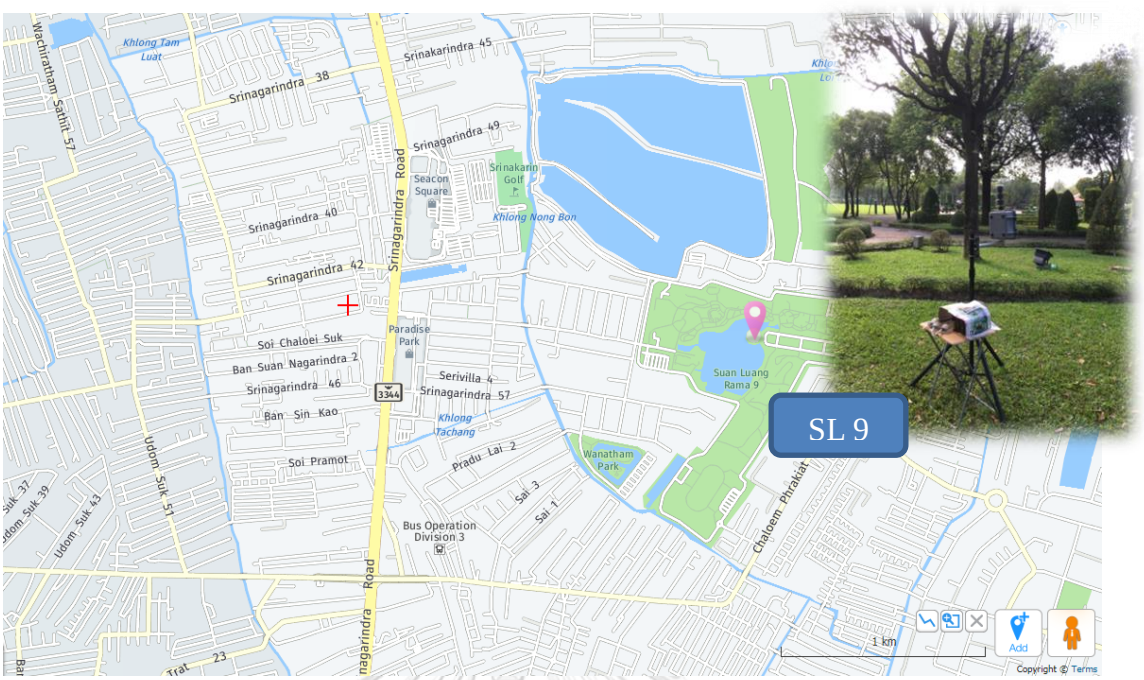


Figure 3.9 Suan Luang Rama IX sampling area at SL 9 (source:https://www.google.com/maps/@13.6894633,100.6651032,2a,75y,182.9h,84.14t/data=!3m6!1e1!3m4!1sjdrvUfrLfIL0Lx43RSmR5A!2e0!7i13312!8i6656)

Figure 3.10 Sampling point of Suang luang Rama IX (SL 9)

3.2 Sampling duration

The samples were collected for 12 hours a day for 5 days from each sampling area. In each sampling area includes 3 weekdays and 2 weekends. The samples were collected in winter (dry season), which considered to be a worst case scenario, from November to December 2018.

3.3 $PM_{2.5}$ and PM_{10} measurement

3.3.1 Measurement equipment

- Microbalance with seven decimals (UMX2, Mettler-Toledo, Mettler-Toledo International Inc, USA)
- Personal measurement pump (224-XR, SKC Inc., USA)
- Mini-volume Air Sampler or MiniVol™ TAS
- Whatman® PTFE 46.2 mm filter
- Dorr-Oliver cyclone air sampler
- Glass fiber filter GA-55 (ADVANTEC®)
- Video recorder
- Desiccator
- Cyclone jar calibrator
- Bubble flow meter
- MiniVol™ calibrator flow meter

3.3.2 Sampling

3.3.2.1) Tapered element oscillating microbalance (TEOM)

A tapered element oscillating microbalance (Fig. 16) is used by the Thai Pollution Control Department for air quality monitoring, and this method has been approved by the United State Environmental Protection Agency (U.S. EPA). The United States Mine Safety and Health Administration has also approved this method for coal dust monitoring in coal mines to determine exposure of miners and protect them from several respiratory diseases.

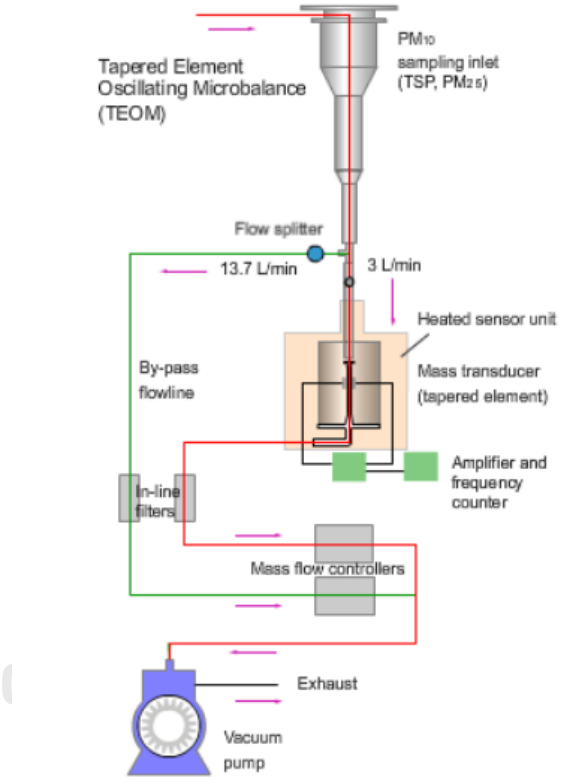


Figure 3.11 The operation and assembly of Tapered Element Oscillating Microbalance (TOEM) instrument.

A TEOM can continuously measure air particle concentrations. This device has a size-selective inlet, allowing sampling of total suspended particulates (TSPs), particles measuring less than 10 micrometers in diameter (PM_{10}), and particles measuring less than 2.5 micrometers in diameter ($PM_{2.5}$). Figure 3.11 illustrates the operation and basic principle of a TEOM. First, samples are drawn into the instrument by the pump at a flow rate of 16.7 L/min; samples pass through an inlet that is designed to allow only specific

size ranges to pass. Then, this air stream is split and a fraction of the sample is directed to a tapered element at 3 L/min, while the remaining fraction is sent to the exhaust. On the tip of a hollow glass tube, a filter cartridge of the tapered element is attached. The tip freely vibrates at its natural frequency, while its base is fixed. After that, the tube oscillates as the frequency changes depending on any additional weight from the particles collected on the filter. An electric circuit sensor detects these changes and calculates the particle mass rate from the frequency changes. Next, the instrument returns to its natural frequency and is ready for the next measurement. The instrument reduces noise by electronically smoothing its reading, and maintaining a constant temperature and flow rate. By dividing the mass rate with flow rate, output of particle mass concentration is determined continuously. The filter on this instrument does not need to be changed as frequently as with other air samplers; as a result, an analyzer can provide additional information such as time of day when the peak of concentration occurs. Furthermore, possible sources of particle emissions can be identified using this instrument with meteorological data (Queensland Government, 2018).

3.3.2.2) $PM_{2.5}$ sampling (MiniVol™)

Figure 3.12 Mini-volume air sampler
(source:https://geneq.com/environment/en/product/airmetrics/air-sampler-minivol-574)

A mini-volume air sampler or MiniVol™ TAS, manufactured by Airmetrics (Fig. 3.12) was used for sampling particulate matter ($PM_{2.5}$, PM_{10}, and Total Suspended Particles). Results from this device are as accurate as the data from Federal Reference Method. This device is ideal for remote areas and temporary sites because it is lightweight and portable.

Although the MiniVol™ portable air sampler can be used to collect $PM_{2.5}$, PM_{10}, and TSP samples, it can measure only one type of particulate matter at a time. The pump of the MiniVol™ draws air at a flow rate of 5 L/min through a 47 mm filter into a particle size separator, which separates particles into 2.5 micron and 10 micron fractions. In order to collect the TSP sample, the impactor needs to be removed. The operation of the device starts when the particulate sample is trapped on the filter, which must be weighed pre- and post-exposure using a microbalance with an accuracy of one microgram. The samples are then determined in unit of microgram/cubic meter ($\mu g/m^3$). This instrument has a battery that can perform continuously for 24 hours and is programmable with 7-day timer. Before it is operated, the instrument should be calibrated to make sure that the sampler has an ambient flow rate of 5 L/min. This calibration method uses differing air temperatures and atmospheric pressures based on elevation and seasonal changes (Airmetrics, 2018).

Before installation of the MiniVol™, it was calibrated with a flow meter set to adjust the actual flow rate to 5 L/min and Whatman® PTFE 46.2 mm filters were used as the sampling filter paper. The MiniVol™ was installed on a footpath 1.5 m above the ground and 3 m away from the nearest lane of the road. The set points of the flow rates, dates, and sampling durations were recorded before and after the measurement. Then, continuous measurements were made for 12 hours using the air sampler. After measurement, the air sampler was turned off and the filter was kept in its cassette. Subsequently, the filter with collected sample was stored in a desiccator for 24 hours to remove humidity, and was weighed to determine the final weight. The concentration of $PM_{2.5}$ was calculated using the PM concentration equation.

3.3.2.3) PM_{10} sampling (Cyclone Air sampler)

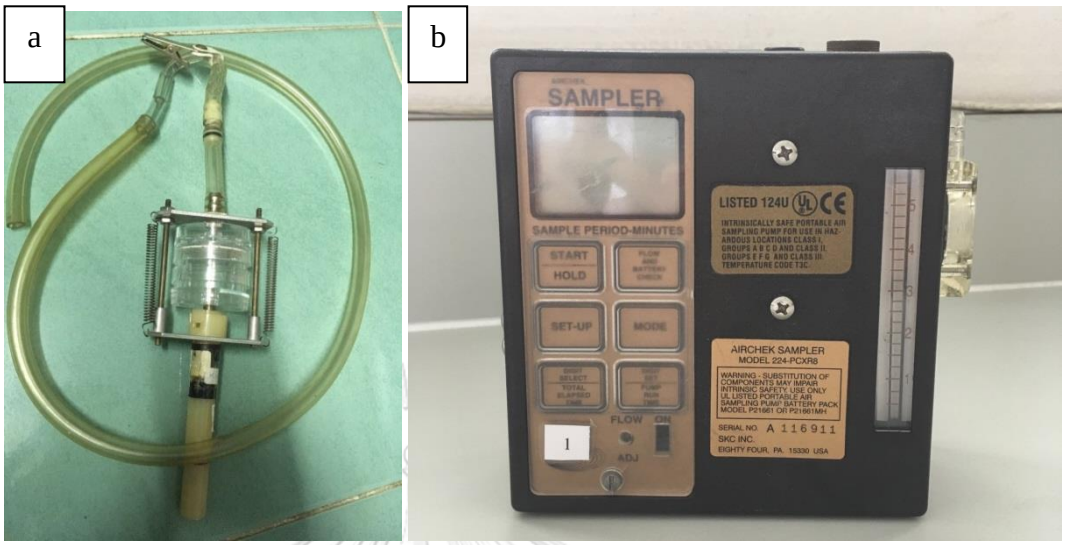


Figure 3.13 (a) Dorr-Oliver Cyclone air sampler, (b) SKC Inc. pump

A Dorr-Oliver cyclone air sampler or Nylon cyclone (Fig. 3.13) is designed to separate inhalable particles allowing it to be collected on a filter cassette. The air passing through this instrument is circulated within its chamber as a cyclone, like in centrifugation. Such rapid circulation separates particles according to their aerodynamic diameters; larger particles fall into grit pot, while small particles are whirled up and collected on the filter. This cyclone air sampler can be used to separate large particles and non-respirable particles from small particles and respirable particles. The Dorr-Oliver type cyclone is assembled with a SKC pump at a specific sampling flow rate of 1.7 L/min to achieve the desired cut-point (SKC Inc, 2018).

The flow rate of the cyclone air sampler was calibrated using the SKC air pump and a bubble flow meter every time before sampling. Air pump flow rate were recorded pre-sampling and post-sampling, and were averaged to represent the actual flow rate after using. The cyclone sampling head was cleaned after it was used to remove residual dust from the chamber. The cyclone air sampler was set at a flow rate of 1.7 L/min and samples were collected for 12 hours using a glass fiber filter GA-55 (ADVANTEC®). The collected filters were placed in cassettes and then stored in a desiccator to protect them from humidity. Finally, they were weighed and the PM_{10} concentration was calculated.

3.4 Sample analysis

3.4.1) PM2.5 and PM10 quantitative Analysis

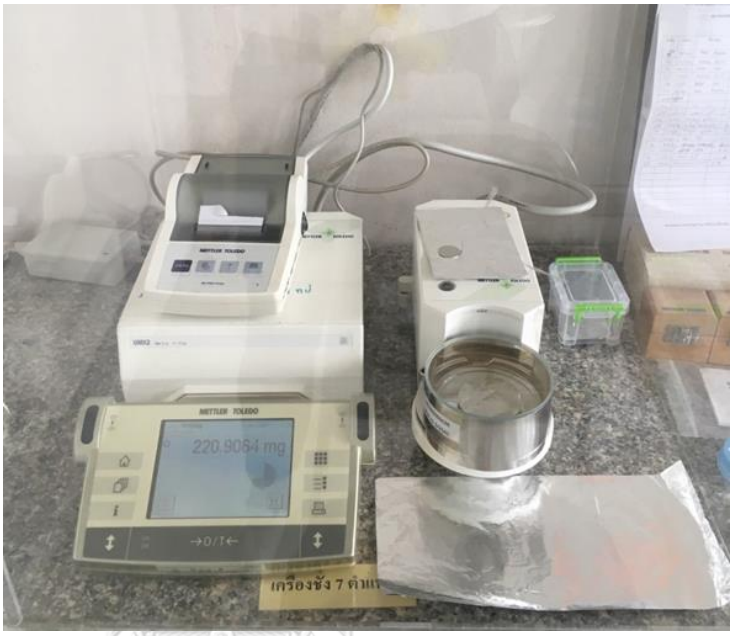


Figure 3.14 Ultra-microbalance in the controlled ambient condition room

Sampling filter papers were prepared by storing them in a humidity-controlled chamber for 24 hours prior to use to remove moisture. Subsequently, they were stored in cassettes when they were moved to the sampling area. The collected samples were also placed in the cassettes after sampling, and then stored in the humidity control chamber for 24 hours. After the collected samples were prepared, $PM_{2.5}$ and PM_{10} mass were determined via a gravimetric method using a UMX2® ultra-microbalance (Mettler Toledo: Columbus, OH) (Fig. 3.14), which can weigh up to seven decimal points, by covering with an aluminum sheet to ensure weight stability. This was conducted in the Environmental Science laboratory of Chulalongkorn University under controlled ambient condition.

3.4.2) $PM_{2.5}$ and PM_{10} concentration

After the collected samples were stored in a desiccator, $PM_{2.5}$ and PM_{10} mass were determined using a gravimetric method with an UMX2® ultra-microbalance (Mettler Toledo: Columbus, OH), which can weigh up to seven decimals, under temperature and humidity controlled conditions. The concentrations of $PM_{2.5}$ and PM_{10} were then calculated using equation 1:

$$C = \frac{w_f - w_i}{V} \times 10^3 \qquad (1)$$

Where; C = concentration of particulate matter ($\mu g/m^3$)

W_f = filter weight after sampling (mg)

W_i = filter weight before sampling (mg)

V = air volume (m^3)

Air volume (V) is calculated using equation 2:

$$V = Q \times T \times 10^{-3} \qquad (2)$$

Where; V = air volume (m^3)

Q = air flow rate (L/min)

T = sampling time (min)

The calculated concentrations are 12-hour average values and represent 1-day average concentration. After that, they are converted to 5-day average values to represent concentrations in each sampling area (n = 5), on weekdays and weekends.

3.4.3) Heavy metals digestion

Heavy metals were extracted from $PM_{2.5}$ and PM_{10} samples using a microwave digester (Milestone, ETHOS SEL) and following EPA 3052 method.

Figure 3.15 Microwave digester (Milestone, ETHOS SEL)

The samples were collected on filter papers, which were cut into small pieces. Subsequently, they were placed in a Teflon vessel and stored in a vacuum hood. After that, 10 mL HNO_3 (65%) was added to the vessel and then the vessel was closed tightly. Next, the vessels were packed and placed in microwave digester (Fig. 3.15), which was operated at 180^{o}C and 1000 W for 20 minutes. After the digestion process, the packed vessels were left in the digester for an exhaustion and cooled down to room temperature. They were then unpacked and the digested residuals were filtered using No. 5 filter papers into 25 mL volumetric flasks so that they are ready to be analyzed as liquid phase. The volume of liquid in the volumetric flask was adjusted with deionized water (18MΩ).

3.4.4) Heavy metal analysis

A Graphite Furnace Atomic Absorption Spectrometer (GFAAS) (PinAAcle™ 900 Series of AA Spectrometers, PerkinElmer®), at a laboratory of Salaya Central Instrument Facility, Mahidol University, was used to analyze and quantify heavy metal concentrations (Fig. 3.16). The graphite furnace, which is an electro-thermal atomizer, was heated high to 3000^{o}C to break the chemical bonds in the graphite tube and produce free ground state atoms. The atoms absorb light energy, and are elevated to an excited state. The concentration of elements increases as the amount of light energy absorbed increases. While a Flame Atomic Absorption Spectrometer can analyze only solution, a Graphite Furnace AAS can analyze small quantities of solution, slurry, and solid samples. The operation of the GFAAS comprises four main stages: Drying, Pyrolysis, Atomization, and Cleaning. Characteristic concentration or sensitivity is defined as the concentration of element required to produce a signal of 1% absorption or 0.0044 absorption. Thus, the heavy metal concentrations are determined using a calibration curve plotted from the standard solution concentrations and absorbance.

Figure 3.16 Graphite Furnace Atomic Absorption Spectrometry (The PinAAcle™ 900 Serie of AA Spectrometers, PerkinElmer®).

The prepared samples were analyzed using element lamps with an auto sampler; each sample (20 µL) was analyzed thrice. The light source lamp had to be warmed up before starting the sampling process. The sampling head was also flushed for cleanliness, fine accuracy, and standard solution. The calibration curve was prepared on the day of the run. Accordingly, series of standard solutions were prepared to obtain heavy metal calibration curves at the following concentrations:

Cd: 0.01, 0.1, 0.25, 0.5, 1.0 (mg/L)

Cu: 1.25, 2.5, 5.0, 12.5, 25.0 (µg/L)

Fe: 0.04, 0.1, 0.5, 1.0, 3.0 (mg/L)

Pb: 2.5, 5.0, 10.0, 25.0, 50.0 (µg/L)

Zn: 0.006, 0.01, 0.1, 0.25, 0.75 (mg/L)

The conditions of analysis including calibration equation, wavelength, slit width, lamp current, and optimum working range are reported in Table. 3.1. Mean, standard deviation, and %RSD of the analysis were auto calculated.

Table 3.1 Heavy metal condition in analysis of Graphite Furnace Atomic Absorption Spectrometry

Analyte	**Calibration Equation Mode**	**Wavelength (nm)**	**Slit Width (nm)**	**Lamp Current (mA)**	**Optimum Working Range**
Cd	Linear Through 0	228.80	0.7	230	0.01 - 1.0 mg/L
Cu	Linear Through 0	324.75	0.7	15	1.25 - 25.0 µg/L
Fe	Linear Through 0	248.33	0.2	30	0.04 - 3.0 mg/L
Pb	Linear Through 0	283.31	0.7	440	2.5 - 50.0 µg/L
Zn	Linear Through 0	213.86	0.7	15	0.006 - 0.75 mg/L

3.4.5) Heavy metal concentration

After the Graphite Furnace Atomic Absorption Spectrometer was used to analyze the extracted samples in 25 mL volumetric flasks for heavy metals (including Cd, Cu, Fe, Pb, and Zn), heavy metal concentration was calculated using the following equation.

$$C = \frac{conc. \times 25 \times 10^{-6}}{w} \qquad (3)$$

C = heavy metal concentration in PM, (mg heavy metal/mg PM)

conc. = heavy metal concentration determined via Graphite Furnace Atomic Absorption Spectrometry (GFAAS; µg/L)

w = amount of PM (mg)

The obtained heavy metal concentration was averaged over 5 days for each of the sampling site as a profile and compared among the sampling sites. Moreover, the correlation between PM and heavy metal, and correlation between each element were determined using IBM SPSS Statistics 22 program based on these data.

3.4.6) Limit of Detection (LOD)

Limit of Detection (LOD) can be termed as Instrumental Detection Limit (IDL), Method Detection Limit (MDL) or Minimum Detectable Level (MDL). LOD is defined as the lowest concentration of an analyte in a sample that can be detected; however, it is not necessary to quantitate under the stated condition of the test. It can also be defined as the concentration of analyte that can produce a signal that is significantly different from that of the negative control or blank. The sample blank method was used to identify the LOD value. The blank for each element was prepared appropriately depending on the working range of analysis. The prepared blank sample was then analyzed

and repeated seven times using the GFAAS. The LOD can be calculated using the following equation

$$LOD = \bar{x} + 3s \quad (1)$$

$\bar{x}$ = average concentration of blank sample

s = standard deviation of blank sample

3.4.4) Limit of Quantification (LOQ)

Limit of Quantification (LOQ) is the lowest concentration of analyte in a sample that can be quantified with acceptable precision and accuracy under the stated condition of the test. The blank samples were used in the same batch with LOD samples and they were repeated the quantification for 7 times in total. LOQ can be calculated using this following equation.

$$LOQ = \bar{x} + 10s \quad (2)$$

$\bar{x}$ = average concentration of the blank sample

s = standard deviation of the blank sample

3.4.7) Traffic data

Traffic data was obtained using a video camera that was set on record for 12 hours a day, concurrently during the PM sampling period. These data were recorded on weekdays and weekends. Subsequently, traffic data were quantified and calculated with the recorded video and reported as traffic flow for 12 h/day.

3.4.8) Statistical analysis

T-test for comparing means ($p < 0.05$ significance) was used to analyze the differences between $PM_{2.5}$, PM_{10}, and heavy metal concentration data collected from areas affected by construction activities and background areas. The spearman's rank correlation was also used to determine the correlation between the concentrations of each species of heavy metal (both $p < 0.05$ and $p < 0.01$) using IBM SPSS Statistics 22 program. The analyzed correlation coefficient values (r) were interpreted using the following criterion.

r^2	Correlation coefficient, r	Interpretation
0.0000 - 0.0625	0.00 - 0.25	No or weak relationship
0.0625 - 0.2500	0.25 - 0.50	Fair degree of relationship
0.2500 - 0.5625	0.50 - 0.75	Moderate to good relationship
0.5625 - 1.0000	0.75 - 1.00	Good to strong relationship

CHAPTER IV
RESULT AND DISCUSSION

4.1 Limit of detection (LOD) and Limit of quantification (LOQ)

Limit of detection (LOD) and Limit of quantification (LOQ) were analyzed with blank samples using a GFAAS. The mean and standard deviation values of LOD and LOQ were calculated using the equation in chapter 2 from the quantified concentrations of samples. The correlation coefficient of the calibration curve (r^2), LOD, and LOQ of selected heavy metal species are reported in Table 4.1.

Table 4.1 Quality control of heavy metal analysis from the calibration curves prepared using GFAAS

Element	Equation	r^2	LOD (ppb)	LOQ (ppb)
Cd	$y = 0.424x + (4 \times 10^{-5})$	0.9992	1.976	19.921
Cu	$y = 0.003x - (3 \times 10^{-5})$	0.9995	0.612	1.392
Fe	$y = 0.002x + (2 \times 10^{-4})$	0.9994	9.966	71.219
Pb	$y = 0.002x + (2 \times 10^{-5})$	0.9996	2.376	6.991
Zn	$y = 0.504x + (4 \times 10^{-5})$	0.9997	6.490	21.300

4.2 $PM_{2.5}$ and PM_{10} concentration

$PM_{2.5}$ and PM_{10} were sampled at four different areas: construction activity affected area (PRS 1 and SRS), traffic affected area (PRS 2), and background area (SL 9). Sampling was performed continuously for 5 days at each sampling site and data from the PCD obtained during the same sampling period was used. The calculated PM concentrations are listed in Table 4.2. The $PM_{2.5}$ concentrations at PRS 1, PRS 2, SRS, and SL 9 were in the ranges of 31.65 - 49.21 µg/m^3, 21.69 - 37.03 µg/m^3, 21.33 - 44.69 µg/m^3, and 13.46 - 22.50 µg/m^3 respectively. The highest $PM_{2.5}$ concentration was recorded at

PRS 1; however, concentrations at PRS 1, PRS 2, and SRS were not much different as all these sites were affected by traffic congestion. Concentrations at SL 9 was the lowest and were markedly different from concentrations at the other sampling sites because it was a background site with no influence from traffic emissions.

Table 4.2 Daily $PM_{2.5}$, $PM_{2.5-10}$, and PM_{10} concentrations at different sampling sites.

Site	Date	Measured (µg/m^3)			PCD (µg/m^3)		
		$PM_{2.5}$	$PM_{2.5-10}$	PM_{10}	$PM_{2.5}$	$PM_{2.5-10}$	PM_{10}
PRS 1	13/11/2018	32.07	20.67	52.74	32.77	10.23	43.00
	15/11/2018	44.97	19.58	64.55	36.77	15.23	52.00
	16/11/2018	49.21	5.52	54.73	23.92	15.08	39.00
	17/11/2018	43.85	16.35	60.20	22.46	6.54	29.00
	18/11/2018	31.65	5.32	36.97	34.23	2.77	37.00
PRS 2	21/11/2018	39.91	4.42	44.33	26.62	16.38	43.00
	22/11/2018	43.90	11.44	55.34	32.09	9.91	42.00
	23/11/2018	38.21	6.62	44.83	19.00	25.00	44.00
	24/11/2018	21.69	18.19	39.89	24.31	8.69	33.00
	25/11/2018	37.03	22.93	59.96	31.42	14.58	46.00
SRS	27/11/2018	44.14	17.09	61.22	28.38	15.62	44.00
	29/11/2018	44.69	18.65	63.34	31.00	11.00	42.00
	30/11/2018	30.54	28.76	59.30	35.00	15.00	50.00
	1/12/2018	29.48	22.93	52.41	43.00	21.00	64.00
	2/12/2018	21.33	24.36	45.68	30.00	14.00	44.00

SL 9	4/12/2018	18.84	9.22	28.06	32.00	26.00	58.00
	6/12/2018	16.76	10.82	27.58	28.60	13.40	42.00
	7/12/2018	22.50	10.88	33.38	27.00	28.00	55.00
	8/12/2018	13.46	4.02	17.49	21.00	8.15	29.15
	9/12/2018	14.84	15.27	30.11	24.00	9.38	33.38

The ranges of PM_{10} concentration at PRS 1, PRS 2, SRS, and SL 9 were 36.97 – 64.55 µg/m^3, 39.89 – 59.96 µg/m^3, 45.68 – 63.34 µg/m^3, and 17.49 – 33.38 µg/m^3 respectively. The highest PM_{10} concentration was found at SRS followed by concentrations at PRS 1 and PRS 2. Similar to the $PM_{2.5}$ concentration trend, concentration at SL 9 was the lowest. Further, the construction activity affected area had the highest $PM_{2.5}$ concentration. When the daily PM concentration was compared with PCD, all measured PM concentrations were higher than those recorded by the PCD monitoring station except PM concentration recorded at SL 9 (control site).

The average $\%PM_{2.5}$ in PM_{10} was 75.8% at PRS 1, 74.1% at PRS 2, 59.4% at SRS, and 49.3% at SL 9. The high $\%PM_{2.5}$ values at PRS 1 and PRS 2 suggest that PM composition at these sites were more strongly influenced by traffic than that at PRS 2 and SL 9 as traffic flow at PRS 1 and PRS 2 is slower (high traffic congestion) and $PM_{2.5}$ is primarily emitted from combustion in vehicle engines during heavy traffic conditions. Similarly, (Lawrence, Sokhi et al., 2016) observed a similar trend of PM contribution as they found about 66% of $PM_{2.5}$ fraction that greater than coarse particle in PM_{10}. On the other hand, $\%PM_{2.5}$ in PM_{10} from SRS implies that construction activities in this area influenced PM_{10} composition more than at other sampling areas. This is similar to the study by (Harrison, Tilling et al., 2003), who they found that PM_{10} mass was composed of 68% of PM fraction. In general, fine particles are associated with combustion sources and secondary particles, which are attributable to exhaust emissions, while coarse particles primarily originate from non-exhaust or crustal sources. Moreover, these results suggest that coarse and fine particles are influenced by traffic volume and meteorological parameters.

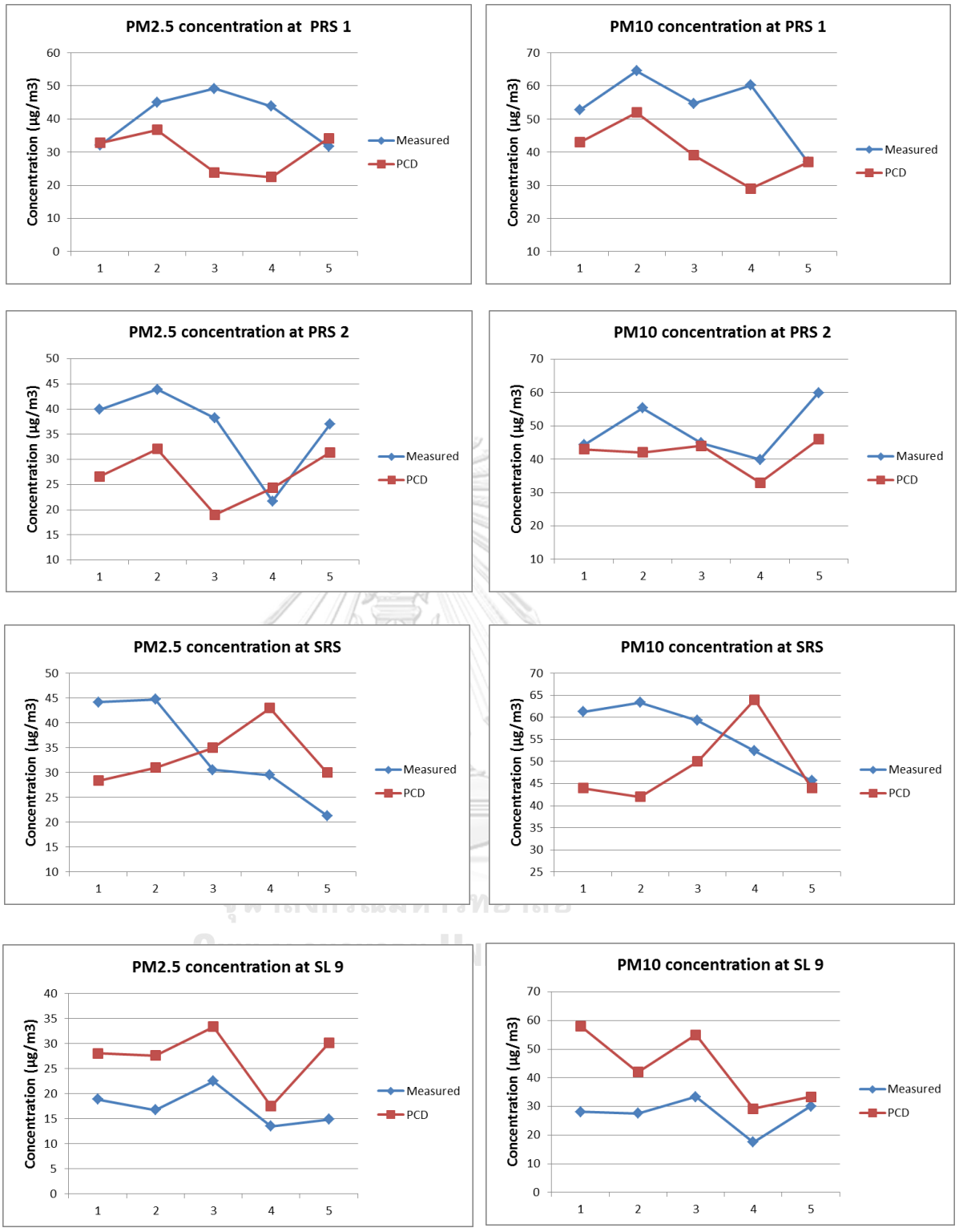


Figure 4.1 Comparison of measured $PM_{2.5}$ and PM_{10} concentrations and concentration recorded by PCD at PRS 1 (a and b), PRS 2 (c and d),SRS (e and f), and SL 9 (g and h)

In Fig. 4.1, the measured $PM_{2.5}$ and PM_{10} concentrations were plotted as a graph of daily concentration against PCD concentration data. This PCD monitoring station is the nearest station to the sampling points. Concentrations at PRS 2 and SL 9 showed a similar direction to that at PCD, implying that PM concentration at the sites the sites were only influenced by traffic conditions. Conversely, PRS 1 and SRS, which are affected by construction activities, showed a somewhat different concentration direction than that at PCD. This difference in data might be due to the additional construction activities along the roads, which in turn may have influenced measured PM concentrations.

4.3 Concentrations of $PM_{2.5}$ and PM_{10} at various sampling areas ($\mu g/m^3$)

$PM_{2.5}$ and PM_{10} concentrations at each sampling area were averaged over 5 days as presented in Table 4.3. In addition, PCD data from Bodindecha Singhaseni monitoring station (61t), which monitors ambient air quality is reported in this table. The highest measured $PM_{2.5}$ concentration (40.35 ± 8.0 $\mu g/m^3$) was measured at PRS 1 in the traffic congested area with construction activities. This was followed by traffic congested area PRS 2 (36.15 ± 8.49 $\mu g/m^3$) and SRS (34.04 ± 10.13 $\mu g/m^3$), while the lowest concentration was obtained at the background site SL 9 (17.28 ± 3.55 $\mu g/m^3$), which was not affected traffic congestion or construction activities. $PM_{2.5}$ is a traffic related pollutant; engines along the roadside emit $PM_{2.5}$ into the air

Table 4.3 Comparison of $PM_{2.5}$ and PM_{10} concentration with PCD data at four sampling areas

Site	$PM_{2.5}$		PM_{10}		$PM_{2.5}$: PM_{10}	
	Measured	**PCD**	**Measured**	**PCD**	**Measured**	**PCD**
Traffic and Construction						
PRS 1	40.35 ± 8.00	30.03 ± 6.43	53.84 ± 10.51	40.00 ± 8.43	0.749	0.751
SRS	34.03 ± 10.13	33.48 ± 5.86	56.39 ± 7.26	48.80 ± 9.01	0.603	0.686
Traffic						
PRS 2	36.15 ± 8.49	26.69 ± 5.39	48.87 ± 8.40	41.60 ± 5.03	0.740	0.642
Background						
SL 9	17.28 ± 3.55	26.52 ± 4.23	27.32 ± 5.95	43.51 ± 12.78	0.633	0.610

(Chuersuwan, Nimrat et al., 2008; Santoso, Lestiani et al., 2012; Chart-Asa and Gibson, 2015). Traffic congestion causes more frequent braking and acceleration of vehicles (Xie and Davy, 2014). PM_{10} concentrations recorded at SRS (56.39 ± 7.26 μg/m^3) and PRS 1 (53.84 ± 10.51 μg/m^3), which are sites influenced by traffic congestion and construction activities, were higher than those recorded at traffic congested area PRS 2 (48.87 ± 8.40 μg/m^3), while the lowest concentration was recorded in SL 9 (27.32 ± 5.95 μg/m^3) at the back ground site. Traffic congestion that is not the only major source of PM_{10}; road construction activities are also an important factor causing increase in PM_{10} (Ahmed and Arocho, 2019). According to the EPA, construction dust has higher proportion of PM_{10} than $PM_{2.5}$, and is primarily composed of coarse particles. Furthermore, road dust re-suspension and background aerosol from construction activities generate coarse particles. Construction activities also lead to traffic congestion. Source specific PM_{10} emission factors are brake wears, petrol exhaust, road surface wear, and especially diesel-exhaust and re-suspension dust (Lawrence, Sokhi et al., 2016). In another study (Ondráček, Schwarz et al., 2011), also reported that re-suspended road dust and

construction aerosols generate coarse particles, resulting in the higher PM_{10} concentrations in construction affected area than in traffic congested area. This implies that increasing of PM_{10} at construction area is the additional concentration of PM_{10} level.

The ratio of $PM_{2.5}$ to PM_{10} concentrations at the different sampling areas was calculated (as shown in Table 4.3) to determine the proportion $PM_{2.5}$ accumulated in PM_{10} (ratio of fine particles to coarse particles); this ratio could also be used to define the possible sources of $PM_{2.5}$ and PM_{10}. High ratios of $PM_{2.5}$ to PM_{10} were observed at PRS 1 (0.749; the traffic congested construction area), and at PRS 2 (0.740; the traffic congested area). These results indicate that the proportion of $PM_{2.5}$ was higher than that of $PM_{2.5\text{-}10}$ in traffic congested areas, where $PM_{2.5}$ emission is dominant. Further,(Jinsart, Tamura et al., 2002; Kozáková, Pokorná et al., 2017) found that more than 70% of the PM_{10} fraction were fine particles. In addition, the ratio of fine particle to coarse particle in high traffic areas was higher than in low traffic areas. Thus, it can be concluded that fine particles in high traffic areas of Bangkok are more attributable to vehicular emission than to soil dust. At PRS 1, the construction area, 2-3 lanes of the road were closed causing slower traffic flow than at PRS 2. The ratio of $PM_{2.5}$ to PM_{10} was slightly lower at SRS (0.603), which was affected by traffic and construction activities. This suggests that the higher proportion of coarse particle is due to construction activities. A similar finding was reported by (Faber, Drewnick et al., 2015) who found that earth works (excavation and traffic on unpaved roads) and road works (asphalt sawing, smashing, soil compacting, and asphalt paving) were the important sources of PM_{10} in the environment. SRS sampling area also has higher traffic flow than PRS 1 and PRS 2, implying that this site was primarily impacted by construction aerosols. In the control area (SL 9), which is a park with no traffic and construction activities, $PM_{2.5}$ was slightly higher than PM_{10}. This might be becuase $PM_{2.5}$ originated from the parking lots and the park's tram.

Table 4.4 Measured $PM_{2.5}$ and PM_{10} concentration ($\mu g/m^3$) comparison with WHO and Thai PCD standard values.

Site	$PM_{2.5}$	PM_{10}
Traffic and Construction		
PRS 1	40.35 ± 8.00	53.84 ± 10.51
SRS	34.03 ± 10.13	56.39 ± 7.26
Traffic		
PRS 2	36.15 ± 8.49	48.87 ± 8.40
Background		
SL 9	17.28 ± 3.55	27.32 ± 5.95
WHO	25	50
PCD	50	120

The average measured PM concentration at the construction sites except the control site exceeded the 24-hour $PM_{2.5}$ and PM_{10} standard of WHO (25 $\mu g/m^3$ and 50 $\mu g/m^3$ respectively) (Table 4.4). Moreover, based on the EPA's air quality categories, the measured $PM_{2.5}$ values can be categorized as poor to very poor for the construction sites and fair for the background site. The average measured PM_{10} values were categorized as poor for the construction areas, and good for the control area. In contrast, the average measured $PM_{2.5}$ and PM_{10} concentrations do not exceed the standard limits established by the Thai PCD, due to the higher upper limit value. However, compliance with the WHO standard should be prioritized as it is relevant to human health.

4.4 A association between PM2.5 and PM10 levels and traffic condition

$PM_{2.5}$ and PM_{10} concentrations were plotted according to the sampling date (which included three week days and two weekend days for each sampling area (Fig. 4.2). The traffic flow data collected on the same date as PM sampling is presented as a line in this graph (Table A3, Appendix). The graph is divided in four sections depending on the sampling area. $PM_{2.5}$ and PM_{10} concentrations are presented in a stacked bar graph, with $PM_{2.5}$ (blue) and $PM_{2.5-10}$ (red) representing total PM_{10}. In the first section (PRS 1), the traffic flow on weekdays and weekend days are not very different, while PM_{10} concentration tended to be lower on weekend days. This could be explained by the construction at PRS 1, where the road was shut down, creating a bottleneck (narrow road). Thus, traffic condition on week days was similar to that on weekend days. At PRS 2, the traffic congested site, a reverse relation was observed between traffic flow and $PM_{2.5}$ and PM_{10} levels. If the traffic flow decreases, PM concentration increases. Similar to (Pandian, Gokhale et al., 2009), they discovered that an increasing of traffic flows after the delayed moment of vehicle increased the emission. The same reverse trend was observed at SRS; as a result, this sampling site also showed high PM concentration. Furthermore, the construction activities at the middle of the road was a significant factor contributing to elevated PM_{10} concentration at this site (Faber, Drewnick et al., 2015). The last section (SL 9) representing the background site showed the lowest concentration amongst all the sampling sites. This implies that the low PM concentration at this site is because it is a park, which is about 10 km away from pollution sources and less affected by construction activities and traffic. $PM_{2.5}$ and traffic flow (n = 15) were found to be inverse correlated ($r^2 = -0.479$), which can be confirmed by the fact that traffic pollution decreases when traffic flow increases. The correlation between PM_{10} and traffic flow (n = 15) was in contrary relationship ($r^2 = -0.082$), but the results are not significant (see Table A1, A2 in Appendix).

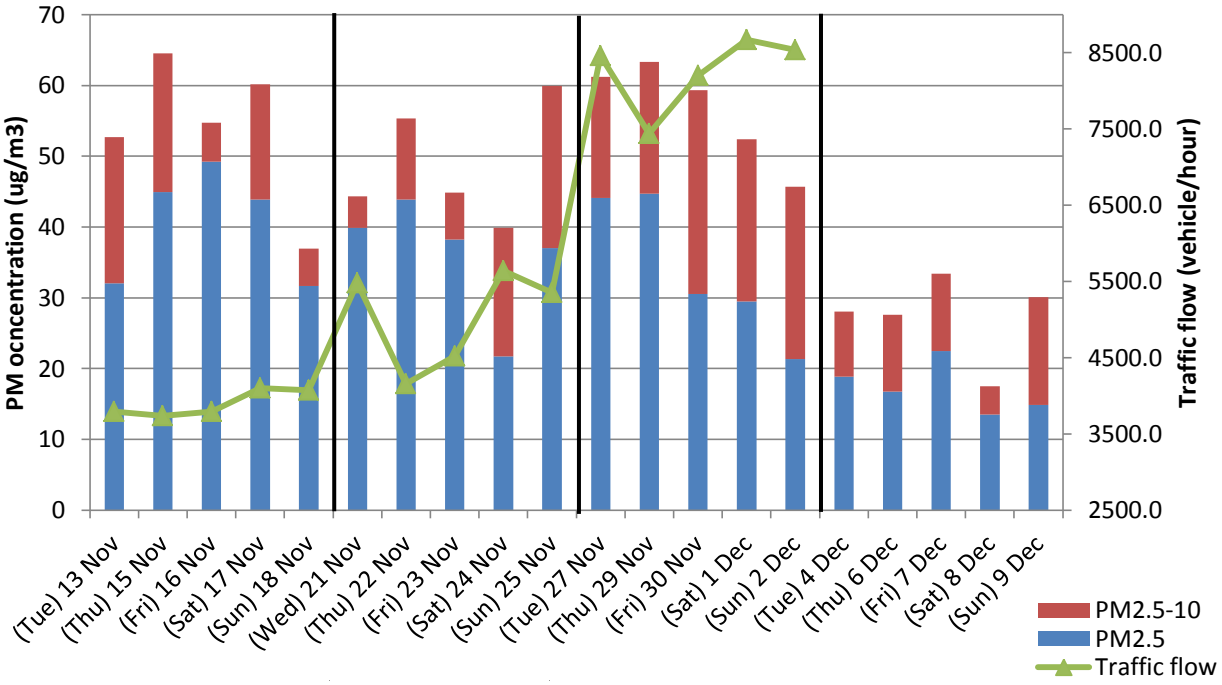


Figure 4.2 Measured $PM_{2.5}$ and PM_{10} concentration at four sampling sites during November 2018 to December 2018. Traffic flow is indicated by the green trend line.

It was presumed that the variance and inaccuracy in the result for PM_{10} was due to construction dust, which is a considerable determinant. This graph also suggests that the higher proportion of $PM_{2.5-10}$ (coarse particles) at PRS 1 and SRS (construction site) than at PRS 2 (traffic site) is due to the additional coarse particles generated from construction activities. This is supported by the finding of (Jung, Kang et al., 2019) that high amount of PM_{10} were emitted from construction works. Further, the PM concentrations were not influenced from the other affecting factors in this study (wind speeds, humidity, and temperature) since the recorded values were not different from each sampling areas. This is related to the urban structure in (Narut, Kraichat et al., 2016) who found that the covered area trapped more pollutants than the open area. Similar to this study, where the sampling area was cover with building and act as semi-confined area. They also found that, in covered area, there were weak or no correlation between affecting factors and PM concentrations.

4.5 Concentrations of heavy metals in $PM_{2.5}$ and PM_{10}

Heavy metal concentrations including Cd, Cu, Fe, Pb, and Zn were plotted according to sampling date as a stacked bar graph with traffic flow line. Each of stacked represented each species of heavy metal and it was found that the largest proportion were Zn and Fe. Referred to those of which in PM2.5, the concentrations were found to be high in PRS 1 and SRS which are the construction and traffic congestion area. Moreover, it was found that in PM10, the accumulation of heavy metal was higher than PM2.5. Low heavy metal concentrations in both PM2.5 and PM10, compared to the other sites were observed at SL 9. Although the traffic flow in SRS was higher in PRS 1, the concentration of PM2.5 in PRS 1 was higher than SRS only in some days. Moreover, the heavy metals in PM10, at SRS where the traffic flow was higher, showed not much different in concentration than PRS 1. This pattern suggested unclear relation between traffic flow and heavy metal concentrations in PM2.5 and PM10, and the heavy metal concentrations was influenced by construction activities more than traffic condition.

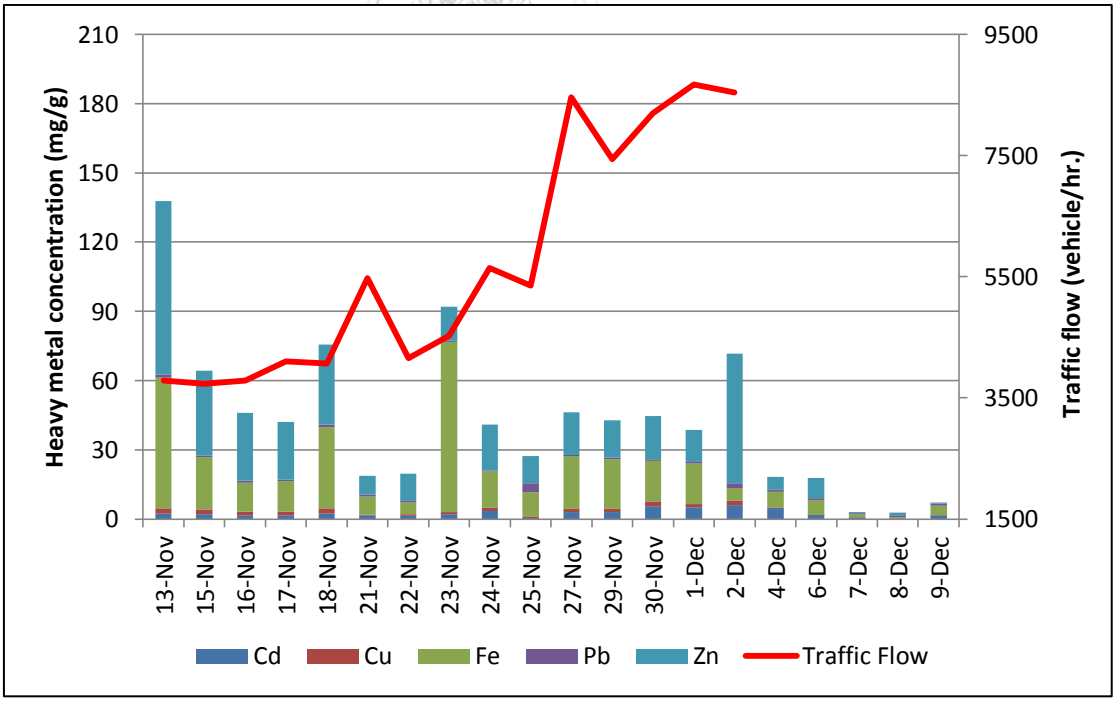


Figure 4.3 Heavy metal concentrations (mg/g) in $PM_{2.5}$ plotted with traffic flow line

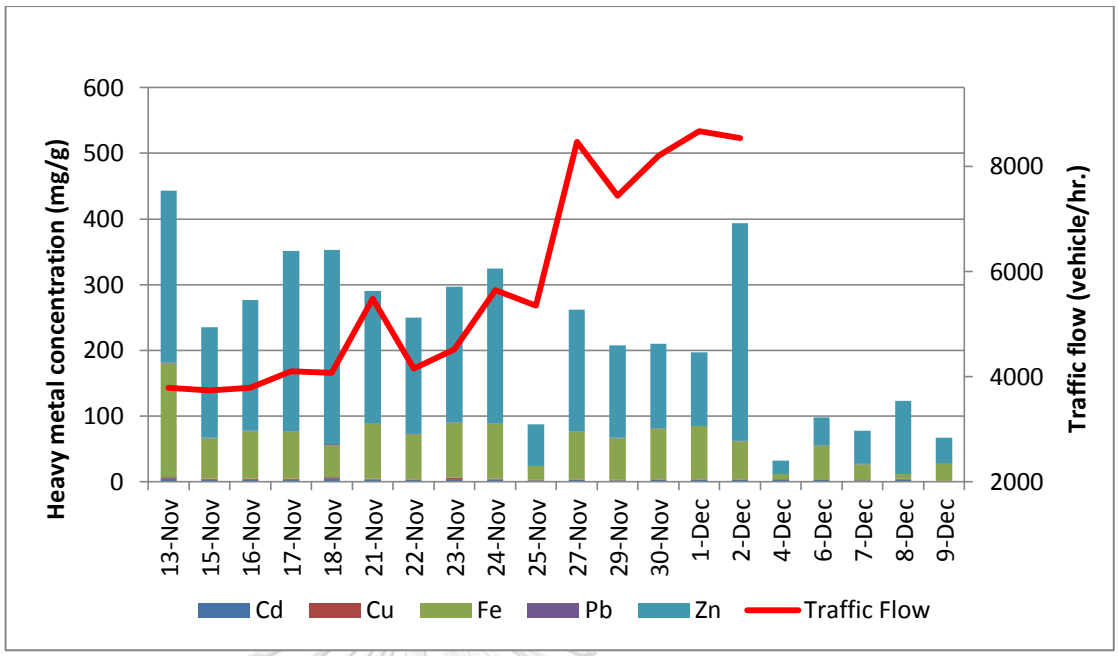


Figure 4.4 Heavy metal concentrations (mg/g) in PM_{10} plotted with traffic flow line

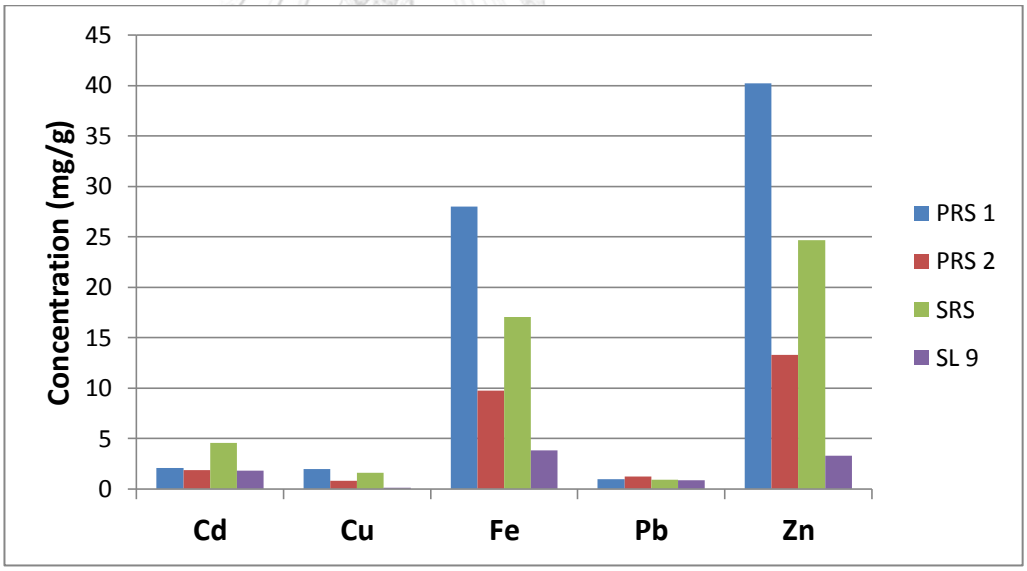


Figure 4.5 Comparison of heavy metals concentrations (mg/g) in $PM_{2.5}$ from the four sampling sites

The graph in Fig 4.3 presents the mean heavy metal concentrations (mg/g): Cadmium (Cd), Copper (Cu), Iron (Fe), Lead (Pb), and Zinc (Zn). They were determined in roadside $PM_{2.5}$ dust at Pattanakarn roadside (PRS) and Srinagarindra roadside (SRS), which are areas with road construction activities, and at Suangluang Rama IX Park (SL 9), which is a control area. As

shown in the graph, the dominant elements were Zn and Fe, accounting for approximately 47% and 42%, respectively, of the total elements. The high concentrations of Zn and Fe are obviously different from those of the other metals. Zn concentration was the highest (40.23 ± 20.03 mg/g) at Pattanakarn roadside 1 (PRS 1), road construction area, while the lowest concentration (3.28 ± 3.72 mg/g) was recorded at Suanluang Rama IX Park (SL 9), which is the control area. Similarly, the highest Fe concentration (27.98 ± 18.47 mg/g) was recorded at PRS 1, while the lowest concentration (3.80 ± 2.82 mg/g) was recorded at SL 9, which is the control area. Contrary, Cu shows the lowest concentration (0.80 ± 0.39 mg/g) at Pattanakarn roadside 2 (PRS 2) that connected with construction area (PRS 1), and (0.12 ± 0.06) at the SL 9 of the control area. Unlike other metals, concentrations of Pb, which were analyzed using the t-test ($p < 0.05$), at construction and control areas were not significantly different. Moreover, lead-gasoline prohibition policy emerged since 1996 (กรมควบคุมมลพิษ, 2018). As a result, lead emission into the environment is low and was considered as a background concentration. In general, the $PM_{2.5}$ fraction classified as traffic-related dust primarily originates from diesel exhaust or fuel combustion, brake and tire abrasion, etc. (Ondráček, Schwarz et al., 2011; Nasser and Inas, 2012; Soleimani, Amini et al., 2018). Another study also reported accumulation of some heavy metals (including Fe and Zn) in $PM_{1.0}$-$PM_{2.5}$ (Narumon, Khajornsak et al., 2006). The heavy metal loads at PRS 1 was higher than those at SRS site, as construction activities and earth work (ground excavation) for road tunnel in PRS 1 was more intensive (Faber, Drewnick et al., 2015). The concentrations of heavy metals at PRS 1 and SRS, which had on-road construction activities, were higher than those at PRS 2; the lowest heavy metal concentration was recorded at SL 9. At SL 9, the control area, which was not affected by construction activities or traffic congestion, only low concentrations of all heavy metal species were present.

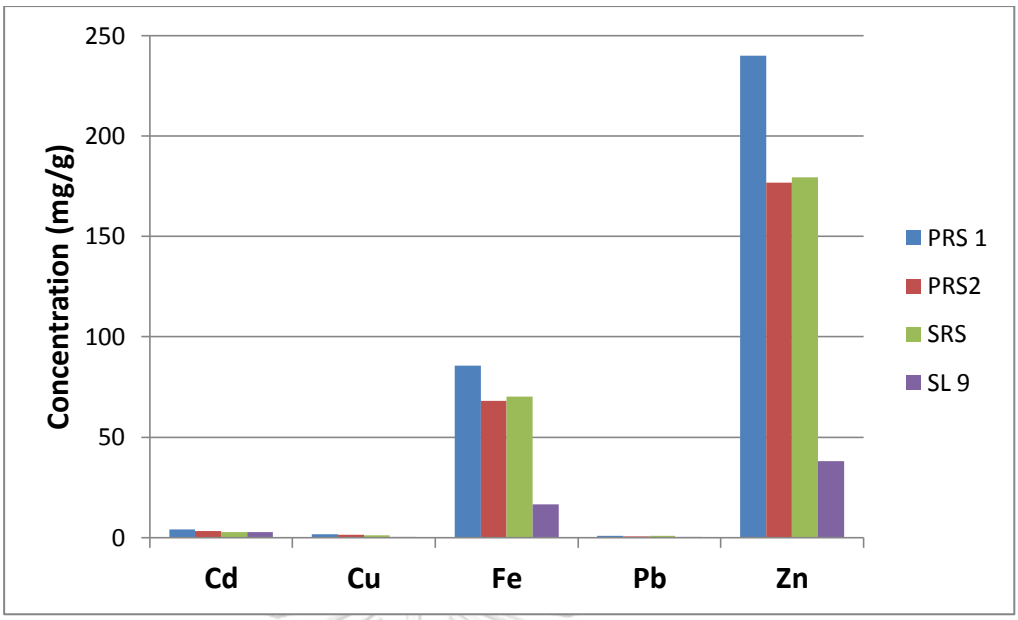


Figure 4.6 Comparison of heavy metals concentration (mg/g) in PM_{10} at four sampling sites

Mean heavy metal concentrations, Cadmium (Cd), Copper (Cu), Iron (Fe), Lead (Pb), and Zinc (Zn) concentrations, in PM_{10} are presented as a graph in Fig 4.4. They were determined, like heavy metal concentrations in $PM_{2.5}$, along the roadside at PRS 1, PRS 2, SRS, and SL 9. Like in $PM_{2.5}$, major elements found in PM_{10} were Zn and Fe. Zn was accountable for 71% and Fe accounted for 27% of the total elements. The highest concentration was still in the same trend as $PM_{2.5}$, which were Zn and Fe levels were the highest among all heavy metals. The highest Zn concentration (239.94 ± 53.61 mg/g) was detected at PRS 1, a construction area, and Zn at SL 9 (38.10 ± 12.90 mg/g), which is the control area. The highest Fe concentration (85.56 ± 49.71 mg/g) was recorded at PRS 1 and Fe (16.51 ± 10.56 mg/g) at SL 9. Similar to heavy metal levels $PM_{2.5}$, the other elements (Cd, Cu, and Pb) were present at lower concentrations than Fe and Zn. There are many PM_{10} emission sources that pollute the environment such as fuel combustion, brake wear, road surface wear, and road dust re-suspension (largest contributor). The percentage of non-exhaust emission sources account for 49% of all PM_{10} emission sources, while exhaust sources account for only 33% (Lawrence, Sokhi et al., 2013). This heavy metal profile may be related to on-road construction activities, which slows down traffic flow along the road and increases heavy metal concentration in the area. Gravel at construction sites, road dust, and heavy-duty trucks are significant anthropogenic sources (Onjefu, Abah et al., 2017). Furthermore, granite pavements and asphalt pavements are sources of PM_{10}, which contain high concentrations of Zn, Pb, and Cr (Sorme, Bergback et al.,

2001). Similarly, in this study, mechanical abrasion of road surfaces is also a major source of road dust, which is composed high levels of heavy metals such as Fe, Mg, Ca, and Al (Ondráček, Schwarz et al., 2011). This suggests that PM_{10} from construction dust is the additional proportion of the traffic pollution. Consequently, this heavy metal profile implies that construction activities induce traffic congestion, resulting in elevated heavy metal levels in the construction areas.

In this study, heavy metals were accumulated in $PM_{2.5}$ and PM_{10}, which primarily originate from traffic (including vehicular emission and vehicle engine parts) and construction activities, at varying levels. Heavy metal concentrations were in the order: Zn > Fe > Cd > Cu > Pb; this is the similar to previous studies (Wahid, Latif et al., 2014; Sah, Verma et al., 2019) that analyzed composition of PM_{10} from a semi-urban area influenced by high traffic volumes and detected heavy metals including Fe, Zn, Pb, Cu, Mn, Cd, and Ni. (Manoli, Voutsa et al., 2002) found high proportions of Zn (95%) and Fe (51%) in fine-sized particles collected from a traffic-impacted urban site. This study reported that the largest source of fine-sized particles was traffic (38%), while road dust was a major source of coarse-sized particle (57%). Likewise, (Zhai, Liu et al., 2014) found Cd, Cu, Pb, and Zn accumulation in $PM_{2.5}$ which originated from automobile exhaust, chemical fuel combustion, secondary aerosols, and re-suspended road dust with industrial emission (Sah, Verma et al., 2019). Increase in Cd levels in $PM_{2.5}$ and PM_{10} were found to be attributable to steel production, plastics, tire wearing, and pigments (Hjortenkrans, Bergback et al., 2006; Hjortenkrans, 2008; Duan and Tan, 2013). Construction activities in the study area were road demolition, road pavement drilling, excavating, reinforced steel-concrete, and concrete-gravel pavement with mixing operation, which emits metal-containing dust along with soil from top layer. Large-sized particles are emitted by various mechanical process such as drilling, sawing, milling, compacting, and grading (Azarmi, Kumar et al., 2014). Concrete and cement at the construction site consisted in several kinds of crustal elements as same as metals dust emitted from mechanical abrasion of tools and machines (Kaegi, 2004). Furthermore, damaged road surfaces, unpaved roads, and temporary roads are significant sources of PM_{10} (Guttikunda, Goel et al., 2014).

4.6 Distribution of heavy metals in $PM_{2.5}$ and PM_{10}

The proportion of heavy metals accumulated in $PM_{2.5}$ and PM_{10} were calculated as the ratio of heavy metal in $PM_{2.5}$ and that in PM_{10}. The highest ratio was calculated for Pb (close to 1), followed by that of Cu and Cd (approximately 0.6). These results suggest that these heavy metals were primarily accumulated in fine particulate matter ($PM_{2.5}$) and may have originated from anthropogenic activities. $PM_{2.5}$ is a major pollutant from vehicular and traffic emissions, implying that Pb and Cu primarily originated from $PM_{2.5}$. The ratio of Cd was close to 0.5, indicating the presence from mixed sources and equal distribution of Cd in fine and coarse particulate matter. However, the ratios of Fe and Zn were markedly low (less than 0.5). This suggests that both Zn and Fe were present in higher concentrations in coarse particulate matter (PM_{10}), which mainly originated from re-suspended road dust and construction activities (Faber, Drewnick et al., 2015). Some other study (Dai, Bi et al., 2015; Zhang, Chai et al., 2018) have reported that Cu and Pb are the dominant elements in fine particulate matter, while Fe and Zn are the major metals in coarse particulate matter (Oucher, Kerbachi et al., 2015).

4.7 Comparison of heavy metals with standard values

The heavy metal concentrations in $PM_{2.5}$ and PM_{10} (Cd, Cu, Fe, Pb, and Zn) were averaged and classified by sites in Table 4.5. They were calculated based on collected air volume ($\mu g/m^3$) and then compared with heavy metal standard values set by OSHA, NIOSH, and ACGIH. Heavy metal present at the highest concentration in $PM_{2.5}$ (1.542 ± 0.539 $\mu g/m^3$) and PM_{10} was Zn (11.692 ± 2.766 $\mu g/m^3$) at the PRS 1 sampling site, followed by Fe in $PM_{2.5}$ (1.026 ± 0.502 $\mu g/m^3$) and PM_{10} (4.036 ± 1.520 $\mu g/m^3$). The background site (SL 9) recorded the lowest concentrations of all heavy metal species. These results were similar to the trend of heavy metal concentration calculated based on the dry weight of PM. Although Zn and Fe were present at high concentrations compared to other heavy metal species, they were not in excess of the heavy metal standard values established by OSHA, NIOSH, and ACGIH.

Table 4.5 Comparison of heavy metal concentrations (μg/m^3) in $PM_{2.5}$ and PM_{10} with relevent OSHA, NIOSH, and ACGIH standards (μg/m^3)

$PM_{2.5}$ (μg/m^3)								
	PRS 1	PRS 2	SRS	SL 9	OSHA	Cal/ OSHA	NIOSH	ACGIH
Cd	0.080 ± 0.011	0.061 ± 0.027	0.144 ± 0.018	0.032 ± 0.035	-	5.000	-	10.0 (tot.) 2.0 (resp.)
Cu	0.078 ± 0.009	0.027 ± 0.008	0.052 ± 0.011	0.002 ± 0.001	100 (fume) 1000 (dust)	100 (fume) 1000 (dust)	100 (fume) 1000 (dust)	200 (fume) 1000 (dust)
Fe	1.026 ± 0.502	0.315 ± 0.070	0.630 ± 0.368	0.066 ± 0.051	10000 (fume)	5000 (fume)	5000 (fume)	5000 (resp.)
Pb	0.038 ± 0.009	0.046 ± 0.055	0.027 ± 0.012	0.014 ± 0.003	-	50	50	50
Zn	1.542 ± 0.539	0.456 ± 0.090	0.743 ± 0.297	0.057 ± 0.065	5000	5000	5000	2000 (resp.)
PM_{10} (μg/m^3)								
	PRS 1	PRS 2	SRS	SL 9	OSHA	Cal/ OSHA	NIOSH	ACGIH
Cd	0.184 ± 0.004	0.148 ± 0.006	0.155 ± 0.018	0.068 ± 0.029	-	5.000	-	10.0 (tot.) 2.0 (resp.)
Cu	0.080 ± 0.016	0.059 ± 0.034	0.057 ± 0.008	0.008 ± 0.004	100 (fume) 1000 (dust)	100 (fume) 1000 (dust)	100 (fume) 1000 (dust)	200 (fume) 1000 (dust)
Fe	4.036 ± 1.520	3.162 ± 1.087	3.968 ± 0.782	0.652 ± 0.526	10000 (fume)	5000 (fume)	5000 (fume)	5000 (resp.)

Pb	0.045 ± 0.006	0.032 ± 0.011	0.040 ± 0.009	0.009 ± 0.006	-	50	50	50
Zn	11.692 ± 2.766	8.207 ± 2.485	9.771 ± 3.601	1.312 ± 0.536	5000	5000	5000	2000 (resp.)

The heavy metal concentrations in $PM_{2.5}$ and PM_{10} (mg/g), based on dry weight, reported in previous topic revealed different outcomes. The heavy metal concentrations in $PM_{2.5}$ and PM_{10} were compared with the Maximum Permissible Concentration (MPC) declared by the WHO (Table 4.6). In $PM_{2.5}$, Cd, Cu, Pb, and Zn levels were higher than the MPC values, while Fe level was within the standard range. Similar to $PM_{2.5}$, all heavy metal species in PM_{10} were present at high levels and exceeded the standard MPC values.

Table 4.6 Comparison of heavy metal concentrations (mg/g) in $PM_{2.5}$ and PM_{10} collected from sampling sites with the Maximum Permissible Concentration (MPC) of WHO.

$PM_{2.5}$ (mg/g)					
Heavy metal species	**Sampling sites**				
	PRS1	**PRS 2**	**SRS**	**SL 9**	**MPC**
Cd	2.05 ± 0.44	1.84 ± 1.15	4.57 ± 1.43	1.79 ± 1.88	0.003
Cu	1.96 ± 0.29	0.80 ± 0.39	1.58 ± 0.32	0.12 ± 0.06	0.1
Fe	27.98 ± 18.47	9.73 ± 4.48	17.05 ± 6.82	3.80 ± 2.82	50
Pb	0.96 ± 0.29	1.25 ± 1.47	0.91 ± 0.69	0.83 ± 0.25	0.1
Zn	40.23 ± 20.03	13.30 ± 4.32	24.68 ± 17.70	3.28 ± 3.72	0.3
PM_{10} (mg/g)					
Heavy	**Sampling sites**				

metal species	PRS1	PRS 2	SRS	SL 9	MPC
Cd	3.90 ± 1.21	3.13 ± 0.63	2.77 ± 0.31	2.63 ± 1.25	0.003
Cu	1.63 ± 0.29	1.25 ± 0.80	1.01 ± 0.06	0.33 ± 0.26	0.1
Fe	85.56 ± 49.71	68.17 ± 27.32	70.13 ± 9.77	16.51 ± 10.56	50
Pb	0.95 ± 0.36	0.68 ± 0.27	0.72 ± 0.14	0.35 ± 0.22	0.1
Zn	239.94 ± 53.61	176.67 ± 66.67	179 ± 89.01	38.10 ± 12.90	0.3

Interesting information provided by EPA (Table 4.7) was also used in the comparison of Reference concentration (RfC) (US EPA, 2017) and the heavy metal concentration in the air. The results only indicated the excess value of Cd to this reference concentration, and suggested that the air was not contaminated in high value.

Table 4.7 Inhalation reference concentration of heavy metals

Heavy metal	RfC (μg/m^3)
Cd	1×10^{-2}
Cu	140
Fe	2450
Pb	0.2
Zn	1050

Although heavy metal concentration calculated based on air volume was not higher than the standard limit, concentration based on PM dry weight exceeded the standard MPC value. $PM_{2.5}$ can penetrate deeper into the lungs and can be inhaled more easily than coarse particles. PM_{10} may deposit on the

bronchioles and alveoli within the lungs, causing respiratory system and heart issues. Large particles like PM_{10} can only enter the body through the throat and are deposited in the extra-thoracic region; these particles can be eliminated by coughing, sneezing, and swallowing (Fairbanks North Star Borough, 2015). These penetrated particles can transport hazardous chemicals present in PM and increase the risk associated with fine and ultrafine particles; however, in this study, coarse particles were found to contain higher amounts of chemical substances, especially heavy metals. This suggests that both fine-sized particles ($PM_{2.5}$) and coarse particles (PM_{10}) are sources of environmental issues and can cause adverse effects on human health.

4.7 Correlation analysis of heavy metals concentration

Table 4.8 shows the correlations between quantified heavy metal concentrations in $PM_{2.5}$ (Fe, Cu, Cd, Pb, and Zn); * indicates correlation at significance level $p < 0.05$ and ** indicates correlation at significance level $p < 0.01$. The strongest correlation was observed between Cu and Zn ($r = 0.943$, $p < 0.01$), while good correlations were observed between Cu and Fe ($r = 0.698$, $p < 0.01$), and Fe and Zn ($r = 0.662$, $p < 0.01$). Similar to this study, (Lawrence, Sokhi et al., 2013), found strong correlations between some heavy metals (Cu, Mn, Pb, and Fe) and good correlations between traffic-related heavy metals (Sb, Zn, and Ni). Their results suggest that metals originate from the same source and are influenced by traffic volume and brake-wear particles, especially on week days. This inter-element correlation trend revealed the emission sources of heavy metal species from roadside construction. Furthermore, Cu and Zn are anthropogenic pollutants originating from diesel exhaust (Cu), road dust, and tire wear (Zn) (Contini, Belosi et al., 2012). In contrast, Pb showed no correlation with any metal. This implies that Pb found in this study was background Pb and not emitted from activities in this area. Pb can be emitted from other sources such as pigments, plastics, leaded gasoline, waste incineration, and steel(Dai, Bi et al., 2015).

Table 4.8 Inter-element correlation of heavy metal species in $PM_{2.5}$. Bolded values indicate strong correlation.

Elements	Cd	Cu	Fe	Pb	Zn
Cd	1.000	0.499*	0.478*	ns	0.513*
Cu		1.000	0.698**	ns	0.943**
Fe			1.000	ns	0.662**
Pb				1.000	ns
Zn					1.000

Table 4.9 Inter-element correlation of heavy metal species in PM_{10}. Bolded values indicate strong correlation.

Elements	Cd	Cu	Fe	Pb	Zn
Cd	1.000	0.528*	ns	0.489*	0.567**
Cu		1.000	0.671**	0.680**	0.755**
Fe			1.000	0.571**	0.562**
Pb				1.000	0.830**
Zn					1.000

Most of the heavy metals in PM_{10} (Table 4.9) showed moderate and good correlations. Cu-Zn ($r = 0.755$, $p < 0.01$) and Pb-Zn ($r = 0.830$, $p < 0.01$) showed strong correlations. According to (Abah, 2014), almost all heavy metal species (including As, Pb, Cr, Cd, Co, Cu, Ni, Mn, V, and Sn) show strong correlations and inter-element correlation trend suggested aerial deposition from urban road construction activities. Similar to the study by (Lawrence, Sokhi et al., 2013) strong correlations were observed between Fe and Cu, suggesting that they were emitted from the same sources. The study (Dai, Bi et al., 2015; Mohiuddin, Strezov et al., 2016) also found the strong correlation between Fe-Zn (0.933) which is steel-related element from metal emission.

These heavy metal correlation data were used to confirm that Cu, Fe, and Zn originated from the same source. Heavy construction at the roadside induced traffic congestion and increased the level of heavy metals in this area. The heavy metals found at the background site were possibly from the construction area as found by (Dai, Bi et al., 2015) who discovered that heavy metal concentrations at the background site was affected by industrial activities. Thus, it can be concluded that construction activities (anthropogenic activities) and traffic congestion are primary sources of heavy metals.

CHAPTER V
CONCLUSION

Conclusion

$PM_{2.5}$ and PM_{10} concentrations and heavy metal species in different sampling areas including construction areas and control areas in Bangkok were quantified. The samples were collected continuously for five days (12 hours per day) at each site during winter, from November to December 2018 (dry season). Statistical data included inter-element correlations between each heavy metal species. The results of this research can be summarized as follows.

$PM_{2.5}$ and PM_{10} concentration

The results of this study revealed obviously higher $PM_{2.5}$ and PM_{10} concentrations in construction areas than in the control area. The highest $PM_{2.5}$ concentration (40.35 ± 8.0 μg/m^3) was recorded at PRS 1, a traffic congested area and construction area, which had the worst traffic flow among all the sampling sites. $PM_{2.5}$ in this area was mainly from combustion sources related to traffic emissions. On the other hand, the lowest $PM_{2.5}$ concentration was recorded at SL 9 (the control site), which was not affected by traffic congestion or construction activities. The highest PM_{10} concentration (56.39 ± 7.26 μg/m^3) was obtained at SRS, and concentration at this site was close to that at PRS 1 (53.84 ± 10.51 μg/m^3) as they were both traffic congested and construction areas. Similarly, the lowest PM_{10} concentration (27.32 ± 5.95 μg/m^3) was recorded at the background site. The higher levels of PM_{10} at SRS and PRS 1 were due to construction activities as PM_{10} was possibly emitted from vehicle engine parts, dust resuspension, and vehicle exhaust. Furthermore, the additional concentration can also be attributable to construction dust and is responsible for the higher level of PM_{10} than $PM_{2.5}$. The mean $PM_{2.5}/PM_{10}$ ratio at the construction area was 0.676, traffic area was 0.740, and background site was 0.633, indicating the higher proportion of $PM_{2.5}$ than PM_{10}; however, the additional PM_{10} emitted from construction activities lowered $PM_{2.5}/PM_{10}$ ratio at SRS. All measured $PM_{2.5}$ and PM_{10} concentrations except at SL 9, which is the background site, were higher than the relevant PCD values. Although the $PM_{2.5}$ and PM_{10} concentrations determined in this study did not exceed the Thai PCD standard values, they exceeded the limit set by the WHO standard. Furthermore, air quality in these

sampling areas can be categorized as poor to very poor for $PM_{2.5}$ and poor for PM_{10}

Heavy metal concentration

The heavy metal species (Cd, Cu, Fe, Pb, and Zn) were extracted from $PM_{2.5}$ and PM_{10} samples collected on filters using a microwave digestion technique. After that, they were quantified using a GFAAS. The major elements detected in $PM_{2.5}$ were Zn and Fe, which were recorded at the highest concentrations (40.23 ± 20.03 mg/g and 27.98 ± 18.47 mg/g respectively) at PRS 1. The lowest concentrations of all the metal species were recorded at the control site (SL 9). Likewise, Zn and Fe concentrations in PM_{10} were the highest concentration amongst all metal species at PRS 1 (239.94 ± 53.61 mg/g and 38.10 ± 12.90 mg/g respectively). Further, the lowest concentrations for all metal species were recorded at the control area (SL 9). In this study, the trends of heavy metal concentration at construction areas and traffic areas were markedly different from those at the background area.

The inter-element correlations between Cd, Cu, Fe, Pb, and Zn in $PM_{2.5}$ were good and strong for all metal species. Strong correlations were observed for Cu-Zn ($r = 0.943$, $p < 0.01$), Cu-Fe ($r = 0.698$, $p < 0.01$), and Fe-Zn ($r = 0.662$, $p < 0.01$), which are traffic-related heavy metals. In contrast, Pb was not significantly correlated with other metals, revealing that no Pb was emitted from vehicles as leaded gasoline has not been used for a decade and considered as a background concentration from another emission source. Moderate and good correlations among all metal species in PM_{10}, with the strongest correlations between Cu-Zn ($r = 0.755$, $p < 0.01$) and Pb-Zn ($r = 0.830$, $p < 0.01$) respectively, revealed their corresponding emission sources (aerial deposition and emissions from construction activities especially earth works and mechanical processes). The intensive construction from ground excavation at PRS 1 contributed to higher levels of heavy metals in the area than at SRS. Heavy metal distribution indicated considerably high Pb ratios, followed by Cu and Cd ratios (> 0.5), while Fe and Zn ratios were low. This suggests that Pb, Cu, and Cd were the major chemical components in fine particles, while Fe and Zn were the major chemical components in coarse particles.

Hazardous substances in particulate matter cause adverse effects on both the environmental and human health. Heavy metal concentrations were calculated based on air volume and compared with OSHA, NIOSH, and ACGIH standards established based on working conditions. Heavy metal

levels in $PM_{2.5}$ and PM_{10} were not in excess of the standard limits. However, almost all heavy metal concentrations in $PM_{2.5}$ and PM_{10} calculated using dry weight were higher than the maximum permissible concentrations (MPCs) set by the WHO. Therefore, considering the harmful effects $PM_{2.5}$ and PM_{10} more attention should be paid to these types of PM. Although $PM_{2.5}$ contains lower concentrations of heavy metals and other chemical substances, it can enter deep into the respiratory system and the lungs, particularly the alveoli and bronchioles, where the chemicals can enter the blood circulation system causing heart diseases, respiratory system impairments or even lung cancer. In case of coarse particles like PM_{10}, although they cannot penetrate as deep as $PM_{2.5}$ and can be blocked by biomechanical systems, they contain large amounts of heavy metals. Effective mitigation strategies should be adopted to solve these environmental issues and for better air quality in maintenance and construction areas. Traffic conditions should be varied appropriately to the traffic conditions during the construction period. Moreover, the duration of construction works should be limited to control the air pollutant levels in the environment. There is a need for more policies on road construction (e.g. limit working duration, construction credits, road surface flushing, water spraying, etc.) in the future to prevent reduction in air quality and, especially, to protect public health. Finally, urban, road or other developments in the future should be sustainable so that those in the following generations are not left bearing the burden.

Research and study about particulate matter and its source in Thailand should be further conducted in the future to have efficient evidences and appropriate prevention since the air pollution was affected by various factors which different in situation of each countries. This study also has the limitation of sampling time that is 12 hours. Moreover, the emission from construction sources is normally generated in various particle size, while this study only focus on $PM_{2.5}$ and PM_{10} which was more hazard than the larger particle. Thus, collecting total suspended particles (TSP) might be another way to confirm this emission.

APPENDIX

Table A.1 Correlation between $PM_{2.5}$ and the other affecting factors

Correlations			PM2.5	Traffic Flow	Humidity	Temp.	Pressure	Wind Speed	Rain
Spearman's rho	PM2.5	Correlation Coefficient	1.000	-.479	.145	.038	.131	-.208	-.265
		Sig. (2-tailed)	.	.071	.541	.875	.582	.379	.259
		N	20	15	20	20	20	20	20

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table A.2 Correlation between PM_{10} and the other affecting factors

Correlations			PM10	Traffic Flow	Humidity	Temp.	Pressure	Wind Speed	Rain
Spearman's rho	PM10	Correlation Coefficient	1.000	-.082	.095	-.096	.201	-.182	-.229
		Sig. (2-tailed)	.	.771	.691	.686	.396	.442	.331
		N	20	15	20	20	20	20	20

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table A.3 Daily Traffic flow collected for 12 hours (7 a.m. – 7 p.m.) in unit of vehicles/hour

	Date	Car	Van	Bus	Motorbike	Truck	Total
PRS 1	13/11/2018	1655	1065	20	1031	18	3789
	15/11/2018	1681	355	22	1670	6	3735
	16/11/2018	1604	891	19	1267	10	3789
	17/11/2018	1833	641	17	1604	7	4103
	18/11/2018	1961	603	17	1482	8	4072
PRS 2	21/11/2018	2494	1493	18	1462	13	5480
	22/11/2018	1948	1239	14	943	11	4153
	23/11/2018	2114	1211	15	1166	16	4522
	24/11/2018	2266	1654	15	1692	16	5642
	25/11/2018	2225	1671	15	1429	15	5354
SRS	27/11/2018	3244	2195	32	2967	26	8464
	29/11/2018	2787	2192	25	2410	24	7439
	30/11/2018	3054	2334	24	2772	15	8199
	1/12/2018	3186	2485	31	2945	25	8671
	2/12/2018	3061	2481	26	2953	16	8536

Table A.4 Meteorological data during sampling period (12 hr.)

	Date	Temperature (^{o}C)	Humidity (%)	Pressure (HectoPa)	Wind speed (knot)	Rain (mL)
PRS 1						
	13-Nov	27.8	80.0	1008.20	2.4	2.0
	15-Nov	31.0	77.8	1009.86	2.0	0
	16-Nov	31.2	75.8	1010.38	3.8	0
	17-Nov	30.7	74.4	1010.57	2.2	1.0
	18-Nov	29.9	75.2	1011.70	3.2	0.1
PRS 2	21-Nov	31.7	63.0	1011.10	2.2	0
	22-Nov	31.6	66.8	1011.51	1.8	0
	23-Nov	30.5	62.4	1012.91	3.6	0
	24-Nov	29.8	64.2	1012.41	2.6	0
	25-Nov	30.0	59.8	1011.54	3.4	0
PRS 3	27-Nov	28.0	63.0	1013.35	3.2	0
	29-Nov	29.6	65.0	1014.10	2.6	0
	30-Nov	30.1	65.8	1013.20	3.4	0
	1-Dec	31.3	63.4	1011.10	4.0	0
	2-Dec	32.0	62.0	1009.81	2.2	0
SRS	4-Dec	32.1	60.6	1010.62	3.8	0

	6-Dec	31.4	60.8	1009.01	2.0	0
	7-Dec	31.5	63.6	1009.28	2.4	0
	8-Dec	26.2	86.2	1011.81	3.2	1.7
	9-Dec	27.8	76.2	1011.53	4.0	0.1

Table A.5 Test of normality in $PM_{2.5}$ and PM_{10} data

Tests of Normality	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
PM2.5	.148	20	.200*	.923	20	.114
PM10	.161	20	.185	.932	20	.168

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Table A.6 T-test compare mean of $PM_{2.5}$

One-Sample Test	Test Value = 17.28					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
PM2.5	8.716	14	.000	19.56405	14.7499	24.3782

Table A.7 T-test compare mean of PM_{10}

One-Sample Test	Test Value = 27.32					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
PM10	11.332	14	.000	25.71284	20.8464	30.5793

Table A.8 T-test compare mean of heavy metal concentrations in $PM_{2.5}$

One-Sample Test	Test Value = 1.79					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cd	2.439	14	.029	1.02888	.1242	1.9336

One-Sample Test	Test Value = 0.123					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cu	8.684	14	.000	1.32451	.9974	1.6516

One-Sample Test	Test Value = 3.799					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Fe	3.764	14	.002	18.73021	8.0584	29.4020

One-Sample Test	Test Value = 0.832					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Pb	.903	14	.382	.20923	-.2877	.7061

One-Sample Test	Test Value = 3.278					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Zn	4.787	14	.000	22.79375	12.5812	33.0063

Table A.9 T-test compare mean of heavy metal concentrations in PM_{10}

One-Sample Test	Test Value = 2.628					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cd	2.769	14	.015	.63891	.1440	1.1339

One-Sample Test	Test Value = 0.330					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cu	7.110	14	.000	.96707	.6753	1.2588

One-Sample Test	Test Value = 0.330					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cu	7.110	14	.000	.96707	.6753	1.2588

One-Sample Test	Test Value = 16.506					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Fe	7.077	14	.000	58.11242	40.4997	75.7252

One-Sample Test	Test Value = 0.354					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Pb	5.945	14	.000	.43092	.2754	.5864

One-Sample Test	Test Value = 38.102					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Zn	8.570	14	.000	160.59480	120.4035	200.7861

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กรมควบคุมมลพิษ. นโยบายป้องกัน และ ขจัดมลพิษภายใต้นโยบายและแผนการส่งเสริมและรักษาคุณภาพสิ่งแวดล้อมแห่งชาติ พ.ศ. 2540-59.

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