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Technical Information

The Long-term Characteristics of PM_{10} and $PM_{2.5}$ in Bangkok, Thailand

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ABSTRACT The long-term characteristics of non-roadside (residential) PM_{10} and $PM_{2.5}$ in Bangkok, Thailand was analyzed by using hourly concentrations of PM_{10} and $PM_{2.5}$ which had been collected from 10 monitoring stations by the Pollution Control Department (PCD) of Thailand from 2006 to 2016. The results showed that most of the stations showed either the decreasing trend or no trend characters. The $PM_{2.5}$ and PM_{10} during weekdays and dry season were higher than during weekends and wet season, respectively. The diurnal variations of both $PM_{2.5}$ and PM_{10} exhibited multi-peaks characteristic, mostly 2 peaks during a day for $PM_{2.5}$ and 2 to 3 peaks depending on the locations for PM_{10}. The $PM_{2.5}$ to PM_{10} ratio of our residential monitoring stations was 0.61 in average which was in the same range as the $PM_{2.5}/PM_{10}$ ratio from the roadside monitoring stations. This shows that the common sources of $PM_{2.5}$ and PM_{10} at both types of monitoring station were similar, probably mainly from the traffic and transportations. However, it was found that $PM_{2.5}/PM_{10}$ ratio during wet season was lower than during dry season indicating the role of emission sources and removal process in each season.

KEY WORDS $PM_{2.5}$ to PM_{10} ratio, Long-term characteristics of $PM_{2.5}$ and PM_{10}, Bangkok, PM_{10}, $PM_{2.5}$

1. INTRODUCTION

Air pollution is one of the important urban environmental issues which globally killed an estimated 4.2 million people per year (WHO, 2018). $PM_{2.5}$ and PM_{10} are major pollutants which link the premature death, the global trend of annual $PM_{2.5}$ and PM_{10} levels during 2008–2013 increased by 8% (WHO, 2016). According to 2018 World Air Quality Report (AirVisual, 2018) the most cities which ranked top in an estimated annual average of $PM_{2.5}$ concentration were in Asia and the Middle East. Among the capital cities, Delhi (India), Dhaka (Bangladesh), and Kabul (Afghanistan) occurred the maximum yearly average concentrations at 113.5, 97.1, and 61.8 $\mu g/m^3$, while Bangkok (Thailand) ranked at 24th with 25.2 $\mu g/m^3$ yearly concentration.

Bangkok, the capital of Thailand, has been rapidly developed and its urbanization accelerated more environmental issues in the city. Bangkok has been experienced the air pollutions for years. The main sources of those pollutants are transportations in the city (Pochanart, 2016). Recently, the situations of Bangkok's air quality, especially $PM_{2.5}$ and PM_{10} during the dry season, have been increasingly concerned by the public. In 2017, the $PM_{2.5}$ average concentrations in Bangkok Metropolitan Region (BMR) exceeded the Thailand's standard, 50 $\mu g/m^3$ in 24 hours, about 40 to 50 days during January to March (PCD, 2018a). In 2018–2019, Bangkok's air quality index (AQI) had been at an unhealthy level for months because of $PM_{2.5}$ concentration crisis (Reuters, 2019). The vision in Bangkok was unclear and masks for protecting $PM_{2.5}$ was in short supply. The local government announced warning to a sensitive group, especially the elderly and children (Lefevre, 2018), and released several solutions such as spraying water into the air by drones and driving trucks but it did not clearly show that the problems were solved by those solutions (Supoj, 2019; TheNation, 2019).

To investigate common characteristics of $PM_{2.5}$ and PM_{10} and their causes in Bangkok, the study mainly focused on (1) the relation between the pollutants and time and (2) the ratio of both pollutants. To achieve the study's goal, the long-term trends, the temporal variation, and the ratio between $PM_{2.5}$ and PM_{10} were analyzed. The daily, weekly, and monthly variations of each pollutant could be related to urban activities, differently by location sources and time of the emission, while the monthly variation may additionally represent the influence of the weather condition to the characteristic of the pollutants. Moreover, the ratio between $PM_{2.5}$ and PM_{10} could also show the relation of the pollution sources and seasonal factors.

2. METHODOLOGY

The concentrations of PM_{10} and $PM_{2.5}$ which were analyzed in this study had been collected from 2006 to 2016, covered all dry season and wet season. According to Thai Meteorological Department (TMD, 2010), Climate of Thailand has been divided into 3 seasons; summer (February–May), rainy season (May–October), and winter (October–February). For this study, the dry season included summers and winters, while the wet season is only rainy seasons.

The raw data, hourly concentrations, had been collected by the Pollution Control Department (PCD) of Thailand, who has collected the air pollution data for decades.

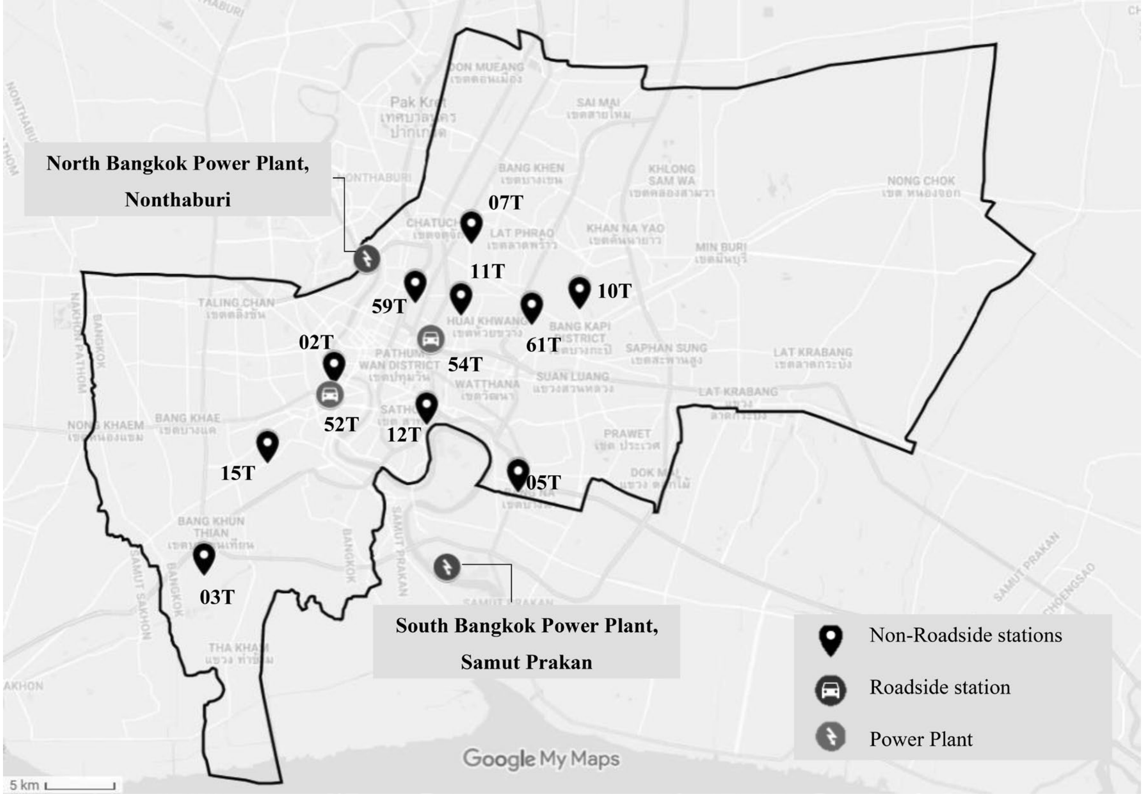


Fig. 1. Map of the locations of the monitoring stations in Bangkok area.

PCD has 2 categories of ambient monitoring station in Bangkok, roadside and non-roadside. There were 10 non-roadside monitoring stations which collected residential pollution concentrations and there were only 3 stations which the $PM_{2.5}$ had been collected. The PM_{10} concentrations which were used in this study had been collected since 2006, while the $PM_{2.5}$ concentration had been collected since 2016 at Bangna station (05T), 2015 at Phayathai station (59T), and 2014 at Wangthonglang station (61T). To compare the ratio, the roadside stations which have been collected both $PM_{2.5}$ and PM_{10} were considered. There are only 2 out of all 6 roadside station which have been monitoring $PM_{2.5}$. Those were Intharaphithak road station (52T) and Dindang road station (54T). The locations of the stations are shown in Fig. 1 and Table 1. The other 4 roadside stations which had not collected $PM_{2.5}$ are not shown in the figure and table.

According to PCD (PCD, 2016), the ambient air pollution has been monitored by using USEPA Federal Reference Method (FRM), gravimetric method for PM_{10} and In-stack Particulate filtration for $PM_{2.5}$, or USEPA Federal Equivalent Methods (FEM) such as Beta Ray Attenuation, Tapered Element Oscillating Microbalance (TEOM), or Dichotomous Air Sampler for both PM_{10} and $PM_{2.5}$. The stations are set at 1.5–6.0 meters above from ground level and 50 meters from main road for non-roadside or residential stations.

The data from all non-roadside stations were used for analyzing the long-term characteristics, while the relation between $PM_{2.5}$ and PM_{10} were developed by using the data from 3 stations, which the $PM_{2.5}$ had been collected. The hourly PM_{10} data which were used in this study covered 71.17% of all data monitoring for 11 years. The $PM_{2.5}$ for 05T, 59T, and 61T covered 52.04%, 83.30%, and 73.25%, respectively. For organizing, and analyzing data and results in this study, commercial spreadsheet software was mainly used.

3. RESULTS AND DISCUSSION

3.1 The Characteristics of PM_{10} and $PM_{2.5}$

The monthly average concentrations for 11 years were plotted for determining long-term trends of PM_{10} at each station, whereas the $PM_{2.5}$ trends were not discovered because of its relative short-term and lacking data. Examples of PM_{10} trend from 10 stations were shown in Fig. 2. The study found that long-term trends of PM_{10} was slightly decreasing in about half of the monitoring stations (02T, 11T, 15T, 59T, and 61T) and increasing in only one station, Ratburana station (03T). The stations with no-trend (not positive or negative) were determined when the correlation coefficient (R-value) were less than 0.1 or there were less than 50% of data at each station which were the cut-off point of the trends. There were four stations (05T, 07T, 10T, and 12T) that did not show positive or negative trends. However, if we look at the PM_{10} trend in the maximum months of the year, nor-

Table 1. The locations of the monitoring stations in Bangkok area.

St. ID	Station	Location		Monitored PM	
		Latitude	Longitude	PM_{10}	$PM_{2.5}$
Non-roadside station					
02T	Thonburi district	13.7330	100.4882	●	○
03T	Ratburana district	13.6144	100.4059	●	○
05T	Bangna district	13.6661	100.6057	●	●
07T	Chatuchak district	13.8200	100.5759	●	○
10T	Bangkapi district	13.7795	100.6457	●	○
11T	Dindang district	13.7755	100.5692	●	○
12T	Yannawa district	13.7080	100.5473	●	○
15T	Chomthong district	13.6842	100.4460	●	○
59T	Phayathai district	13.7831	100.5405	●	●
61T	Wangthonglang district	13.7698	100.6146	●	●
Roadside station					
52T	Intharaphithak road	13.7276	100.4866	●	●
54T	Dindang road	13.7626	100.5504	●	●

●: PM concentration had collected; ○: PM concentration had not collected

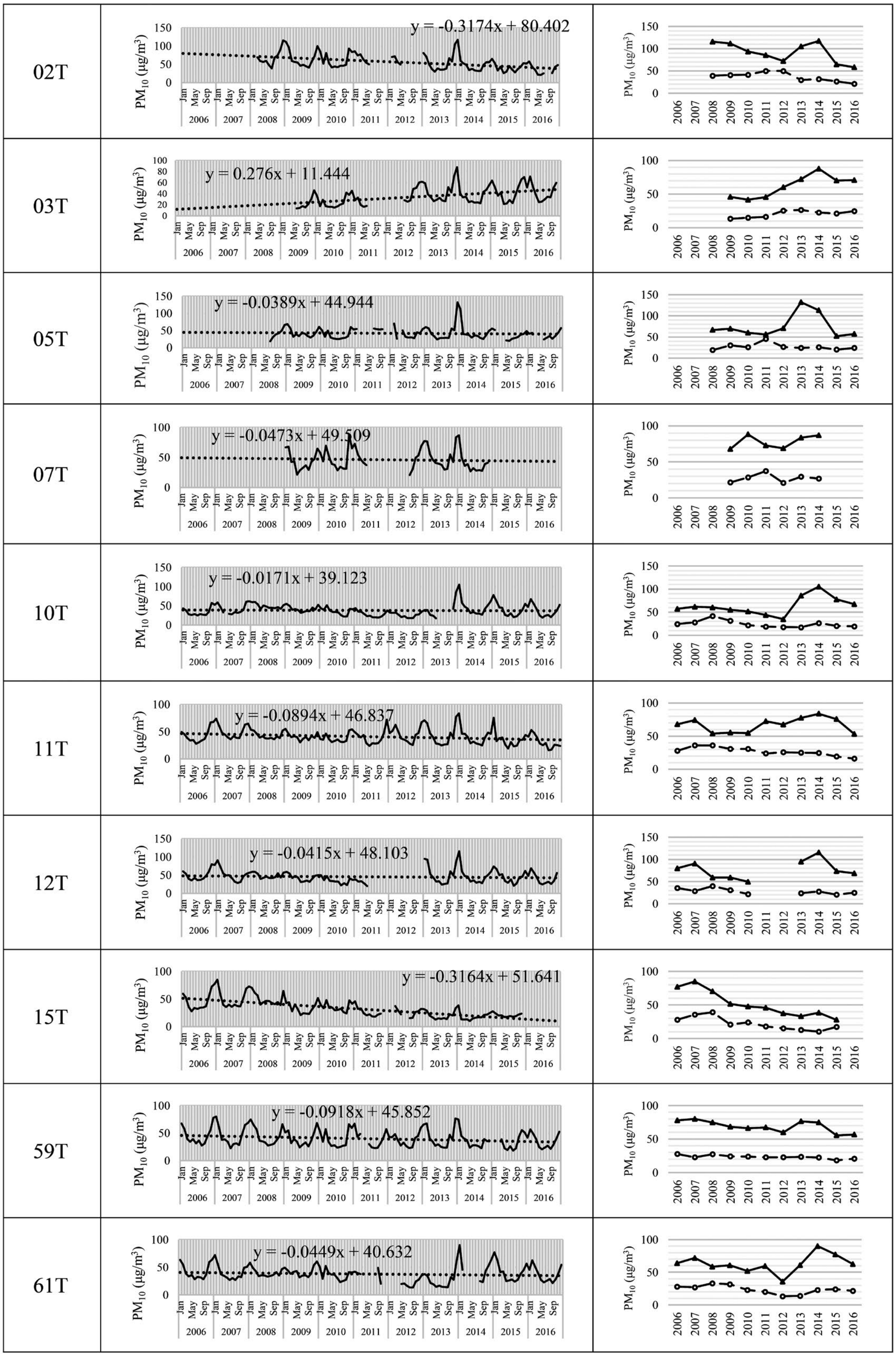


Fig. 2. The long-term trends of PM_{10} at each station (left), and the maximum and minimum monthly average PM_{10} of each year (right).

mally in dry season, and the minimum months year, normally in wet season, it appears that the decreasing trends are found in the wet season, while most stations in the dry season show positive trends. This is the main reason for recent pollution episode in Bangkok during dry season.

The decreasing trends probably showed that Bangkok strategies to solve long-term urban PM_{10} issue such as enhancing the fuel and vehicle standard and monitoring mobile sources in Bangkok were efficiently implemented, with the exception of the dry season PM_{10} and $PM_{2.5}$ episodes.

The hourly concentrations of PM_{10} and $PM_{2.5}$ were averaged by various time scales - hour, days of the week, and month - as shown in Fig. 3. The study showed that season and sources have a role in determining the pollution concentrations. As shown in the seasonal variations of PM_{10} and $PM_{2.5}$, the average concentrations were decreasing in the wet season and increasing in the dry season. For PM_{10}, the maximum monthly average concentrations which were normally in January and December ranged between 50.38–88.28 μg/m^3, while the minimum monthly average concentrations which were normally in August, September, and May ranged from 21.72 to 39.04 μg/m^3. The maximum concentrations of each station were 193%–265% higher than the minimum. For $PM_{2.5}$, the maximum monthly average concentration for $PM_{2.5}$ ranged from 36.38 to 45.42 μg/m^3, while the minimum ranged from 13.60 to 27.10 μg/m^3. The maximum concentrations of each station were 266%–334% higher than the minimum. The seasonal variations of $PM_{2.5}$ were normally high in January and December and low during the mid-year. The high dry season and low wet season concentrations of PM_{10} and $PM_{2.5}$ are common characteristics found similarly for other air pollutants such as ozone and carbon monoxide in Thailand as well (Pochanart *et al.*, 2003; Pochanart *et al.*, 2001).

The meteorological factors in the season influenced the character of the PM_{10} and $PM_{2.5}$. The removal process by rain in the wet seasons probably has a role in reducing the pollutants, moreover, the weather condition in the dry seasons is always more stagnant and may be the cause of PM_{10} accumulating during the season. Biomass burning is another important source that characterize the differences between wet and dry season. More biomass burning during dry season produces high-

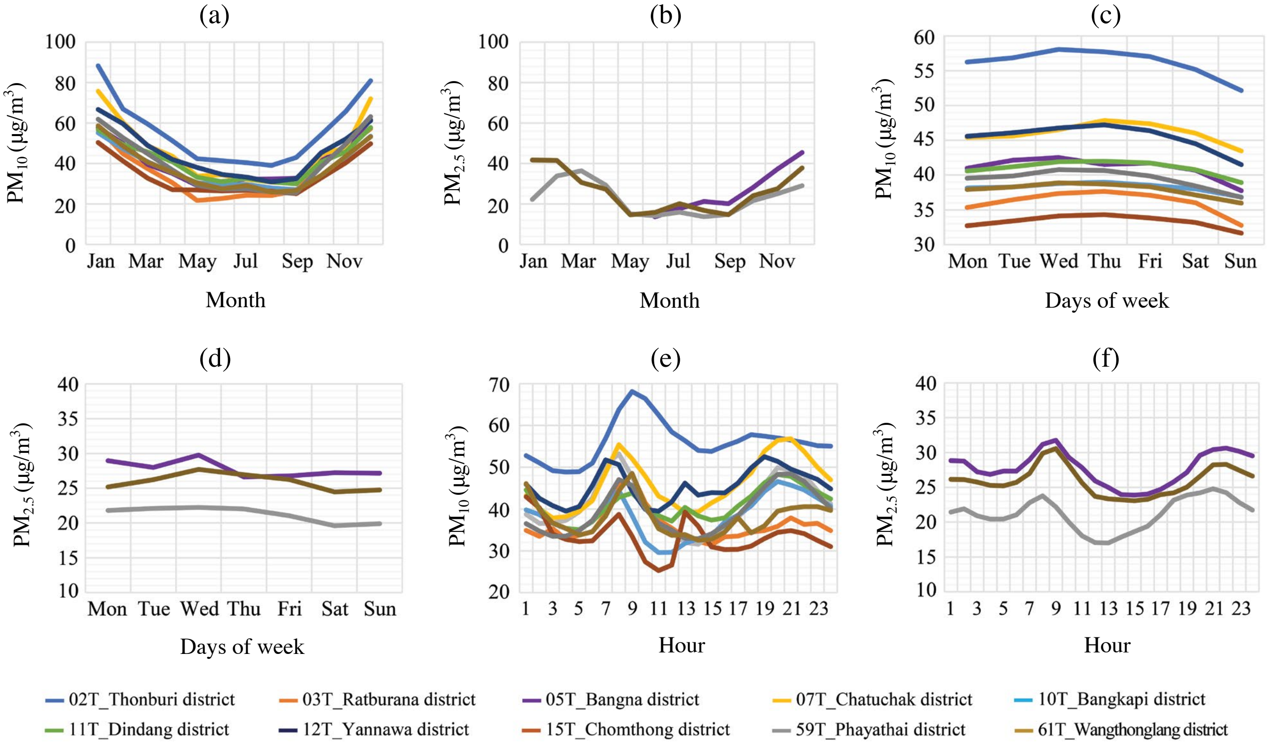


Fig. 3. The characteristics of PM_{10} and $PM_{2.5}$ (a) the seasonal variations of PM_{10}, (b) the seasonal variations of $PM_{2.5}$, (c) the days of week variations of PM_{10}, (d) the days of week variations of $PM_{2.5}$, (e) the diurnal variations of PM_{10}, and (f) the diurnal variations of $PM_{2.5}$.

er $PM_{2.5}$ and PM_{10} concentration. Although the levels of $PM_{2.5}$ and PM_{10} in wet and dry season are different, the characteristic of $PM_{2.5}$ and PM_{10} in other time scale, weekend/weekdays and diurnal variation, are still similar.

The PM_{10} and $PM_{2.5}$ concentrations were normally higher during weekdays. For PM_{10}, the weekdays' average concentrations among the stations were about 3.01%–7.91% greater than the weekends'. The daily average concentrations were always highest on Wednesday and Thursday, and lowest on Sunday. Like PM_{10}, the weekdays' concentrations of $PM_{2.5}$ were about 2.97%–10.62% higher than the weekends' and the maximum values of $PM_{2.5}$ were on Wednesday. But the lowest concentrations were normally on Saturday, except Bangna station (05T) which does not show the consistency in the minimum. The results could mean that there were fewer pollution sources on weekends or the sources during weekdays probably generated more pollutants. During weekdays, there were not only more traffic in rush hour, but also other sources from activities such as combustion in factory and construction work which generally do during the weekdays. In addition, when we look at the PM_{10} concentrations during long holidays which generally have less traffic in Bangkok compared to non-holidays, the PM_{10} concentrations during the long holidays, New Year holiday (31st December–2nd January) and Songkran Festival (13th–15th April, Thai New Year) are normally lower than the concentrations during the non-holidays in the same month, January and April.

For diurnal variations of PM_{10} and $PM_{2.5}$, the common characteristic was that there were morning peaks. The peaks always occurred during rush hours which have heavy traffic. However, the diurnal variation of PM_{10} and $PM_{2.5}$ were slightly different. The study revealed that $PM_{2.5}$ had 2 peaks in the morning (hour 8–9) and the evening (hour 21–22). The morning peaks of $PM_{2.5}$ were normally as high as the evening one. On the other hand, PM_{10} in 6 stations (02T, 03T, 05T, 07T, 10T, and 59T) normally showed 2 peaks and showed 3 peaks patterns in other 4 stations (11T, 12T, 15T, and 61T), but the morning peaks were generally higher than the other peaks. For example, PM_{10} shows one peak (hour 9) at 02T (Thonburi station), 2 peaks (hour 8 and 21) at 07T (Chatuchak station), and 3 peaks (hour 7, 13, and 19) at 12T (Yannawa station). The different number of peak hours means that the locality, such as traffic intensity, urban activities, and local meteorological condition in each area, probably had a role in determining the characteristic of the particulate matters' concentration at each station.

For PM_{10} among the stations, the result found that Thonburi station (02T) had the highest average concentration, 56.18 $\mu g/m^3$, while Chomthong station (15T) had the lowest, 33.32 $\mu g/m^3$. The difference was 68.63%. It was found that the 3-highest PM_{10} concentration stations (02T, 07T, and 12T) are located in the center of Bangkok, while the 3 lowest PM_{10} stations (61T, 03T, and 15T) are located at the outskirt of Bangkok. For $PM_{2.5}$, there were only 3 monitoring stations and the concentrations at each station did not show large differences.

The differences of the pollutant levels and patterns of each station probably mean that the characteristics of PM_{10} and $PM_{2.5}$ were influenced by local factors, such as the local sources, weather or locations. The morning and evening peaks were probably affected by traffic, while other peaks may be caused by other minor sources (PCD, 2018b). Meanwhile, the baseline movement of $PM_{2.5}$ may reflect the pollution transport from somewhere else. At the same station, the main sources of the PM_{10} and $PM_{2.5}$ may be common, but the minor sources are different. Normally, both $PM_{2.5}$ and PM_{10} were high when the traffic was dense, in the morning and evening.

3.2 The Relation between $PM_{2.5}$ and PM_{10}

3.2.1 The Roadside and Non-roadside Ratios

The $PM_{2.5}$ and PM_{10} concentration showed a strong correlation when we used linear regression, the correlation equation is $[PM_{2.5}] = m[PM_{10}]$, when m is a slope of relation between $PM_{2.5}$ and PM_{10}. The $PM_{2.5}$ and PM_{10} concentrations at the same hour were plotted using a scatter plot as shown in Fig. 4 (Noted that the irrational or invalid results, i.e. the hour that $PM_{2.5}$ were higher than PM_{10} or there were only either PM_{10} or $PM_{2.5}$ concentrations, were removed which may cause slight bias of the information).

Table 2 showed that the slopes of relation between $PM_{2.5}$ and PM_{10} at non-roadside stations and roadside stations which ranged from 0.53 to 0.73. When compared the non-roadside stations with the roadside stations, we did not find distinct difference between the ratios. The results probably meant that sources of $PM_{2.5}$ and PM_{10} from the roadside and non-roadside stations were common. The R^2 of each station ranged from 0.46

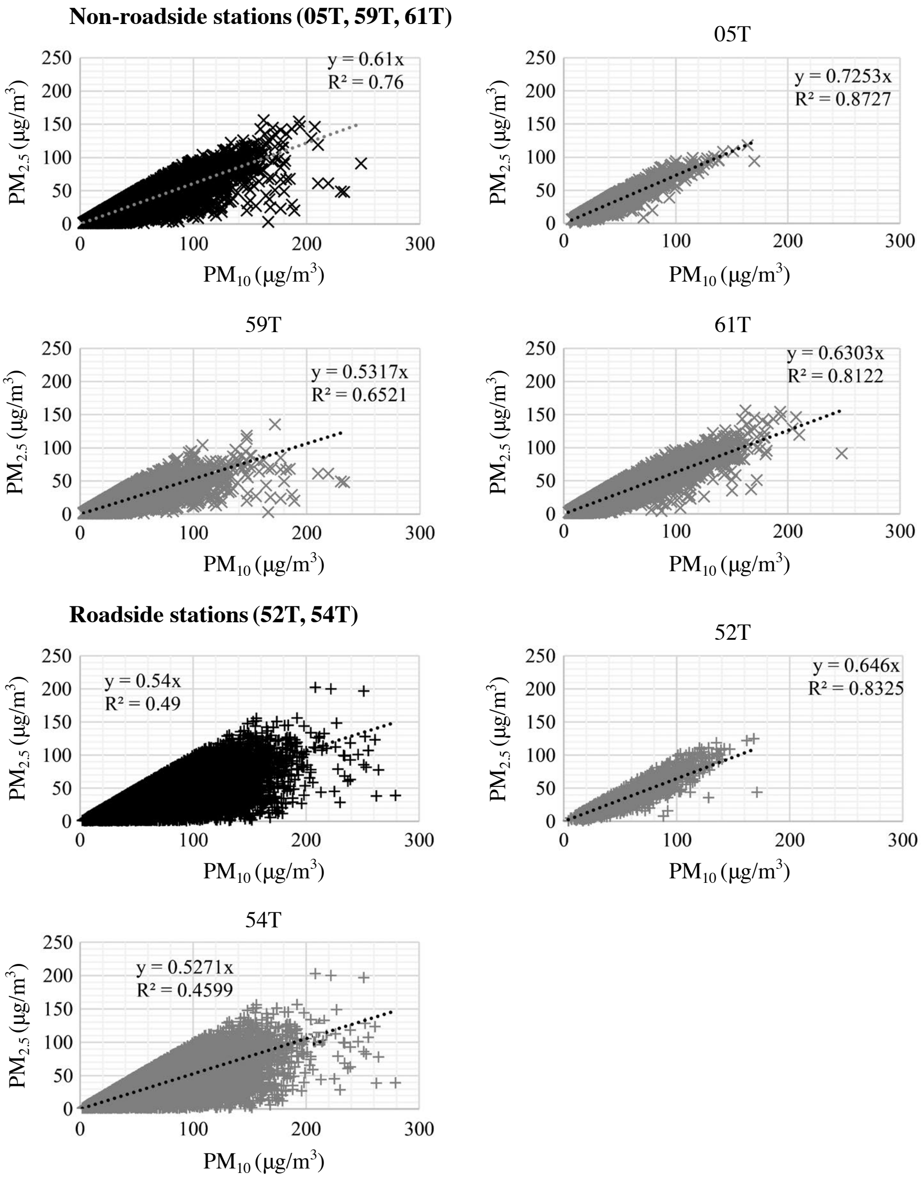


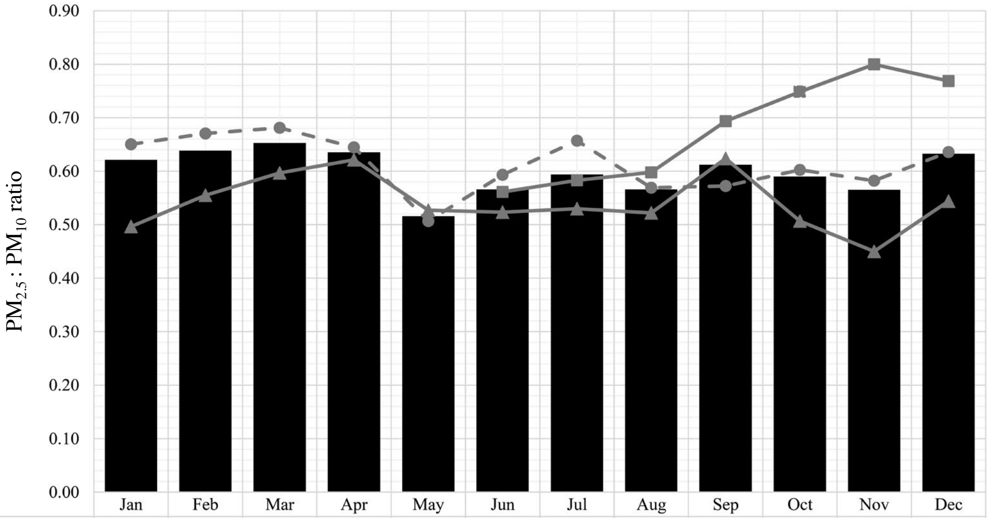
Fig. 4. The relation between $PM_{2.5}$ and PM_{10} for non-roadside and roadside stations.

Table 2. The relation between $PM_{2.5}$ and PM_{10}.

Stations	$PM_{2.5} : PM_{10}$	R^2
Non-roadside stations	0.53–0.73 (0.61 average)	0.65–0.87
05T - Bangna district	0.73	0.87
59T - Phayathai district	0.53	0.65
61T - Wangthonglang district	0.63	0.81
Roadside station	0.53–0.65 (0.54 average)	0.46–0.83
52T - Intharaphithak road	0.65	0.83
54T - Dindang road	0.53	0.46

to 0.87, regardless of station type. This may indicate that the number of common sources and emission characteristics at each station could be difference. The station with higher R^2 may have lower numbers of common source but with more intensity of emission and shorter distance to the source. While the lower R^2 probably represents the influence of the various common sources, some with less intensity or longer distance from monitoring station. Local meteorological factors also determine the correlation.

According to Fig. 4, the distributions of PM_{10} at each



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
■ All (3 stations)	0.62	0.64	0.65	0.64	0.52	0.57	0.59	0.57	0.61	0.59	0.57	0.63
—■— 05T						0.56	0.58	0.60	0.69	0.75	0.80	0.77
—▲— 59T	0.50	0.55	0.60	0.62	0.53	0.52	0.53	0.52	0.62	0.51	0.45	0.54
–●– 61T	0.65	0.67	0.68	0.64	0.51	0.59	0.66	0.57	0.57	0.60	0.58	0.64

Fig. 5. The seasonal variation of $PM_{2.5}$ to PM_{10} ratios.

station are similar with concentrations normally ranged from 0 μg/m^3 to ~< 300 μg/m^3, but the $PM_{2.5}$ distribution pattern among the station are more disperse with the maximum concentration ranged from ~< 150 μg/m^3 to ~< 200 μg/m^3 at different sites. The difference in $PM_{2.5}$ concentration range could influence the R^2 value and the ratio. It is noticed that the more dispersed $PM_{2.5}$ in the relation to that of PM_{10} could lead to the lower R^2. The stations with lower R^2 typically show more dispersed concentration of $PM_{2.5}$ as compared to the stations with higher R^2 despite the similar PM_{10} concentration ranges among sites.

3.2.2 The Seasonal Ratios

The seasonal variations of $PM_{2.5}$ to PM_{10} ratios for non-roadside stations (Fig. 5) showed that the ratios in the wet season were normally lower than the dry season.

The seasonal ratios were calculated by data from 3 continuous-months during the dry season and the wet season of each station. The results also showed that the dry season ratios were higher than the wet season ratio. As shown in Fig. 6, the $PM_{2.5}$ to PM_{10} ratio in the dry season was 0.64 with $R^2 = 0.76$, while it was 0.58 with $R^2 = 0.56$ in the wet season. According to Kim Oanh *et al.* (2006), the city averaged ratios between $PM_{2.5}$ to PM_{10} at Bangkok during 2001–2004 were 0.64 for the dry season and 0.47 for the wet season. The dry season ratio was as same as the previous study, while the wet season ratio was higher for this study. Noted that the Bangkok city averaged ratios by Kim Oanh *et al.* (2006)

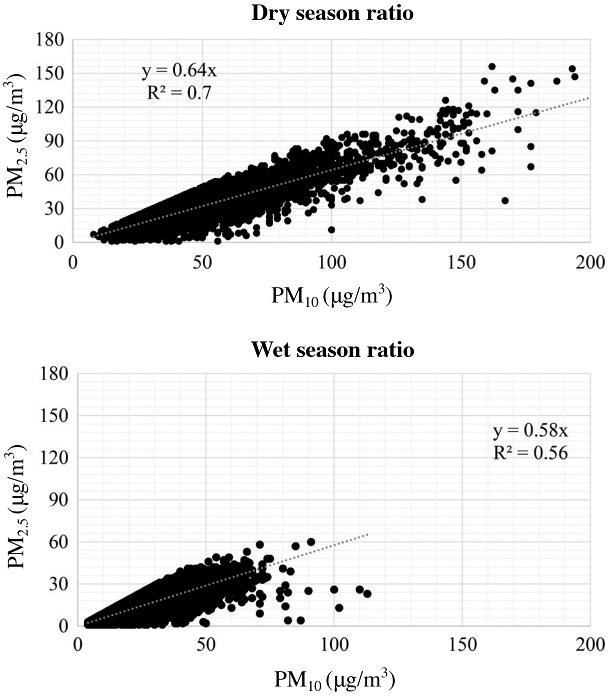


Fig. 6. The $PM_{2.5}$ to PM_{10} ratios in dry and wet season at non-roadside stations (05T, 59T, and 61T).

Table 3. The $PM_{2.5}$ to PM_{10} ratios in other countries.

City/country	$PM_{2.5}$ to PM_{10} ratios	Remarks
UK (Munir, 2016)	0.65	ranged 0.4–0.8
Scotland (Sykes, 2016)	0.66	ranged 0.56–0.80
Canada (Brook, Dann & Burnett, 1997)	0.51	Urban sites
Hongkong (EPD, 2012)	0.71	Annual ratio
	0.75	Daily ratio
Wuhan, China (Xu *et al.*, 2017)	0.62 ± 0.22	Urban sites
Beijing, China (Kim Oanh *et al.*, 2006)	0.60	Dry season
	0.58	Wet season
Chennai, India (Kim Oanh *et al.*, 2006)	0.30	Dry season
	0.32	Wet season
Bandung, Indonesia (Kim Oanh *et al.*, 2006)	0.63	Dry season
	0.61	Wet season
Manila, Philippines (Kim Oanh *et al.*, 2006)	0.61	Dry season
	0.68	Wet season
Hanoi, Vietnam (Kim Oanh *et al.*, 2006)	0.74	Dry season
	0.62	Wet season

were from upwind, traffic, urban, and residential sites.

The result means that the emission characteristics of $PM_{2.5}$ and PM_{10} were different during wet and dry season. According to a study on urban air pollution improvement in Asia (Kim Oanh, 2017), the major sources of $PM_{2.5}$ were diesel vehicles and biomass burning. During the wet season, the diesel vehicles sources were about 1.8%–4.3% higher than the biomass burning. On the other hand, the biomass burning in the dry season was about 10.6%–14.7% higher than the vehicles sources. The fresh burning during dry season which release high $PM_{2.5}$ proportion could contribute to the higher $PM_{2.5}$ and PM_{10} mixing ratio during the dry months. Moreover, the removal process can also affect to the $PM_{2.5}$ and PM_{10} concentration. During the wet season, there are both wet and dry depositions, while there is only dry deposition in the dry season. More removal processes during wet season could result in lower concentrations of $PM_{2.5}$ and PM_{10} in the wet season.

3.2.3 The Comparison between Bangkok's and Other Cities' Ratios

To compare with the $PM_{2.5}$ to PM_{10} ratios in other cities, the city averaged ratios were in the same ranged as this study, both developed and developing countries. As shown in Table 3, the mean ratios normally ranged between 0.6 to 0.8, except Chennai site. Compared to the ratio in Bangkok with 0.61 averaged for the non-roadside area, the ratio is in the same range as most cities. That implies that the major sources of urban $PM_{2.5}$ and PM_{10} in Bangkok and other cities are probably similar. According to Watson and Chow (2000), the ratios from combustion and burning are normally over 0.80, while the ratios from physical processes, such as road dust and construction site, are lower than 0.30. The result probably indicates that most urban areas normally have common sources of the $PM_{2.5}$ and PM_{10} which are mainly generated by combustion or burning. On the other hand, the major sources of $PM_{2.5}$ and PM_{10} in Chennai may be the pollutant from the physical processes.

CONCLUSION

The long-term trends of PM_{10} are negative in most residential areas in Bangkok, while the trends in some areas did not show any positive or negative. During the dry season, the trends are generally increasing, while the trends are decreasing during the wet season. The $PM_{2.5}$ and PM_{10} characteristics are influenced by meteorological factors and sources. The meteorological factors such as deposition and air transportation have a role in determining the characteristic. As shown in seasonal characteristic, the pollutions in the wet season are generally lower than in the dry season because of more deposition process, less stagnant weather, and lower emission from biomass burning. The $PM_{2.5}$ and PM_{10} sources also determine their characteristics. The days of week characteristics and the difference between long holidays and non-holidays concentrations show that the pollution concentrations during weekends and holidays which have fewer mobile sources in urban area are normally less than during weekdays and non-holidays which has more urban activities. For the diurnal characteristics, there are common peaks, normally in the morning and evening, which occurs during heavy traffic hour. However, the other peaks probably show the influence of local sources which were differently observed at the sites.

The relation between $PM_{2.5}$ and PM_{10} is shown as the $PM_{2.5}$ to PM_{10} ratio. The study shows that the ratio of residential areas in Bangkok is 0.61. The seasonal variation of the ratios shows that the ratios are normally higher during the dry season, average 0.64 for the dry season and 0.58 for the wet season. The different major pollution sources in 2 seasons and deposition processes could affect to the ratios. More fresh burning in dry seasons may have a role in increasing $PM_{2.5}$ part, while wet deposition which mainly occurs only in wet season may have a role in removing the pollutants from the atmosphere. Compared to other cities, in developed and developing countries, Bangkok's ratio is in the same range as most cities. The result could mean that the source of $PM_{2.5}$ and PM_{10} of most cities are common, mostly from combustion and burning process.

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