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Assessment of the $PM_{2.5}/PM_{10}$ ratio in the Bangkok Metropolitan Region during 2011-2017

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Abstract: Airborne particles are recognized for their adverse effects on human health and atmospheric visibility reduction, with more severe impacts in case of fine particles. Recent studies have revealed that the $PM_{2.5}/PM_{10}$ ratio can be used to estimate $PM_{2.5}$ concentrations in the absence of direct measurements. This study investigated $PM_{2.5}/PM_{10}$ ratios and relationships with meteorological parameters and others gases, including temporal trends in the Bangkok Metropolitan Region (BMR). The results showed that the overall $PM_{2.5}/PM_{10}$ ratio during 2011-2017 was 0.64, pointing out that the BMR air quality is significantly affected by combustion related emission sources, in particular from on-road transport. Also, a difference in seasonality was observed since it was found that the overall ratio during 2011-2017 was 0.67 for the dry season, and 0.60 for the wet season. The $PM_{2.5}$ to PM_{10} ratio values were found to be the highest at roadside stations followed by ambient and ambient-roadside stations. The $PM_{2.5}$ to PM_{10} ratios exhibited an upward temporal trend. The ratios showed a positive association with rain and O_3, and a negative association with wind speed and temperature. Wind speed in BMR is low and stable and it was observed that the $PM_{2.5}/PM_{10}$ ratio varied with location with a significant influence from local emission sources. A maximum $PM_{2.5}/PM_{10}$ ratio was reached during the dry season because of stable of wind speed, low temperature, low scavenging rate from rain and high concentration of O_3 in the BMR. These results should contribute providing $PM_{2.5}$ management and mitigations options in the BMR.

Keywords: $PM_{2.5}$, $PM_{2.5}/PM_{10}$ ratio, Analysis, Bangkok Metropolitan Region, Thailand.

1. Introduction

A number of epidemiological studies have found that exposure to air pollution especially particulate matter can cause a series of negative impacts on human health. There has been an increasing number of hospital admission and mortality, especially related to cardiovascular and respiratory diseases because of exposure to air pollutants [1-2].

Particulate matter, one of the major air pollutants of concern with regard to public health, is a complex mixture of liquid and solid particles in the air. Based on the aerodynamic diameter, particulate matter can be further classified into PM_{10}, coarse particles with diameters lesser than 10 µm, and $PM_{2.5}$, fine particles with diameters lesser than 2.5 µm [3]. PM can be both primary and secondary pollutants. The primary part is directly emitted to the atmosphere from different anthropogenic emission sources, including traffic, incomplete combustion process, constructions, etc. [4]. The secondary part results from the chemical reaction of gases present in the atmosphere [5]. Particulates differ in terms of physical and chemical properties depending on their emission sources and formation processes, and hence lead to different impacts on human health. $PM_{2.5}$, with a smaller particle size, has a longer lifetime in the atmosphere and is able to penetrate deeper into the lungs and even the circulatory system, thus inflicting higher human health risks [6-7].

As $PM_{2.5}$ is actually a subset of all particulates present in the atmosphere, its concentration can be estimated as a fraction of PM_{10} [8-9]. In the last decade, studies have been conducted to investigate the proportional relationship between $PM_{2.5}$ and PM_{10}, and to use the associate proportionality factor to estimate $PM_{2.5}$ concentrations from PM_{10} monitoring data. For example, Hwa-Lung and Chih-Hsin [10] demonstrated a retrospective prediction of fine particles in Taipei and found that the ratios of $PM_{2.5}$ to PM_{10} could provide a good estimation of $PM_{2.5}$ concentration over time and space; or, the study of Xu *et al.* [11] that investigated $PM_{2.5}/PM_{10}$ ratios to estimate $PM_{2.5}$ concentration without any direct measurement in the city of Wuhan. In addition, recent studies have shown that the $PM_{2.5}/PM_{10}$ ratio varies with seasons and as a function of time and location [12-13].

The Bangkok Metropolitan Region (BMR), represents one of the major metropolitan areas in the world that face nascent health impacts due to ambient air particulate matter pollution [14-15]. The Pollution Control Department (PCD) of the Air Quality and Noise Management Bureau of Thailand reported in the "Thailand Air and Noise Pollution Situation 2017 Report" that the overall air quality in Thailand seemed to be improving but that the BMR is still facing air pollution problems. This is especially so with $PM_{2.5}$ that has been exceeding the 50 µg/m^3 for 24-hr average Thailand national air quality standard about 40 to 50 days per year during January to March since 2011 [16]. The air quality monitoring station that was first operated in Bangkok to measure $PM_{2.5}$ concentrations was set up in 2011; there was only one station performing this kind of measurement in Thailand at that time [14].

This study investigated $PM_{2.5}/PM_{10}$ ratios and their relationships with other air pollutants, i.e. NOx, NO_2, NO, CO, SO_2 and O_3 and meteorological parameters, including, temperature, relative humidity rain, wind speed, and wind direction. Temporal trends were also investigated based on data records from the PCD during 2011–2017 in the BMR.

2. Methodology

2.1 Study Area

Bangkok, the capital city of the Kingdom of Thailand, is located in the Chao Phraya River delta in the central plain region of the country. Bangkok and its five surrounding provinces, including Nonthaburi, Samut Prakan, Pathum Thani, Samut Sakhon, and Nakhon Pathom, together form the Bangkok Metropolitan Region, or BMR in short (Figure 1). It is one of the major metropolis in the world. With an area of 7,762 km^2, BMR houses about 11 million people and is the central hub for commerce and tourism in the Southeast Asian (SEA) region [17]. The climate in the BMR is primarily affected by the Asian Monsoon. From November to February, the BMR is dominated by the northeast monsoon which brings dry conditions and light winds, while from May to October, the southwest monsoon brings warm, humid, and unstable air masses, as well as considerable precipitations from the oceans.

2.2 Air Quality Monitoring Data

In the BMR, air quality data are monitored in real-time at 21 air quality monitoring stations operated by the Pollution Control Department (PCD). The spatial distribution of the stations is shown in Figure 2. Stations are categorized into three types: (1) roadside stations for those located within 10 m to main roads, (2) ambient stations for those situated about 50 m away from major roads, and (3) ambient-roadside stations for those locate between 10–50 m from the main road.

All of the 21 stations are set for monitoring PM_{10}, but only seven of them are equipped for $PM_{2.5}$ measurement. The seven station locations are described in more details in Table 1 and displayed in Figure 2. In the BMR, $PM_{2.5}$ monitoring started in 2011 at the station 54T, while PM_{10} has been measured since 2000. Particulate matter concentrations are measured on an hourly basis by Beta-ray method (see Table 2). Hourly concentration data of $PM_{2.5}$, $PM_{10,}$ meteorological parameters and other gaseous during 2011–2017 were obtained from the PCD and analysed. It should be noted that there was a large variation in the completeness of the data between the stations, in particular, several stations possessed only two or three years of $PM_{2.5}$ concentration data.

2.3 Data Analysis

Hourly monitoring data of $PM_{2.5}$, PM_{10} NO_X, NO_2, NO, CO, SO_2, O_3, wind speed, wind direction, temperature relative humidity, and rain were used in this study. Monitoring stations characterised by more than 25% of missing data during a year were not considered. $PM_{2.5}/PM_{10}$ ratios were investigated by pairing the daily average of $PM_{2.5}$ and PM_{10} concentrations, and calculating seasonal averages (dry and wet seasons) for each station. The assessments were categorised based on station types (roadside, ambient and ambient-roadside stations). The year was divided into two seasons as suggested by Oanh *et al*. [18], i.e. dry season from November to April, and wet season from May to October. The ratios and their relationships with other air pollutants, i.e, NO_X, NO_2, NO, CO, SO_2 and $O_{3,}$ and meteorological parameters, i.e. temperature, relative humidity, rain, wind speed and wind direction, were investigated. Finally, the trends of $PM_{2.5}/PM_{10}$ ratios in the BMR were investigated. The data were processed using the R software (version 3.4.4) [19] and its package open air [20].

Table 1. Description of air quality monitoring stations measuring $PM_{2.5}$ in BMR.

Station	Location	Duration	Air Quality Measurement	Description
05T	Bangkok	2016–2017	$PM_{2.5}$, PM_{10}, CO, SO_2, NO, NO_2, NO_X, Relative humidity, Temperature, Wind direction, Wind speed, Rain	Ambient station; located at Thai Meteorological Department in Bangna district, 80 m from Sukhumvit Road.
08T	Samut Prakan	2016–2017	$PM_{2.5}$, PM_{10}, CO, SO_2, NO, NO_2, NO_X, Relative humidity, Temperature, Wind direction, Wind speed, Rain	Ambient station; locate at Vocational Rehabilitation Center for Persons with Disabilities in Phra Pradaeng district, 500m from Industrial Ring Road in suburb.
27T	Samut Sakhon	2013–2017	$PM_{2.5}$, PM_{10}, SO_2, NO, NO_2, NO_X, Temperature, Wind direction, Wind speed, Rain	Ambient-Roadside station; located at Samut Sakhon Wittayalai School in Mueang Samut Sakhon district, 20m from Rama II road.
52T	Bangkok	2016–2017	$PM_{2.5}$, PM_{10}, CO, SO_2, NO, NO_2, NO_X, Relative humidity, Temperature, Wind direction, Wind speed, Rain	Roadside station; located at MEA Substation Thonburi, next to Phet Kasem Road and Intharaphithak Road.
54T	Bangkok	2011–2016	$PM_{2.5}$, PM_{10}, CO, SO_2, NO, NO_2, NO_X, Relative humidity, Temperature, Wind direction, Wind speed, Rain	Roadside station; located at Public Community Din Daeng residential area, next to a busy Din Daeng Road, and about 200m from Chaloem Maha Nakhon Expressway .
59T	Bangkok	2015–2017	$PM_{2.5}$, PM_{10}, CO, NO, NO_2, NO_X, Relative humidity, Temperature, Wind direction, Wind speed, Rain	Ambient station; located at Government Public Relations Department in the governmental offices area, 400m from Siraj expressway.
61T	Bangkok	2014–2017	$PM_{2.5}$, PM_{10}, SO_2, NO, NO_2, NO_X, Temperature, Wind direction, Wind speed	Ambient station; located at Bodindecha (Sing Singhaseni) School in residential area

All of these stations were recoded $PM_{2.5}$ and PM_{10} concentrations by Beta-ray method

Table 2. Measurement methods at air quality monitoring stations in the Bangkok Metropolitan Region.

Air quality	Methodology	Height	Range
$PM_{2.5}$, PM_{10}	Beta-ray method	3 m	0–1000 µg/m^3
CO	Non-Dispersive Infrared Detection	3 m	0–50 ppm
SO_2	UV-Fluorescence	3 m	0–500 ppb
NO, NO_2, NO_X	Chemiluminescence	3 m	0–500 ppb
Relative Humidity	Thin Film Polymer Capacitor	3 m	0–100 %RH
Temperature	Multistage solid state thermistor, highly linearized	3 m	(-50)–50 ºC
Wind Direction	Wind Vane	10 m	0–360 deg
Wind Speed	Cup propeller	10 m	0–50 m/s
Rain	Tipping Bucket	3 m	mm/h

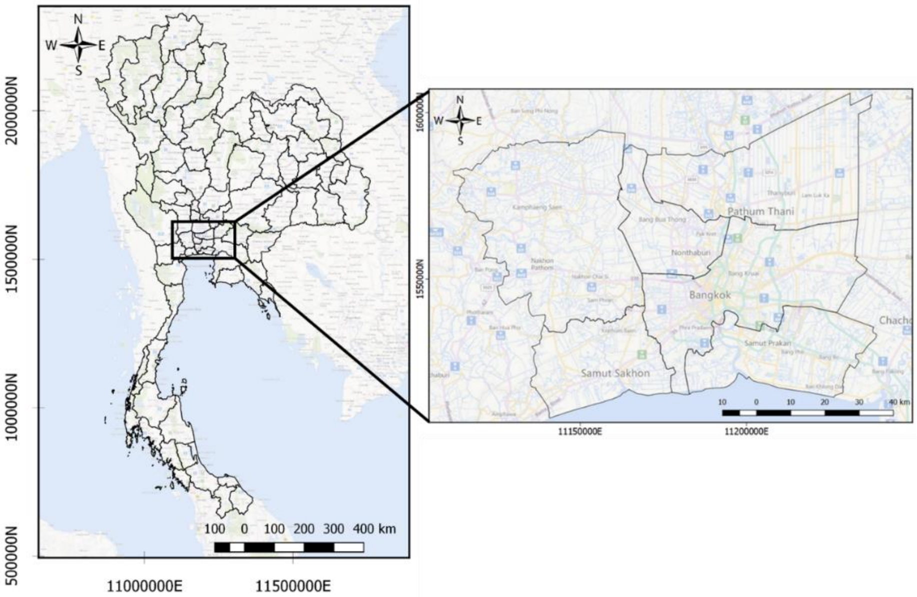

Figure 1. Map of the Bangkok Metropolitan Region in Thailand.

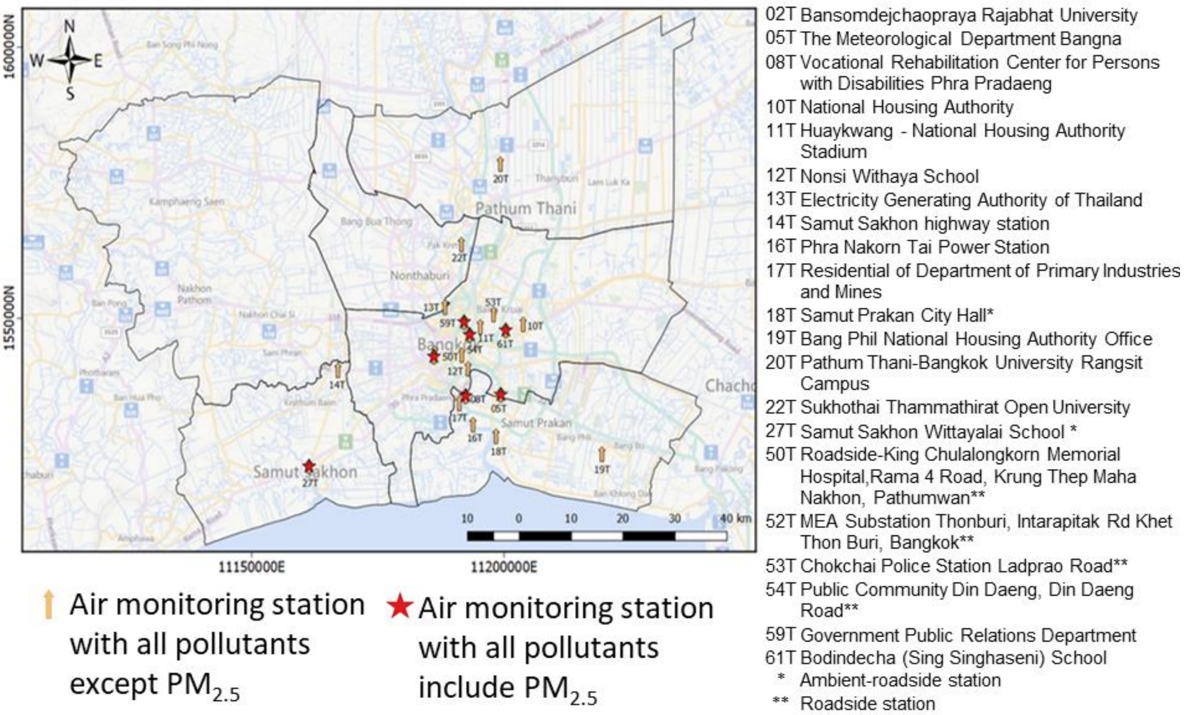

Figure 2. Location of air quality monitoring stations in the Bangkok Metropolitan Region.

3. Results and Discussion

3.1 PM_{10} and $PM_{2.5}$ Concentration Profiles

A typical profile of PM_{10} and $PM_{2.5}$ daily concentrations over the period of 2011–2017 is illustrated in Figure 3, using monitoring data in BMR. From Figure 3, a clear depiction of the seasonal variation patterns of both pollutants is noticed. Indeed, annual PM_{10} and $PM_{2.5}$ concentrations are observed to rise during the dry seasons, peaking in January or February. Lower values are observed during the wet season, bottoming around July or August.

PM_{10} and $PM_{2.5}$ exhibit fairly concordant trends, as they tend to reach the highest and lowest concentrations concurrently. The difference in concentration between PM_{10} and $PM_{2.5}$ appears to vary over time with a larger difference observed during the dry season. PM_{10} concentrations also display greater fluctuations than $PM_{2.5}$, with more significant daily variations. Thailand has set the national ambient air quality standards for PM_{10} and $PM_{2.5}$ at 120 $\mu g/m^3$ and 50 $\mu g/m^3$, respectively, for 24-hour average concentrations. As shown in Figure 3, PM_{10} daily concentrations appeared to be lower than the standard most of the time over the period of 2011–2017, with only a few days during the dry season exceeding the 120 $\mu g/m^3$ limit. In contrary, the $PM_{2.5}$ daily concentrations were above the 50 $\mu g/m^3$ standard very frequently during the dry season, especially from January to March, suggesting that more intensive monitoring of $PM_{2.5}$ concentrations would be useful to support the formulation of policy measures and action plans in order to bring the high concentration down to attain the national standard.

The seasonal average concentrations of both $PM_{2.5}$ and PM_{10} are shown in Table 3. The $PM_{2.5}$ concentration was found to be in the range 29.23–53.07 $\mu g/m^3$ for the dry season and 12.57–29.24 $\mu g/m^3$ for the wet season. The overall average $PM_{2.5}$ concentration was assessed to be 39.07±17.49 $\mu g/m^3$ for the dry season and 20.60±08.66 $\mu g/m^3$ for the wet season. In addition, the seasonal average PM_{10} concentration was found to be in the range 58.84–25.96 $\mu g/m^3$ for the dry season and 34.59–12.89 $\mu g/m^3$ for the wet season. The overall average PM_{10} concentration was assessed to be 39.07±17.49 $\mu g/m^3$ for the dry season and 20.60±08.66 $\mu g/m^3$ for the wet season. These results confirm that both $PM_{2.5}$ and PM_{10} concentrations in the BMR were higher during the dry season compared to the wet season over the period 2011–2017. These findings are in line with the study by Chuersuwan *et al*. [21] which identified biomass burning and the lack of rain scavenging during the dry season as main contributing factors to the higher levels of particulate matter observed during that period of time.

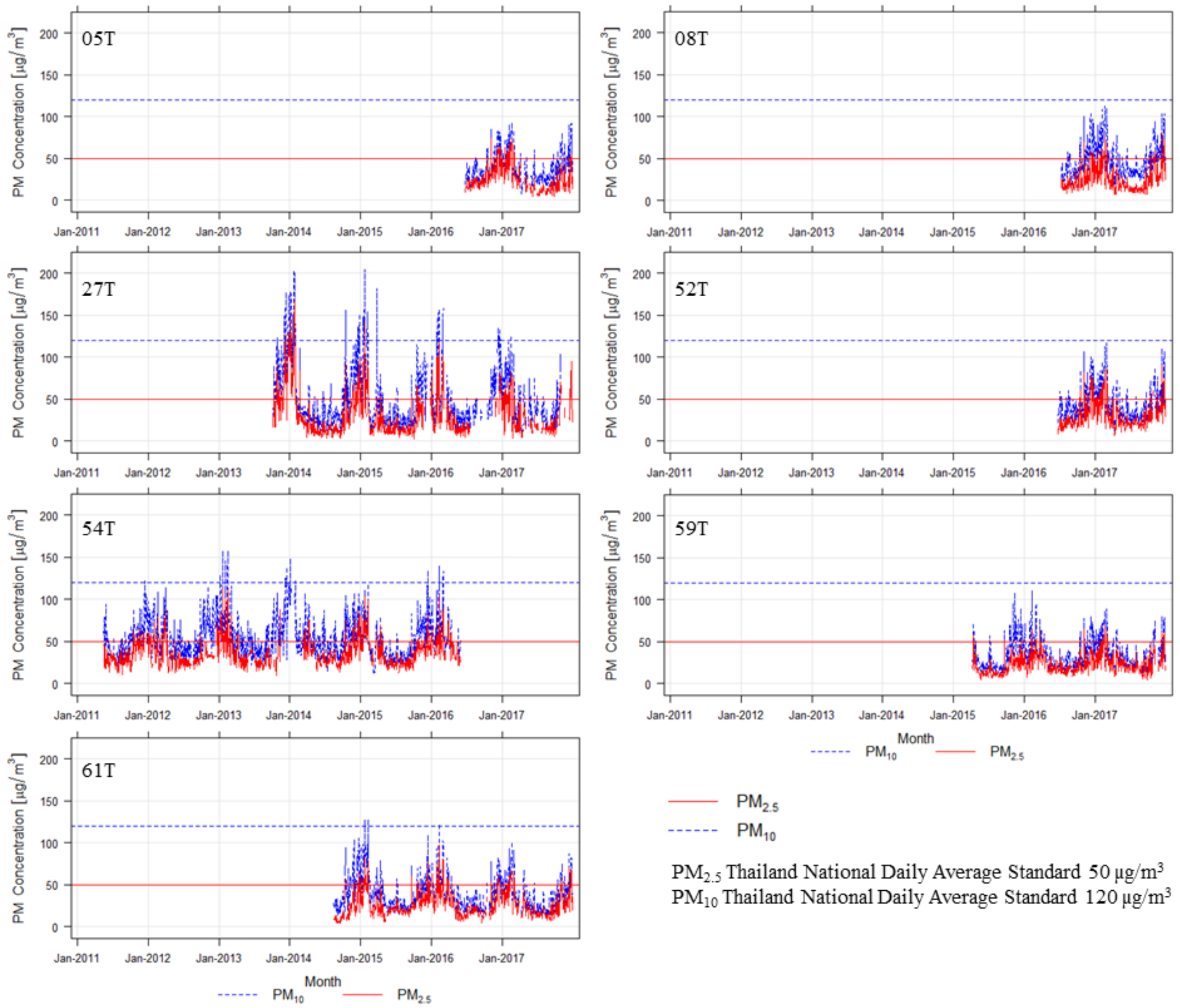

Figure 3. $PM_{2.5}$ and PM_{10} daily average concentrations in the BMR, with Thailand's standards of 50 $\mu g/m^3$ for $PM_{2.5}$ and 120 $\mu g/m^3$ for PM_{10} represented as red-solid and blue-dash lines, respectively.

Table 3. $PM_{2.5}$ and PM_{10} concentrations and ratios in different seasons in the BMR.

Station	Year	$PM_{2.5}$ Concentration		PM_{10} Concentration		$PM_{2.5}/PM_{10}$ ratios	
		Dry	Wet	Dry	Wet	Dry	Wet
05T	2016	-	21.35 ± 06.73	-	30.70 ± 09.35	-	0.71 ± 0.11
	2017	39.31 ± 14.54	13.85 ± 06.77	46.08 ± 20.10	29.82 ± 10.56	0.82 ± 0.06	0.44 ± 0.09
08T	2016	-	19.61 ± 07.41	-	35.89 ± 10.80	-	0.55 ± 0.09
	2017	32.47 ± 14.73	17.89 ± 08.55	60.30 ± 20.38	37.74 ± 11.09	0.52 ± 0.08	0.46 ± 0.09
27T	2014	53.07 ± 38.30	16.52 ± 12.69	76.44 ± 49.08	34.74 ± 20.83	0.67 ± 0.09	0.46 ± 0.08
	2015	39.98 ± 25.10	16.32 ± 11.03	66.85 ± 39.53	30.34 ± 17.86	0.58 ± 0.08	0.52 ± 0.10
	2016	36.87 ± 22.47	13.77 ± 04.99	60.16 ± 32.78	28.64 ± 10.03	0.62 ± 0.08	0.55 ± 0.08
	2017	37.43 ± 21.03	18.97 ± 11.01	62.71 ± 31.34	36.87 ± 17.17	0.62 ± 0.09	0.54 ± 0.09
52T	2016	-	22.01 ± 07.84	-	36.86 ± 09.57	-	0.58 ± 0.09
	2017	39.69 ± 17.39	23.09 ± 07.58	54.65 ± 22.20	34.12 ± 10.76	0.71 ± 0.06	0.69 ± 0.08
54T	2011	-	29.04 ± 09.71	-	46.85 ± 15.04	-	0.63 ± 0.14
	2012	42.06 ± 16.06	27.68 ± 07.58	65.30 ± 20.76	45.60 ± 15.37	0.69 ± 0.11	0.65 ± 0.11
	2013	42.67 ± 18.56	27.09 ± 07.99	68.71 ± 27.22	46.15 ± 17.63	0.64 ± 0.13	0.61 ± 0.12
	2014	45.08 ± 13.94	29.24 ± 08.91	67.04 ± 26.69	46.30 ± 15.95	0.76 ± 0.11	0.64 ± 0.12
	2015	47.95 ± 17.12	26.49 ± 08.59	57.21 ± 22.86	37.21 ± 14.24	0.77 ± 0.12	0.72 ± 0.10
	2016	46.60 ± 12.89	29.21 ± 05.81	67.80 ± 20.60	49.73 ± 16.39	0.70 ± 0.12	0.69 ± 0.08
59T	2015	-	17.38 ± 7.28	-	25.41 ± 12.20	-	0.58 ± 0.08
	2016	29.23 ± 09.85	17.38 ± 5.59	48.52 ± 17.12	24.51 ± 07.91	0.61 ± 0.14	0.70 ± 0.10
	2017	29.53 ± 11.95	19.41 ± 7.72	44.67 ± 17.05	27.49 ± 09.39	0.66 ± 0.09	0.70 ± 0.13
61T	2014	-	12.57 ± 10.39	-	31.34 ± 16.17	-	0.36 ± 0.10
	2015	30.63 ± 15.74	21.79 ± 08.34	57.04 ± 22.69	28.06 ± 10.28	0.52 ± 0.08	0.76 ± 0.15
	2016	38.04 ± 13.87	15.88 ± 19.18	49.72 ± 18.36	25.59 ± 07.72	0.77 ± 0.07	0.63 ± 0.14
	2017	33.50 ± 13.78	17.35 ± 07.45	47.10 ± 19.18	25.70 ± 10.08	0.73 ± 0.09	0.67 ± 0.08
Overall		39.07±17.49	20.60 ± 08.66	58.84 ± 25.96	34.59 ± 12.89	0.67 ± 0.10	0.60 ± 0.10

3.2 $PM_{2.5}/PM_{10}$ Ratio

Table 3 provides information on the seasonal annual average values of $PM_{2.5}$ and PM_{10} concentrations, and $PM_{2.5}/PM_{10}$ ratios at each station in the BMR over the period 2011-2017. The seasonal average values of the $PM_{2.5}$ to PM_{10} ratio was found to vary with values in the range 0.52–0.82 for the dry season and 0.36–0.76 for the wet season. In addition, the overall average value of the $PM_{2.5}/PM_{10}$ ratio was found to be 0.67±0.10 for the dry season and 0.60±0.10 for the wet season, leading to an annual average value of 0.64±0.10 over the period 2011–2017. The overall ratio of $PM_{2.5}$ to PM_{10} in this study was observed to be greater than 0.50 indicating that the proportion of $PM_{2.5}$ within PM_{10} dominates at most station. This shows that the pollution in particulate matter in the BMR is significantly affected by combustion related emission sources, in particular from on-road transport. The overall average value of the $PM_{2.5}$ to PM_{10} ratio identified in this study is higher than the general values identified in Asian countries; this includes that of Thailand during 2000–2003 which was reported to be below 0.5 [22]. This shows that there has been an increase in the proportion of $PM_{2.5}$ released to the atmosphere over the past decade. One of the main anthropogenic sources of $PM_{2.5}$ is diesel vehicles [21, 23]. A recent study by Cheewaphongphan *et al.* [24] showed that the cumulative number of vehicles registered in the BMR over the past decade (since 2007) has increased and that diesel is the fuel that is the most consumed volume-wise.

Table 4 provides a comparison of the $PM_{2.5}/PM_{10}$ ratio in the BMR and some Chinese cities also faced with issues of $PM_{2.5}$ pollution. The ratio of $PM_{2.5}$ to PM_{10} in the BMR (0.63) is somewhat comparable to that reported in Wuhan city (0.62) and Chengdu (0.64). However, it is lower than the ratio value reported for Beijing (0.69), indicating that fine particulate matter pollution is of even greater concern in that city [11, 25-26].

Table 4. $PM_{2.5}/PM_{10}$ ratios in the BMR and selected Chinese cities.

Country	City	Year	$PM_{2.5}/PM_{10}$ ratio	References
Thailand	BMR	2011-2017	0.63	This study
China	Beijing	2013	0.69	[25]
	Chengdu	2013-2014	0.64	[26]
	Wuhan	2013-2015	0.62	[11]

Table 5 presents results relating to seasonal average values of $PM_{2.5}$ and PM_{10} concentrations as well as $PM_{2.5}/PM_{10}$ ratios categorized based on types of monitoring stations. The results show that the ratios are the highest at roadside stations (dry season: 0.71 and wet season: 0.65) followed by ambient (dry season: 0.63 and wet season: 0.56) and ambient-roadside stations (dry season: 0.63 and wet season: 0.52). These results along with the observation that particulate matter pollution has seen an increase in fine particulate matter pollution over the last decade, along with variations based on seasons and locations, and with ratio values similar to those reported for some cities in China, suggests that $PM_{2.5}/PM_{10}$ ratios should be used to estimate $PM_{2.5}$ concentrations at air quality monitoring stations where only PM_{10} is monitored in the BMR.

Table 5. $PM_{2.5}$ and PM_{10} concentrations and ratios by seasons and type of stations in the BMR.

Station	Year	$PM_{2.5}$ Concentration		PM_{10} Concentration		$PM_{2.5}/PM_{10}$ ratios	
		Dry	Wet	Dry	Wet	Dry	Wet
Ambient	2014		12.57 ± 10.39		31.34 ± 16.17		0.36 ± 0.10
	2015	30.63 ± 15.74	19.59 ± 07.81	57.04 ± 22.69	26.74 ± 11.24	0.52 ± 0.08	0.67 ± 0.12
	2016	33.64 ± 11.86	18.56 ± 09.73	49.12 ± 17.74	29.17 ± 08.95	0.69 ± 0.11	0.65 ± 0.11
	2017	33.70 ± 13.75	17.13 ± 07.62	49.54 ± 19.18	30.19 ± 10.28	0.68 ± 0.08	0.57 ± 0.10
	Overall	32.66 ± 13.78	16.96 ± 08.89	51.90 ± 19.87	29.36 ± 11.66	0.63 ± 0.09	0.56 ± 0.11
Ambient-Roadside	2014	53.07 ± 38.30	16.52 ± 12.69	76.44 ± 49.08	34.74 ± 20.83	0.67 ± 0.09	0.46 ± 0.08
	2015	39.98 ± 25.10	16.32 ± 11.03	66.85 ± 39.53	30.34 ± 17.86	0.58 ± 0.08	0.52 ± 0.10
	2016	36.87 ± 22.47	13.77 ± 04.99	60.16 ± 32.78	28.64 ± 10.03	0.62 ± 0.08	0.55 ± 0.08
	2017	37.43 ± 21.03	18.97 ± 11.01	62.71 ± 31.34	36.87 ± 17.17	0.62 ± 0.09	0.54 ± 0.09
	Overall	41.84 ± 26.73	16.40 ± 09.93	66.54 ± 38.18	32.65 ± 16.47	0.62 ± 0.09	0.52 ± 0.09
Roadside	2011		29.04 ± 09.71		46.85 ± 15.04		0.63 ± 0.14
	2012	42.06 ± 16.06	27.68 ± 07.58	65.30 ± 20.76	45.60 ± 15.37	0.69 ± 0.11	0.65 ± 0.11
	2013	42.67 ± 18.56	27.09 ± 07.99	68.71 ± 27.22	46.15 ± 17.63	0.64 ± 0.13	0.61 ± 0.12
	2014	45.08 ± 13.94	29.24 ± 08.91	67.04 ± 26.69	46.30 ± 15.95	0.76 ± 0.11	0.64 ± 0.12
	2015	47.95 ± 17.12	26.49 ± 08.59	57.21 ± 22.86	37.21 ± 14.24	0.77 ± 0.12	0.72 ± 0.10
	2016	46.60 ± 12.89	25.61 ± 06.83	67.80 ± 20.60	43.30 ± 12.98	0.70 ± 0.12	0.64 ± 0.09
	2017	39.69 ± 17.39	23.09 ± 07.58	54.65 ± 22.20	34.12 ± 10.76	0.71 ± 0.06	0.69 ± 0.08
	Overall	44.01 ± 15.99	26.89 ± 08.17	63.45 ± 23.39	42.79 ± 14.57	0.71 ± 0.11	0.65 ± 0.11

3.3 Relationship between $PM_{2.5}/PM_{10}$ Ratios and Air Quality Parameters

The correlation coefficient values between $PM_{2.5}/PM_{10}$ ratios and other air quality parameters were found to be different depending on seasonal changes and locations (monitoring stations) in the BMR during 2011–2017. Figure 4 shows the overall correlation between $PM_{2.5}/PM_{10}$ ratio, relative humidity, wind speed, wind direction, temperature, rainfall, NO_X, NO_2, NO, CO, SO_2 and O_3 in different seasons in the BMR. The ratios were positively associated with rain (the strongest correlation at station 08T dry season (r = 0.28) and O_3 (the strongest correlation at station 05T dry season (r = 0.57)) in both the dry and wet season indicating that the proportion of $PM_{2.5}$ within PM_{10} increases when there is more rain in the atmosphere. The relationship between $PM_{2.5}$ and O_3 is complex as O_3 is an oxidant which can change the concentration of free radicals and therefore the formation of $PM_{2.5}$ as secondary pollutant [27]. The positive correlation between the $PM_{2.5}/PM_{10}$ ratio and rain can be explained by the size of particles as larger particles can have greater scavenging rates than smaller particles. A study in Lanzhou, China showed that the scavenging rates of coarse particles are greater than those of fine particles as a result of precipitation. Additionally, it was reported that the scavenging rates of precipitation had very little influence on the concentration of all kinds of particles for a 3 hr-rainfall of less than 1.00 mm. However, for a 3 hr-rainfall exceeding 1.00 mm a greater impact on the concentration of particulate matter was observed. In addition, rainfall makes the ground wet, which helps to depress re-suspension, mainly coarse particles, generated by soil blowing, dust blowing, traffic and other human activities [28].

The ratios were found to be negatively associated with wind speed (the strongest correlation at station 52T wet season (r = -0.52)) and temperature (the strongest correlation at station 52T dry season (r = -0.46)) in both dry and wet seasons indicating that when the wind speed and temperature are decreasing, the $PM_{2.5}$ concentration is rising and therefore its proportion within PM_{10}. These results are similar to a study in Bahrain that showed that the ratios of $PM_{2.5}$ to PM_{10} were negatively correlated with temperature and wind speed. The concentration of PM_{10} was found to increase in the atmosphere on windy days characterized by higher ambient temperature [29]. Although strong wind can blow ambient particulate matter to distant places, strong wind can also re-suspend coarse particles, dusts and soil from the ground, impacting the ratio of $PM_{2.5}$ to PM_{10}. Lower wind speed may lead to greater concentrations of $PM_{2.5}$ as result of the accumulation of fine particles from vehicle combustion, and to lower resuspensions of coarse particles [30]. $PM_{2.5}/PM_{10}$ ratios can reach a maximum value during colder weather conditions as a result of the phenomenon of temperature inversion. This leads to an accumulation of $PM_{2.5}$ in the atmosphere as result of low wind speed [11, 31]. Therefore, the ratios of $PM_{2.5}$ to PM_{10} are higher during the dry season as windy days are lower and an inversion layer can also form during certain periods of time in the BMR.

The relative humidity, wind direction, CO and SO_2 were found to be correlated with $PM_{2.5}/PM_{10}$ ratios at different air quality monitoring stations. NO_X, NO_2 and NO were also correlated with $PM_{2.5}/PM_{10}$ ratios at different air quality monitoring stations.

In terms of wind speed and wind direction, the pattern of $PM_{2.5}/PM_{10}$ ratios is different in each season and station. Figure 5 shows the association between $PM_{2.5}/PM_{10}$ ratios, and wind speed and wind direction. Wind speed in the BMR was observed to be quite stable and low, less than 3 m/s over a year. Figure 5 also shows that the $PM_{2.5}$ to PM_{10} ratios were higher during the dry season. Stations 05T, 08T and 27T were mostly under the influence of a west southerly wind during the dry season. During the wet season, for stations 05T and 08T were mostly influenced by a north easterly wind with wind speed in the range 0.5–2.5 m/s. Station 27T on the other hand was mostly under the influence of a west southerly wind with wind speed of 2.5 m/s and an east southerly wind with low wind speed (not exceeding 0.5 m/s). For the roadside stations 52T and 54T, high $PM_{2.5}$ to PM_{10} ratio values were mostly observed for multidirectional wind characterized by very low speed both for the dry and wet season. The higher ratios observed during the dry season is also an indication of the influence of local sources to this ratio. Station 59T is located in a governmental office area as shown in Figure 2. As, it is characterized by high traffic, the

$PM_{2.5}$ to PM_{10} ratios were influenced by local sources of emissions. The highest ratio was generally observed during the dry season under condition of west southerly wind with wind speed of 1.5 m/s. At station 61T, $PM_{2.5}$ to PM_{10} ratios were under the influence of westerly winds. High ratios were observed under the conditions of west-northerly wind with wind spend of 2.5 m/s and west southerly wind with wind speed of 2.5 m/s. Overall wind speed in the BMR was observed to be low and stable, therefore, the ratios of $PM_{2.5}$ to PM_{10} were significantly affected by combustion related emission sources, in particular from on-road transport.

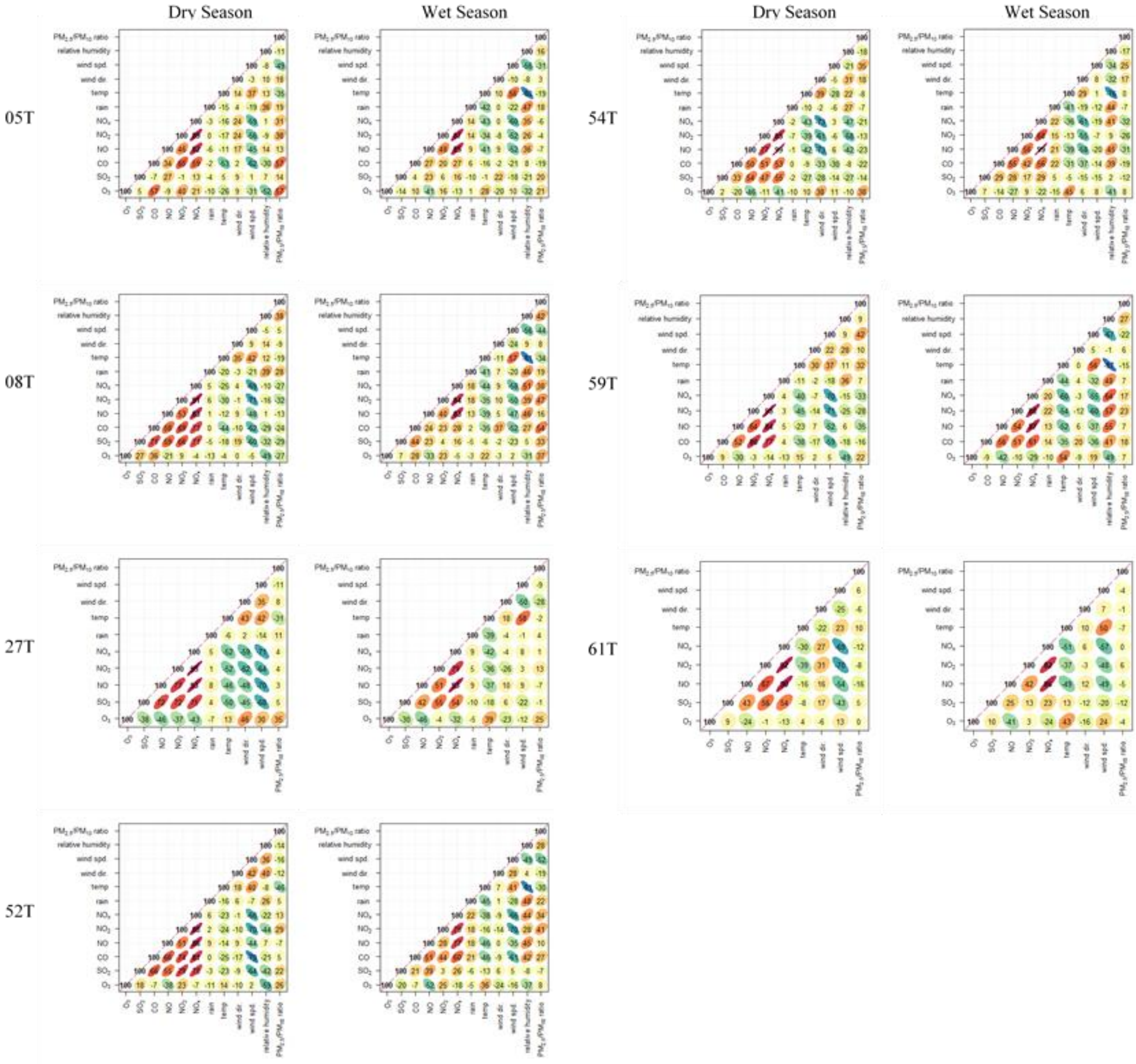

Figure 4. Correlation matrices of $PM_{2.5}/PM_{10}$ ratios, relative humidity, wind speed (wind spd.), wind direction (wind dir.), temperature (temp), rain, NO_X, NO_2, NO, CO, SO_2 and O_3 in different seasons at stations 05T (2016 – 2017), 08T (2016 – 2017), 27T (2014 – 2017), 52T (2016 – 2017), 54T (2011 – 2016), 59T (2015 – 2017) and 61T (2014 – 2017) in the BMR.

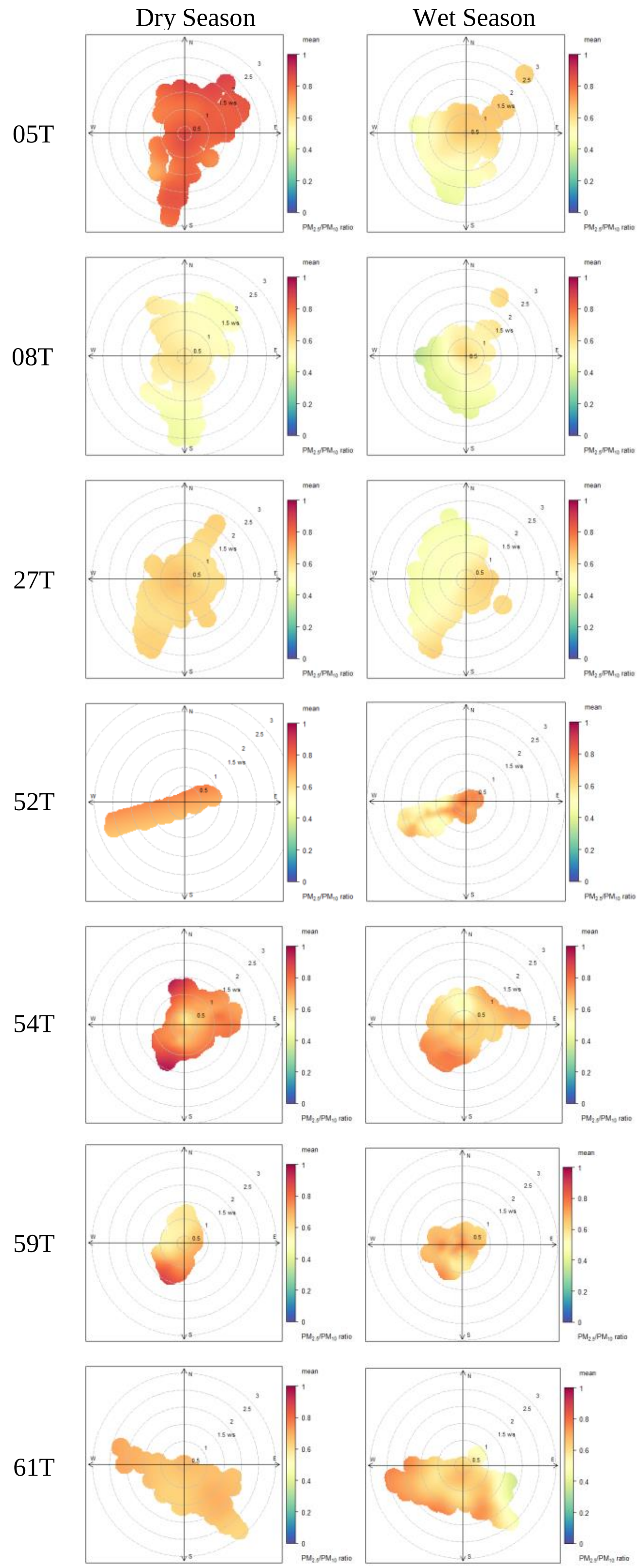

Figure 5. Polar plots of wind speed, wind direction and $PM_{2.5}/PM_{10}$ ratios in different seasons at stations 05T (2016 – 2017), 08T (2016 – 2017), 27T (2014 – 2017), 52T (2016 – 2017), 54T (2011 – 2016), 59T (2015 – 2017) and 61T (2014 – 2017) in the BMR.

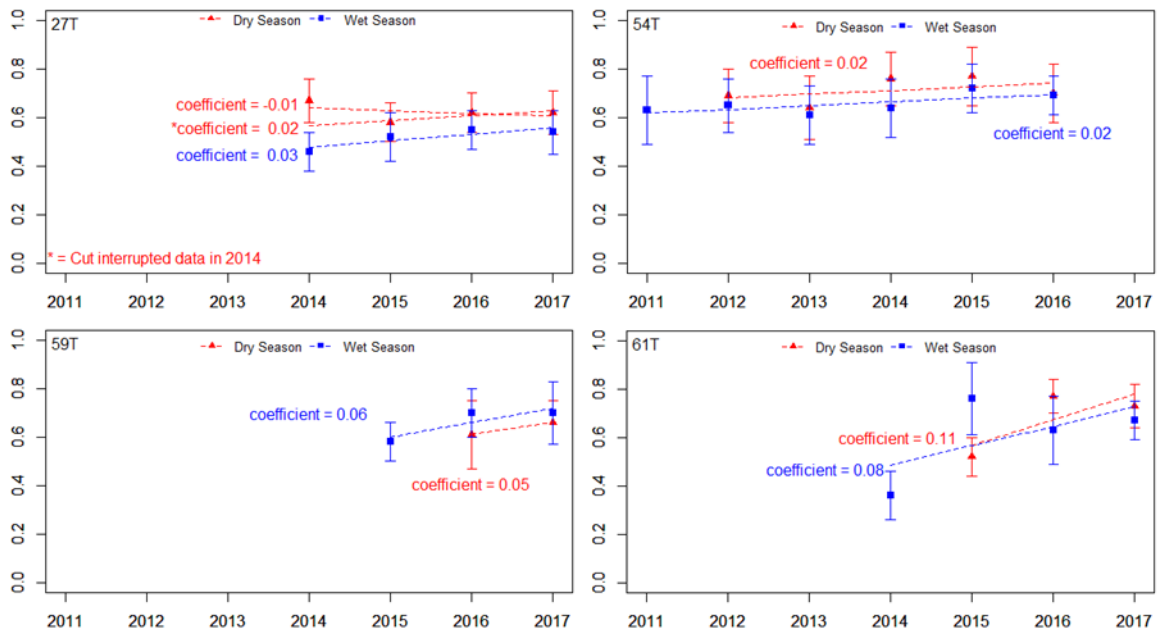

Figure 6. Seasonal trends of $PM_{2.5}/PM_{10}$ ratios in the BMR during 2011–2017.

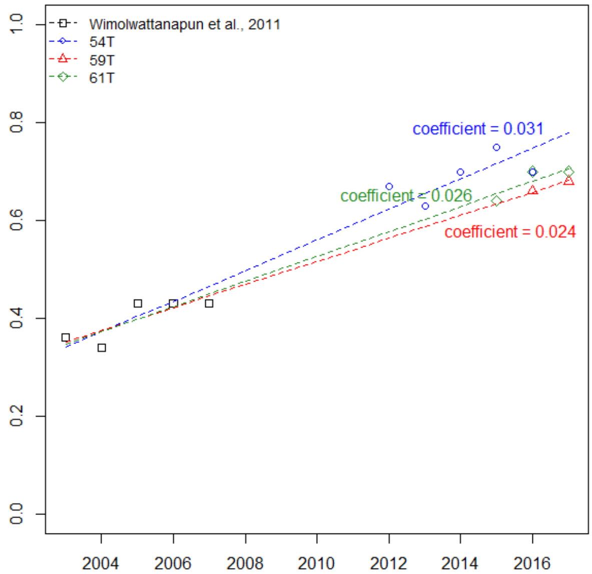

Figure 7. Annual trends of $PM_{2.5}/PM_{10}$ ratios in the BMR during 2003–2017.

3.4 Trends of $PM_{2.5}/PM_{10}$ ratios in the BMR

The trend of $PM_{2.5}/PM_{10}$ ratios at four air quality monitoring stations which have at least three years' data are reported in Figure 6. It was observed that at the ambient-roadside station in Samut Sakhon (27T), the $PM_{2.5}/PM_{10}$ ratio increased by about 2% annually for the dry season and 3% for the wet season. At Din Daeng roadside station (54T), a 2% annual increase was observed for both the dry and wet season. For the ambient station at the Public Relations Department (59T), a 5% and 6% annual increase was observed for the dry season and the wet season respectively. Finally, at the Bodindecha School ambient station (61T), an 11% and 8% annual increase was observed for the dry season and the wet season respectively. Over the period 2011-2017, an upward trend was observed for the $PM_{2.5}$ to PM_{10} ratio in the BMR over the dry and wet season. This indicates that the proportion of $PM_{2.5}$ within PM_{10} has been increasing over that period of time. These results are in agreement with a previous study in Bangkok which demonstrated that the $PM_{2.5}/PM_{10}$ ratio had increased over the period 2003–2007 [32]. The extrapolation from the study by Wimolwattanapun *et al.* [32] to the three Bangkok stations located nearby in this study (see Figure 7) show that the ratios of $PM_{2.5}$ to PM_{10} increased by 3.1%, 2.6% and 2.4% from 2003 to 2017 at stations 54T, 59T and 61T, respectively. These findings show that there has been an increase in the concentration of $PM_{2.5}$ and proportion of $PM_{2.5}$ within PM_{10} in Bangkok [32].

4. Conclusions

This study investigated the seasonal ratios of $PM_{2.5}$ to PM_{10} and relationships with meteorological parameters and other gases in the BMR during 2011–2017. The ratios were found to vary with time and space. The overall annual ratio was determined to be 0.64±0.10. The overall ratio for the dry season (0.67 ± 0.10) was found to be higher than that of the wet season (0.60 ± 0.10). $PM_{2.5}/PM_{10}$ ratios can be used to quantify the concentration of $PM_{2.5}$ at air quality monitoring stations where only PM_{10} is monitored. The $PM_{2.5}$ to PM_{10} ratios were observed to be the highest at roadside stations followed by ambient and ambient-roadside stations. A positive association with rain and O_3 and negative association with temperature and wind speed were also identified. Overall, an increase in the $PM_{2.5}$ to PM_{10} ratio was observed in the BMR over the period 2011-2017. Therefore, an understanding of the factors leading to fine particulate matter pollution is imperative to identify mitigation options and strategies enabling to improve air quality in the BMR.

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