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Temporal Variations and Potential Source Areas of Fine Particulate Matter in Bangkok, Thailand

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ABSTRACT: Particulate matter (PM) less than 2.5 micron ($PM_{2.5}$) issue is 1 of the important targets of concern by the United Nations' Sustainable Development Goals. Bangkok is a megacity and facing air pollution problems. This study analyzed PM, $PM_{2.5}$ and PM less than 10 micron (PM_{10}), monitoring data from stations located in Bangkok, and aimed to present their variations in diurnal, weekly, and intra-annual timescales. High PM concentrations are related to calm wind. The diurnal variation of $PM_{2.5}/PM_{10}$ suggested a greater accumulation of $PM_{2.5}$ than PMcoarse during the low wind speed. Potential source areas affecting PM rising at each monitoring station were identified using statistical technique, bivariate polar plot, and conditional bivariate probability function. Results showed that Ratchathewi District Monitoring Station identified 3 potential source areas related to emissions from transportation sources creating rising PM concentrations. The first potential source was located in the northwest direction, namely, the Rama VI Road close to the conjunction with Ratchawithi Road. The second potential source area was located around the cross-section between Phaya Thai Road and Rama I Road, while the third was located at the intersection of the Phaya Thai Road to Yothi Street and Rang Nam Road. These potential source areas constitute useful information for managing and reducing PM.

KEYWORDS: $PM_{2.5}$, PM_{10}, $PM_{2.5}/PM_{10}$ ratio, potential source area, Bangkok

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Introduction

Ambient air pollution has been reported by the World Health Organization (WHO) that caused 4.2 million premature deaths annually in both cities and rural areas.[1] Particulate matter (PM) air pollution has been revealed by the WHO to cause approximately 800 000 premature deaths yearly and is ranked as the 13th leading cause of mortality worldwide.[2] Particulate matter less than 10 micron (PM_{10}) and PM less than 2.5 micron ($PM_{2.5}$) are coarse and fine particles, respectively, that are small enough to pass through the thoracic region of the respiratory system. Particulate matter affects respiratory and cardiovascular morbidity including asthma, respiratory symptoms, and increased hospital admissions. Moreover, long-term effects from $PM_{2.5}$ and PM_{10} have resulted in mortality from cardiovascular and respiratory diseases including lung cancer. Related studies have reported that PM demonstrated strong effects on the cardiovascular system, and long-term exposure to PM was related to a significantly higher cardiovascular incidence and mortality rate. In addition, short-term acute exposure obviously increases the rate of cardiovascular events within days of a pollution peak.[3] Moreover, some studies have reported that exposure to high fine PM levels may also cause various symptoms, including low birth weight among infants, preterm deliveries, and possibly fetal and infant deaths. In addition, $PM_{2.5}$ exposure may also result in shortness of breath (dyspnea), chest discomfort and pain, and coughing and wheezing.[4]

Environmental conditions and quality are a part of the United Nations' Sustainable Development Goals (SDGs) that countries are endeavoring to achieve. The concentration level of PM, especially $PM_{2.5}$, has been used as an SDG indicator.[5] However, PM problems in the atmosphere, that Thailand has been experiencing, such as haze in the northern region, high PM_{10} levels in ambient air in Saraburi Province (quarrying activity), and air pollution issues in Bangkok,[6-9] constitute obstacles to achieving the SDG goals. Many studies have provided scientific information that haze issues in northern Thailand are related to transboundary pollution, open burning, and potential source area.[6,10-13] The resuspended dust and mechanical dust are major causes of severe PM_{10} concentrations in Saraburi Province.[7,14] In addition, the problem of air pollution in Bangkok is complicated, especially concerning $PM_{2.5}$.

Bangkok has been facing air pollution issues for over a decade. The National Ambient Air Quality Standards (NAAQs) of $PM_{2.5}$ are 25 and 50 μg/m^3 for annual average and 24-hour average, respectively.[9] Notably, the NAAQ values are higher than the guideline values suggested by the WHO, 10 and 25 μg/m^3 for annual average and 24-hour average, respectively.[15] The annual average of $PM_{2.5}$ concentrations over Bangkok in 2011 was 33 μg/m^3. The later annual average levels vary year by year and remained over the NAAQs level until 2017 when the annual average equaled the standard value. The number of days that the $PM_{2.5}$ level exceeded the standard

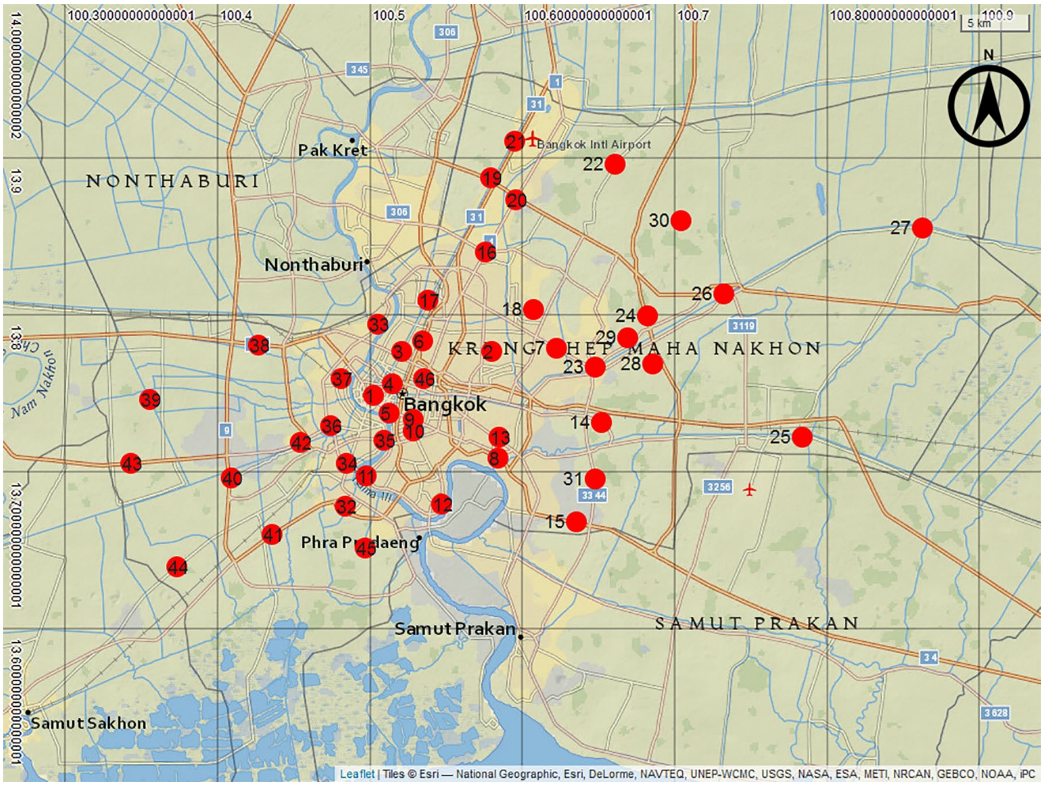

Figure 1. Locations of air quality monitoring sites. The graticule lines show meridional and zonal lines with resolution 0.1° (~11 km).

value of 24-hour average in 2011 was 22, but the number exceeding the standard in 2017 was 42 days. Considering emission sources affecting $PM_{2.5}$ in ambient air is required for effective management. Studies have suggested that traffic congress, construction, and open burning of agricultural residue impacts $PM_{2.5}$ concentration levels in Bangkok.[16,17] From source analysis using the receptor model of chemical mass balance, 2 major sources comprised transportation and biomass burning. The transportation sector contributes 27.4% and 23.0% during wet and dry seasons, respectively. Biomass burning contributes 28.4% and 33.9% during wet and dry seasons, respectively.[18] This useful information reveals the significant types of $PM_{2.5}$ emission sources in Bangkok. Also, long-range transportation would carry $PM_{2.5}$ from remote areas, eg, Vietnam, Cambodia, Lao People's Democratic Republic, and other parts of Thailand, to Bangkok.[18]

A study investigating places not far away, having higher $PM_{2.5}$ emission, and affecting the receptors (monitoring stations) would be useful. These places are named the potential source areas. Therefore, we aimed to identify the potential source areas of $PM_{2.5}$ in Bangkok. The result will make $PM_{2.5}$ reduction actions more effective, and implement interventions in crucial areas rather than throughout Bangkok.

Method

Monitoring data

According to alertness on $PM_{2.5}$ and PM_{10} concentrations, the Bangkok Metropolitan Administration (BMA) started to install PM monitoring stations in 2018 for each district over the area. Therefore, we used hourly PM, wind direction (wd), and wind speed (ws) monitoring data in 2018 from the BMA for analyses to determine the capability of data on capturing PM behaviors. Particulate matter less than 2.5 micron and PM_{10} were measured in units of μg/m^3. The units of wd and ws comprised degree from north and m/s, respectively. Forty-six monitoring sites distributed throughout Bangkok are shown in Figure 1. Forty-five sites used the Environmental Beta-Attenuation Mass Monitor (BAM 1020) from Met One Instruments to monitor PM for each district. Another site involved air quality monitoring stations using the Continuous Ambient Particulate Monitor (Model 5014i Beta) from Thermo Scientific to monitor $PM_{2.5}$ and the Continuous Particulate Monitor (BAM-1020) from Met One Instruments to monitor PM_{10}. In all, 19, 26, and 1 station monitor PM_{10}, $PM_{2.5}$, and both, respectively. All data were checked for outlier and error before analysis. The completeness of the PM dataset and site details are shown in Supplemental Table S1.

Analysis method

The time series plot is useful to present a variety of pollutant concentrations changing across various timescales. The intra-annual, weekday, and diurnal variations of time series plots were used to present the situations of $PM_{2.5}$ and PM_{10}. Also, many studies using time variations revealed trends, cycles, and magnitudes of pollutants.[8,19-21] Only 1 site collected both $PM_{2.5}$ and PM_{10} data, used to determine the $PM_{2.5}/PM_{10}$ ratio.

The ratio is useful to inform the classification of source type as Munir et al[19] mentioned

> It is important to emphasize that resuspended and windblown dusts are mostly in the coarse range (PM_{10}—$PM_{2.5}$); therefore, a low $PM_{2.5}/PM_{10}$ ratio. In contrast, PM emitted by combustion processes are mostly in the fine particulate ($PM_{2.5}$) range and exhibit a higher $PM_{2.5}/PM_{10}$ ratio.

Two statistical techniques had been used to identify the potential source area of pollutants that affect the level of air quality at the measurement location.[22-24] The bivariate polar plot (BVP) function and conditional probability function (CPF) of openair package[25] wrapped by the R program[26] was used to study and determine the potential source areas for each monitoring station. The construction of BVP is based on the concept of pollutant concentration-wind dependence on a polar coordinate that presents pollutant concentrations on the polar coordinate of wind speed and wind direction. Partitioning of concentration, wind speed, and wind direction is used to separate the data and place it in wind speed-wind direction bins. The numbers of wind direction and wind speed intervals that can reveal the behavior of the concentration distribution are 10° and 30° intervals, respectively. The interesting statistical index (such as mean concentrations) and wind component data were used to plot on the surface of polar coordinates, and the detail of BVP calculation and construction was described by Uria-Tellaetxe and D. C. Carslaw.[22] Another technique is based on the idea of resident time to diagnose the potential source area contributing to high pollutant concentrations at receptor locations. The potential region can be determined by the spatial probability distribution of air mass placement at a given time interval in the past. The probability (P) of an event where air mass placed in the interested area or grid cell can be calculated using $P = n / N$, where (n) represents the number of air mass samples in the cell and (N) is the total number of air mass samples, whereas the probability of an air mass exhibiting high concentrations of pollutant can be determined using $P_{high\_conc} = m / N$, where (m) is the number of air mass samples at high concentration in the cell and (N) represents the total number of air mass samples. To determine the potential source area, the CPF is defined as the ratio of P_{high_conc} to P , which is written for polar coordinates as $CPF_{\Delta\theta,\Delta ws,i} = m_{\Delta\theta,\Delta ws,i} / n_{\Delta\theta,\Delta ws}$, where $m_{\Delta\theta,\Delta ws,i}$ comprises the number of air mass samples in a given wind direction interval $(\Delta\theta)$, wind speed interval (Δws), and concentration interval (i) .[22,27] Both techniques constitute another kind of receptor model, and the result presents the level shading in polar coordinates, which cannot be compared with monitoring data similar to an application of the dispersion model.[28] Because the graphic result given by the BVP or conditional bivariate probability function (CBPF) does not have a spatial scale incorporated in its information, it could be compared with the geographic image to reveal the consistency of the source areas affecting the level of pollutants at the monitoring stations.[22] The technique is used to effectively identify potential source areas in various places including the area of point source influencing the pollution level in rural communities[29] and the area of mobile and industrial sources affecting the VOC level at receptors located near industrial estates.[30]

Results and Discussion

Average concentrations of each monitoring station and each PM level were determined. The spatial graphic of $PM_{2.5}$ and PM_{10} average concentrations is shown in Figure 2. The result showed the minimum and maximum values of $PM_{2.5}$ were 22.3 and 63.2 μg/m³ at Lak Si and Bang Na districts, respectively. The spatial-wise average of $PM_{2.5}$ throughout Bangkok was 33.6 μg/m³. These were 2.2, 6.3, and 3.4 times the WHO guideline value (10 μg/m³), respectively. However, the minimum value was not greater than the annual NAAQS of Thailand (25 μg/m³). The PM_{10} minimum and maximum values were 32.2 and 75.1 μg/m³ at Chom Thong and Prawet districts, respectively. The spatial-wise average of PM_{10} was 53.4 μg/m³. Three were over the annual average of the WHO guideline value for PM_{10} (20 μg/m³) at 1.6, 3.8, and 2.7 times. However, the NAAQS of Thailand was 50 μg/m³; these results in the minimum value were not over the standard level. Differences in using the threshold as the standard value resulted in differences in exceedance levels. It could be said that the air pollution problem of $PM_{2.5}$ and PM_{10} still exceeds the WHO guideline value throughout Bangkok. Because $PM_{2.5}$ is a part of PM_{10}, PM having size between 2.5 and 10 has been defined as PMcoarse. The coarse fraction is related to emissions from mechanical activity; the fine fraction is more related to the combustion process.[19] Mitigation of emission sources producing $PM_{2.5}$ and PM_{10} would be effective knowing whether fine or coarse particles comprised the majority. The ratio of $PM_{2.5}$ to PM_{10} would be useful to provide this information.

The ratio of $PM_{2.5}/PM_{10}$ was 0.63 determined by spatial-wise average of $PM_{2.5}$ divided by PM_{10} that implied that overall Bangkok presented more fine PM than coarse fraction. More fine particle fractions are related to higher emissions from fuel combustion processes such as emissions from vehicle tailpipes than emissions from mechanical processes such as construction. The spatial-wise $PM_{2.5}/PM_{10}$ ratio was in agreement with a related study in Bangkok reporting the ratio was 0.6.[31] In other countries, studies have reported the ratio for urban areas.[32,33] Xu et al[32] reported the annual average of $PM_{2.5}/PM_{10}$ was 0.62 in urban sites in Wuhan, China, and the ratio was lowest in summer (0.55) and highest during winter (0.75). For the ratios determined in the urban traffic areas in the United Kingdom, the values ranged from 0.58 to 0.79.[33] Thus, time variation of $PM_{2.5}$ and PM_{10} could be investigated to see the present low and high values of the ratio. Nevertheless, only 1 station monitored both $PM_{2.5}$ and PM_{10}, namely, the monitoring station at Ratchathewi district. The mean values were 24.4 and 45.5 μg/m³ for $PM_{2.5}$ and PM_{10}, respectively.

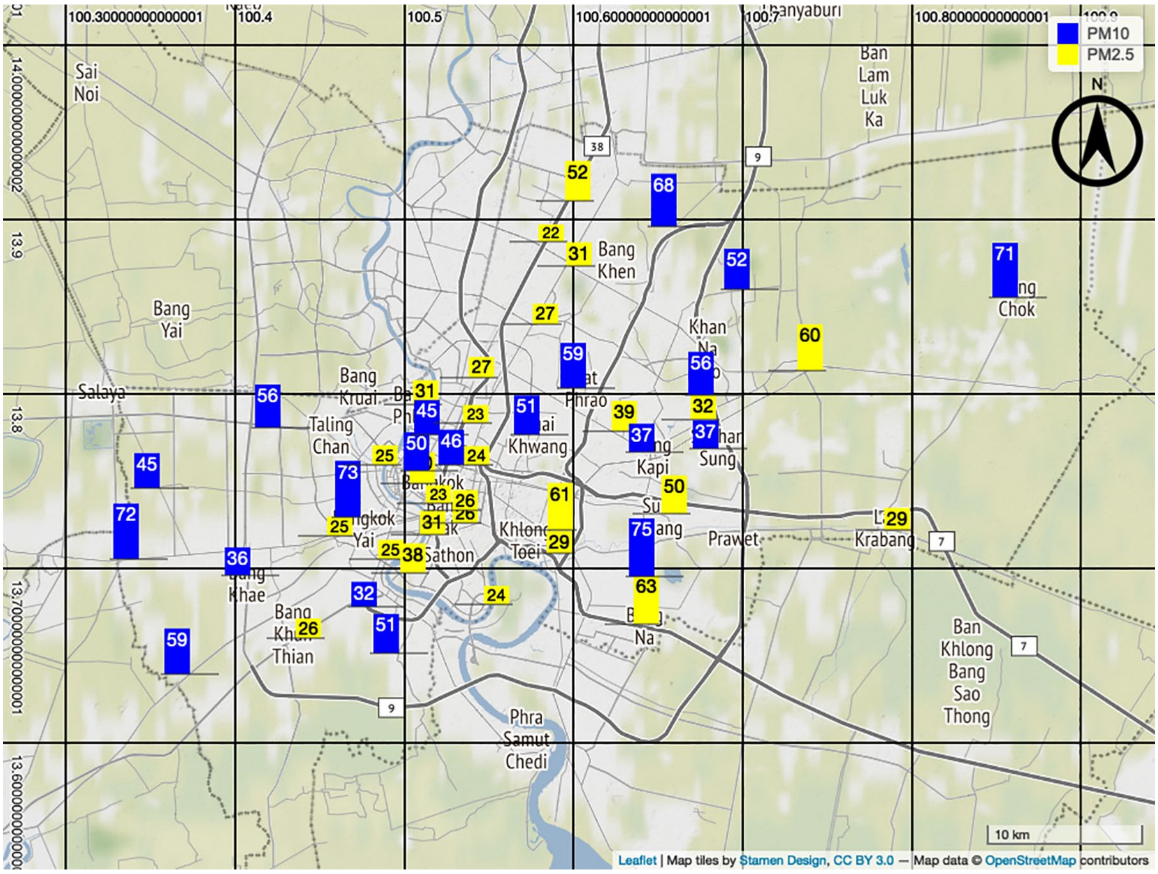

Figure 2. Mean concentrations of $PM_{2.5}$ (yellow) and PM_{10} (blue) at various locations throughout Bangkok. The graticule lines show meridional and zonal lines with resolution 0.1° (~11 km), and the concentration unit is μg/m³.
PM indicates particulate matter.

The ratio of $PM_{2.5}/PM_{10}$ is 0.54. This means a little more fine PM was found than the coarse fraction. To reduce the level of $PM_{2.5}$ and PM_{10} in Bangkok, fine and coarse emission sources could be controlled related to the timescale in their rising levels.

Temporal variations of $PM_{2.5}$ and PM_{10}

Variations of intra-annual, weekly, and diurnal cycles of PM at Ratchathewi district are presented in Figure 3. The diurnal cycles of $PM_{2.5}$ and PM_{10} (bottom-left panel) revealed lower concentrations in the early morning (before 06:00 hours) than the level during late morning. The highest concentration presented at 09:00 hours, and reduced concentration appeared lowest at 15:00 hours, increasing in the evening (after 18:00 hours). The diurnal cycle pattern did not differ much between days in a week. However, it seemed the patterns on Mondays during the late morning and evening were less sharp than other days. This pattern was quite similar to the other PM diurnal cycles at various districts presented in Figures S1 and S2. Further observations in relation to the $PM_{2.5}/PM_{10}$ ratio should be made (Figure 4). During low concentration before 06:00 hours, the ratio was higher than 0.55 and the maximum was 0.65. This means greater $PM_{2.5}$ contribution was found in PM_{10}, but the concentration of PM_{10} during the early morning was lower than the level of PM_{10} during the late morning. Therefore, higher $PM_{2.5}$ concentration corresponding to low PM_{10} concentration would be related to reduce PMcoarse resulting in a high $PM_{2.5}/PM_{10}$ ratio. The wind speed was also very low close to calm conditions (ws < 0.5 m/s) (Figure 5) resulting in a very stable condition with less pollutant removal by transportation processes. Later times had higher concentrations of both PMs, and the ratio decreased to around 0.54 until noon when wind speed increased slightly. The decreased ratio implied reduced $PM_{2.5}$ contributed to PM_{10}, and was possibly related to a greater removal of $PM_{2.5}$ by the higher wind speed due to it having smaller particle size than PM_{10}. On the other hand, decreased $PM_{2.5}/PM_{10}$ ratio meant that an increase in PMcoarse was caused by the mechanical activities. This was related to the time when people start commuting to work. In the afternoon, wind speed increased to the highest level during the day, resulting in greater removal of PM, and lower concentrations were exhibited. Also, the ratio still decreased caused by $PM_{2.5}$ being more diluted than PM_{10}, which was influenced by the high wind speed. After 18:00 hours, wind speed decreased with the presence of nocturnal conditions resulting in increasing $PM_{2.5}$ and PM_{10} levels. However, less wind speed, resulting in a greater accumulation of $PM_{2.5}$ than PM_{10}, revealed a higher $PM_{2.5}/PM_{10}$ ratio.

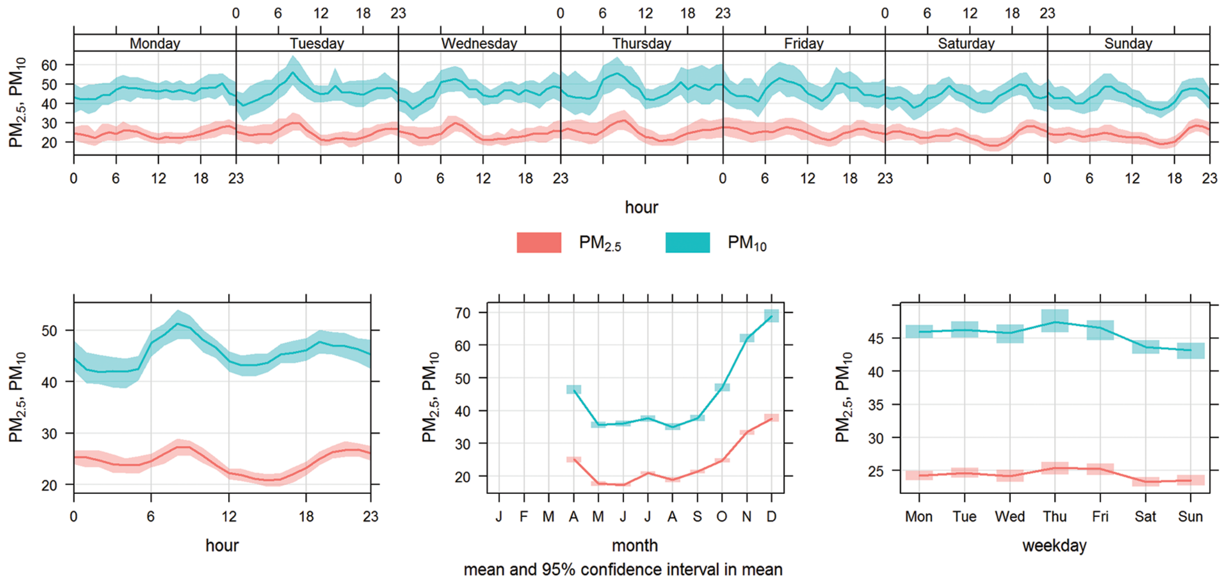

Figure 3. Intra-annual, weekly, and diurnal cycles of mean $PM_{2.5}$ and PM_{10} concentrations (μg/m³) at Ratchathewi district. PM indicates particulate matter.

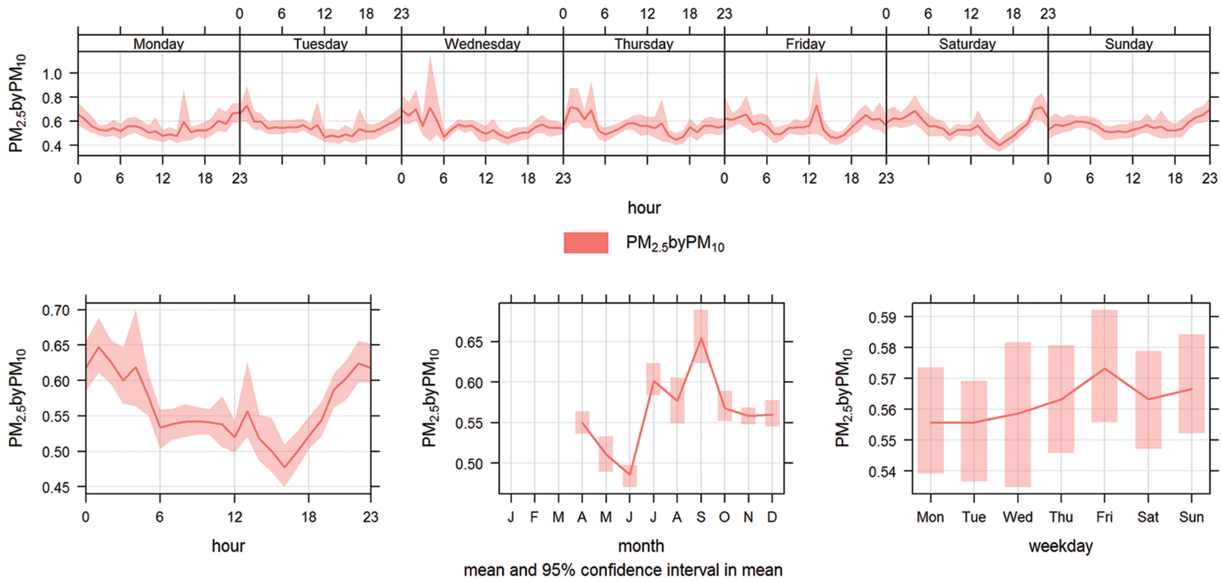

Figure 4. Intra-annual, weekly, and diurnal cycles of mean $PM_{2.5}/PM_{10}$ ratio at Ratchathewi district. PM indicates particulate matter.

The weekly cycle, presented in the bottom right panel of Figure 3, shows the concentration levels of $PM_{2.5}$ and PM_{10} during the weekend were lower than those during the weekday period. This was related to the commuting of most people working from Monday to Friday, whereas Saturday and Sunday are holidays. However, some companies work on Saturday. These resulted in reduced pollutant emissions during the weekend. For weekly cycles of the $PM_{2.5}/PM_{10}$ ratio and wind speed, we observed small variations between the highest and lowest values within a week. Their differences were 0.02 and 0.05 m/s for the $PM_{2.5}/PM_{10}$ ratio and wind speed, respectively, as shown in Figures 4 and 5, respectively. Even though, PM concentration was low during the weekend, proportions of $PM_{2.5}$ and PMcoarse to PM_{10} varied less during the week. These were caused by decreased activities emitting fine and coarse particles during weekend with similar percentages of $PM_{2.5}$ and PMcoarse decreasing.

For the intra-annual cycle, climatic factors were used to consider $PM_{2.5}$ and PM_{10} variations. The wet season of Thailand is related to the summer monsoon and the moving of the Intertropical Convergence Zone (ITCZ) presenting from June to October.[34] The dry season, influenced by the winter monsoon, starts and lasts from November to February.[35] The bottom-middle panel of Figure 3 shows lower PM concentrations during the summertime than those of the wintertime. The cause is related to washout and rainout processes during the summer season that remove pollutants from the atmosphere. Another factor is the variation of the planetary

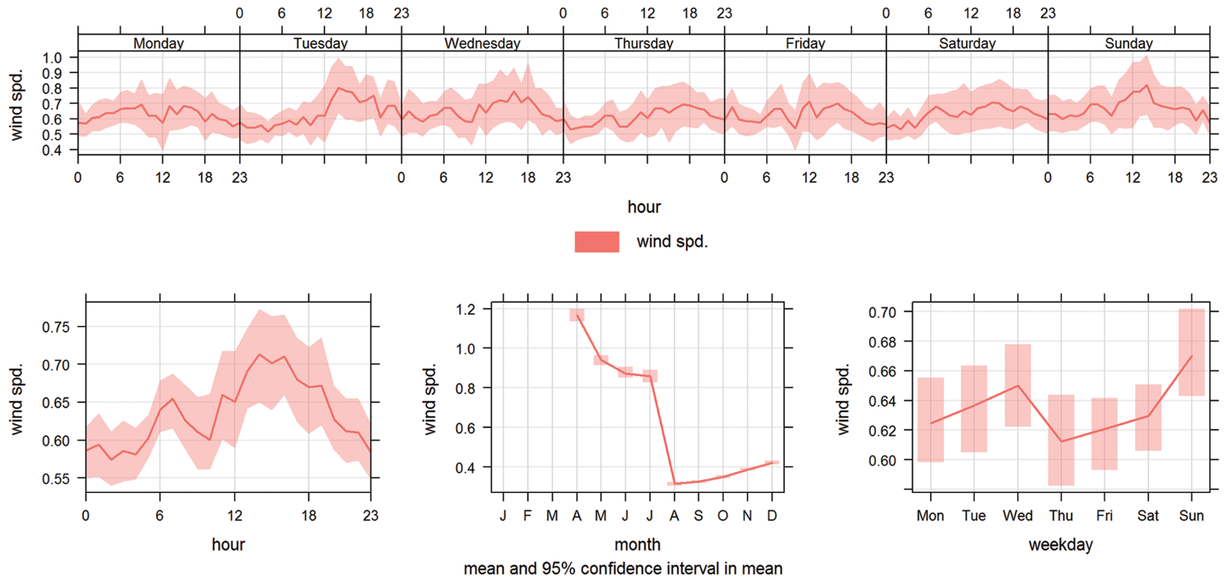

Figure 5. Intra-annual, weekly, and diurnal cycles of mean wind speed (m/s) at Ratchathewi district.

boundary layer (PBL). The PBL, representing the height that air mass can mix well in the layer, is lowest during the winter season in the northern hemisphere. In the tropics zone, the average PBL is reduced from 2100 to 1800 km approximately over terrestrial areas.[36] A height decrease of 14% means the volume of air would also decrease by 14%. In the case the PM mass in the atmosphere is constant, reduced PBL affects the decreased air mixing volume. The concentration represents the pollutant mass by air volume; therefore, pollutant concentration increases in relation to shortened PBL. Figure 5 shows the wind speed in a calm state from August throughout the winter. This condition also increased the level of PM in ambient air, in addition to the effect of PBL. These meteorological factors strengthened the PM concentration in Bangkok during the winter season.

Thailand's rainy season is related to the summer monsoon and moving of the ITCZ that presents from June to October,[34] whereas the dry season is influenced by the winter monsoon that starts from November to February.[35] More precipitation over Thailand is exhibited during the summer monsoon,[37] resulting in less photochemical reactions during the rainfall period. Therefore, removal processes are enhanced in reduced PM and gaseous pollutants.[38] However, the removal efficiency of PM by rainfall depends on emission rates of pollutants in the ambient air and the amount of rainfall. The obvious reduction of pollutants by rainfall prefers the condition of large amounts of rain of more than 1 mm.[38] Wind speed during the rainy season is stronger than the speed in the dry season (Figure 5 bottom-middle). This is a cause of lower PM concentration presented during the rainy season as shown in Figure 3. The intra-annual variation of the $PM_{2.5}/PM_{10}$ ratio shown in Figure 4 (bottom-middle panel) appears to have a high ratio during the rainy season. The $PM_{2.5}/PM_{10}$ ratio appears to have a higher ratio during the rainy season than that during the dry season. Based on the assumption that emission sources do not change much in a year and remain quite constant, especially mobile and industrial sources, an increased $PM_{2.5}/PM_{10}$ ratio implies rereduction of removal processed on PMcoarse. Even though coarse PM's properties are nonhygroscopic and largely insoluble,[39] a greater reduction of coarse particles emitted from mechanical processes and less of resuspended dust result in low PM_{10} concentrations during the rainy season. Another reason is higher $PM_{2.5}$ levels during rainy season than dry season. A study reports the contribution percentages of each emission source type. Traffic, biomass burning, and secondary inorganic aerosol are significant sources of $PM_{2.5}$. The contributions are 27.4%, 28.4%, and 25.1%, and 23.0%, 33.9%, and 16.6% for rainy and dry seasons, respectively.[18] Therefore, the differences between rainy and dry seasons (rainy season – dry season) are 4.4%, −5.5%, and 8.5% for traffic, biomass burning, and secondary inorganic aerosol, respectively. The difference values for traffic and secondary inorganic aerosol are positive. These imply a greater impact on the $PM_{2.5}$ level during the rainy season caused by traffic source and secondary inorganic aerosol than during the dry season. Thus, tailpipe exhaust, secondary aerosol formation, greater reduction of particles emitted from mechanical processes, and less resuspended dust are possible reasons for the high $PM_{2.5}/PM_{10}$ ratio during rainy season. However, the different values for biomass burning show a negative value during dry season meaning the biomass burning source is an influential factor enhancing $PM_{2.5}$ during the dry season.

From the time series analysis above, we can say that the diurnal and weekly variation of PM concentration would be related to their varying associated emissions and diurnal weather cycles. Nevertheless, the intra-annual cycle of the PM level depends on intra-annual climatic variability. The effects of biomass burning are greater during the dry season. Transportation and secondary inorganic aerosol exhibit reduced contributions to the $PM_{2.5}$ level during the dry season. The role of secondary inorganic aerosol is important and would be studied in the future.

Potential source area

This section presents results using statistical techniques to analyze and classify the monitoring data at receptor locations. The BVP gives the spatial mean concentration of $PM_{2.5}$ associated with various emission source locations identified by wind direction and speed. Many stations showed higher $PM_{2.5}$ concentration than the NAAQS of Thailand as Watthana, Bang Na, Don Mueang, and Min Buri districts (Table S1). Overall, potential source area is not far from the monitoring station. Distance between them is no longer than 3 km that implied to the short-range transportation of air mass. Noteworthy is that there are $PM_{2.5}$ mean concentrations of 4 stations of more than 50 μg/m³, which are 13. Watthana district station 15.Bang Na district station 21.Don Mueang district station, and 26.Min Buri district station. Their observed concentration was mostly influenced by the potential source areas that representing to street. However, the potential source area located at lower right of the Bang Na district station is the area of industrial and logistic area. Airport located at the east of the Don Mueang district station and close to the highway is also its potential source area. For the Min Buri district station, the potential source areas located at north and west of the station are industrial area, and the area at east of the station is residential area. All of them are near the street. Figure 6 shows 2 obvious potential source areas that affected PM concentration at the Ratchathewi District Monitoring Station. The first potential source is located in the northwest direction of the monitoring station, which is an area related to mobile sources. The area identified Rama VI Road close to the conjunction with Ratchawithi Road. Also, over the Rama VI Road is the Si Rat Expressway close to a section leading to the Victory Monument. These road areas have the potential for increasing $PM_{2.5}$ concentrations, at the mean level, around 80 μg/m³, at the Ratchathewi District Monitoring Station. The second potential source area is located around the cross-section between the Phaya Thai Road and the Rama I Road. The surrounding area of the second location comprises many popular department stores and hotels resulting in high traffic density. Moreover, the Siam station of BTS sky train serves as a transit station to other lines and remains a very cloudy station. However, the yellow area (60 μg/m³) shown in Figure 6 is located in the north not far from the station. To emphasize the areas affecting increasing high concentrations at the monitoring station, the CBPF was used to present the potential source areas related to the presence of high concentrations in a range of 80 to 100 percentile. Figure 7 shows a plot using the results from the CBPF analysis. The high probability (red shading in Figure 7) implies the potential source area result shows high concentrations (80-100 percentile), present in 3 areas. Two are at the same locations indicated by the BVP and are intersections in the northeast and south directions. The third is located at the intersection of the Phaya Thai Road to Yothi Street and Rang Nam Road.

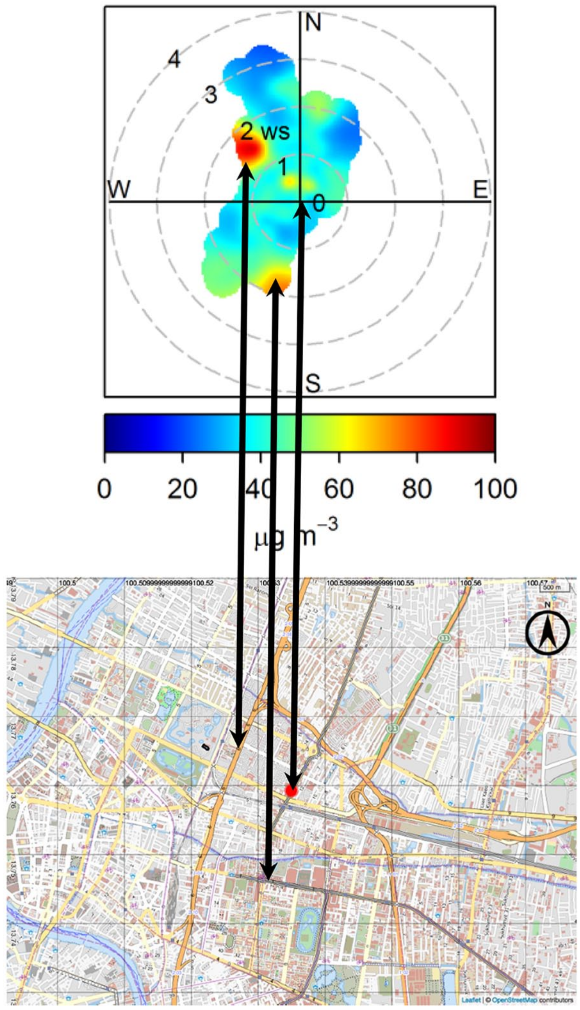

Figure 6. Bivariate polar plot of $PM_{2.5}$ concentrations at Ratchathewi district (top) and its map (bottom). The red dot represents the monitoring station. The graticule lines show meridional and zonal lines with resolution 0.01° (~1.1 km).
PM indicates particulate matter.

This area presents a great probability to emit high concentration resulting in enhancing the $PM_{2.5}$ level at the monitoring station to the 80 to 100 percentile, but overall, it exhibits a lower mean concentration than the other 2 areas. One possible reason is the low concentrations of this area would be smaller than the low concentrations of the other 2 stations. Therefore, these 3 potential source areas are related to emissions from transportation sources, and should be the main focus to control and reduce emissions than other surrounding areas.

Moreover, BVP analysis was performed for the PM_{10} and $PM_{2.5}/PM_{10}$ ratio. Figure 8A presents the potential source areas of PM_{10} that are similar to the results indicated by analyzing $PM_{2.5}$ data. This implied that the potential source areas of $PM_{2.5}$ and PM_{10} are the same. These are potential areas to emit $PM_{2.5}$ and PM_{10} affecting the rising concentrations at the

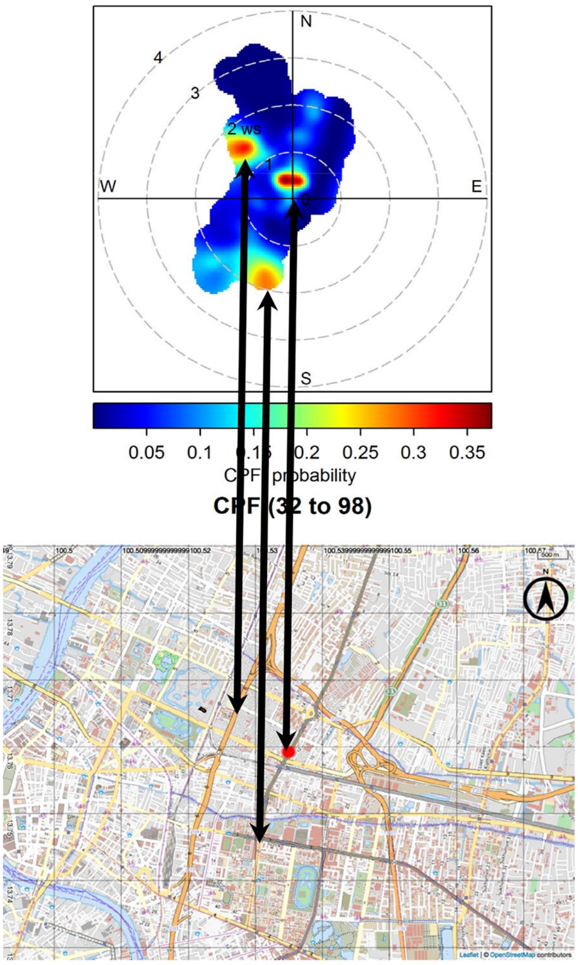

Figure 7. The CBPF plot of $PM_{2.5}$ concentrations in a range of 80 to 100 percentile. The numbers in brackets are concentrations related to 80 and 100 percentile, respectively. The graticule lines show meridional and zonal lines with resolution 0.01° (~1.1 km).
CBPF indicates conditional bivariate probability function; PM, particulate matter.

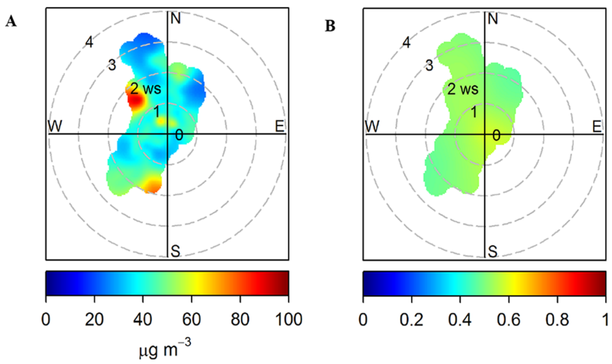

Figure 8. (A) Bivariate polar plot of PM_{10} concentrations. (B) Bivariate polar plot of the $PM_{2.5}/PM_{10}$ ratio.
PM indicates particulate matter.

Ratchathewi District Monitoring Station. Air pollutant reducing measures should be implemented at the potential areas as a first priority, to obtain the benefits of reduced $PM_{2.5}$ and PM_{10} emissions. Another concern is the BVP of the $PM_{2.5}/PM_{10}$ ratio as shown in Figure 8B. Focusing on this ratio reveals whether $PM_{2.5}$ or PMcoarse is the major contribution to PM_{10}. The spatial pattern of $PM_{2.5}/PM_{10}$ does not present any significant potential areas and reveals a likely monotone. The ratio values are in the range of 0.55 to 0.6. This means that the surrounding area of the monitoring station plays a similar role to influence the PM level at the station. The small value of the ratio implied more coarse fractions that originated mostly from mechanical processes, whereas a high ratio was related to emissions from anthropogenic sources.[40] A study in China reported the ratios of $PM_{2.5}/PM_{10}$ of urban, urban fringe, and suburban areas were 0.617, 0.630, and 0.680, respectively.[32] The results of this study agreed with those of related studies.[32,33,40]

Reducing and controlling $PM_{2.5}$ at these areas involves possible mitigations. Vehicles are well known to be significant emission sources in urban areas. They can emit PM from tailpipes and nonexhaust processes. The nonexhaust processes generating road wear particles include brake wear, tire wear, and road pavement abrasion, but their contribution to total $PM_{2.5}$ in urban centers including London, Tokyo, and Los Angeles is less (0.27%).[41] Improving fuel quality and reducing the number of vehicles on the road would be useful.

Large numbers of vehicles on the road emit more particles than fewer vehicles.[42] However, variation of traffic volume was not strongly related to $PM_{2.5}$ variation, and was not a significant factor for the variations of increasing PM.[43] Also, older vehicles tend to emit more $PM_{2.5}$ to ambient air.[42] Both emissions of gasoline- and diesel-fueled vehicles can contribute to $PM_{2.5}$. For example, gasoline-fueled vehicles contribute 17.2% and diesel vehicles contribute 8.1% to $PM_{2.5}$ in Seoul, Korea.[44] However, low sulfur content in fuel produces less amount of $PM_{2.5}$ emissions.[42] Therefore, vehicle population, vehicle age, and fuel quality are factors resulting in changed $PM_{2.5}$ levels.

Another strategy to reducing $PM_{2.5}$ is using natural methods such as increasing green area and eco-forests performing as a buffer to protect $PM_{2.5}$ dispersion from the transportation source. The study in Leicester city, UK, presented that $PM_{2.5}$ deposition on trees could decrease $PM_{2.5}$ by 2.8%, and deposition on the grass could remove 0.6%. Urban trees have the ability to decrease air pollution in street canyon areas by aerodynamic and deposition processes. The aerodynamic process occurring by rough change due to increasing numbers of trees results in an increase in turbulence production and a decrease in stable conditions suitable for pollutant accumulation.[45] Plants can reduce PM from the ambient air and improve air quality. A wide variety of PM sizes including fine and coarse particles suspended in ambient air were deposited on leaf surfaces and trapped by waxes.[46] While building surfaces had a much lower ability to trap $PM_{2.5}$,[45] green walls can be used to improve their ability to reduce pollutants.[47]

To enhance the capability of reducing $PM_{2.5}$ in the ambient air in cities such as Bangkok, identifying all potential source areas of $PM_{2.5}$ given by all the air quality monitoring stations over Bangkok is required. This study also provides additional potential source areas of $PM_{2.5}$ for other monitoring locations in Bangkok as shown in the Supplemental Material. All potential source areas around Bangkok can provide information to design green corridors to improve Bangkok air quality. The concept of connectivity can be used to increase green areas[47-49] by connecting built-up green zones at all potential source areas to serve as green corridors.

Conclusions

The 2018 PM monitoring data provided by BMA stations in Bangkok were analyzed to present their time variations and potential source areas. The diurnal cycle of $PM_{2.5}$ and PM_{10} at Ratchathewi district station revealed lower concentrations in the early morning (before 06:00 hours), the highest concentration at 09:00 hours, and the lowest at 15:00 hours before increasing after 18:00 hours. The diurnal variation is related to diurnal change in wind speed. High concentrations were related to calm wind, whereas strong wind resulted in reduced concentrations. The diurnal variation of $PM_{2.5}/PM_{10}$ suggested a greater accumulation of $PM_{2.5}$ than PMcoarse during low wind speed. Also, the diurnal cycle patterns of PM at other stations did not differ. The $PM_{2.5}/PM_{10}$ ratio was high during the rainy season implying a greater reduction of course than fine particles. Potential source areas were identified using BVP and CBPF analysis. Ratchathewi District Monitoring Station identified 3 potential source areas: (1) the Rama VI Road, (2) the cross-section between Phaya Thai Road and Rama I Road, and (3) the intersection of the Phaya Thai Road to Yothi Street and Rang Nam Road related to emissions from transportation sources creating rising PM concentrations. These areas should receive a greater focus of controlling and reducing emissions than other surrounding areas of the monitoring stations. Moreover, this study provided potential source areas for other monitoring stations in Bangkok. All potential source areas around Bangkok can be used as information to design green corridors to improve Bangkok air quality and implement other policies to reduce the PM level. However, the annual data provided by the BMA were used limitedly. This study could be improved by using more yearly data and data from other monitoring stations not belonging to the BMA.

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Author Contributions

SK collected and prepared the input data, discussed the results, and proofed the manuscript. SS analyzed the data, discussed the results, and composed the manuscript. AP discussed the results and contributed to the final manuscript. PW contributed to the final manuscript.

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Supplemental Material

Supplemental material for this article is available online.

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