# Relationships between Meteorological and Particulate Matter Concentrations (PM2.5 and PM10) during the Haze Period in Urban and Rural Areas, Northern Thailand

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# Relationships between Meteorological and Particulate Matter Concentrations ($PM_{2.5}$ and $PM_{10}$) during the Haze Period in Urban and Rural Areas, Northern Thailand

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**ABSTRACT:** Meteorological parameters play a crucial role in the ambient air quality of urban and rural environments. This study aims to investigate the relationship between meteorological parameters (including temperature, relative humidity, and wind speed) and the concentrations of $PM_{2.5}$ and $PM_{10}$ in the urban area and the rural area, northern Thailand during the haze period (January to April) from 2016 to 2020. Statistical analyses of the Spearman-Rank correlation coefficient and the multivariate gaussian regression were used to investigate the relationships. The secondary data of ambient $PM_{2.5}$ and $PM_{10}$ concentration and meteorological parameters were acquired from the Thai Pollution Control Department. The measurements are obtained using the Beta Ray attenuation method. The results showed that approximately 24% to 65% of daily average $PM_{2.5}$ concentrations in the urban area over the study period exceeded Thailand's National Ambient Air Quality Standards. The average $PM_{2.5}/PM_{10}$ ratios in the urban and the rural areas over the haze period were 0.69 and 0.66, respectively. Our analysis established a significant correlation between atmospheric temperature ($r = 0.624$) and relative humidity ($r = -0.722$) with the concentrations of $PM_{2.5}$ and $PM_{10}$. In both areas, $PM_{2.5}$ and $PM_{10}$ concentrations were also positively correlated with temperature. In contrast, relative humidity was significantly related with the decrease of $PM_{2.5}$ and $PM_{10}$ concentrations. However, wind speed does not affect $PM_{2.5}$ and $PM_{10}$ concentrations. Additionally, the daily backward trajectories using the hybrid-single particle Lagrangian integrated trajectory model also demonstrated air mass movement in March mostly came from the southwesterly direction, which moved through the highlands, the large biomass burned areas, upwind neighboring provinces, and transboundary transports before reaching the air monitoring stations. Our findings improve the understanding of particulate matter pollution and meteorological patterns during annual haze periods in the urban and rural areas. We expect the output of this study can help improve existing haze mitigation measures for improving the prediction accuracy of air pollution under variable meteorological parameters.

**KEYWORDS:** $PM_{2.5}$, $PM_{10}$, haze pollution, meteorological parameters, northern Thailand

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## Introduction

In Thailand, the main contributing sources of emission are transportation, industries, and biomass burning (Outapa & Ivanovitch, 2019; Pochanart, 2016). The air pollutants which exceeded the criteria levels of National Ambient Air Quality Standards (NAAQS) include particulate matter less than 2.5 µm ($PM_{2.5}$), particulate matter less than 10 µm ($PM_{10}$), tropospheric ozone ($O_3$), and Volatile organic compounds (VOCs). In 2020, the PCD air quality data collected from automatic air pollution monitoring stations in 37 provinces (68 stations) reports improvement in air quality from the previous year. However, the air pollutant levels in 2020 that are greater than the standard for more than 70 days, especially in the northern provinces. In addition, haze pollution in northern Thailand is a regional problem that occurs annually during the dry season (January–April) as farmers practice open burning and there are higher incidences of natural forest fires. Due to natural forest fires and human-initiated burning activities, particularly open burning of agricultural residues, a huge quantity of atmospheric pollutants is emitted during the dry season in northern Thailand. Therefore, many residents suffer from breathing ailments during this period (PCD, 2020).

Due to the deterioration in air quality, many countries have implemented decisive action to enforce pollution regulations and stepped-up efforts to strictly enforce emission controls to improve air quality. Thailand is pushing for and driving initiatives to solve the country's pollution problem under the 20-year national strategy (2018–2037) which focuses on achieving sustainable development goals to improve human lives and protect the environment. For countries committed to reducing air pollution emissions and its impacts on human health, it is essential to understand the current situation of air quality in the monitored areas. Despite high levels of air pollution recorded in many areas, public awareness of air pollution is still low in areas where real-time monitoring is limited (WHO, 2019). Hence high air quality data collected at the air monitoring stations are extremely important to assess health impacts and determine pollution management scenarios. However, the nationwide $PM_{10}$ and $PM_{2.5}$ monitoring networks are not evenly positioned throughout the region.

In urban area that monitor air pollution, more than 80% of residents are exposed to air quality levels that exceed WHO guideline limits, with low- and middle-income countries suffering from the highest exposure levels, both indoors and outdoors (WHO, 2019). Sources of these air pollutants are typically more concentrated in urban areas, although pollutants can be carried downwind of urban sources and contribute to pollutant levels in surrounding areas (Strosnider et al., 2017). Human health in rural areas also is highly threatened by air pollution caused by widespread open burning of biomass from agricultural activities, wildfires, and indoor coal and biomass cookstoves. Researchers found that the concentrations of air pollutants were lower in rural areas, but the effects of air pollution on the health effect of rural residents were higher than those of urban residents (Liu et al., 2020).

Atmospheric pollution has significant negative impacts on the environment and human health. A wide range of adverse health effects caused by ambient air pollution has been well documented by studies conducted in various parts of the world (Kim et al., 2015; Mabahwi et al., 2014; Shah et al., 2013; Sierra-Vargas & Teran, 2012; WHO, 2019). The health effects of air pollution are serious—one-third of deaths from stroke, lung cancer and heart disease are caused by air pollution. World Health Organization (WHO) data shows the air we breathe is growing dangerously polluted: 9 out of 10 people breathe in polluted air, which kill about 7 million people every year.

Respirable and fine particulate matters, also known as $PM_{10}$ and $PM_{2.5}$, pose the biggest challenge to environment, mainly because of their adverse effects on human health. Fine particles which could penetrate deep into the respiratory tract subsequently increase mortality risk from respiratory infections and diseases, lung cancer, and cardiovascular disease. Particulate matters could become more toxic if they are caused by the formation of certain gases such as sulfur dioxide and nitrogen oxide. They could also affect urban and regional air quality and visibility and has a significant impact on global climate change (Pienkosz et al., 2019; U.S.EPA, 2019b). An extensive body of scientific evidence shows long- and short-term exposures to $PM_{2.5}$ could cause premature death and pose harmful risks for the cardiovascular system, including increased likelihood of hospital admissions and emergency department visits for heart attacks and strokes. Scientific evidence also links particulate matters to harmful respiratory effects, including asthma attacks (Huang et al., 2019; Sierra-Vargas & Teran, 2012; U.S.EPA, 2019a).

The impacts of the air pollution problem vary according to the characteristics of the geographic area, atmospheric conditions, and emission sources. Although preventive measures for air pollution have played a significant role in reducing emission in the country, air pollution incidences could still occur due to stagnant meteorological conditions, emissions from open burning incidents and emissions from motor vehicles and factories within the region (Bai et al., 2018; EEA, 2020; Wang et al., 2020). Therefore, further research is needed to understand the coupled relationship between emissions and meteorological conditions. Previous research showed that both $PM_{10}$ and $PM_{2.5}$ are influenced by meteorological parameters. It was found that the relationships between meteorological factors and PM concentrations were statistically significant (Chotamonsak & Lapya, 2018; Kanchanasuta et al., 2020; Kayes et al., 2019; Kwanma et al., 2019; Pengjan et al., 2019; Pongkaset et al., 2020; Suburairat & Bunjongsiri, 2020; Yang et al., 2017; Zhao et al., 2014). In addition, geography can have a direct effect on the weather in different regions (Chotamonsak & Lapya, 2018). The relationships between air pollutant concentration and meteorological factors not only vary with the geographic locations, but also with seasons (Yang et al., 2017).

Particulate matters are generally produced by different sources. Brochu et al. (2011) found that annual $PM_{2.5}$ and $PM_{10}$ were higher in urban locations compared with rural locations, especially near the Pittsburgh, Philadelphia, and New York City metropolitan areas. Lin et al. (2018) indicated that $PM_{2.5}$ concentrations in urban areas were higher than in rural areas in all provinces over Eastern China from 2001 to 2015. The higher $PM_{2.5}$ concentrations in urban areas are due to more human activities, greater energy consumption, and higher emissions of air pollutants. Moreover, Chansuebsri et al. (2022) investigated $PM_{2.5}$ compositions in Northern Thailand in 2019 and revealed that urban $PM_{2.5}$ sources were secondary inorganic aerosols from traffic gas conversion in contrast with rural $PM_{2.5}$ which were mainly from biomass burning. Several studies were conducted to characterize particle pollution by the $PM_{2.5}/PM_{10}$ ratios in the urban area (Chirasophon & Pochanart, 2020; Kanchanasuta et al., 2020; Pengjan et al., 2019; Ryu et al., 2007; Sahanavin et al., 2016; Spandana et al., 2021; Suburairat & Bunjongsiri, 2020; Thongyen, 2009; Xu et al., 2017). However, a few studies have been focused on the $PM_{2.5}/PM_{10}$ ratios in the rural area (Clements et al., 2016; Sopajaree & Pengchai, 2007).

This study investigates the relationship between meteorological parameters and ambient concentrations of $PM_{2.5}$ and $PM_{10}$ for urban and rural areas in northern Thailand during the haze period. Furthermore, analysis on average $PM_{2.5}/PM_{10}$ ratios, the wind rose diagrams, and backward trajectories were conducted for both study areas. Our findings could be used to improve the understanding of $PM_{2.5}$ and $PM_{10}$ concentration patterns during the haze period in both urban and rural areas. This information will be key to policymakers in providing vital evidence for conducting epidemiological health studies, setting up effective compliance monitoring, implementing a health warning system in northern Thailand, and valuable in designing effective air pollution control strategies.

## Materials and Methods

### *Description of the Chiang Mai and Nan areas*

In this study, two study areas, Chiang Mai and Nan provinces were chosen to represent the urban and rural areas, respectively. They are in the upper north region of Thailand in a valley surrounded by high mountains. Chiang Mai province is the second-largest province in the country and the largest province in northern Thailand with an area of approximately 52,077 km$^2$. Nan province is a rural province in northern Thailand surrounded by forested mountains with an area of approximately 29,713 km$^2$. Both areas are popular destinations in northern Thailand for both Thai and overseas tourists, renowned for its natural landscapes, misty mountains, colorful hill tribe villages and local culture conservation. Approximately 70% and 61% of Chiang Mai and Nan provincial areas are covered by forest areas, respectively (RFD, 2019). The peak tourist period is from November to February during the dry season where the weather is cooler. Annual average meteorological conditions for temperature and relative humidity are approximately 28°C and 74%, respectively. During the peak tourist period, the average temperature has decreased to 25°C to 28°C. In 2021, Chiang Mai has a population of about 1.8 million people while Nan has 475,875 people (DOPA, 2021). The number of tourists visiting Chiang Mai and Nan provinces in 2019 was about 11.1 million visitors and 953,895 visitors, respectively. However, the number of tourists visiting Chiang Mai and Nan provinces has decreased to about 6 million visitors and 645,167 visitors in 2020, respectively. The decreasing number of tourists is a result of the coronavirus disease 2019 (COVID 19) pandemic situation (MOTS, 2021).

### *Air quality monitoring stations and data collection*

The air quality monitoring stations are constructed by the Pollution Control Department (PCD), Thailand's Ministry of Natural Resources and Environment. There are 15 automatic air quality monitoring stations in nine northern provinces including nine monitoring stations in suburban areas, five in rural areas, and one in urban area. In this study, air quality monitoring stations in Chiang Mai and Nan were chosen to represent urban and rural areas, respectively. The air quality station in Chiang Mai province is located at Yupparaj Wittayalai School (18°47′32″N, 98°59′16″E), near a busy road in the city. In Nan province, the air quality station is located at Chalermprakiet Hospital (19°34′33″N, 101°04′ 54″E), about 100 m away from a quiet street situated in a rural area. The locations of the selected air quality monitoring stations in this study are shown in Figure 1.

The haze situation in northern Thailand is severe from March to April every year. This was mainly due to a widespread agricultural waste burning and the rapid spread of forest fires caused by dry weather (PCD, 2021). The secondary data including hourly ambient concentrations and meteorological parameters during the haze period in January to April from 2016 to 2020 obtained from the PCD. The researchers also analyzed the daily average $PM_{2.5}$ and $PM_{10}$ concentrations calculated from hourly concentrations measured by the Beta Ray attenuation method for both monitoring stations, following the United States Environmental Protection Agency (USEPA) reference method. The beta attenuation particulate sampling technique measures the rate of absorption of beta radiation by solid particles extracted from air flow as they pass through PM collected on a filter media. Their intensity is measured by a suitable electron counter. The beta gage instrument measures the volume of gas extracted from the stack/duct for each sample interval and calculates its mass concentration (U.S.EPA, 2000).

In addition, the research also conducted analysis on hourly meteorological parameters including atmospheric temperature (T), relative humanity (RH), wind speed (WS), and wind direction (WD).

### *Data analysis of relationships between meteorological parameters and particulate matter concentrations ($PM_{2.5}$ and $PM_{10}$)*

Firstly, descriptive statistics were calculated for $PM_{2.5}$, $PM_{10}$ concentrations and meteorological data. Spearman-Rank correlation coefficient and the multivariate gaussian regression analyses were used to investigate the relationship between daily $PM_{2.5}$ and $PM_{10}$ concentrations, and meteorological parameters over the period of January to April from 2016- to 2020 using a statistical software module from SPSS. The average $PM_{2.5}/PM_{10}$ ratios, wind rose diagrams using WRPLOT view version 8.00.2, and backward trajectories using the hybrid-single particle Lagrangian integrated trajectory (HYSPLIT) model available from the National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL) were also conducted for both study areas.

## Results and Discussion

### *Data overview of PM concentrations and meteorological parameters*

Table 1 shows the summary statistics of $PM_{2.5}$ and $PM_{10}$ concentrations (μg/m$^3$), and meteorological parameters based on daily average in the urban and rural areas during the haze period (January–April) from 2016 to 2020. Overall, the $PM_{2.5}$ and $PM_{10}$ concentrations ranged from about 2 to 262 μg/m$^3$ and about 3 to 308 μg/m$^3$ among two study areas, respectively. Moreover, the average concentrations of $PM_{2.5}$ in urban and rural areas were 52.57 ± 29.09 and 45.41 ± 39.15 μg/m$^3$, respectively. The average concentrations of $PM_{10}$ in the urban and rural areas were 73.86 ± 33.98 and 64.58 ± 47.43 μg/m$^3$, respectively. On the other hand, the meteorological parameters among two study areas that is, temperature, relative humidity, and wind speed ranged from 7°C to 36°C, 28% to 98%, and 0 to 2 m/s, respectively. The average temperature, relative humidity, and wind speed in the urban area were 28.35 ± 3.80°C, 54.16 ± 13.19%, and 0.44 ± 0.21 m/s, respectively. The average temperature, relative humidity, and wind speed in the rural areas were 22.32 ± 3.58°C, 68.23 ± 9.63%, and 1.11 ± 0.27 m/s, respectively.

The trends of daily average $PM_{2.5}$ and $PM_{10}$ concentrations in urban and rural areas during the haze period (January–April) from 2016 to 2020 are illustrated in Figure 2. Time-series data showed that $PM_{10}$ and $PM_{2.5}$ concentrations in both areas had similar trend during the haze period. The highest concentrations of $PM_{2.5}$ and $PM_{10}$ throughout the study period were regularly observed in March of 2019 and studies showed PM concentrations in the rural area were higher than in the urban area. For both areas, approximately 7% to 45% and 15% to 22%

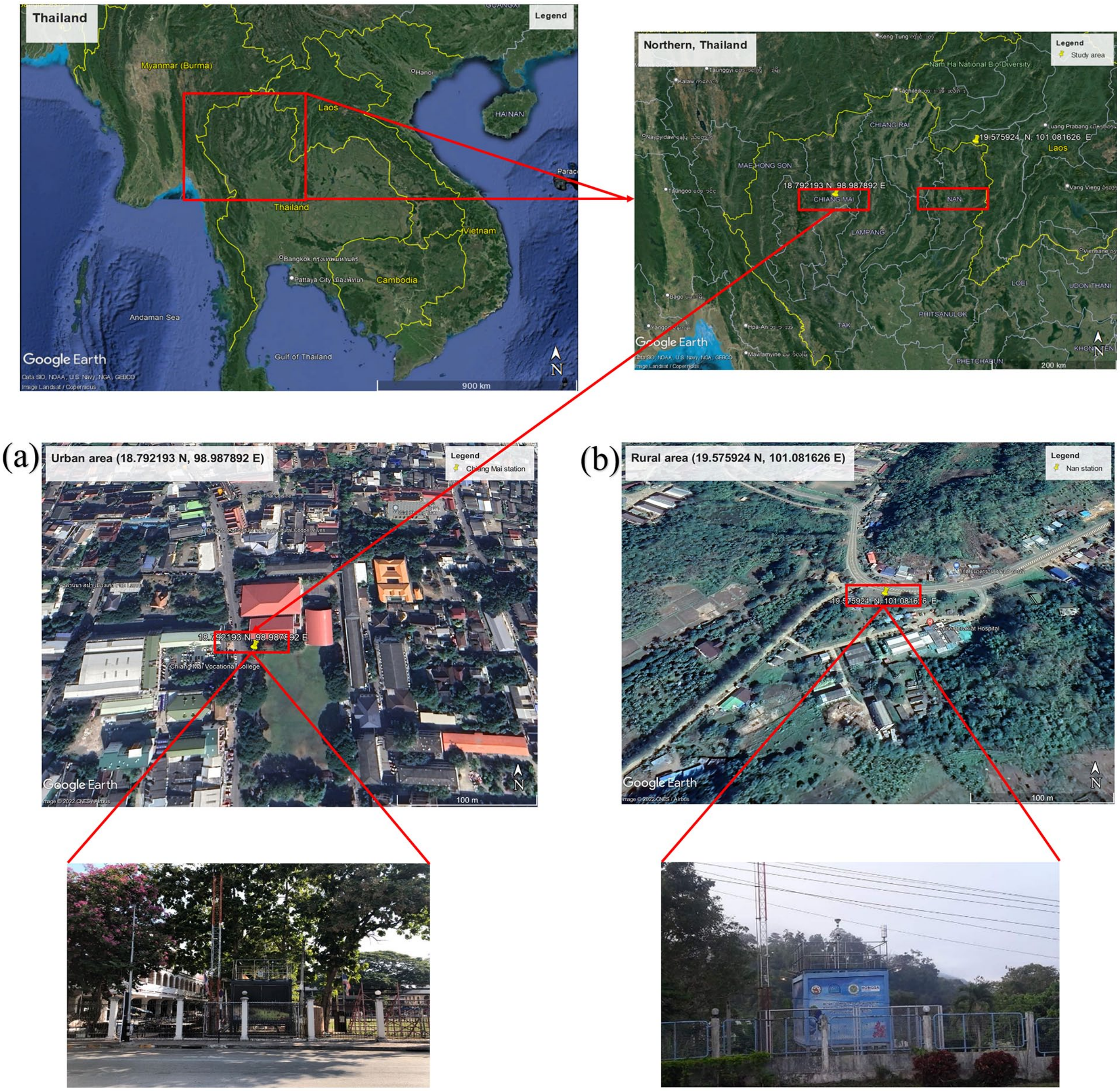


**Figure 1.** Locations of the study areas: (a) locations of air quality monitoring stations in urban area (Yupparaj Wittayalai School, Chiang Mai province) and (b) locations of air quality monitoring stations in rural area (Chalermprakiet Hospital, Nan province).

daily average of $PM_{2.5}$ and $PM_{10}$ concentration over the study period exceeded the Thailand's National Ambient Air Quality Standards (NAAQS) of 50 and 120 μg/m$^3$, respectively. In the urban area, approximately 24% to 65% and 1% to 21% of daily average of $PM_{2.5}$ and $PM_{10}$ concentrations over the study period exceeded the NAAQS, respectively. In addition, the maximum levels of $PM_{2.5}$ and $PM_{10}$ concentrations were four times and two times higher than the NAAQS, respectively. As for the rural area, the maximum levels of $PM_{2.5}$ and $PM_{10}$ concentrations were about five times and three times higher than the NAAQS, respectively.

In addition, the trends of daily average meteorological parameters in urban and rural areas including temperature (T), relative humidity (RH), and wind speed (WS) during the haze period (January–April) from 2016 to 2020 are showed in Figure 3. There were similar patterns of meteorological parameters for both urban and rural areas over the study period. The temperature values were higher in the urban area than those in the rural area. However, the relative humidity and wind speed in the rural area were greater than values measured in the urban area. The spatial variation could influence of patterns of $PM_{2.5}$ and $PM_{10}$ concentrations in this study. Differences in emission sources and dispersion conditions controlled by topographical and meteorological factors in the study areas could reflect variation of $PM_{2.5}$ and $PM_{10}$ concentrations (Chen et al., 2020; Chotamonsak & Lapya, 2018; Yang et al., 2017). The urban area could be more influenced by traffic volume whereas local agricultural burning activities and forest fires in mountainous areas could contribute significantly to air pollution

**Table 1.** Summary Statistic of $PM_{2.5}$ and $PM_{10}$ Concentrations (µg/m³), and Meteorological Parameters Based on Daily Average in Urban and Rural Areas During the Haze Period (January–April) from 2016 to 2020.

| AREA | PARAMETER | $PM_{2.5}$ (µG/M³) | $PM_{10}$ (µG/M³) | T (°C) | RH (%) | WS (M/S) |
|---|---|---|---|---|---|---|
| Urban (Chiang Mai province) | Average ±*SD* | 52.57 ± 29.09 | 73.86 ± 33.98 | 28.35 ± 3.80 | 54.16 ± 13.19 | 0.44 ± 0.21 |
| | Median | 47.52 | 69.92 | 28.64 | 54.00 | 0.40 |
| | Min | 5.96 | 9.52 | 10.13 | 27.63 | 0.00 |
| | Max | 209.71 | 229.58 | 36.10 | 95.79 | 1.78 |
| Rural (Nan province) | Average ±*SD* | 45.41 ± 39.15 | 64.58 ± 47.43 | 22.32 ± 3.58 | 68.23 ± 9.63 | 1.11 ± 0.27 |
| | Median | 35.52 | 54.13 | 21.99 | 68.50 | 1.08 |
| | Min | 2.32 | 3.40 | 6.89 | 41.43 | 0.28 |
| | Max | 262.21 | 307.92 | 32.65 | 98.00 | 2.15 |

Thailand's National Ambient Air Quality Standards (NAAQS) of 50 µg/m³ for $PM_{2.5}$, and 120 µg/m³ for $PM_{10}$.
T = atmospheric temperature (°C); RH = relative humidity (%); WS = wind speed (m/s).

levels in the rural areas. The topography of Chiang Mai is characterized by a basin surrounded by a wall of high mountains which reduces dispersion potential resulting in an accumulation of air pollutants. Also, temperature inversions in winter could cause PM to remain in the study areas for a prolonged time (Chantara, 2012).

A fluctuating trend is evident throughout the study period for $PM_{2.5}$ and $PM_{10}$ concentrations as well as in meteorological parameters. Haze in northern Thailand regularly occurs during the north-east monsoon season and the transition period between cold weather and the summer period from January to April each year. The tropical climate conditions in Thailand result in extreme temperatures, rainfall, and relative humidity. High trends were observed from March to April in both urban and rural areas. The trend of $PM_{2.5}$ and $PM_{10}$ concentrations remains almost the same every year as farmers practice open burning and there are higher incidences of natural forest fires during the dry season. In addition, there is a low amount of rain and high air pressure, leading to air pollutant accumulation (Chantara, 2012; Kliengchuay et al., 2021). The level decreased in the middle of April due to rain precipitation. Janta et al. (2020) also indicated that the hotspot and PM levels showed high levels in the biomass burning season and the highest in March.

### *$PM_{2.5}/PM_{10}$ ratios*

The daily average $PM_{2.5}/PM_{10}$ concentration ratios were also calculated in this study. Figure 4 demonstrates the daily average $PM_{2.5}/PM_{10}$ ratios of both areas during the haze period. Result found that the daily average $PM_{2.5}/PM_{10}$ concentration ratios ranged from about 0.30 to 1.14 and 0.27 to 1.57 in the urban area and the rural area, respectively. The average $PM_{2.5}/PM_{10}$ ratios in the urban and rural areas over the study period were 0.69 and 0.66, respectively. Similar patterns of the daily average $PM_{2.5}/PM_{10}$ ratios were observed in both monitoring stations. During 2017 to 2019, the daily average $PM_{2.5}/PM_{10}$ ratios in the urban area was higher than those in the rural area. It might be caused by traffic emissions sources and human-initiated burning activities in the area. The $PM_{2.5}/PM_{10}$ ratios in this study were compared with the other studies, as presented in Table 2. It was found that the $PM_{2.5}/PM_{10}$ ratios in this study is similar to those reported by other studies (Clements et al., 2016). However, previous studies mostly focused on the $PM_{2.5}/PM_{10}$ ratios in the urban area. Conversely, our results provided further information about the $PM_{2.5}/PM_{10}$ ratios in the rural area. Variation in $PM_{2.5}/PM_{10}$ ratios might be the result of different emission sources, meteorological conditions, and terrain characteristics in each area.

These study results indicated the dominant particulate matter in both areas was fine particles ($PM_{2.5}$). Approximately 66% to 69% of average $PM_{10}$ mass concentration was accounted by fine particles ($PM_{2.5}$), meaning $PM_{2.5}$ is important for $PM_{10}$ mass concentrations since it constituted more than half of the mass. Our results are in agreement with previous research in Thailand (Chirasophon & Pochanart, 2020; Kanchanasuta et al., 2020; Pengjan et al., 2019; Sahanavin et al., 2016; Sopajaree & Pengchai, 2007; Suburairat & Bunjongsiri, 2020; Thongyen, 2009), which demonstrated that the $PM_{2.5}/PM_{10}$ ratios were in the range of 0.53 to 0.72. Similarly, the ratios found in this study were similar in range to those found in Central China, India, Korea, and the USA, which ranged from 0.31 to 0.79. In agreement with our results, the study in the USA found that the traffic-influenced sites in Denver had average $PM_{2.5}/PM_{10}$ ratios of 0.56 to 0.70, higher than at residential sites in Denver or Greeley (Clements et al., 2016).

This result is consistent with the study by Pengjan et al. (2019) which showed how the pattern of $PM_{2.5}/PM_{10}$ ratios vary in each station and season. Previous studies also showed

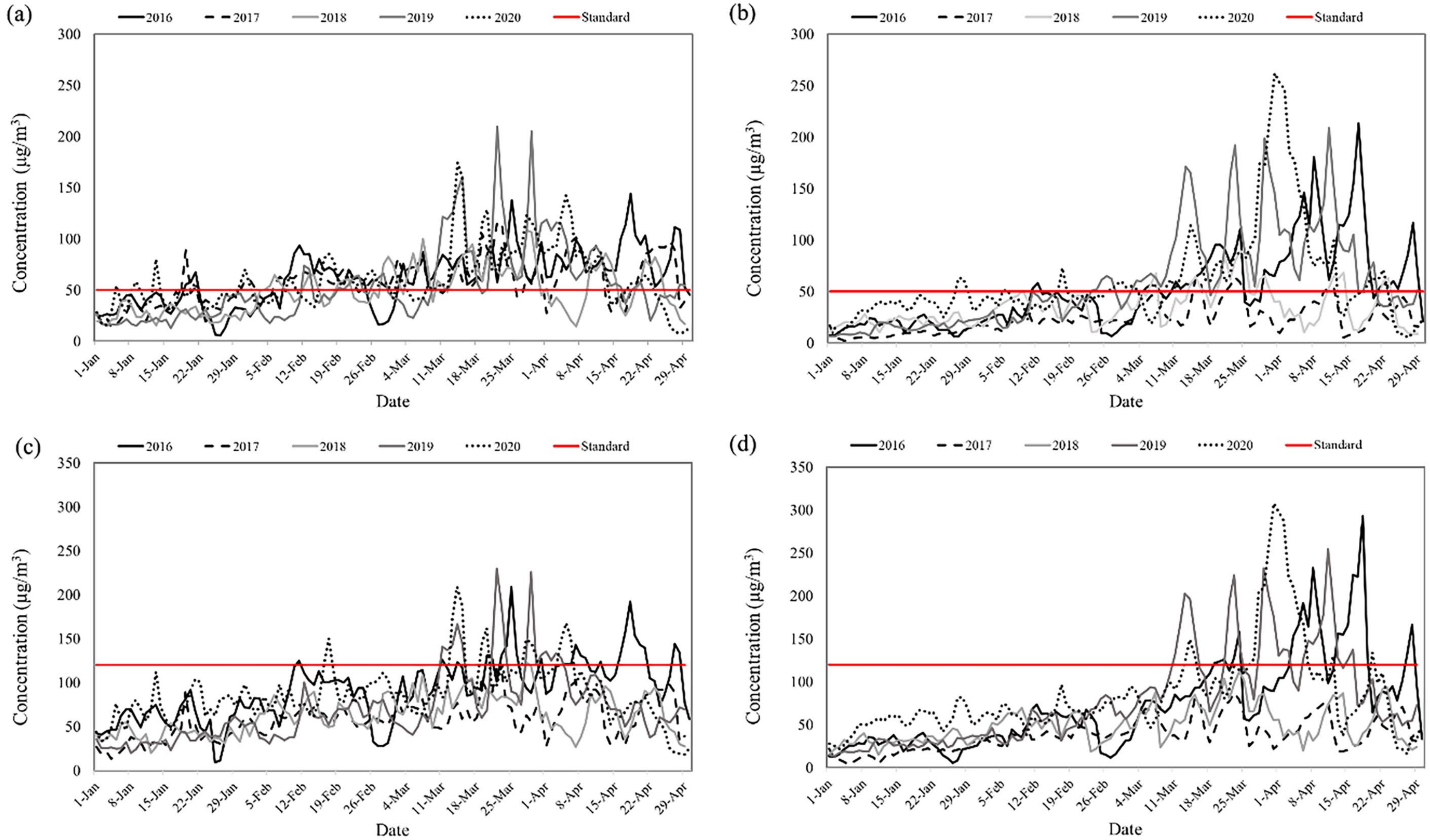


**Figure 2.** Trends of daily average concentrations of $PM_{2.5}$ and $PM_{10}$ concentrations in urban and rural areas during the haze period (January–April) from 2016 to 2020: (a) $PM_{2.5}$ in urban area (Chiangmai), (b) $PM_{2.5}$ in rural area (Nan), (c) $PM_{10}$ in urban area (Chiangmai), and (d) $PM_{10}$ in rural area (Nan)

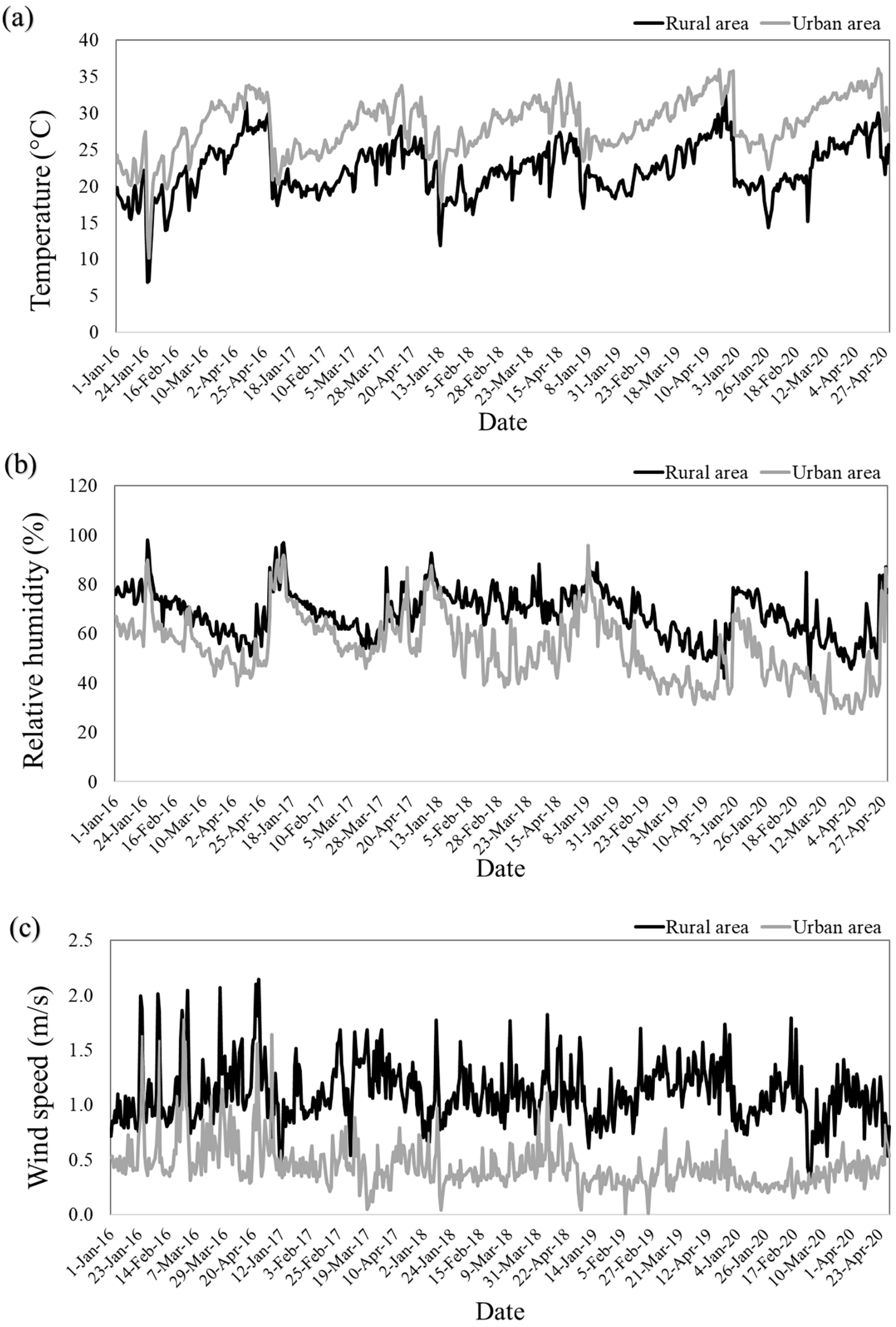


**Figure 3.** Trends of daily average meteorological parameters in rural and urban areas during the haze period (January–April) from 2016 to 2020: (a) atmospheric temperature, (b) relative humidity, and (c) wind speed.

that the $PM_{2.5}/PM_{10}$ ratios were higher during the dry season. The higher ratios observed during the dry season were influenced by local sources of emissions. In addition, low wind speeds, low temperature, low humidity, and low rainfall promote higher concentrations of $PM_{2.5}$ and $PM_{10}$, especially during the dry season (Kwanma et al., 2019).

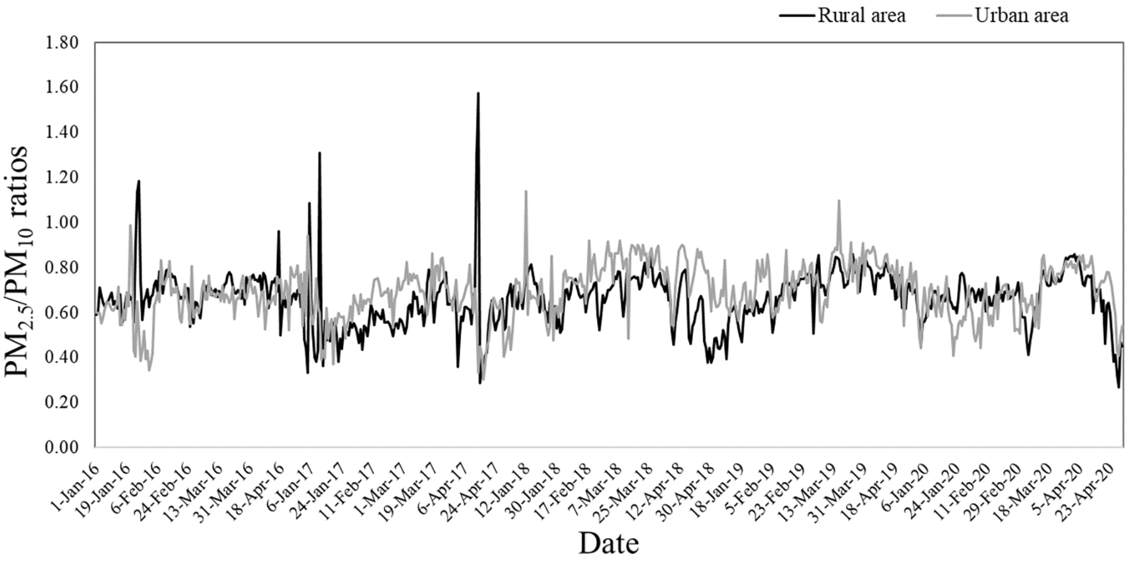


**Figure 4.** $PM_{2.5}/PM_{10}$ ratios during the haze period (January–April) from 2016 to 2020 in urban and rural areas.

### *Relationships between meteorological parameters and particulate matter concentrations ($PM_{2.5}$ and $PM_{10}$) during the haze period*

The relationships between meteorological parameters (T, RH, and WS) and particulate matter concentrations ($PM_{2.5}$ and $PM_{10}$) in the both areas during the haze period from January to April 2016 to 2020 were quantified using the Spearman-Rank correlation coefficient as shown in Table 3. Interpretation of the Spearman Rank correlation coefficients is based on Leclezio et al. (2015). The result of the Spearman-Rank analysis proves that $PM_{2.5}$ concentrations in the urban and the rural areas has a strong positive correlation with $PM_{10}$, with the correlation coefficients ($r$) reaching 0.948 and 0.985, respectively.

From Table 3, $PM_{2.5}$ and $PM_{10}$ concentrations had strong positive correlation with atmospheric temperature in the urban area and the rural area, respectively. The positive correlation between atmospheric temperature and particulate matters during the haze period can be explained by the climatic characteristics of the dry season and burning activities during this period. These activities may have resulted in photochemical reaction and the formation of precursor particles which are affected by increasing temperature (Wang & Ogawa, 2015).

In the case of relative humidity, $PM_{2.5}$ and $PM_{10}$ concentrations in both areas resulted strong negative correlation with relative humidity in the urban area ($r = -0.620$ and $r = -0.600$), and the rural area ($r = -0.691$ and $r = -0.722$), respectively. The reason for the negative correlation is that relative humidity influences particle movement, and it can cause particulate matters to settle down on the ground. Therefore, with the increase in relative humidity the concentrations of air pollutants become lower (Giri et al., 2008; Kayes et al., 2019).

However, $PM_{2.5}$ and $PM_{10}$ concentrations had no relationship with wind speed in the urban area and the rural area. The Spearman-Rank correlation coefficients between meteorological parameters and particulate matters during the haze period in the urban area were lower than those values in the rural areas. However, the two study areas showed similar correlation trends with different correlation coefficients between particulate matters and meteorological parameters, agreeable with the result by Kayes et al. (2019). This result suggests that atmospheric temperature and relative humidity were significantly correlated with the concentration of $PM_{2.5}$ and $PM_{10}$, but wind speed has no relationship with the concentration of $PM_{2.5}$ and $PM_{10}$.

Our results are consistent with the previous studies (Chotamonsak & Lapya, 2018; Kliengchuay et al., 2021; Kwanma et al., 2019; Suburairat & Bunjongsiri, 2020). The study of the meteorological factors related to $PM_{10}$ during the haze season (January–April) of the year 1998 to 2012 in Chiang Mai province by Chotamonsak and Lapya (2018) indicated during the peak air pollution, the daily maximum temperature was positively correlated while the daily minimum temperature was negatively correlated with the $PM_{10}$ concentration. Relative humidity was found to be negatively correlated with $PM_{10}$ concentrations. These results are consistent with the results conducted in Chiang Rai province by Kliengchuay et al. (2021) which concluded that relative humidity displayed negative relationships, although the temperature is positively correlated with $PM_{10}$ concentrations in the dry season. In addition, the study of the relationship between meteorological factors and the concentration of $PM_{10}$ concentration in Na Phra Lan, Saraburi over 10 years (2006–2015) showed relative humidity, air temperature and wind speeds had a significant relationship with the concentration of $PM_{10}$, with $r = -0.581$, $-0.440$, and $-0.402$, respectively (Kwanma et al., 2019). Moreover, the result by Pongkaset et al. (2020) from 2008 to 2017 showed a significant negative correlation between relative humidity and $PM_{10}$ in Yala Province ($r = -0.214$, $p < 0.05$). These previous studies indicated that this relationship is stronger during the dry season than during the rainy season; low wind speeds, low temperature, low humidity, and

**Table 2.** The $PM_{2.5}$ to $PM_{10}$ Ratios in this Study and Other Studies.

| COUNTRY/CITY | $PM_{2.5}/PM_{10}$ RATIO | AREA | REFERENCE | REMARKS |
|---|---|---|---|---|
| Bangkok | 0.53–0.73 | Urban (non-roadside stations) | Chirasophon and Pochanart (2020) | 2003–2016 |
|  | 0.53–0.65 | Urban (roadside stations) |  |  |
| Bangkok | 0.67 | Urban-roadside area | Thongyen (2009) | 2008–2009 |
|  | 0.66 | Urban-background area |  | Dry season |
| Bangkok | 0.64 | Urban | Pengjan et al. (2019) | 2011–2017 |
|  | 0.67 | Urban |  | Dry season |
|  | 0.60 | Urban |  | Wet season |
| Bangkok | 0.60 | Urban | Sahanavin et al. (2016) | 2013 |
| Bangkok | 0.63 | Urban | Kanchanasuta et al. (2020) | 2018 |
| Thailand | 0.63 | Urban | Suburairat and Bunjongsiri (2020) | 2014–2018<br>Dry season |
| North | 0.72 | Urban |  |  |
| Northeast | 0.67 | Urban |  |  |
| East | 0.66 | Urban |  |  |
| Central | 0.65 | Urban |  |  |
| South | 0.47 | Urban |  |  |
| Thailand | 0.60–0.65 | Urban | Sopajaree and Pengchai (2007) | 2005–2006 |
| North | 0.68 | Rural |  | Dry season |
| Central China | 0.62 | Urban | Xu et al. (2017) | 2013–2015 |
| India | 0.31–0.65 | Urban | Spandana et al. (2021) | 2017–2019 |
| Korea | 0.79 | Rural | Ryu et al. (2007) | Haze period |
| USA, Colorado | 0.49–0.53 | Rural | Clements et al. (2016) | 2009–2012 |
|  | 0.51–0.70 | Urban |  |  |
| This study | 0.66 | Rural |  | 2016–2020 |
|  | 0.69 | Urban |  | Haze period |

**Table 3.** Spearman-Rank Correlation Coefficients (*r*) between Meteorological Parameters and Particulate Matters in the Urban and Rural Areas during the Haze Period (January–April) from 2016 to 2020.

| PARAMETERS | $PM_{2.5}$ |  | $PM_{10}$ |  |
|---|---|---|---|---|
|  | URBAN AREA | RURAL AREA | URBAN AREA | RURAL AREA |
| Temperature | 0.600$^{a}$ | 0.581$^{a}$ | 0.528$^{a}$ | 0.624$^{a}$ |
| Relative humidity | −0.620$^{a}$ | −0.691$^{a}$ | −0.600$^{a}$ | −0.722$^{a}$ |
| Wind speed | −0.034 | 0.172$^{a}$ | −0.037 | 0.167$^{a}$ |

$^{a}$Correlation is significant at 0.01 level two-tailed.

low rainfall promote a higher concentration of particulate matter, especially during the dry season.

The light wind speed (<2 m/s) and more calm winds (<0.5 m/s) in the study areas could be associated with particulate matter variations. The light wind restricts the turbulence and could blow away the pollutants within a certain geographical area. The strong atmospheric stability could create favorable conditions that reduce dispersion potential and result in the accumulation of pollutants (Chantara, 2012; Li et al., 2015). Therefore, the correlation

**Table 4.** Regression equations and corresponding $R^2$ in the urban and rural areas.

| STUDY AREA | MODEL | $R^2$ |
|---|---|---|
| Urban area | $[PM_{2.5}] = [148.208 + 2.042T - 2.175RH]$ | 0.439 |
| | $[PM_{10}] = [177.553 + 3.078T - 2.662RH]$ | 0.495 |
| Rural area | $[PM_{2.5}] = [54.768 + 1.756T - 0.960RH]$ | 0.377 |
| | $[PM_{10}] = [100.545 + 1.401T - 1.226RH]$ | 0.352 |

of particulate matters and wind speed was found to be insignificant in this study.

Additionally, the relationships between particulate matters and meteorological parameters were determined through multivariate gaussian regression analysis using a statistical software module from SPSS. The $PM_{2.5}$ and $PM_{10}$ concentrations were used as the dependent variables, while meteorological parameters (temperature (T), and relative humidity (H) were the independent variables. It assumed that the dependent variable follows a normal distribution and that meteorological parameters are independent of each other. The desirable model to estimate the concentration of $PM_{2.5}$ and $PM_{10}$ among the correlated meteorological parameters (T and RH) for urban and rural areas is presented in Table 4. In the urban area, the $R^2$ values indicated why regression equations could explain variation in concentration of $PM_{2.5}$ and $PM_{10}$ approximately 43.9% and 49.5% at the 0.01 level respectively was statistically significant. For the rural area, the equations could explain variation in concentration of $PM_{2.5}$ and $PM_{10}$ approximately 37.7% and 35.2%, respectively.

Our study findings indicate that relationships among meteorological parameters could be responsible for particulate matter concentrations. In conclusion, meteorological parameters including RH and T were found to considerably affect particulate matter concentrations in the study areas. Moreover, this result suggests that the high particulate matter concentrations at the monitoring stations could be caused by the complex valley terrain and human activities such as open burning, especially the burning of agricultural residues and forest fires, transportation, and regional transboundary, contributing to haze pollution in the upper northern region.

### *Analysis of wind speeds and wind directions*

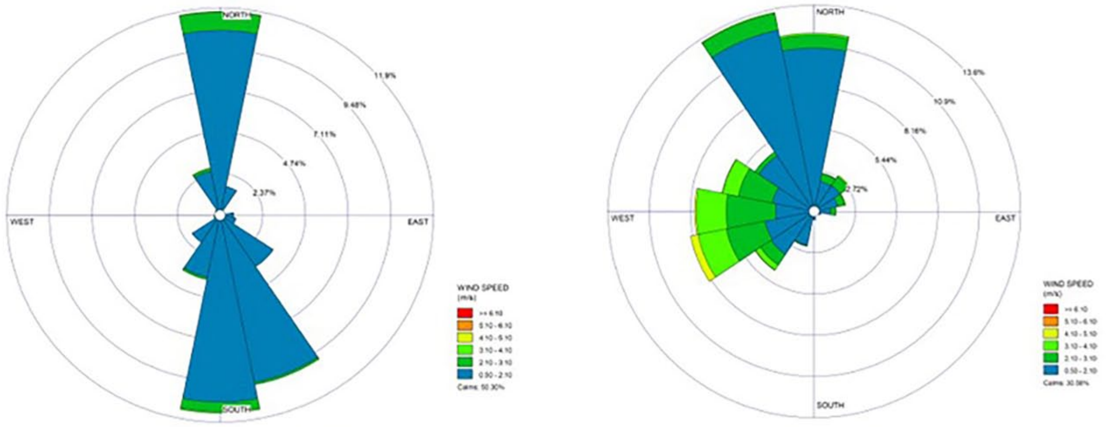
Wind influences horizontal dispersion and can play an important role in modulating pollutant concentrations (Yang et al., 2017). The wind rose diagram provides a graphical summary of the frequency distribution of wind direction and wind speed in urban and rural areas. As shown in Figure 5, the wind roses from hourly observations during the haze period from 2016 to 2020 were considered. The air mass in the urban area during the dry season was mostly under the influence of the southeasternly and the northern winds, with an average wind speed of 0.3 m/s (approximately 64% calm wind). On the other hand, the air mass in the rural area was mostly under the influence of the northwesterly and the west winds with an average wind speed of 1.8 m/s (approximately 28% calm wind). Wind speed in the urban area was observed to be more stable (not exceeding 0.5 m/s) and lower than that in the rural area. However, similar patterns of lower wind speed and direction in both areas were observed over the study period. The low average wind speeds and the high percentages of calm wind observed could have resulted in the high concentrations of particulate matters in the study areas. The particulate pollutants might have affected the monitoring stations and residential areas along the wind directions.

These results indicate the importance of the meteorological effects on the levels of $PM_{2.5}$ and $PM_{10}$ concentrations in the study areas. In addition, the concentrations and the ratios of $PM_{2.5}$ to $PM_{10}$ were significantly affected by the emission sources and the local winds. These effects will be more significant if they are coupled with substantial emissions. Light winds during the haze period were observed in the study areas and consequently high $PM_{2.5}$ to $PM_{10}$ concentrations were observed over the study period. In the dry season, the air conditions of low humidity, and calm winds resulted in stagnant air conditions. Accordingly, emissions from forest fires and open burning could accumulate in the air for a long time. At the same time, high air pressure originating from China also had an influence over the study areas, as it enhanced the gradually sinking air mass (Sirimongkonlertkul et al., 2013; TMD, 2013). As a result, emissions caused by forest fires and open burning activities could not readily disperse out from these areas, which contributed to the increasing pollutant levels in the atmosphere. Amnuaylojaroen and Kreasuwun (2012) indicated that the strong atmospheric stability and light wind over the Chiang Mai basin create favorable conditions for particulate matter accumulation. High particulate matter concentrations in this study are linked to high percentages of calm wind (64%) (Figure 5), consistent with the diurnal variation of $PM_{2.5}/PM_{10}$ which suggested a greater accumulation of $PM_{2.5}$ than $PM_{10}$ during low wind speed.

### *Transboundary transport during haze period*

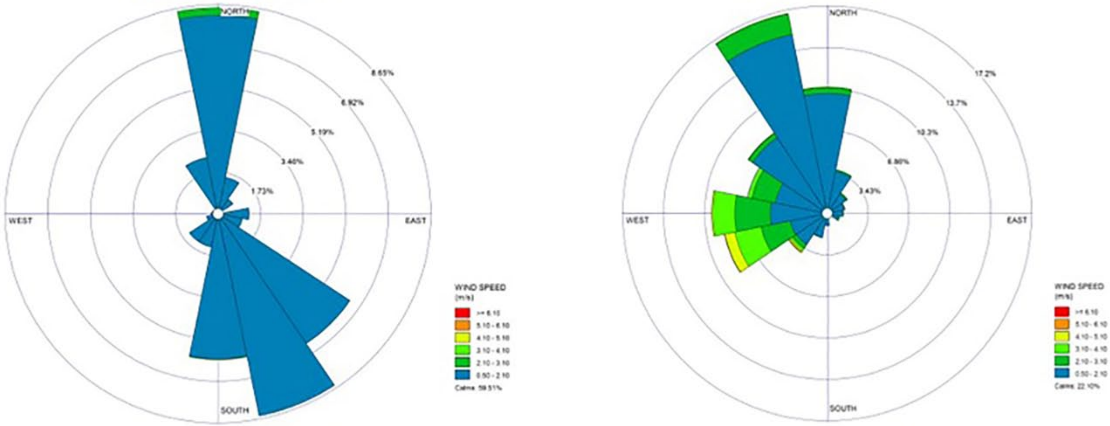
This research conducted an analysis of the daily backward trajectories to determine the origin of air masses and establish source-receptor relationships. It also conducted tests using the hybrid-single particle Lagrangian integrated trajectory (HYSPLIT) model in each study area. This model can be run online at http://ready.arl.noaa.gov/HYSPLIT.php (NOAA Air Resources Laboratory, 2022). A common application of a back-trajectory analysis is to determine the origin of air masses and establish source-receptor relationships. Daily backward trajectories to the air quality monitoring stations in the urban and rural areas were investigated on the day with the results of the highest concentrations of $PM_{2.5}$ and $PM_{10}$ to analyze the possibility that wind patterns and directions could have transported air pollutants to each study area. The height of air trajectories was set as 100, 500, and 1,000 m above ground level (AGL).

For the urban area, the highest concentrations of $PM_{2.5}$ (210 μg/m$^3$) and $PM_{10}$ (230 μg/m$^3$) were observed on 23 March 2019. The backward trajectory pattern in Chiang Mai province is illustrated in Figure 6a. The result shows that the air mass movements were mainly carried from the southwest direction across the southwestern part of Chiang Mai Province where has been the highland and the large biomass burned area. If pollutant sources such as open burning and forest fires were mostly conducted within Chiang Mai province, and in neighboring provinces (Mae Hong Son), their impact on particulate matter levels could be more significant. The additional impact from air mass movement from neighboring countries (Myanmar) via southwest winds before moving to the monitoring station located in the urban area.



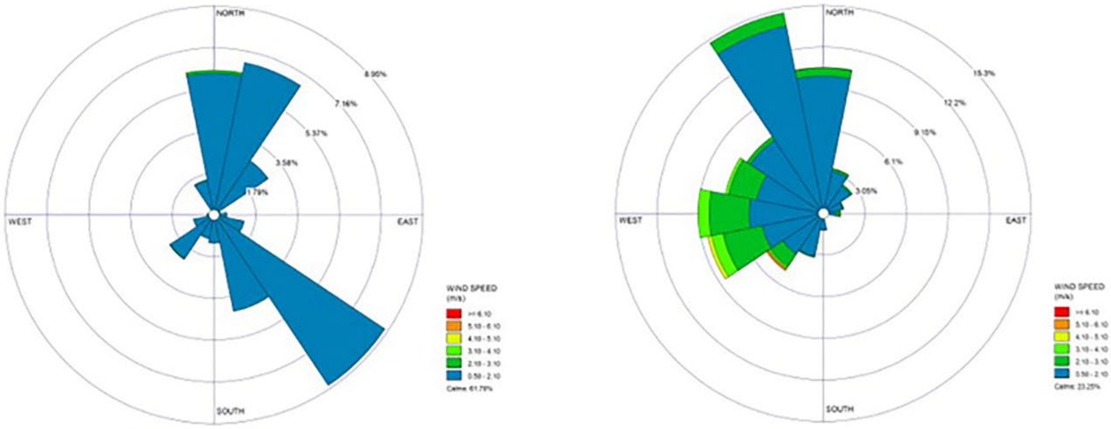
Chiang Mai, 2016

Nan, 2016



Chiang Mai, 2017

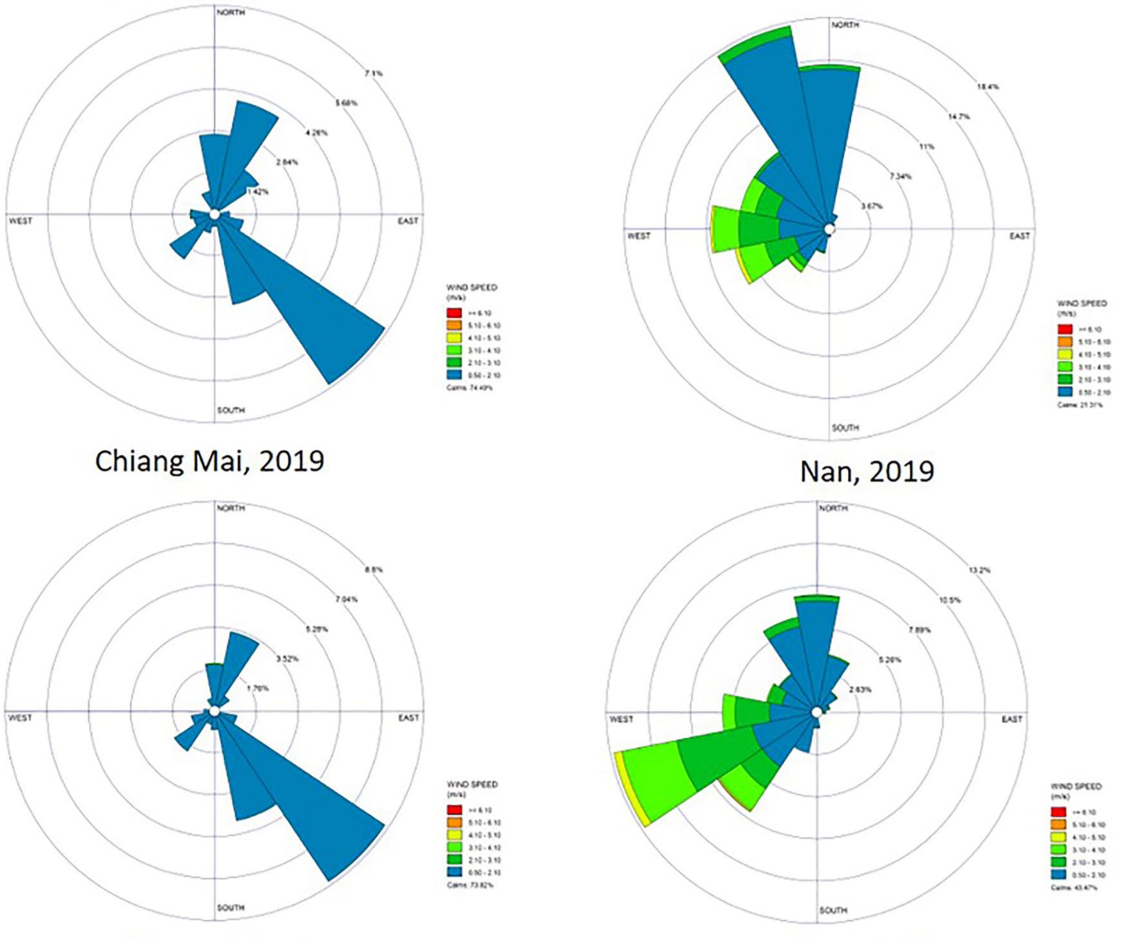
Nan, 2017



Chiang Mai, 2018

Nan, 2018

**Figure 5.** *(Continued)*



Chiang Mai, 2019

Nan, 2019

Chiang Mai, 2020

Nan, 2020

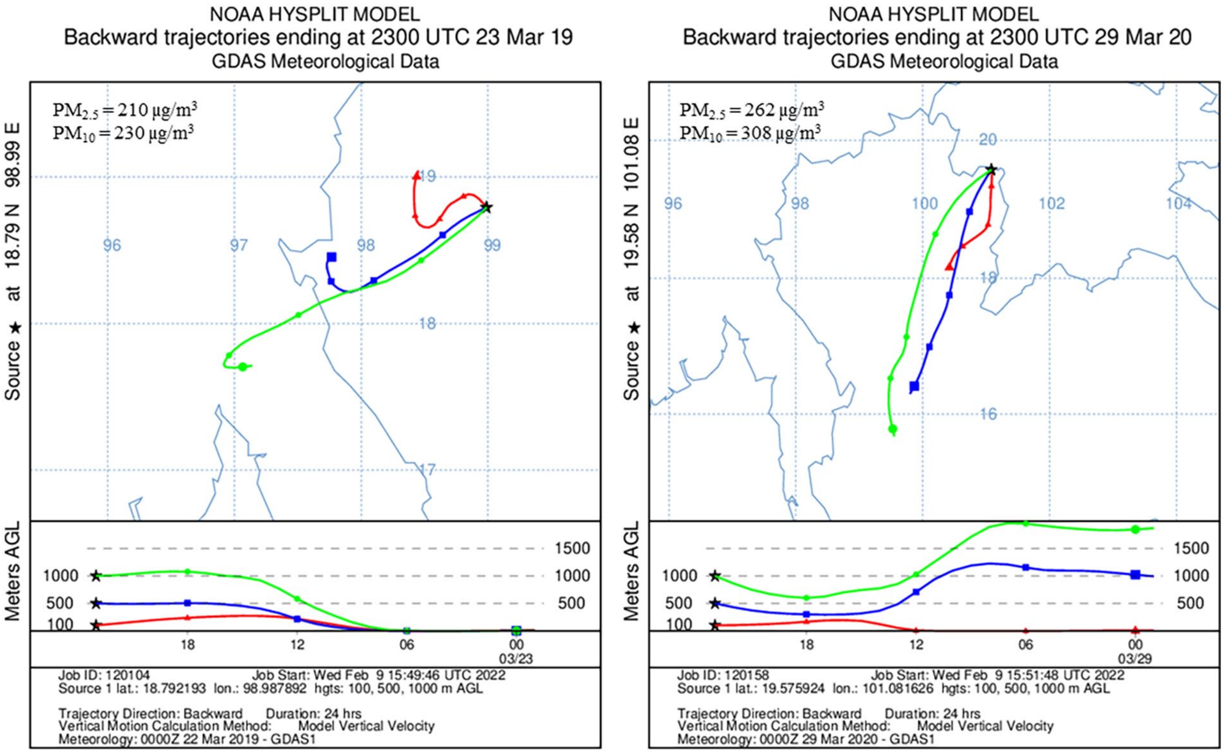
**Figure 5.** Wind rose diagram of hourly average wind directions and wind speeds in the urban area (Chiang Mai province) and the rural area (Nan province) during the haze period (January-April) from 2016 to 2020.

For the rural area, the highest concentrations of $PM_{2.5}$ (262 μg/m³) and $PM_{10}$ (308 μg/m³) were observed on 31 March 2020. The daily backward trajectory pattern in Nan province is illustrated in Figure 6b. The daily backward trajectory pattern in the area shows that the air mass movements were mainly carried from the southwest direction. If open burning was mostly conducted within Nan province, and in neighboring provinces (Phrae and Phayao, Uttaradit, Sukhothai, Kamphaeng Phet, Phitsanulok, and Nakhon Sawan provinces), these upwind locations could have a more significant impact on particulate matter levels.

The topography of Chiang Mai province formed a basin which made weak wind suitable for reducing dispersion potential and the accumulation of pollutants within it. As stated in Chotamonsak and Lapya (2018), the wind direction related to the above standards of $PM_{10}$ mostly blew from the southwest of Chiang Mai area, where the highlands and the large biomass burned areas are. Together with Chiang Mai topography, the wind blew pollutants from the burned area and deposited it in the basin. Besides, high $PM_{10}$ concentration events are usually observed when high air pressure moves over Chiang Mai province (Chotamonsak & Lapya, 2018). Likewise, the study of the smoke and haze problem in Chiang Mai province by Yasanga et al. (2010), showed that $PM_{10}$ exceeding NAAQA standards were influenced by open burning in long-range upwind regions.

For Nan province, there are high mountains, most of which are above 2,000 m in height. These mountains are located on a north-south axis and are adjacent to the Thai–Laos boundary. They can influence the wind direction and limit the dispersion characteristics of pollutants in this study area. Farmers in northern Thailand and neighboring countries in the region commonly burn their fields during this dry season to prepare their land for the next year. Therefore, it could also result in elevated levels of particulate pollutants in the rural area at that time. This study enhances the understanding of the behaviors of particulate pollutants in northern Thailand during the haze periods.

The analysis of backward trajectories using the HYSPLIT model demonstrated air mass movement in March was mostly in the southwest direction, which moved through the highland, the large biomass burned areas, and upwind neighboring



(a) Chiang Mai province (Urban area)

(b) Nan province (Rural area)

**Figure 6.** Daily backward trajectories to the air quality monitoring stations in the urban and rural areas during the day when the highest concentrations of $PM_{2.5}$ and $PM_{10}$ occurred: (a) in Chiangmai province on 23 March 2019 and (b) in Nan province on 31 March 2020.

provinces before reaching the air monitoring stations, which might have contributed to elevated particulate pollutants levels recorded by the air monitoring stations. GISDA (2019) reported on the number of Moderate Imaging Spectroradiometer (MODIS) fire hotspot locations in Southeast Asia occurring between January and April 2019, which indicated hotspots mostly occurred in March. The $PM_{2.5}$ and $PM_{10}$ concentrations over the study period has a similar trend to the frequency of fire hotspots which increased between January and March. The highest concentrations of $PM_{2.5}$ and $PM_{10}$ throughout this study period were also observed in March of 2019. The number of hotspot locations in Myanmar twice that of Thailand under the influence of southwesterly winds that might have bought air pollutants from neighboring countries to northern Thailand. In addition, major contributors of hotspot locations were found in upwind neighboring provinces, including Chiang Rai province, Chiangmai province, Mae Hong Son province, and Nan province, which accounted for 65% of hotspots. Amnuaylojaroen et al. (2020) reported the number of hotspot locations in Southeast Asia between January and April 2016 which indicated Myanmar and Laos were the major contributors of hotspot locations in March and April, representing approximately 37% and 28% of hotspot locations in Southeast Asia. Biomass burning in neighboring countries has a greater potential of contributing to air pollution in northern Thailand during the haze period.

Therefore, this study has shown the importance of regional transport of pollutants, which indicates both domestic and transboundary transport contribute to the smoke haze problem in the study areas. However, it is possible that the pollutant emissions traveling in the air mass would be less concentrated when they arrived in each impacted area. This result is in accordance with the previous study of the HYSPLIT backward trajectory that has been applied to track the source contribution of $PM_{2.5}$ in northern Thailand in March 2016. It indicates that the pathway of $PM_{2.5}$ begins in India and Bangladesh, then moves across Burma to northern Thailand (Inkham & Amnuaylojaroen, 2018).

## Conclusions

The impacts of air pollution are different depending on the characteristics of the geographic area, atmospheric conditions, and emission sources. Meteorological parameters play a crucial role in the ambient air quality of urban and rural environments. This study has investigated the relationships between meteorological parameters (including temperature, relative humidity, and wind speed) and ambient $PM_{2.5}$ and $PM_{10}$ concentrations in the urban and rural areas during the haze period from 2016 to 2020. The results showed the highest concentrations of $PM_{2.5}$ and $PM_{10}$ throughout the study period were regularly observed in March. Approximately 24% to 65% of daily average $PM_{2.5}$ concentration in the urban area over the study period exceeded the NAAQS. The temperature values were higher in the urban area than those in the rural area, whereas the relative humidity and the wind speed in the rural area were greater than those values in the urban area. The average $PM_{2.5}/PM_{10}$ ratios in the urban and rural areas over the study period were 0.69 and 0.66, respectively, suggesting $PM_{2.5}$ mass concentration is important for $PM_{10}$ mass concentration since it constituted more than half of the mass. The atmospheric temperature and relative humidity were significantly correlated with the concentration of $PM_{2.5}$ and $PM_{10}$, but wind speed does not have significant impact in both areas. Additionally, the wind rose diagram showed similar patterns of low wind speed and direction with high percentages of calm wind over the study period in both areas. The daily backward trajectories using HYSPLIT model demonstrated air mass movement in March mostly moved in the southwest direction through the highlands, the large biomass burned areas, and upwind neighboring provinces before reaching the air monitoring stations. This study indicated both domestic and transboundary transport could have contributed to the smoke haze problem in the study areas. Further studies are necessary to identify emission sources in each area to reduce $PM_{2.5}$ and $PM_{10}$ concentration levels during the haze period.

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## Author Contributions

T.P. (Ph.D. Lecturer) contributed to the design and implementation of the research. S.D. (Ph.D. Lecturer) and T.P. (Ph.D. Lecturer) contributed to the analysis of the results and the writing of the manuscript.

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## REFERENCES

Amnuaylojaroen, T., Inkom, J., Janta, R., & Surapipith, V. (2020). Long range transport of Southeast Asian PM2.5 pollution to northern Thailand during high biomass burning episodes. *Sustainability*, 12(23), 10049. https://doi.org/10.3390/su122310049

Amnuaylojaroen, T., & Kreasuwun, J. (2012). Investigation of fine and coarse particulate matter from burning areas in Chiang Mai, Thailand using the WRF/CALPUFF. *Chiang Mai Journal Science*, 39(2), 311–326.

Bai, L., Wang, J., Ma, X., & Lu, H. (2018). Air pollution forecasts: An overview. *International Journal of Environmental Research and Public Health*, 15(4), 1–44. https://doi.org/10.3390/ijerph15040780

Brochu, P. J., Yanosky, J. D., Paciorek, C. J., Schwartz, J., Chen, J. T., Herrick, R. F., & Suh, H. H. (2011). Particulate air pollution and socioeconomic position in rural and urban areas of the Northeastern United States. *American Journal of Public Health*, 101(Suppl. 1), S224–S230. https://doi.org/10.2105/AJPH.2011.300232

Chansuebsri, S., Kraisitnitikul, P., Wiriya, W., & Chantara, S. (2022). Fresh and aged PM2.5 and their ion composition in rural and urban atmospheres of Northern Thailand in relation to source identification. *Chemosphere*, 286, 131803. https://doi.org/10.1016/j.chemosphere.2021.131803

Chantara S. (2012). PM10 and its chemical composition: A case study in Chiang Mai, Thailand. In K. Sunil (Eds.), *Air quality—monitoring and modeling*. InTech. .ISBN: 978-953-51-0161-1.

Chen, Z., Chen, D., Zhao, C., Kwan, M. P., Cai, J., Zhuang, Y., Zhao, B., Wang, X., Chen, B., Yang, J., Li, R., He, B., Gao, B., Wang, K., & Xu, B. (2020). Influence of meteorological conditions on PM2.5 concentrations across China: A review of methodology and mechanism. *Environment International*, 139, 105558. https://doi.org/10.1016/j.envint.2020.105558

Chirasophon, S., & Pochanart, P. (2020). The long-term characteristics of PM10 and PM2.5 in Bangkok, Thailand. *Asian Journal of Atmospheric Environment*, 14(1), 73–83. https://doi.org/10.5572/ajae.2020.14.1.073

Chotamonsak, C., & Lapya, D. (2018). Meteorological factors related to air pollution in Chiang Mai Province. *Journal of Research Unit on Science, Technology and Environment for Learning*, 9(2), 237–249.

Clements, N., Hannigan, M. P., Miller, S. L., Peel, J. L., & Milford, J. B. (2016). Comparisons of urban and rural $PM_{10-2.5}$ and $PM_{2.5}$ mass concentrations and semi-volatile fractions in northeastern Colorado. *Atmospheric Chemistry and Physics*, 16, 7469–7484. https://doi.org/10.5194/acp-16-7469-2016

DOPA. (2021). *Official statistics registration systems*. Department of Provincial Administration. https://stat.bora.dopa.go.th/stat/statnew/statMenu/newStat/home.php

EEA. (2020). *Dispersal of air pollutants*. https://www.eea.europa.eu/publications/2599XXX/page005.html

Giri, D., Krishna Murthy, V., & Adhikary, P. R. (2008). The influence of meteorological conditions on PM10 concentrations in Kathmandu Valley. *International Journal of Environmental Research*, 2(1), 49–60.

GISDA. (2019). *Fire report 2019*. https://fire.gistda.or.th/fire_report/Fire_2562.pdf

Huang, M., Ivey, C., Hu, Y., Holmes, H. A., & Strickland, M. J. (2019). Source apportionment of primary and secondary PM2.5: Associations with pediatric respiratory disease emergency department visits in the U.S. State of Georgia. *Environment International*, 133(Pt A), 105167. https://doi.org/10.1016/j.envint.2019.105167

Inkham, J., & Amnuaylojaroen, T. (2018). *Analysis of long-range transport of PM2.5 influences on air pollution in northern Thailand using HYSPLIT model* [Conference session]. The 3rd KU SRC Annual Conference 2018, Kasetsart University (Sriracha Campus), Chonburi Province, Thailand.

Janta, R., Sekiguchi, K., Yamaguchi, R., Sopajaree, K., Plubin, B., & Chetiyanukornkul, T. (2020). Spatial and temporal variations of atmospheric PM10 and air pollutants concentration in upper northern Thailand during 2006–2016. *Applied Science and Engineering Progress*, 13(3), 256–267.

Kanchanasuta, S., Sooktawee, S., Patpai, A., & Vatanasomboon, P. (2020). Temporal variations and potential source areas of fine particulate matter in Bangkok, Thailand. *Air Soil and Water Research*, 13, 1–10. https://doi.org/10.1177/1178622120978203

Kayes, I., Shahriar, S. A., Hasan, K., Akhter, M., Kabir, M. M., & Salam, M. A. (2019). The relationships between meteorological parameters and air pollutants in an urban environment. *Global Journal of Environmental Science and Management*, 5(3), 265–278. https://doi.org/10.22034/GJESM.2019.03.01

Kim, K.-H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment International*, 74, 136–143. https://doi.org/10.1016/j.envint.2014.10.005

Kliengchuay, W., Worakhunpiset, S., Limpanont, Y., Meeyai, A. C., & Tantrakarnapa, K. (2021). Influence of the meteorological conditions and some pollutants on PM10 concentrations in Lamphun, Thailand. *Journal of Environmental Health Science and Engineering*, 19(1), 237–249. https://doi.org/10.1007/s40201-020-00598-2

Kwanma, P., Pukngam, S., & Arunpraparu, W. (2019). Meteorological factors affecting concentration of PM10 at Na Phra Lan sub-district, Chaloem Phra Kiat district, Saraburi province. *PSRU Journal of Science and Technology*, 4(2), 85–94.

Leclezio, L., Jansen, A., Whittemore, V. H., & de Vries, P. J. (2015). Pilot validation of the tuberous sclerosis-associated neuropsychiatric disorders (TAND) checklist. *Pediatric Neurology*, 52(1), 16–24. https://doi.org/10.1016/j.pediatrneurol.2014.10.006

Lin, C., Lau, A., Li, Y., Fung, J., Li, C., Lu, X., & Li, Z. (2018). Difference in PM2.5 variations between urban and rural areas over eastern China from 2001 to 2015. *Atmosphere*, 9(8), 312. https://doi.org/10.3390/atmos9080312

Liu, Z., Shen, L., Yan, C., Du, J., Li, Y., & Zhao, H. (2020). Analysis of the influence of precipitation and wind on PM2.5 and PM10 in the atmosphere. *Advances in Meteorology*, 2020, 1–13. https://doi.org/10.1155/2020/5039613

Li, Y., Chen, Q., Zhao, H., Wang, L., & Tao, R. (2015). Variations in PM10, PM2.5 and PM1.0 in an urban area of the Sichuan Basin and their relation to meteorological factors. *Atmosphere*, 6(1), 150–163. https://doi.org/10.3390/atmos6010150

Mabahwi, N. A. B., Leh, O. L. H., & Omar, D. (2014). Human health and wellbeing: Human health effect of air pollution. *Procedia - Social and Behavioral Sciences*, 153, 221–229. https://doi.org/10.1016/j.sbspro.2014.10.056

MOTS. (2021). *Annual report: Tourism statistics*. https://www.mots.go.th/more_news_new.php?cid=411

NOAA Air Resources Laboratory. (2022). *The HYSPLIT model*. https://www.ready.noaa.gov/HYSPLIT.php

Outapa, P., & Ivanovitch, K. (2019). The effect of seasonal variation and meteorological data on PM10 concentrations in Northern Thailand. *GEOMATE Journal*, 16(56), 46–53.

PCD. (2020). *Thailand state of pollution report 2019*. Pollution Control Department. https://www.pcd.go.th/wp-content/uploads/2020/09/pcdnew-2020-09-03_08-10-17_397681.pdf/

PCD. (2021). *Thailand state of pollution report 2020*. Pollution Control Department. https://www.pcd.go.th/ebook/book1/

Pengjan, S., Fan, C., Bonnet, S., & Garivait, S. (2019). Assessment of the PM2.5/PM10 ratio in the Bangkok Metropolitan Region during 2011-2017. *Journal of Sustainable Energy & Environment*, 10, 75–84.

Pienkosz, B. D., Saari, R. K., Monier, E., & Garcia-Menendez, F. (2019). Natural variability in projections of climate change impacts on fine particulate matter pollution. *Earth s Future*, 7(7), 762–770. https://doi.org/10.1029/2019ef001195

Pochanart, P. (2016). The present state of urban air pollution problems in Thailand's large cities: Cases of Bangkok, Chiang Mai, and Rayong. *Journal of Environmental Management*, 12(1), 114–133.

Pongkaset, A., Supapwanich, C., & Sonbut, J. (2020). Meteorological factors related to PM10 and health risk assessment for resident exposed to PM10 in Yala City, Yala Province. *The Public Health Journal of Burapha University*, 15(2), 39–49.

RFD. (2019). *Forestry statistics data 2018*. Royal Forest Department. http://forestinfo.forest.go.th/55/Content.aspx?id=10370

Ryu S. Y., Kwon B. G., Kim Y. J., Kim H. H., & Chun K. J. (2007). Characteristics of biomass burning aerosol and its impact on regional air quality in the summer of 2003 at Gwangju, Korea. *Atmospheric Research, 84*(4), 362–373. https://doi.org/10.1016/j.atmosres.2006.09.007

Sahanavin, N., Tantrakarnapa, K., & Prueksasit, T. (2016). Ambient PM10 and PM2.5 concentrations at different high traffic-related street configurations in Bangkok, Thailand. *The Southeast Asian Journal of Tropical Medicine and Public Health*, 47(3), 528–535.

Shah, A. S., Langrish, J. P., Nair, H., McAllister, D. A., Hunter, A. L., Donaldson, K., Newby, D. E., & Mills, N. L. (2013). Global association of air pollution and heart failure: A systematic review and meta-analysis. *Lancet*, 382(9897), 1039–1048. https://doi.org/10.1016/S0140-6736(13)60898-3

Sierra-Vargas, M. P., & Teran, L. M. (2012). Air pollution: Impact and prevention. *Respirology (Carlton, Vic)*, 17(7), 1031–1038. https://doi.org/10.1111/j.1440-1843.2012.02213.x

Sirimongkonlertkul, N., Upayokhin, P., & Phonekeo, V. (2013). Multi-temporal analysis of haze problem in northern Thailand: A case study in Chiang Rai Province. *Kasetsart Journal (Natural Science)*, 47, 768–780.

Sopajaree, K., & Pengchai, P. (2007). *Investigation of ambient air particulate matters in Chiang Mai and Lamphun*. Department of Environmental Engineering, Chiang Mai University.

Spandana B., Rao S. S., Upadhya A. R., Kulkarni P., & Sreekanth V. (2021). PM2.5/PM10 ratio characteristics over urban sites of India. *Advances in Space Research, 67*(10), 3134–3146. https://doi.org/10.1016/j.asr.2021.02.008

Strosnider, H., Kennedy, C., Monti, M., & Yip, F. (2017). Rural and urban differences in air quality, 2008–2012, and community drinking water quality, 2010–2015 — United States. *MMWR Surveillance Summaries*, 66(13), 1–10. https://doi.org/10.15585/mmwr.ss6613a1

Suburairat, K., & Bunjongsiri, K. (2020). The quantitative relationships of particulate matter (PM10 and PM2.5) in each region and season. *Huachiew Chalermprakiet Science and Technology Journal*, 6(1), 94–103.

Thongyen, T. (2009). *Source apportionment of polycyclic aromatic hydrocarbons in size-selected particulate matter in Bangkok Metropolitan Area*. Chulalongkorn University. http://cuir.car.chula.ac.th/handle/123456789/15939

TMD. (2013). *Weather*. https://www.tmd.go.th/thailand.php

U.S.EPA. (2000). *Current knowledge of particulate matter (PM) continuous emission monitoring*. https://www3.epa.gov/ttnemc01/cem/pmcemsknowfinalrep.pdf

U.S.EPA. (2019a). *Air pollution: current and future challenges*. https://www.epa.gov/clean-air-act-overview/air-pollution-current-and-future-challenges

U.S.EPA. (2019b). *Particulate matter (PM) pollution*. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#:~:text=PM%20stands%20for%20particulate%20matter,seen%20with%20the%20naked%20eye

Wang, J., & Ogawa, S. (2015). Effects of meteorological conditions on PM2.5 concentrations in Nagasaki, Japan. *International Journal of Environmental Research and Public Health*, 12(8), 9089–9101. https://doi.org/10.3390/ijerph120809089

Wang, S.-H., Hung, R.-Y., Lin, N.-H., Gómez-Losada Pires, J. C. M, Shimada, K, Hatakeyama, S, & Takami, A. (2020). Estimation of background PM2.5 concentrations for an air-polluted environment. *Atmospheric Research*, 231, 104636. https://doi.org/10.1016/j.atmosres.2019.104636

WHO. (2019). *Ambient air pollution: Health impacts*. https://www.who.int/airpollution/ambient/health-impacts/en/

Xu G., Jiao L., Zhang B., Zhao S., Yuan M., Gu Y., Liu J., & Tang X. (2017). Spatial and temporal variability of the PM2.5/PM10 ratio in Wuhan, Central China. *Aerosol and Air Quality Research, 17*, 741–751. https://doi.org/10.4209/aaqr.2016.09.0406

Yang, Q., Yuan, Q., Li, T., Shen, H., & Zhang, L. (2017). The relationships between PM2.5 and meteorological factors in China: Seasonal and regional variations. *International Journal of Environmental Research and Public Health*, 14(12), 1510. https://doi.org/10.3390/ijerph14121510

Yasanga, N., Traisathit, P., & Prasitwattanaseree, S. (2010). *Identification of backward trajectory air transport patterns to Chiang Mai and Bangkok using cluster analysis* [Conference session]. 11th Statistics and Applied Statistics Conference, Chiang Mai, Thailand.

Zhao, C. X., Wang, Y. Q., Wang, Y. J., Zhang, H. L., & Zhao, B. Q. (2014). [Temporal and spatial distribution of PM2.5 and PM10 pollution status and the correlation of particulate matters and meteorological factors during winter and spring in Beijing]. *Huan Jing Ke Xue*, 35(2), 418–427.