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Air Quality Analysis in the Selected Urban and Suburban Areas in Central Thailand by Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors (CUPI-G)

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Abstract

Air pollution is a major environmental issue in Asian developing nations because of its negative consequences. In Thailand, it is a serious problem, not only in metropolitan areas, but also throughout large areas of the country. Ratchathewi district was selected as an urban observation site due to its location, and Mueang Samut Sakhon district was chosen as a suitable suburban observation site with many small industries. The main objective of the study is to investigate the temporal variations and correlations in $PM_{2.5}$ and trace pollutant gases in relation to the meteorological conditions at the urban and suburban sites during the observation period using the Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors (CUPI-G). The air quality observations were conducted for two weeks respectively from 11th to 25th February 2023 at the Ratchathewi site and from 14th to 28th November 2022 at the Mueang Samut Sakhon site using the CUPI-G. During the observations, air pollutant concentrations detected at the Ratchathewi site were in the range of 9.8-248.9 $\mu g/m^3$ for $PM_{2.5}$, 526.2-2221.2 ppb for CO, 20.9-1888.4 ppb for NO, 18.1-155.5 ppb for NO_2, 27.4-213.5 ppb for O_x and 1.1-88.9 ppb for O_3. At the Mueang Samut Sakhon site, they ranged from 3.4-172.5 $\mu g/m^3$ for $PM_{2.5}$, 426.5-989.9 ppb for CO, 10.4-321.5 ppb for NO, 6.8-95.3 ppb for NO_2, 1.5-143.3 ppb for O_x and 5.3-57.7 ppb for O_3. Compared with the ambient air quality standards for Thailand, the results showed that both sites experienced pollution from photochemical oxidants in addition to particulate matter. The CUPI-G showed that it was an applicable instrument for air quality observations in both urban suburban areas. Due to the different correlations between air pollutants in each area, additional research is necessary to address specific atmospheric patterns in order to tackle the air pollution issues in Thailand.

Keywords : CUPI-G; air pollution; urban area; suburban area; Thailand

Introduction

Air pollution in metropolitan centers of Asian developing nations is a major environmental problem due to its high levels and the related negative consequences on human health, ecosystems and climate [1]. In 2019, air pollution ranked among the top 10 risk factors for death, accounting for about 8% of all fatalities (more than 41 thousand) in Thailand. Thailand's life expectancy was lowered by 1 year due to air pollution [2]. Thailand's poor air quality is a serious issue, not just in metropolitan areas but throughout large areas of the nation [3]. Pollutant concentrations are greatly influenced by topography, land use and meteorological factors such as rain intensity, temperature, and wind speed. Thailand has a tropical climate with an average temperature of about 30°C, with temperature changes throughout the seasons because it is located 15° above the equator [4].

The conventional method for managing air quality, assessing trends and estimating exposure for epidemiological analysis has been to measure air pollutant concentrations at fixed-location monitoring sites. Despite an increase in the number of monitoring sites around the world, coverage is insufficient. It is frequently limited to major cities to reliably assess exposure in the many and varied regions where people reside [5]. Miniaturization has increased the prominence of a generation of devices that are sometimes referred to as "low-cost sensors," even though the great majority of these observations still use established analytical reference procedures [6]. In fact, they may differ from earlier technologies not just in price but also in weight, size, and power consumption. They are a sort of device that spans a wide range of technologies, and as a result, they generate measurements with a wide range of accuracy [6]. Together with the conventional instruments used in atmospheric studies, they can contribute to providing some further information.

The compact and useful $PM_{2.5}$ instrument with gas sensors (CUPI-G) is made up of a palm-sized optical $PM_{2.5}$ sensor created by Nagoya University and Panasonic Corporation, a temperature and humidity sensor, and four electrochemical sensors for gaseous pollutants (CO, NO, NO_2, and O_x) from Alphasense Company, UK. The CUPI-G was started to be used in the Aakash Project, which deals with air pollution brought on by massive post-harvest burning of rice straw in the states of Punjab and Haryana in northwest India, in October and November in 2019 [7]. In account of its suitability for multipoint observations, it can be beneficial to obtain useful results, especially in developing nations where the large and expensive standard instruments can be installed so infrequently to find the reliable data on air quality.

As of 2017, the population density in Mueang Samut Sakhon district was 596.94/km^2 while it was 10,146.50/km^2 in Ratchathewi district [8]. In central Thailand, Ratchathewi district in the heart of Bangkok is surrounded by neighborhoods of urban areas. Due to its central location in the city, the area is home to many well-known landmarks, educational institutions and medical facilities. Therefore, it can well represent the urban area in the central part of Thailand. On the other hand, Mueang Samut Sakhon is the capital district of central Thailand's Samut Sakhon province: formerly an agricultural and fisheries-based province which currently has many small factories. Small businesses lack the funds to install environmental equipment that would aid in environmental protection. As a result, Samut Sakhon is one of the country's most polluted provinces [9]. Samut Sakhon province had the worst polluted air in Thailand in 2018 [10]. It was therefore selected as a suitable suburban site for the air quality study.

Although previous studies were conducted in India [7] and in Japan [11] by using the CUPI-G, there is a gap in the understanding of its applicability in the atmospherically relevant conditions in Thailand. Furthermore, different conclusions have been reached under the influence of complex topography, meteorological conditions, and pollutant emissions because the relationship between photochemical smog and particulate pollutants is difficult to quantify and has shown great differences in research areas, time scales, and research methodologies [12]. Therefore, the main objectives of the study are to apply the CUPI-G in the urban area, Ratchathewi district and the suburban area of Mueang Samut Sakhon district and to investigate the temporal variations and correlations in $PM_{2.5}$ and trace pollutant gases in relation to the meteorological conditions during the observation period.

Methodology

Monitoring Instrument

The compact and useful $PM_{2.5}$ instrument with gas sensors (CUPI-G) was mainly used in this study. The CUPI-G has dimensions of 18 cm x 21cm x 30 cm and weighs only 5 kg. It is simple to operate, low-cost, easy to handle, and low power consumption. The price of the small sensors is 1/100 of large standard instruments. Moreover, the data can be stored inside for more than one year and can be transmitted to internet cloud server via mobile phone network. It can be operated by using solar panels all day long without any power supply for more than one year [13]. It is controlled with a CPU Raspberry pi A^{+}. It consists of a SHT3x-ARP sensor from the Sensirion Sensor Company for temperature and relative humidity, a palm-sized optical $PM_{2.5}$ sensor developed by Nagoya University and Panasonic Corporation for $PM_{2.5}$, and four electrochemical sensors from the Alphasense Company, UK: a CO-B4 sensor for carbon monoxide (CO), a NO-B4 sensor for nitric oxide (NO), a NO2-B43F sensor for nitrogen dioxide (NO_2), and an Ox-B431 sensor for oxidizing gas O_x (O_3+NO_2) as shown in Figure 1. When primary pollutants, primarily nitrogen oxides (NO_x) and hydrocarbons (HCs) emitted from factories and automobiles, are exposed to sunlight, photochemical reactions take place and produce secondary pollutants with strong oxidizing power called photochemical oxidants (O_x) [14]. O_3 and NO_2 are measured together using the Ox-B431 sensor. Therefore, in order to calculate the O_3 concentration, the NO_2 concentration must be subtracted from the O_x concentration.

The limits of the performance warranties for different electrochemical sensors are as follows: 1000 ppm for the CO-B4 sensor, 20 ppm for the NO-B4 sensor, 20 ppm for the NO2-B43F sensor, 20 ppm for O_3 and 20 ppm for NO_2 for the Ox-B431 sensor [15-18]. The palm-sized $PM_{2.5}$ sensor can detect particles with a diameter as small as 0.3 μm by estimating particle size from the distribution of light scattering intensities from single particles. Based on previous laboratory and field studies, it could measure $PM_{2.5}$ concentrations as high as 600 $\mu g/m^3$ with constant sensitivity [19]. Field observations revealed that it provided accurate data in both urban and suburban locations and was in strong agreement with the closest reference instruments [19, 20]. To connect with the raspberry pi for the data editing and data transfer from CUPI-G, the SCP software was downloaded and installed on the PC. A small LED display within the CUPI-G displays the data (date and time, $PM_{2.5}$ value, software version, and temperature) a few minutes after the instrument is turned on. Once the LAN adaptor and PC are connected, the observation data can be downloaded using the SCP software and CUPI-G's data response time is 31 seconds per one time.

The relationships identified in the field are only valid for a certain location, chemical climatology, and brief period, according to the studies, which show that the validation responses of gas sensors evaluated in the laboratory and the field observations commonly diverge [21]. The CUPI-G was validated with the collocated standard instruments by the mathematical correction method that considered the effects of temperature and relative humidity before the air quality observations [23-26].

Air Quality Observations

By the time the main source of air pollution in Bangkok and its vicinity was from road transport [27], the observations were conducted for 14 days respectively using the CUPI-G near the roadside (approximately 100 meters) in an urban area and a suburban area in central Thailand to analyze the variations and correlations of air pollutants during the study period. The air quality observation sites with CUPI-G instrument are described in Figure 2. The topographic map was created using ArcGIS software with permission from Esri, Maxar, Earthstar Geographics, and the GIS User Community (base map from Esri, HERE, Garmin, OpenStreetMap Contributors, and the GIS User Community).

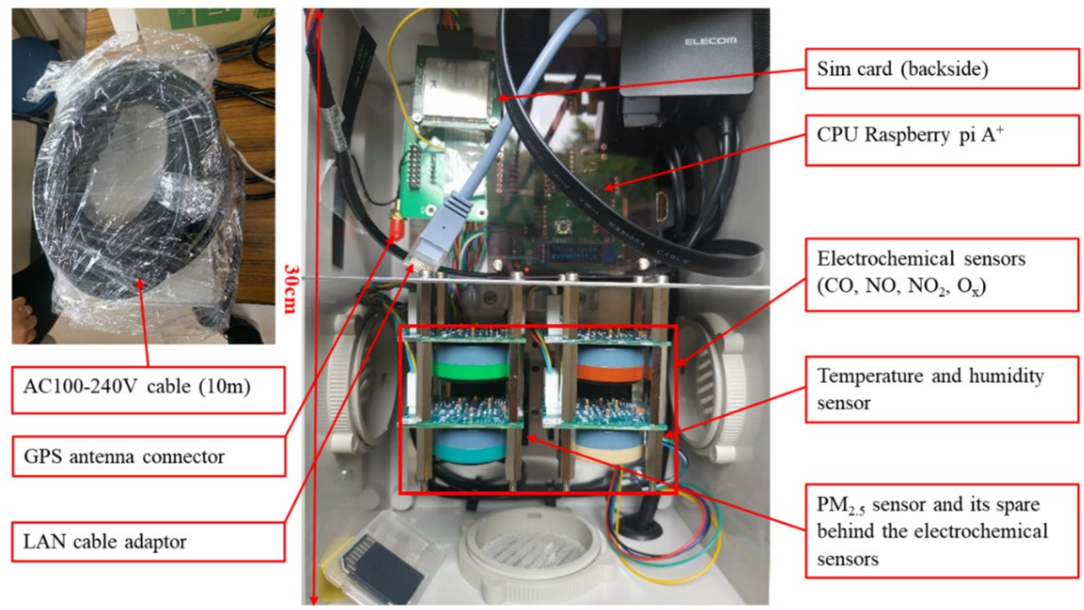

Figure 1 Composition of the CUPI-G instrument

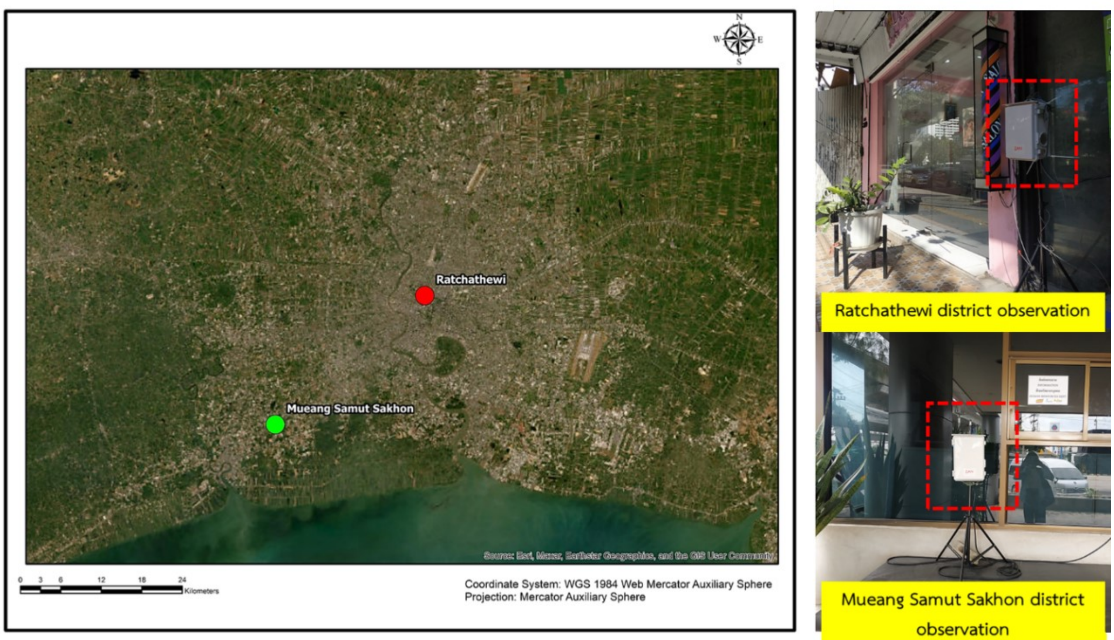

Figure 2 Air quality observation locations observed by the CUPI-G in central Thailand

In the urban area of Ratchathewi district, we observed the air quality using the CUPI-G from 11th to 25th February 2023. According to [28], the observation period was considered to be the end of the cool season in Thailand. At the Mueang Samut Sakhon district suburban site, the air quality was observed using the CUPI-G from 14th to 28th November 2022. Although [28] claimed the study period as the start of the cool season, the rainy season was not yet over at that time. At both sites, the CUPI-G was installed under the roof because it needs to be in a location that can block off direct sunlight for the best results. Detailed information about the observation sites is described in Table 1.

Table 1 Detailed information of air quality observation locations

Observation site	Area	Location	Study Period
Ratchathewi (13°45'34.90"N, 100°32'8.00"E)	Urban	Ground floor in front of a residential building, Ratchathewi district, Bangkok province	February 11-25, 2023
Mueang Samut Sakhon (13°35'34.90"N, 100°20'12.30"E)	Suburban	Ground floor of Sathaporn Co., Ltd., Mueang Samut Sakhon district, Samut Sakhon province	November 14-28, 2022

Data Analysis

The output data from CUPI-G instrument at the observation sites were calculated with the validated equations to provide reliable data for these locations. Due to the high time resolution of CUPI-G (31 seconds), the sample size (n) of Ratchathewi site was 37883 and (n) of Mueang Samut Sakhon site was 37782 during the observation period. A Pearson correlation analysis was conducted to analyze the correlation between each air pollutant and meteorological data to achieve better understanding of air pollution patterns in each area. In this study, the R Openair Package was mainly used for time series analysis to recognize the temporal variations of the air pollutants in each area which are important to reveal the regular air pollution patterns on a daily and weekly basis. The temporal variation plots used bootstrap resampling to calculate the 95% confidence interval in the mean, which can produce more accurate estimates than applying assumptions based on normality, especially when there are few data available [29].

Results and Discussions

Correlation between the Air Pollutants and Meteorological Factors

According to the Pearson correlation analysis, all the findings were significant with $p < 0.01$. As shown in Figure 3, at the Ratchathewi site, temperature had strong positive correlations with NO_2 (r=0.62), O_x (r=0.69) and O_3 concentrations (r=0.64), whereas it had a moderate positive correlation with CO concentrations (r=0.34). Moreover, there was a small negative correlation between temperature and $PM_{2.5}$, (r=0.22) while a small positive correlation was between temperature and NO (r=0.27). Humidity had strong negative correlations with NO_2 (r=0.80), O_x (r=0.81) and O_3 concentrations (r=0.65) while it possessed a weak negative correlation with CO concentrations (r=0.26) and NO concentration (r=0.24). $PM_{2.5}$ had weak positive correlations with NO_2 (r=0.29) and O_x concentrations (r=0.25). CO had a strong positive correlation with NO concentration (r=0.66) while it had moderate positive correlations with NO_2 (r=0.46), O_x (r=0.46) and O_3 concentrations (r=0.35). NO had moderate positive correlations with NO_2 (r=0.46) and O_x concentrations, (r=0.41) although it possessed a small positive correlation with O_3 concentrations (r=0.26). NO_2 had strong positive correlations with O_x (r=0.94) and O_3 concentrations (r=0.66). O_x had a high positive correlation with O_3 concentrations (r=0.88).

At the Mueang Samut Sakhon site, temperature had strong positive correlations with CO (r=0.64), NO_2 (r=0.62), O_x (r=0.78) and O_3 concentrations (r=0.79) while humidity had strong negative correlations with them to be 0.59, 0.58, 0.76, and 0.79 respectively and a moderate positive correlation with $PM_{2.5}$ (r=0.31) In contrast to the Ratchathewi site, $PM_{2.5}$ had weak negative correlations with O_x (r=0.23) and O_3 concentrations (r=0.23). CO had strong positive correlations with O_x (r=0.54) and O_3 concentrations (r=0.53) while it had a moderate positive correlation with NO_2 concentrations (r=0.45). NO had a moderate positive correlation with NO_2 concentrations (r=0.41) although it possessed a small positive correlation with O_x concentrations (r=0.25). NO_2 had strong positive correlations with O_x (r=0.90) and O_3 concentrations (r=0.62). O_x had a high positive correlation with O_3 concentrations (r=0.90).

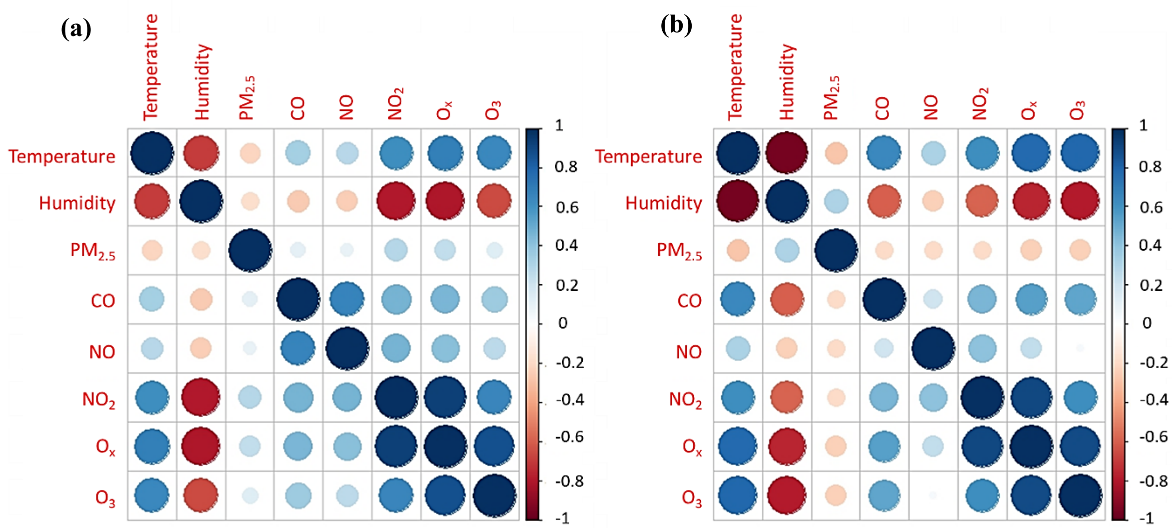

Figure 3 Correlation between the air pollutants and meteorological factors at **(a)** the Ratchathewi and **(b)** Mueang Samut Sakhon observation sites

It was discovered that the relationship between temperature and photochemical oxidant concentration was linear [30, 31] and the simulations predicted that O_3 increased with temperature in both urban and polluted rural settings [32]. In this study, the positive correlation between temperature and photochemical oxidants was significantly discovered at both urban and suburban sites. Furthermore, in different areas and at different times, $PM_{2.5}$ and O_3 have displayed varying relationships. The correlation between $PM_{2.5}$ and O_3 in the Changsha-Zhuzhou-Xiangtan district (Hunan province, in Central China) is positive in the summer, negative in the winter, and primarily negative during the rest of the year [33, 34]. In this study, it was found that there were different small correlations between $PM_{2.5}$ and the photochemical aerosols at both sites.

At Ratchathewi site, the positive correlation possibly occurred because the secondary particles were formed by photochemical reactions under the strong solar radiation at the end of the cool season [19, 33]. However, in Mueang Samut Sakhon site, a negative correlation was possibly found because high $PM_{2.5}$ concentrations might reduce the visibility and sunlight intensity which determined the formation of surface ozone [35, 12]. The other possibility might be that the rain can wash out the particulate matter during the observation period [34]. CO had positive correlations with tropospheric ozone and its precursors at both observation sites. According to [36, 37], the sequence of reactions, equation (1), equation (2), and equation (3) reveals the chain mechanism for ozone production in which the CO oxidation by O_2 is catalyzed by the HO_x chemical family ($HO_x = H + OH + HO_2$) and by NO_x as shown below.

$$CO + OH \overset{O_2}{\rightarrow} CO_2 + HO_2 \qquad (1)$$

$$HO_2 + NO \rightarrow OH + NO_2 \qquad (2)$$

$$NO_2 + hv \overset{O_2}{\rightarrow} NO + O_3 \qquad (3)$$

Temporal Variations of Air Pollutants at Ratchathewi Site

At the Ratchathewi site, it was raining on February 15, 2023, during the sampling period according to [38], $PM_{2.5}$ concentration was slightly decreased with NO_2 and O_x concentrations. Although repetitively comparable patterns occurred for all air pollutants, they reached their peaks in the afternoon of February 17 as shown in Figure 4. During this observation period, air pollutant concentrations per 31 seconds detected at the Ratchathewi site were in the range of 9.8-248.9 μg/m^3 for $PM_{2.5}$, 526.2-2221.2 ppb for CO, 20.9-1888.4 ppb for NO, 18.1-155.5 ppb for NO_2, 27.4-213.5 ppb for O_x and 1.1-88.9 ppb for O_3.

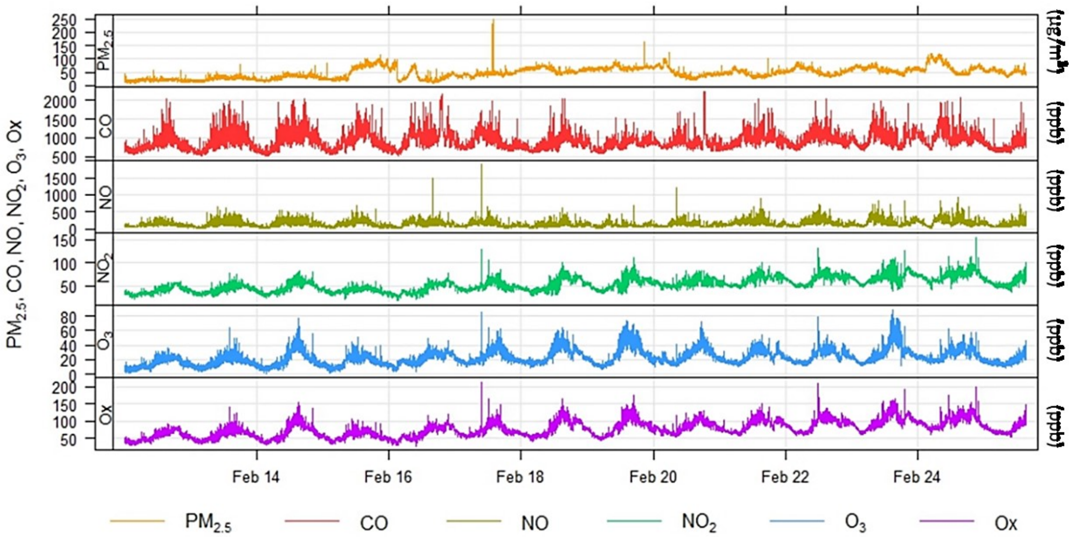

Figure 4 Time Series of air pollutants at Ratchathewi site on 31 seconds resolution in February 2023

According to [39], at the Bangkok city center, the morning rush hour starts from 6:00 AM with the average speed of 32 km/h, and the most congested time in the morning is from 7:00 AM to 8:00 AM with the average travel speed of 26 km/h. The evening rush hour starts from 3:00 PM with the average speed of 28 km/h, and the most congested time in the evening is from 5:00 PM to 6:00 PM with the average speed of 22 km/h. Figure 5 illustrates the hourly variations of $PM_{2.5}$ concentration, which peaked during morning rush hour, gradually decreased, and then surged again from evening rush hour. As the wind speed was not strong enough to disperse, the $PM_{2.5}$ was still suspended in the nighttime. The trace gases started to rise slightly during morning rush hour, peaked at midday, and then started to decline gradually. Traffic-related pollutants photochemically interacted with sunlight to form tropospheric ozone, as described in the preceding section.

Temporal Variations of Air Pollutants at Mueang Samut Sakhon Site

At the Mueang Samut Sakhon site, it was raining for seven days on 15^{th}, 16^{th}, 17^{th}, 23^{rd}, 24^{th}, 25^{th}, and 26^{th} November 2022 according to [38]. $PM_{2.5}$ concentration was found in a fluctuating pattern opposite to photochemical oxidizing gases as shown in Figure 6. CO concentration was found to be high on November 16, 2022, but was not too high on other days with the reason that might be the unusual traveling in Samut Sakhon Province. For the hosting of APEC Economic Leaders' Week in 2022, the Thailand government established three special public holidays on November 16-18 in Bangkok, Nonthaburi, and Samut Prakan Provinces [40]. At the Mueang Samut Sakhon site, the measured pollutant concentrations per 31 seconds ranged from 3.4-172.5 $\mu g/m^3$ for $PM_{2.5}$, 426.5-989.9 ppb for CO, 10.4-321.5 ppb for NO, 6.8-95.3 ppb for NO_2, 1.5-143.3 ppb for O_x and 5.3-57.7 ppb for O_3.

As it was raining on most of the days, the temporal variations might not be considered to be representative as those of the Ratchathewi site. For the hourly variations, $PM_{2.5}$ concentration was highest during the morning rush hour, decreased sharply, and then slightly rose from the evening rush hour as shown in Figure 7. Ozone concentration gradually increased starting from 6:00 AM, reached its highest around 2:00 PM, and decreased gradually although the other pollutants did not change much. Both rainfall intensity and its land use might have been important factors affecting the air quality besides the traffic volume during the observation period. However, the air pollution patterns were not clearly identified because of rain during the observation period.

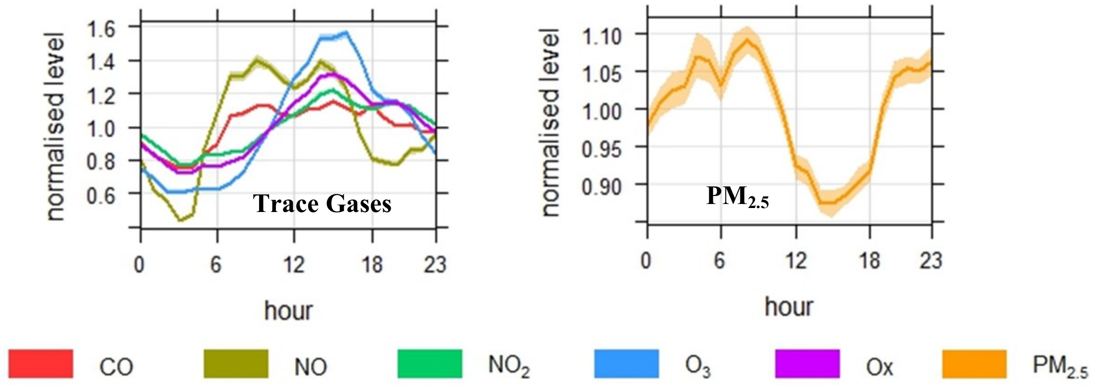

Figure 5 Diurnal variations of air pollutants on 31 seconds resolution at Ratchathewi site

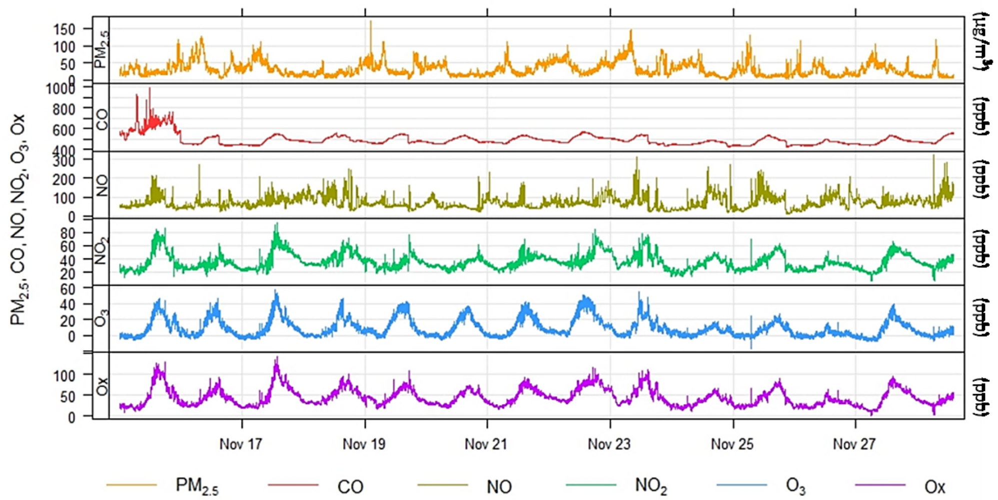

Figure 6 Time series of air pollutants at Mueang Samut Sakhon site on 31 seconds resolution in November 2022

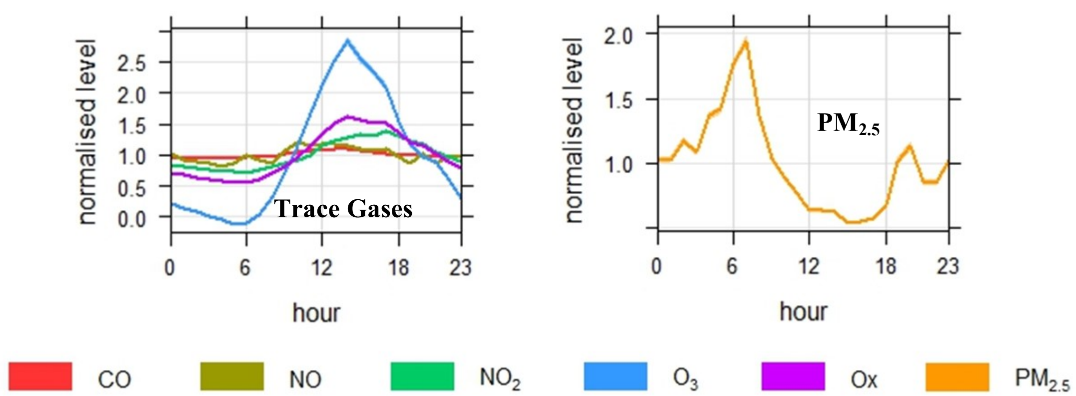

Figure 7 Diurnal variations of air pollutants on 31 seconds resolution at Mueang Samut Sakhon site

Comparison of Averaged Air Quality Results

In Ratchathewi observation, the 1h average results showed that the concentrations of air pollutants (CO, NO_2, and O_3) were observed under the national ambient air quality standards in Thailand [41]. The 1h average data from the Mueang Samut Sakhon observation revealed that the levels of air pollutants (CO, NO_2, and O_3) were below permissible limits for the national ambient air quality standards. According to the Thailand State of Pollution Report, CO levels in Thailand have been below the acceptable range [42]. Although there is no information about the O_x concentration in Thailand's air quality standard, if we compare it to Japan's air quality standard of 60 ppb, it might be said that both observation sites experience pollution from photochemical oxidants in addition to particle matter [43]. Over the past ten years, ozone levels in Thailand have exceeded the national guideline of 100 ppb. The maximum 1h average value of ozone has been recorded at 123 ppb, reaching the Thailand threshold by 193 ppb, according to monitoring stations across the nation [3].

When $PM_{2.5}$ standard is based on 24h, it is necessary to compare with the 24h average CUPI-G results. Therefore, as shown in Figure 8, at the Ratchathewi study site, the 24h average $PM_{2.5}$ concentrations were detected higher than the old standard on 15th, 18th, 19th, 22nd, 23rd, 24th, and 25th February 2023. The maximum detected value was 70.5 µg/m^3 on 24th February 2023 during the observation period. In the Mueang Samut Sakhon observation, the 24h average $PM_{2.5}$ concentrations were below the old national standard during the study period. The Ratchathewi urban site had significantly higher air pollutant concentrations than the Mueang Samut Sakhon suburban area.

Table 2 Comparison of 1h average air quality results at the observation sites

Parameter	Mean ± Standard Deviation		National Ambient Air Quality Standards [41]
	CUPI-G (Ratchathewi District)	CUPI-G (Mueang Samut Sakhon District)	
Temperature (°C)	30.1 ± 2.7	29.5 ± 2.3	-
Humidity (%)	57.3 ± 13.8	74.7 ± 10.1	-
$PM_{2.5}$ Concentration (µg/m^3)	47.7 ± 20.4	30.6 ± 20.5	< 50 (old) < 37.5 (from 1st June 2023) (24 hours)
CO Concentration (ppb)	903.2 ± 214.0	493.2 ± 50.5	< 30 x 10^3
NO Concentration (ppb)	143.9 ± 86.2	70.5 ± 32.0	-
NO_2 Concentration (ppb)	53.5 ± 14.7	35.7 ± 11.9	< 170
O_3 (O_x-NO_2) Concentration (ppb)	22.8 ± 10.4	9.2 ± 11.4	< 100
O_x Concentration (ppb)	76.4 ± 22.9	44.9 ± 20.9	-

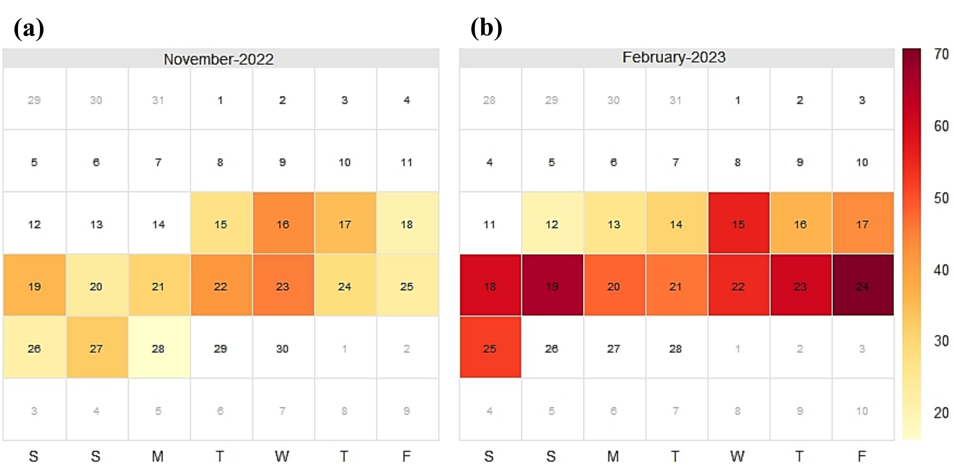

Figure 8 Calendar plots of 24h average $PM_{2.5}$ concentrations at **(a)** Mueang Samut Sakhon site, and **(b)** Ratchathewi site

Conclusion

The air quality observations were conducted for 14days using CUPI-G in the Ratchathewi district urban area, and the Mueang Samut Sakhon district suburban area to investigate the specific temporal variations and air pollution patterns. During the observation period, air pollutant concentrations detected at the Ratchathewi site were 47.7±20.4 μg/m^3 for $PM_{2.5}$, 903.2±214.0 ppb for CO, 143.9±86.2 ppb for NO, 53.5±14.7 ppb for NO_2, 22.8±10.4 ppb for O_3, and 76.4±22.9 ppb for O_x. Conversely, at the Mueang Samut Sakhon site, the measured pollutant concentrations were 30.6±20.5 μg/m^3 for $PM_{2.5}$, 493.2±50.5 ppb for CO, 70.5±32.0 ppb for NO, 35.7±11.9 ppb for NO_2, 9.2±11.4 ppb for O_3, and 44.9±20.9 ppb for O_x. In this study, the CUPI-G showed that it was an applicable compact instrument for atmospheric studies in both urban and suburban areas in Thailand although the observation span was limited. In both observations, it proved as an auxiliary instrument to check the technical problems or the necessity of periodical calibrations and maintenance of standard instruments in the governmental monitoring stations.

We discovered that the air pollution patterns in particular locations were substantially influenced by meteorological conditions. They were possibly impacted by the land use patterns in different urban and suburban observation sites and unfortunately, land use analysis was not discovered in this study. The results showed that both particulate matter and photochemical oxidant pollution occurred in the urban and suburban observation sites. According to the different correlations of $PM_{2.5}$ and concentrations of oxidizing gases, photochemical formation of small secondary particles might happen in the urban site, while high $PM_{2.5}$ might reduce the formation of surface ozone in the suburban site. We found that the correlations of particulate matter and photochemical oxidants showed obvious spatial and temporal differences in this study. Due to the complex atmospheric chemistry in each specific area, additional research is needed to address air pollution issues and understand the air pollution pattern particularly in order to tackle the air pollution problems in Thailand.

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