*Sensors and Materials*, Vol. 37, No. 2 (2025) 759–772
MYU Tokyo


S & M 3954

# Spatiotemporal Analysis of Air Pollutants in Vientiane, Laos via Mobile Sensing

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(Received November 18, 2024; accepted February 25, 2025)

***Keywords:*** particulate matter (PM), air quality, remote sensing, Sniffer4D

In this study, we investigated the spatiotemporal distribution and characteristics of air pollutants in Vientiane, Laos. Despite regulatory efforts, the city continues to face severe air quality issues, primarily due to the high concentrations of particulate matter (PM). Using both ground-based and mobile measurements, we determined that the major emission sources were roadside traffic, industrial activities, and night markets. The $PM_{10}$ concentrations reached up to 1139 μg/m³ in night market areas, primarily due to outdoor grilling. Ground-based measurements were conducted using an optical particle counter (OPC), and mobile measurements were conducted using Sniffer4D sensors mounted on vehicles. Mobile measurements provided real-time data on air pollutant distribution, revealing several hotspots that are not covered by existing monitoring networks. The highest PM concentrations were found near congested roads, industrial areas, and night markets. Our findings highlight the inadequacy of the current air quality monitoring network and emphasize the need for its expansion, as well as specific regulations to target specific emission sources. This study highlights the importance of mobile

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https://doi.org/10.18494/SAM5484

ISSN 0914-4935 
https://myukk.org/

air pollution monitoring using sensor technology, particularly the Sniffer4D system, which provides real-time, high-resolution data on PM distributions. By integrating this mobile sensing approach with stationary monitoring networks, we can achieve a more comprehensive understanding of air quality variations, addressing gaps in traditional monitoring methods.

## 1. Introduction

Air quality is determined by numerous factors, such as the relative contribution of vehicles (e.g., diesel- and gasoline-powered vehicles), natural sources (e.g., wildfires and dust), and transboundary transport.[1,2] In Southeast Asia, emission sources of natural and anthropogenic air pollutants have been associated with rapid economic growth and industrial activity,[3–9] household fuel usage,[10–13] biomass burning,[14,15] and climate change.[16,17] Southeast Asian countries, including Laos, have experienced severe haze events and episodes of high concentrations of particulate matter (PM) with aerodynamic diameters less than or equal to 2.5 μm ($PM_{2.5}$),[16–18] which are 5–10 times higher than the World Health Organization (WHO) standard.[17] Air pollution impacts human health by increasing the incidence of cancer and mortality, including in Southeast Asian countries.[19,20] Furthermore, regional emissions have increased owing to climate change.[20,21] Despite the increased air quality awareness of the public and academic communities, high-PM-concentration cases continue to occur in Southeast Asia.[22–24] Recently, anthropogenic emissions from Southeast Asia have decreased because of the various consequences of the coronavirus disease 2019 (COVID-19) pandemic caused by the novel coronavirus SARS-CoV-2, which first occurred in December 2019 in China and spread worldwide. Nevertheless, the aerosol optical depth (AOD) increased from 0.44 in 2019 to 0.99 in 2020 over Vientiane in Laos.[23] An increase in AOD was strongly associated with biomass burning, local emissions, and meteorological conditions. Moreover, depending on seasonal characteristics, the air quality over Southeast Asia has deteriorated because of haze under dry weather conditions during the pre-monsoon season.[25,26]

In 2021, the Laotian government implemented regulations for environmental protection and management policies for air quality improvement, including pollution control.[26] Accordingly, the Natural Resource and Environment Research Institute operates a network of four $PM_{2.5}$ monitoring stations over Vientiane. Nevertheless, there are spatiotemporal limitations of ground-based measurement for analyzing air quality characteristics and local emission effects over Laos. Therefore, detecting and determining the origin of changes in air quality over Laos has proven to be complicated.

To understand the characteristics of air pollutant distribution emitted from Southeast Asia, various studies have been conducted using observational data[13,27,28] and modeling.[27,28] Despite these studies, spatiotemporal limitations still exist in observing and identifying the regional emissions and characteristics of air pollutants. It has been suggested that sensor and remote sensing observations can overcome the limitations of current studies.[23–28] Moreover, Sniffer4D, a type of mobile remote-sensing measurement system, plays a crucial role in addressing the limitations of traditional stationary air quality monitoring networks. By providing high-resolution, real-time spatial distributions of air pollutants, Sniffer4D enables a more comprehensive understanding of localized pollution sources, which are often overlooked by fixed monitoring stations. This methodology enhances air quality assessment in developing urban areas with limited monitoring infrastructure.(29)

Researchers in various fields have used Sniffer4D. Volcano emissions have been measured using drones and by on-foot on-site observation of gases emitted from volcanoes; predictions of possible volcanic explosions can be made by observing changes in measured parameter values.(30) To measure vehicle emission, Sniffer4D has been used to measure nitrogen dioxide concentrations along highways, considering the distance and altitude from the road, and has also been applied to soil and groundwater monitoring systems adjacent to highways.(31) In Wisconsin, USA, researchers performed measurements using Sniffer4D and revealed variability in air quality because of changes in vehicle emissions due to the COVID-19 lockdown.(32) The researchers also revealed that the PM concentration increased by 220–307% because of increased traffic volume after the lockdown.(32) In a 2022 study, researchers showed that in Kandy, Sri Lanka, the average $PM_{2.5}$ concentration decreased from 116.7 to 92.3 μg/m$^3$ after the implementation of the emission reduction policy.(33) To measure heating emissions, Sniffer4D was used to conduct on-foot mobile observations at a height of 1.5 m from the ground in Sunyang City, Eastern China, to investigate PM concentration variability and its influencing factors associated with heating operations in the backdrop of recent urbanization and industrialization.(34) To measure industrial emission in the Banwol industrial area, South Korea, Sniffer4D was mounted on cars for the mobile observation of air quality and was confirmed to be a reliable instrument in comparison with a fixed urban air quality network system; the differences between the results were small (1–2 μg/m$^3$).(35) A growing number of studies have focused on regional air quality using Sniffer4D to overcome spatiotemporal limitations.(32–37) Therefore, we analyzed the regional characteristics of air pollutants using ground-based and mobile measurements in Vientiane, Laos.

We measured the concentrations of regional air pollutants to investigate their distribution and characteristics in Vientiane, Laos. We aimed to acquire fundamental data for local emission management by identifying the distribution and characteristics of air pollutants emitted from nearby downtown and industrial areas.

## 2. Methods

### 2.1 Study area

Laos is a landlocked country bordered by Thailand, Vietnam, Cambodia, China, and Myanmar. The capital city, Vientiane, located along the Mekong River near the Thai border, serves as the political and economic center of the country (Fig. 1). This region has undergone rapid urbanization and industrialization driven by its strategic position as a hub for regional transportation and trade. The population of Vientiane is approximately 700000, and its rapid growth has resulted in increased vehicular emissions, industrial activities, and urban sprawl, all of which contribute significantly to air pollution.(38)

The Vientiane area has a tropical monsoon climate characterized by distinct wet and dry

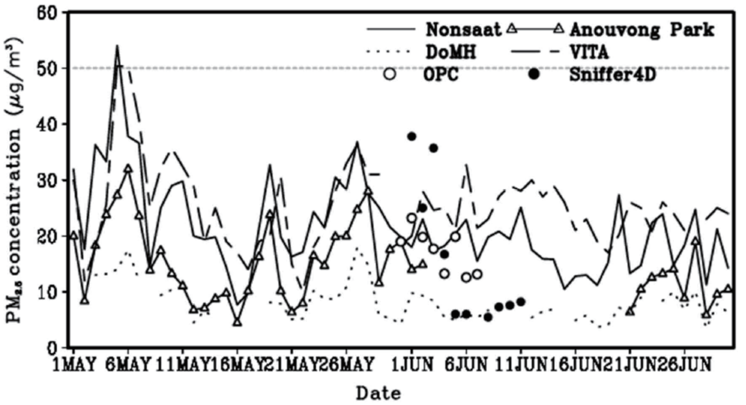


Fig. 1. Daily $PM_{2.5}$ concentrations over Vientiane obtained National Resource and Environment Research Institute datasets from 1 May 2022 to 30 June 2022 with OPC and Sniffer4D during study periods.

seasons, which have a significant impact on air pollution concentrations. During the wet season (May to October), high humidity and frequent rainfall typically reduce PM concentrations through wet deposition. Conversely, the dry season, from November to April, is marked by lower humidity and increased atmospheric stability, often leading to higher pollutant concentrations due to reduced atmospheric dispersion.(39) These seasonal variations are compounded by the geographical features of the city, which can inhibit the dispersion of pollutants, particularly during temperature inversions, which are common during the dry season.(38,39)

The air quality in Vientiane is further exacerbated by its expanding industrial base and the intensification of biomass burning during the dry season. These activities are major sources of PM, particularly $PM_{2.5}$ and $PM_{10}$, which have been closely linked to increased respiratory and cardiovascular diseases among the population.(40) Research studies indicate that pollutant concentrations are particularly high in areas close to industrial zones and congested roadways, with localized hotspots identified around night markets and in areas with heavy traffic congestion.

The primary sources of emissions from Vientiane include biomass burning, transportation, night markets, and industrial facilities. The city's night markets, popular with both locals and tourists, generate substantial amounts of airborne pollutants through outdoor grilling. Additionally, major pollution sources, such as industry, transportation, and power generation, have significant impacts on climate change and public health in the region.(38) In 2021, the annual mean $PM_{2.5}$ concentration in Vientiane was recorded at 30 μg/m³, which is six times higher than the WHO recommended standard of 5 μg/m³. Furthermore, according to the 2022 Environmental Performance Index, Laos was ranked 144th out of 180 countries in terms of air quality, indicating severe pollution problems.(38)

### 2.2 Observations and analysis

A comprehensive monitoring campaign was conducted from May 31 to June 7, 2022 to evaluate the spatiotemporal distribution of air pollutants in Vientiane. High-resolution measurements were obtained using a combination of mobile sensors (Sniffer4D V2, China) and stationary observations with an optical particle counter (OPC, portable aerosol spectrometer, model 1.109, Grimm, Germany).[41] This methodological approach enabled the detailed mapping of PM concentrations across key urban areas, providing reliable data for subsequent analyses.

To study the spatial distribution patterns of PM in Vientiane, mobile sensor-based observations were conducted using Sniffer4D mounted on a vehicle, with data collection performed at a height of 1.5 m above ground level. Sniffer4D is well suited for mobile monitoring and can be mounted on drones or vehicles to measure air pollutants at speeds below 80 km/h. The Sniffer4D system was equipped with sensors to measure the concentrations of $PM_{1.0}$, $PM_{2.5}$, and $PM_{10}$. The device includes a compact laser photometer that operates on the basis of light scattering principles, with a particle sensor resolution of 1 μg/m³. Sniffer4D records pollutant concentration data every second and includes a global positioning system module that logs coordinates and altitudes, allowing the precise spatial mapping of pollution levels. Prior to data collection, the Sniffer4D sensors were calibrated against an OPC to ensure measurement accuracy. The reliability of Sniffer4D and its data quality were verified by comparing the measurements made with Sniffer4D with measurements made at the Thermo Scientific superstation installed at the Department of Environmental Engineering at Jinan University in China (Guangzhou);[29] the correlation coefficient was $R^2 = 0.88–0.95$.

Sniffer4D was installed on a vehicle positioned 1.5 m above ground level. During the mobile observations, real-time air pollutant concentrations were measured as the vehicles traveled along the designated routes. The vehicle speed was adjusted to approximately 20 km/h to optimize data collection. Computational adjustments were made to account for the effects of vehicle speed and wind velocity on air intake, ensuring that the wind speed effects at each sampling point were effectively mitigated.

Mobile measurements using Sniffer4D were performed over four days from May 31 to June 3, 2022. The first phase involved setting a measurement route that included downtown Vientiane, Wattay International Airport, and the night market area, with measurements taken three times daily from May 31 to June 2. On June 3, additional measurements were conducted in the Vientiane Industrial and Trade Area (VITA) in the morning and downtown areas in the afternoon. In areas where vehicle access was restricted, such as night markets, the equipment was carried on foot, with observers recording real-time data and noting operational anomalies.

For stationary measurements, the widely used OPC has been employed to measure airborne particles.[43] The OPC operates on the basis of the principle of light scattering and detects particles with diameters ranging from 0.25 to 32 μm. It measures the number of particles and mass concentrations of total suspended particulates, $PM_{10}$, $PM_4$, $PM_{2.5}$, $PM_{1.0}$, and coarse-mode PM. In this study, one OPC unit was installed in the downtown area (102.597°E, 17.968°N), and continuous observations were conducted over eight days, from May 31 to June 7, 2022. In this study, we used data on hourly ambient $PM_{2.5}$ concentrations in micrograms per cubic meter (μg/m³) obtained using a Beta Attenuation Monitor (BAM-1022). To verify the measurement equipment used in Laos, daily $PM_{2.5}$ concentrations were compared with data from an air pollution monitoring system located in Vientiane and nearby industrial areas. Data from one industrial site, one background site, and two urban sites were selected after rigorous screening for quality and availability. These comparisons ensured that the data collected were consistent and reliable across different locations.

Meteorological conditions that could affect the dispersion of air pollutants were monitored during the study period. Temperature, wind speed, wind direction, and humidity data were obtained using a surface-monitoring system operated by the Natural Resources and Environment Research Institute. During the research period, the average temperature was 29.48 ℃, with an average wind speed of 1.38 m/s and prevailing winds from the south. The average relative humidity was 71.03% from May 31 to June 7, 2022. Notably, rainfall in the morning of May 31 contributed to lower pollutant concentrations, reflecting the characteristic washout effect observed in Southeast Asia.

## 3. Results

### 3.1 General distribution characteristics of PM2.5 concentration

To understand the general behavior of air quality over Vientiane, the daily concentration of $PM_{2.5}$, measured at four stations around the downtown area, is shown in Fig. 1. The $PM_{2.5}$ concentrations show a distinct spatiotemporal pattern. The industrial areas of Nonsaat village (Dongmakkhai; red line) and VITA Park (Nonethong; hereafter VITA; orange line) were associated with the highest $PM_{2.5}$ concentration, exceeding the Laos $PM_{2.5}$ concentration standard within the first week of May 2022; the second-highest $PM_{2.5}$ concentration was recorded in Anouvong Park (Xieng Yeun village; green line) near the downtown and the Department of Meteorology and Hydrology (DoMH; blue line). The daily $PM_{2.5}$ concentration showed increasing or decreasing patterns for all stations, affected by the weekly effect. Notably, the concentrations of daily $PM_{2.5}$ at VITA were extremely high, whereas those at DoMH were quite low, indicating that $PM_{2.5}$ concentrations in the downtown area are relatively lower than those in the industrial area.

The ground-based measured $PM_{2.5}$ concentrations in Anouvong Park and DoMH were higher than those at other stations; these patterns were similar to those observed in VITA. However, there are some spatiotemporal limitations to note, such as differences in measurement periods and stations. Nonetheless, the $PM_{2.5}$ concentrations over the downtown area in this study were much higher than the general-distribution $PM_{2.5}$ concentarations determined by the Natural Resources and Environment Institute, indicating the need to identify the sources of air pollution emissions and expand the measurement stations considering high-emission areas. Accordingly, in this study, we focused on determining the spatial distribution characteristics of air pollutants through mobile measurements to identify the emission sources and high-emission areas in the downtown areas of Vientiane.

### 3.2 Spatiotemporal distribution of air pollutants

Mobile measurements were conducted to investigate the variability in air pollutants in downtown Vientiane. The characteristics of PM distribution were identified during the research period. First, the daily average $PM_{10}$ and $PM_{2.5}$ concentrations with the measurement date considerd were 20.44 and 19.05 μg/m$^3$ on May 31, respectively, and we found that the concentrations were affected by the washed out effect of precipitation in the morning. On June 1, 2022, the daily average $PM_{10}$ and $PM_{2.5}$ concentrations were 38.14 and 35.68 μg/m$^3$, respectively, which were approximately 1.8 times the concentrations measured on May 31, and the temperature and humidity were lower on that day. On June 2, the daily average $PM_{10}$ and $PM_{2.5}$ concentrations were 44.09 and 41.40 μg/m$^3$, respectively, which were 1.16 times higher than those obtained on June 1, and the temperature had increased and humidity had decreased. On June 3, the daily average $PM_{10}$ and $PM_{2.5}$ concentrations were 36.72 and 34.04 μg/m$^3$, respectively, which indicate a decrease compared with the corresponding PM concentrations on June 2, likely due to the extension of the existing mobile measurement route to include the road to VITA. Nonetheless, the $PM_{2.5}$ concentrations during measurements were higher than the atmospheric environment standard of 15 μg/m$^3$ applied in Laos.

### 3.2.1 Mobile monitoring on the road

We measured PM concentrations in urban road areas in Vientiane for four days from May 31 to June 3, 2022 (Fig. 2). We used Sniffer4D, which was mounted on a vehicle moving at a low speed, to record air pollutant concentrations. The study routes were set up along the roads around Wattay International Airport and those within the downtown areas on May 31–June 2 [Figs. 2(a) and 2(b)] and along the roads leading to the industrial area in the morning of June 3 [Fig. 2(c)]. In addition, we checked the main emission sources using onsite photographs [Fig. 2(d)].

The distribution of PM along the road around Wattay International Airport showed high concentrations of $PM_{10}$ and $PM_{2.5}$ [maximum concentrations of 270 and 266 μg/m$^3$, respectively; Fig. 2(a)]. High PM concentrations around Wattay International Airport were associated with vehicle emissions, as the measurement sections had narrow roads and were highly congested

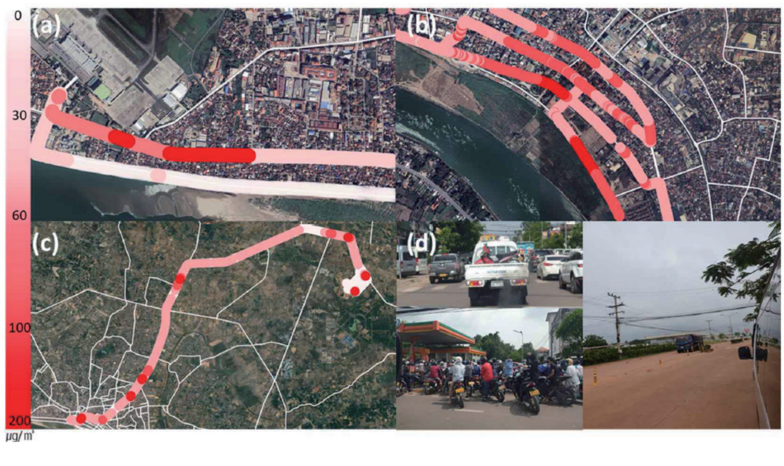


Fig. 2. (Color online) Sniffer4D 2D maps in the road around (a) Wattay International Airport, (b) the city, (c) VITA industrial areas, and (d) local on-site emissions during measurements.

around the intersections because of frequent traffic congestion. Therefore, we concluded that air pollutants concentrations on roads are affected by several factors such as the age of vehicles, motorcycles, and vans.

The distributions of PM along the urban road showed that the $PM_{10}$ and $PM_{2.5}$ concentrations, namely, 877 and 716 μg/m$^3$, respectively, are relatively higher than those measured along other roads [Fig. 2(b)]. These distributions were highly affected by emissions from food trucks operating mainly around night markets and beaches within the city.

The route along the road from the urban area to the industrial area was 48 km long [Fig. 2(c)]. Additionally, measurements were obtained while traversing the route in both directions. This route included congested intersections, roadsides, and industrial areas. The mean $PM_{10}$ and $PM_{2.5}$ concentrations measured from the downtown area to VITA were 137 and 132 μg/m$^3$, respectively, which were attributed to vehicle idling, traffic congestion at intersections, fires and incineration on the roadside, and soil dust. In addition, in the opposite direction, that is, from VITA to the downtown area, the $PM_{10}$ and $PM_{2.5}$ concentrations were 144 and 140 μg/m$^3$, respectively, which were similar to those from the downtown area to VITA. The main causes of high PM concentrations along this route were emissions from vehicles during congestion on the roadside and exhaust gases emitted from old vehicles, diesel vehicles, and motorcycles, implying air quality degradation.

To examine the impact of vehicle congestion, which is the main cause of the high PM concentrations on roadsides, we examined mobile measurement data. The data were collected from vehicle observations at distances per hour of less than 0.5 km, and the distances per second were less than 14 cm, excluding pedestrian observations. The mean concentrations and standard deviations of $PM_{2.5}$, $PM_{10}$, and $NO_2$ during vehicle idling and driving were analyzed, as shown in Fig. 3 and Table 1. High $NO_2$ concentrations were observed during idling on all observation dates; the $NO_2$ concentration during idling was higher than that during driving by 69.32, 29.07, 38.98, and 32.67% from May 31 to June 3, respectively. In contrast, the $PM_{10}$ and $PM_{2.5}$ concentrations during idling decreased by 6.62 and 5.82% on May 31 and 15.13 and 15.84% on

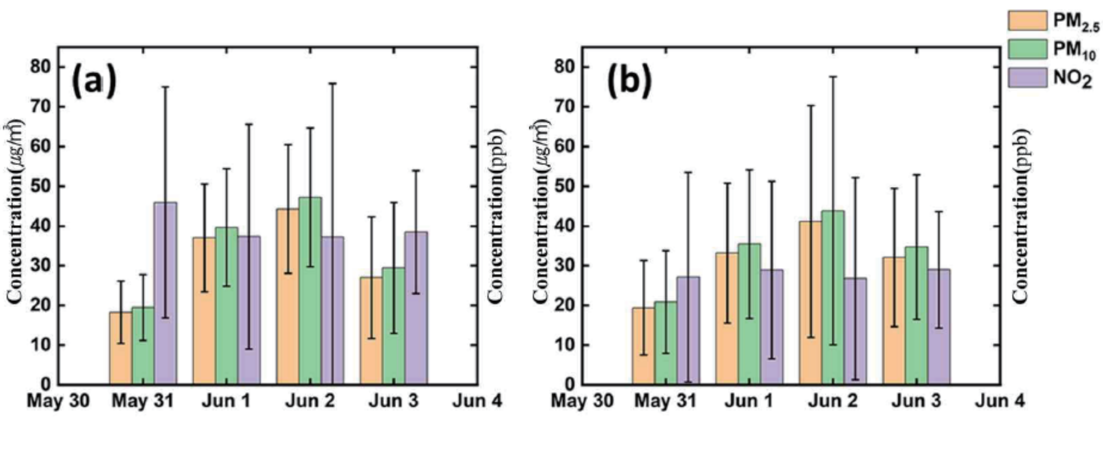


Fig. 3. (Color online) Means and standard deviations of concentrations of $PM_{2.5}$, $PM_{10}$, and $NO_2$ measured during (a) idling and (b) driving.

Table 1
(Color online) Means and standard deviations of concentrations of $PM_{2.5}$, $PM_{10}$, and $NO_2$ measured during idling and driving.

| Type / Date | Stopped | | | Driving | | |
|---|---|---|---|---|---|---|
| | $PM_{2.5}$ (μg/m³) | $PM_{10}$ (μg/m³) | $NO_2$ (ppb) | $PM_{2.5}$ (μg/m³) | $PM_{10}$ (μg/m³) | $NO_2$ (ppb) |
| 2022-05-31 | 18.27 ± 7.82 | 19.48 ± 8.27 | 45.93 ± 29.06 | 19.40 ± 11.89 | 20.86 ± 12.90 | 27.14 ± 26.39 |
| 2022-06-01 | 37.01 ± 13.58 | 39.62 ± 14.82 | 37.30 ± 28.29 | 33.19 ± 17.60 | 35.44 ± 18.71 | 28.90 ± 22.35 |
| 2022-06-02 | 44.29 ± 16.20 | 47.19 ± 17.48 | 37.19 ± 38.66 | 41.16 ± 29.18 | 43.83 ± 33.78 | 26.76 ± 25.46 |
| 2022-06-03 | 27.00 ± 15.30 | 29.44 ± 16.47 | 38.46 ± 15.47 | 32.08 ± 17.40 | 34.69 ± 18.21 | 28.99 ± 14.67 |

June 3, respectively, compared with those during driving. Furthermore, unlike the $NO_2$ concentrations, the PM distributions during idling showed relatively small increases on June 1 and 2, increasing by 11.65 and 7.64%, respectively, each day.

Figure 4 shows the points where vehicle congestion occurred; the route had complex intersections with heavy traffic congestion. The major congested sections were the Asean Road intersection near the airport [Fig. 4(a)], the Souphanouvong Avenue intersection in the downtown area [Figs. 4(a)–4(c)], the Rue Samsenthai intersection, and the gas station area (Fig. 4). Clearly, roadside air pollutants in Vientiane exhibit high concentrations because of the various sources of vehicle emissions.

### 3.2.2 Industrial area monitoring

To investigate the impact of industrial areas near the city center of Vientiane, measurements were conducted using Sniffer4D on the morning of June 3; the measurement routes were set around the VITA for 1 h. Figure 5 shows the distribution of the concentrations of PM ($PM_{10}$ and $PM_{2.5}$) emitted from around the industrial area, with maximum concentrations of 218 and 212 μg/m$^3$, respectively. Although there was no clear evidence of distinctively high concentrations of air pollutants inside the industrial area during the measurement period, we detected plume effects around the chimneys of the industrial facilities, indicating that air pollutants were dispersed into the surrounding areas. Additionally, the intersection near the VITA was extremely and frequently congested. The emission sources include old vehicles, incineration sites, fire, and dust, resulting in high concentrations of air pollutants dispersed in the surrounding areas.

### 3.2.3 Night market monitoring

Nighttime markets are formed and operate during the night in the downtown area of Vientiane. Outdoor grilling with charcoal frequently occurs. The emission of air pollutants from the grilling process during night market operations affects the surrounding air quality, and there

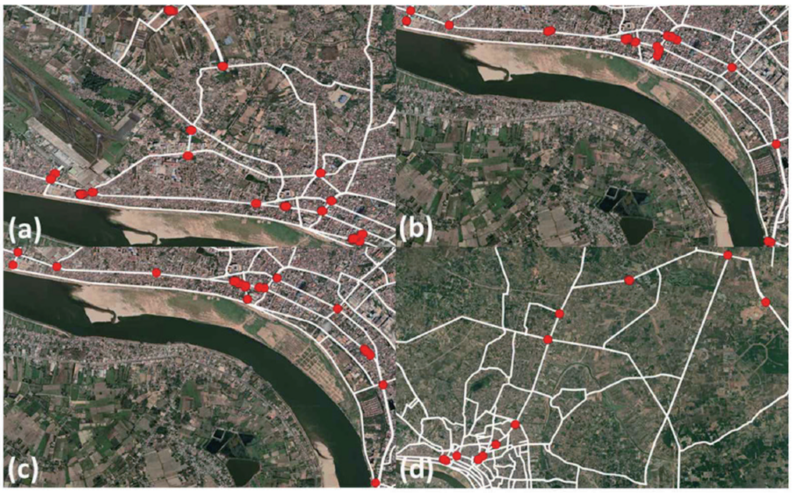


Fig. 4. (Color online) 2D maps in the idling area on (a) May 31, (b) June 1, (c) June 2, and (d) June 3.


Fig. 5. (Color online) Sniffer4D 2D map in the VITA industrial area.

is a need for the efficient management of these emission sources by the government. We investigated nighttime market emissions using mobile measurements to determine the spatial distribution of air pollutants.

Figure 6 shows the PM concentration distribution and on-site emissions at the night market area. The highest concentrations of PM were 1139 μg/m$^3$ for $PM_{10}$ and 1071 μg/m$^3$ for $PM_{2.5}$, indicating that extremely high concentrations of air pollutants were generated during outdoor grilling. Moreover, it was confirmed that the high PM concentrations in night markets area were caused by incomplete combustion resulting from the flame directly touching the meat,


Fig. 6. (Color online) Sniffer4D 2D maps and cooking emissions in the city night market area on (a), (b) June 1 and (c), (d) June 3.

depending on the grilling process. Previous studies have shown that grilling emits high concentrations of air pollutants.(44,45) High-PM-concentration cases are frequently observed because of grilling of food in night market areas.

## 4. Conclusion

In this study, we examined air pollution emissions and identified key hotspots in Vientiane, Laos, by both in situ (OPC) and mobile (Sniffer4D) measurements. Our findings revealed that PM concentrations were consistently higher along roadsides, in industrial areas, and in night market areas. However, these pollution hotspots were not yet fully accounted for in the national air quality control system, highlighting the need for an expanded monitoring framework.

Air quality in Vientiane is significantly affected by various emission sources, with the highest concentrations observed near roadsides, industrial facilities, and night market areas. However, the current air-monitoring network operated by the government does not adequately capture the localized emission characteristics, limiting its effectiveness in air quality management.

The $PM_{2.5}/PM_{10}$ ratio in Vientiane exceeded 0.9, significantly higher than the typical range of 0.4 to 0.6 reported in other Southeast Asian cities.(46) This discrepancy can be attributed to the following multiple factors:

Biomass burning and open-fire cooking: Unlike Hanoi, where vehicular emissions and industrial sources contribute significantly to $PM_{10}$ concentrations, Vientiane relies heavily on biomass fuels for household cooking and night market operations, generating high $PM_{2.5}$ emissions.

Limited industrial activities: With fewer industrial facilities than Hanoi, Vientiane produces relatively lower coarse-mode $PM_{10}$ emissions, resulting in a higher $PM_{2.5}/PM_{10}$ ratio.

Climatic conditions: Frequent rainfall in Vientiane preferentially removes larger $PM_{10}$ particles while allowing finer $PM_{2.5}$ to remain suspended in the atmosphere, further elevating the $PM_{2.5}/PM_{10}$ ratio.

Our findings emphasize the importance of mobile remote-sensing technology in air quality monitoring, particularly in regions with limited infrastructure. The integration of Sniffer4D mobile sensing with stationary monitoring networks has proven effective in identifying pollution hotspots. These results underscore the necessity of expanding real-time monitoring capabilities to provide a more comprehensive understanding of air quality dynamics.

Although this study provides valuable insights into air pollution sources in Vientiane, certain limitations should be acknowledged. The short duration of measurements and the lack of continuous monitoring may affect the representativeness of long-term pollution trends. Future studies should prioritize the establishment of a denser air quality monitoring network in Vientiane to address the current lack of measurement sites. Expanding the network will provide more comprehensive data for effective air quality management, enabling better regulatory decisions and pollution control strategies. Additionally, expanding the national air-monitoring network to better capture high-emission areas and implementing targeted regulations for emission sources will be critical in improving the air quality in Vientiane.

## Acknowledgments

This research was supported by a National Research Foundation of Korea Grant from the Korean Government: Ministry of Science and ICT—MSIT [NRF-2023M1A5A1090715] and by the Particulate Matter Management Specialized Graduate Program through the Korea Environmental Industry & Technology Institute (KEITI) funded by the Ministry of Environment (MOE).

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