Assessing the impact of a waste incinerator on the environment using the MAIAC-AOD and AERMOD models

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The distribution and concentration of air pollutants from infectious waste incineration between 2019 and 2021 were examined in this study using an AERMOD model, including sulfur dioxide (SO_2), nitrogen dioxide (NO_x), and particulate matter ($PM_{2.5}$). The MAIAC-AOD value at a 1 km resolution was used to develop a regression model with meteorological information for predicting $PM_{2.5}$, which was then compared with the concentration from the AERMOD simulation. The following maximum 1-h, 24-h, and annual average concentrations of all pollutants were found to have occurred in 2019. The distribution of SO_2 and NO_x in 1 h was largest in 2020 at 1,000 m to the northwest, with concentrations of 37.68 and 93.99 µg/m^3, respectively. The 24-h concentrations of SO_2 and NO_x were greatest in 2021 at 3.63 and 8.90 µg/m^3, respectively, 720 m northeast of the stack. The annual concentrations of SO_2 and NO_x were highest in 2019 at 0.56 and 1.36 µg/m^3, respectively. The highest annual $PM_{2.5}$ concentration was 0.033 µg/m^3, 730 m to the northeast in 2019. The predicted $PM_{2.5}$ using MAIAC-AOD correlated with the simulated value from AERMOD, with R^2 values of 0.7630, 0.7607, and 0.6504 for 2019, 2020, and 2021, respectively, which were higher closer to the stack than outside. As a result, investigations into the distribution of air pollution should benefit from the integration of air modeling and satellite information.

KEYWORDS

AERMOD, MAIAC-AOD, $PM_{2.5}$, waste incinerator, regression model, SO_2, NO_x

1 Introduction

The negative effects of air pollution on our lives have increased significantly. An important environmental risk factor for the development of lung cancer and cardiopulmonary disease is prolonged exposure to fine particle air pollution caused by combustion (Pope et al., 2002). Hospital admission for acute respiratory infections was associated with short-term ambient air pollution exposure, and the main air pollutants compromising respiratory health were PM_{10}, $PM_{2.5}$, and NO_2 (Xia et al., 2017). According to the health impact assessment, chronic exposure to $PM_{2.5}$ causes over 50,000 fatalities each year in Thailand. Based on the worth of a statistical life, the overall expense of this excess mortality in 2016 amounted to close to 15% of Thailand's GDP (Mueller et al., 2021). It is primarily brought about by human actions or behaviors, such as population growth, fuel demand, and resource scarcity. Industry, transportation, agriculture, waste management, and transportation are some of the main sources of air pollution. Nonetheless, $PM_{2.5}$ may

influence weather conditions, such as the frequency and duration of precipitation, as $PM_{2.5}$ may serve as sufficient cloud condensation nuclei for precipitation, resulting in lower precipitation on polluted days than on clean days (Zheng et al., 2020), with recent evidence suggesting that if $PM_{2.5}$ was controlled, cloud condensation nuclei would be reduced (Wang et al., 2023).

The amount of infectious waste generated by hospitals under the Ministry of Public Health, hospitals under the Department of Academic Affairs within the Ministry of Public Health, sub-district hospitals for health promotion, hospitals associated with other ministries, private hospitals, private clinics, animal hospitals, and a dangerous infection laboratory was 47,962 tons in 2020, down 10% from 2019. Of this amount, 47,440 tons (98.91%) were appropriately managed (Pollution Control Department PCD, 2020). Sulfur dioxide, oxide of nitrogen, and particulate matter were the primary air pollutants produced by infectious waste incineration. These pollutants were tracked to ensure that the emissions requirement was met (Walker and Cooper, 1992).

The National Meteorological Society of the United States, the American Meteorological Society, and the Environmental Protection Agency developed the AERMOD model (American Meteorological Society and U.S. Environmental Protection Agency Regulatory Model) (U.S.EPA, 2021). It was employed to estimate how pollutants will disperse in the atmosphere near the surface. The most popular model for predicting the concentration of pollution spreading from its source over a radius of up to 50 km is AERMOD. There are three primary sections of the information required to prepare AERMOD air models for import: meteorological data obtained from the preparation; data on the area's height from the preparation's AERMET subprogram; and information on the AERMEP subprogram and air pollution source. In Thailand, AERMOD was used to model the level of air pollution arising from industrial sources (Jittra et al., 2015; Khamyingkert and Thepanondh, 2015). The level of air pollutants at surrounding receptors and the potential of pollutant reduction resulting from suggested clean technology solutions were evaluated using AERMOD [9 2]. AERMOD was used as part of the environmental impact assessment to investigate the NO_2 emissions from a cement complex (Seangkiatiyuth1 et al., 2011) and assess the impact of SO_2 emissions from the coal-fired power plant's exhaust stack (Srirattana and Piaowan, 2020). AERMOD was used to determine the ground-level concentrations of air pollutants from the municipal solid-waste incinerators (Srivieng et al., 2021).

However, the ground-based monitoring site did not cover all the areas of air emission sources. The Multi-Angle Implementation of Atmospheric Correction (MAIAC-AOD) technique simultaneously retrieves aerosol optical depth (AOD) at a 1 km spatial resolution with a temporal series of MODIS measurements on a daily basis (Lyapustin and Wang, 2008). Using the retrieved 1-km AOD and Supplementary Data, such as meteorological and land cover, the regional distribution of $PM_{2.5}$ was approximated more precisely than with the 3-km AOD (Hu et al., 2014; Chen et al., 2021). In Thailand, it was proposed that MAIAC-AOD would validate the predicted $PM_{2.5}$ based on MODIS surface reflectance (Nakapan and Hongthong, 2022). MAIAC-AOD showed high accuracy in East Asia and significant heterogeneity among study sites, and it performed well in areas with high vegetation cover and flat terrain (Wang et al., 2022). Even on high terrain, it produced an

excellent representation of ground-level fine particulate matter, which was beneficial for monitoring $PM_{2.5}$ and comprehending variation in $PM_{2.5}$ pollution. (He et al., 2021). Additionally, it was used to forecast the daily ground $PM_{2.5}$ concentration to assess the impacted area for air pollution management mitigation (Xiao et al., 2017; Han et al., 2018).

With the readily available spatial and temporal data of the MAIAC-AOD and the advantage of the AERMOD mathematical model, this study aimed to examine the possibilities of using MAIAC-AOD to determine the concentration and distribution of particulate matter ($PM_{2.5}$) from infectious waste incinerators using the linear regression model. However, the distribution of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) was also analyzed using AERMOD as they were the primary pollutants from the incinerator. We obtained the daily MAIAC-AOD data incorporated with the meteorology data for the AERMOD simulation. Then, the validation of air pollutant concentrations between predicted $PM_{2.5}$ by MAIAC-AOD and $PM_{2.5}$ by AERMOD was performed to investigate the relationship and possibility of using MAIAC-AOD to investigate the environmental and health impact assessment of the sensitive area surrounding an infectious waste incinerator, as normally, air quality monitoring of infectious waste stacks was carried out twice a year in accordance with regulations, which could be too late to detect the risk of air pollution from a waste incinerator. As a result, preliminary $PM_{2.5}$ estimation using MAIAC-AOD, which has a high temporal (daily) and spatial distribution (1 km), should be particularly beneficial for assessing the environmental and health impacts of stationary emission sources.

2 Materials and methods

2.1 Study domain

The infectious waste incinerator of Mae Fah Luang University is located at coordinates 59°65′30″N and 22°17′16″E in Chiang Rai province, northern Thailand. The incinerator consisted of two controlled air chambers and used LPG as a fuel. The capacity of the incinerator was 2 tons/day, and the working time was approximately 60–70 h/month. It produced 8%–10% of bottom ash from the incineration process and released approximately 10% of fly ash from the air pollution control process. The air pollution control devices were a Muti Cyclones Separator for fly ash and a backhouse filter for dioxin. The incinerator has been operated since 2019 by receiving infectious waste from healthcare facilities, such as hospitals and district health promotion hospitals, inside the province. It is surrounded by a forest and communities, and there are twelve sensitive places within a 10 km^2 radius, including public areas, temples, and schools, as indicated in Figure 1 and Table 1.

2.2 Data collection

Surface meteorological information in the SCRAM format, including wind speed, wind direction, ceiling height, dry bulb temperature, total cloud cover, and opaque cloud cover, was collected from the Wyoming University website and the Chiang

FIGURE 1
The infectious waste stack and sensitive areas.

TABLE 1 Identified sensitive area information.

Point	Receptors	X coordinate	Y coordinate
A1	Maha Mongkhol Temple	598,475	2,216,475
A2	Ban Pang Lao School	599,005	2,216,950
A3	Mae Fah Luang University Dormitory Area	593,507	2,216,377
A4	Mae Fah Luang University Hospital Center	592,060	2,215,327
A5	Long Neck Village	592,999	2,213,670
A6	Mae Fah Luang University Lecture Area	593,520	2,216,810
A7	Vanasom Resort	595,335	2,217,930
A8	Huay Charoen Wittaya School	599,669	2,218,768
A9	Phra Metta	592,883	2,214,040
A10	Pha Na Kong Kha Ram Temple	598,263	2,218,961
A11	Pra Cha Roum Mit Temple	599,539	2,217,450
A12	Thung Tom Temple	599,922	2,218,437

Rai Meteorological Station in Thailand. Albedo, Bowen ratio, and surface roughness length included the upper air meteorological variables acquired from https://ruc.noaa.gov/raobs/. The information on air pollutants released from the infectious incinerators including nitrogen dioxide (NO_x), sulfur dioxide (SO_2), and particle matter ($PM_{2.5}$) was gathered from the annual monitoring report of the infectious waste incinerator of Mae Fah Luang University. The information on the infectious waste stack and emissions, which was used in the AERMOD model calculation, is displayed in Supplementary Table S1. Terrain data in the format of STRM DEM (Shuttle Radar Topography Mission) with a height of 90 m resolution were obtained from https://earthexplorer.usgs.gov. The daily MAIAC-AOD at a 1 km resolution with 550 nm in HDF4 format (DAAC) was collected from https://search.earthdata.nasa.gov/.

2.3 Data analysis

The following surface meteorological variables were input into AERMET and subsequently translated to the SPC and PFL formats for further AERMOD simulation: wind speed, wind direction, ceiling height, dry bulb temperature, total cloud cover, opaque cloud cover, albedo, and surface roughness length (US EPA, 2004; US EPA, 2009). AERMOD received information about the concentrations of SO_2, NO_x, and $PM_{2.5}$ from the stack. Finally, AERMOD performed simulations of all three types of data to estimate SO_2, NO_x, and $PM_{2.5}$ dispersions within a 10 km^2 area surrounding the infectious waste stack, as shown in Supplementary Figure S1. The annual average MAIAC-AOD and wind speed data were used to develop a linear regression model for predicting $PM_{2.5}$ concentration because temperature

TABLE 2 The maximum concentrations of SO$_2$, NO$_x$, and PM$_{2.5}$ simulated by the AERMOD model.

| Year/period	SO$_2$ (µg/m^3)			NO$_x$ (µg/m^3)			PM$_{2.5}$ (µg/m^3)		
	1 h	24 h	Annual	1 h	24 h	Annual	1 h	24 h	Annual
2019	36.57	2.71	0.56	89.61	6.65	1.36	-	-	0.033
2020	37.68	3.45	0.53	93.33	8.46	1.30	-	-	0.031
2021	32.57	3.63	0.44	79.83	8.90	1.08	-	-	0.026
Location of max. concentration between 2019 and 2021	1,000 m from NW	720 m from NE	720 m from NE	1,000 m from NW	730 m from NE	730 m from NE			730 m from NE
Standard	780	300	100	320	-	57	-	50	25

NW, northwest; NE, northeast.
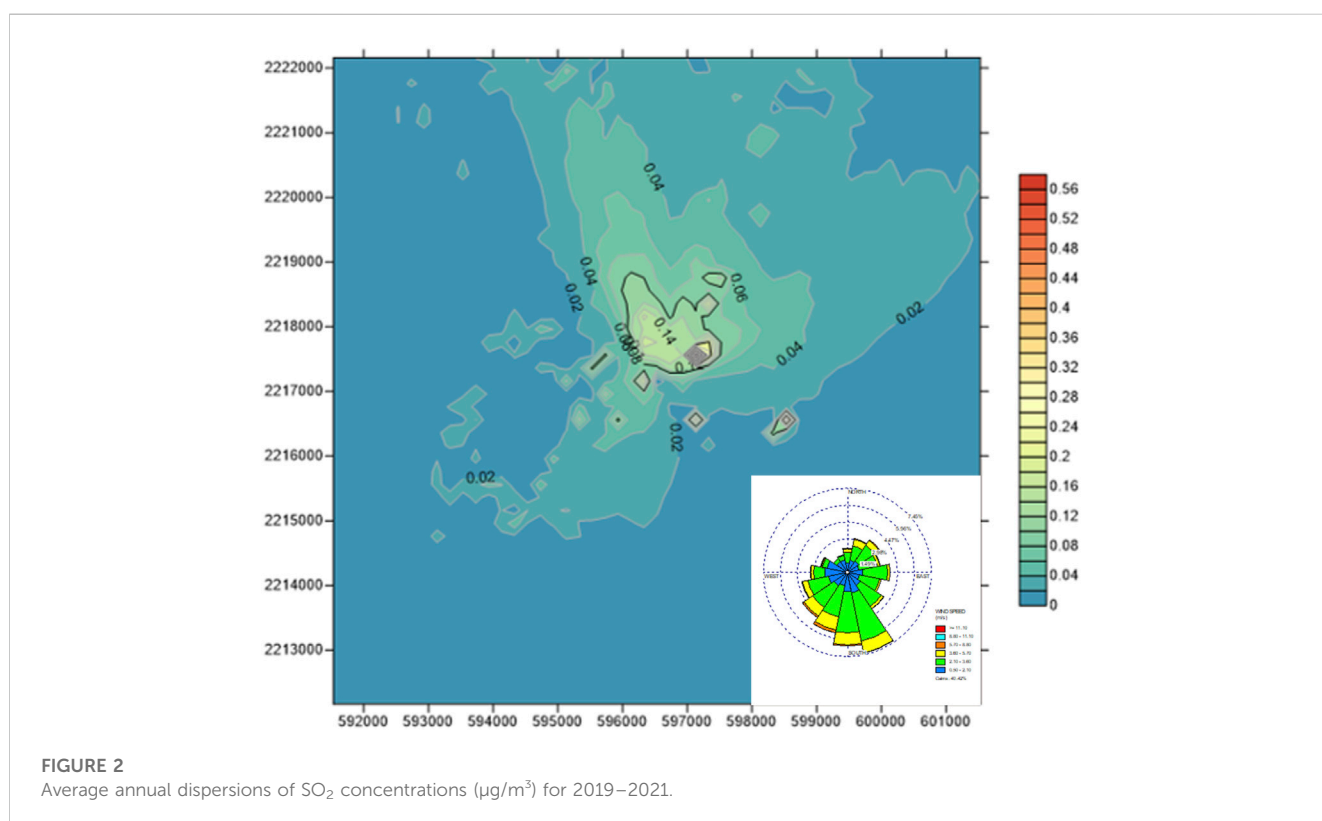
FIGURE 2
Average annual dispersions of SO$_2$ concentrations (µg/m^3) for 2019−2021.

and humidity were equal in the 10 km^2 area; therefore, data were not included in the linear regression model development. The PM$_{2.5}$ predicted by MAIAC-AOD was then compared with the PM$_{2.5}$ predicted by AERMOD. The annual average estimated PM$_{2.5}$ by MAIAC of the 1-km grid cell within the 10 km^2 area surrounding the stack was overlaid on the AERMOD simulated pollution distribution map.

3 Results

The distribution of air pollutants included SO$_2$, NO$_x$, and PM$_{2.5}$, which were emitted from the infectious waste incinerator, and were

simulated by the AERMOD model for the three average time periods, including at 1 h, 24 h, and annually. The simulated concentration was compared with National Ambient Air Quality Standards (NAAQS); the maximum simulated concentration of air pollutants complied with these standards for 1, 24 h, and the entire year, as shown in Table 2. The result from our study was similar to the health risk assessment for the municipal solid-waste incinerators in the five provinces of Thailand, Lamphun, Khon Kaen, Rayong, Phra Nakhon Si Ayutthaya, and Surat Thani, where the levels of SO$_2$ and NO$_x$ complied with the National Ambient Air Quality Standards (Srivieng et al., 2021). The AERMOD simulation also identified the location and distance of the highest pollutant concentration from the stack. The highest SO$_2$ and NO$_x$

concentrations in 1 h occurred in 2020 at 1,000 m in the northwest, with values of 37.68 and 93.33 μg/m^3, respectively. The 24-h concentrations of SO_2 and NO_x were highest in 2021, with values of 3.63 and 8.90 μg/m^3, respectively, 720 m northeast of the stack. Figures 2, 3 show the annual SO_2 and NO_x concentrations, which were highest in 2019, with respective values of 0.56 and 1.36 μg/m^3, 720 m and 730 m to the northeast, respectively. However, the other investigation found that the greatest radii of SO_2 and NO_x distributions from the stack were within 500 m (Koomsang et al., 2015; Afzali et al., 2016), which might have been caused by the wind speed in the area. The maximum PM$_{2.5}$ concentration of 0.033 μg/m^3 was discovered in 2019, 730 m to the northeast. The distribution of SO_2 over 24 h was much more diffused than the annual one, as shown in Supplementary Figure S2. By contrast, as shown in Supplementary Figure S3, the annual NO_x dispersion and concentration between 2019 and 2021 were distinct from the 24-h and annual NO_x dispersion because the annual NO_x was dispersed to the north, whereas the 24-h NO_x was not.

According to AERMOD simulation results, the wind direction had the largest effect on PM$_{2.5}$ dispersion, which gradually decreased with increasing distance downwind (Eibedingil et al., 2022). As illustrated in Figures 4–6, the annual average of the MAIAC-AOD value within a 10 km^2 radius in 2019 was higher than in 2020 and 2021, with values ranging between 0.59 and 0.88, 0.48–0.65, and 0.49–0.66, respectively. However, the distribution pattern of AOD indicated that the PM$_{2.5}$ concentration was correlated with the value of AOD and was higher in the vicinity of the stack than in the outside area. When the predicted PM$_{2.5}$ by MAIAC-AOD was

overlaid on the AERMOD findings, it was revealed that it had a greater concentration of PM$_{2.5}$ than the area closest to it. The findings of numerous studies support the hypothesis that the MAIAC-AOD was related to the PM$_{2.5}$ concentration as it demonstrated good agreement between the predicted and measured PM$_{2.5}$ concentrations (Arvani et al., 2016). In addition, the value of MAIAC-AOD was high in several sensitive locations, such as in 2019, when AOD at A1 was 0.88 with a predicted PM$_{2.5}$ by AOD of 0.014 μg/m^3, in 2020, when AOD at A10 was 0.62 with a predicted PM$_{2.5}$ by AOD of 0.013 μg/m^3, and in 2021, when AOD at A1 was 0.66 with a predicted PM$_{2.5}$ by AOD of 0.013 μg/m^3; these areas contained temples and therefore the high AODs were influenced by cremations. Over a 24-h period, the SO_2 and NO_x concentrations produced by AERMOD's simulation of cremation were 3.29 and 17.54 μg/m^3, respectively (Couper et al., 2012), which was slightly greater than the study's finding that cremation was a potential additional source of PM$_{2.5}$ in the two areas (A1 and A10). However, most sensitive areas were not impacted by the infectious waste incinerator pollution, but some of the areas still have high levels of MAIAC-AOD, thus it is crucial to investigate the other sources of PM$_{2.5}$ emission in the future. Additionally, as the World Health Organization has suggested an annual mean background concentration of PM$_{2.5}$ of 10 μg/m^3 (Voogt et al., 2009), when the simulated PM$_{2.5}$ was combined with the background concentration, it did not exceed the standard air quality of 15 μg/m^3. Supplementary Table S2 shows the average annual predicted PM$_{2.5}$ by MAIAC-AOD for each 1 km grid cell for each designated sensitive area within the 10 km^2 area of waste
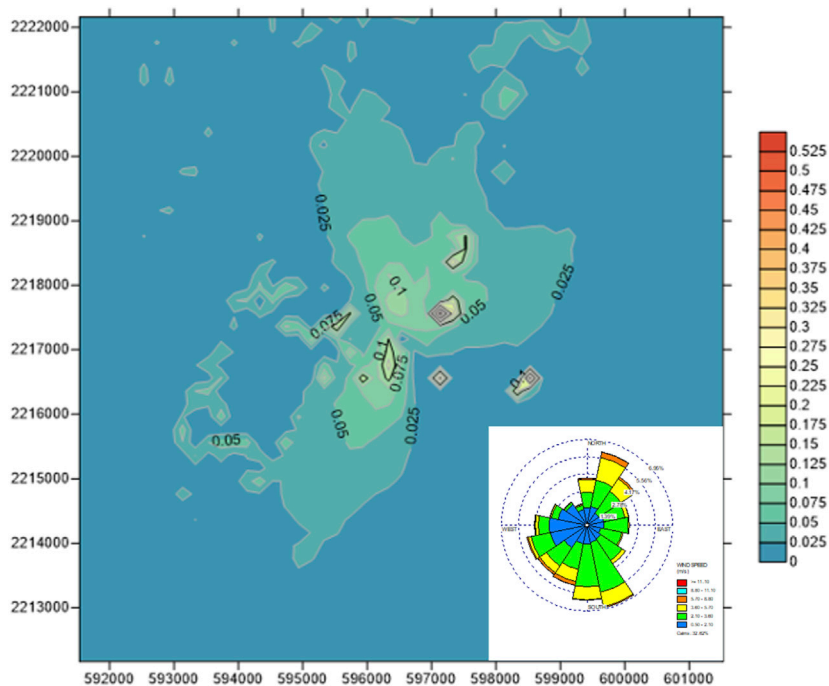

FIGURE 3
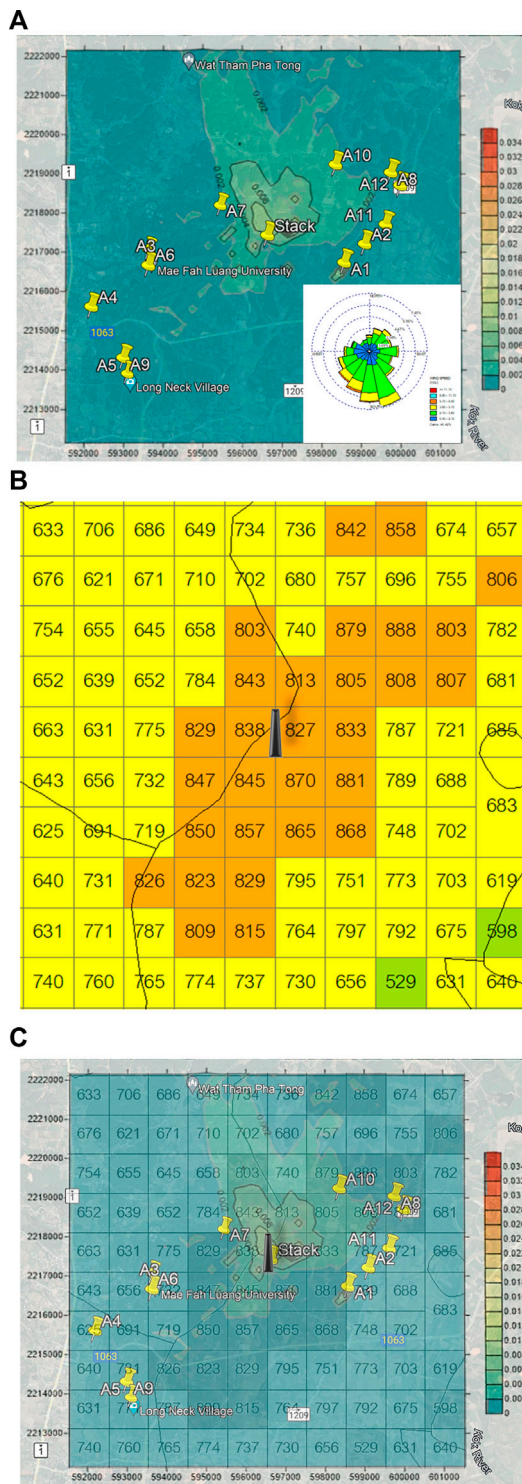Average annual dispersions of NO_x concentrations (μg/m^3) for 2019−2021.

FIGURE 4
Dispersions of simulated PM$_{2.5}$ concentrations (μg/m^3) from the infectious waste incineration and MAIAC-AOD. **(A)** Annual average PM$_{2.5}$ concentration by AERMOD. **(B)** MAIAC-AOD 1 km resolution. **(C)** MAIAC-AOD overlaid on the average PM$_{2.5}$ concentration in 2019.
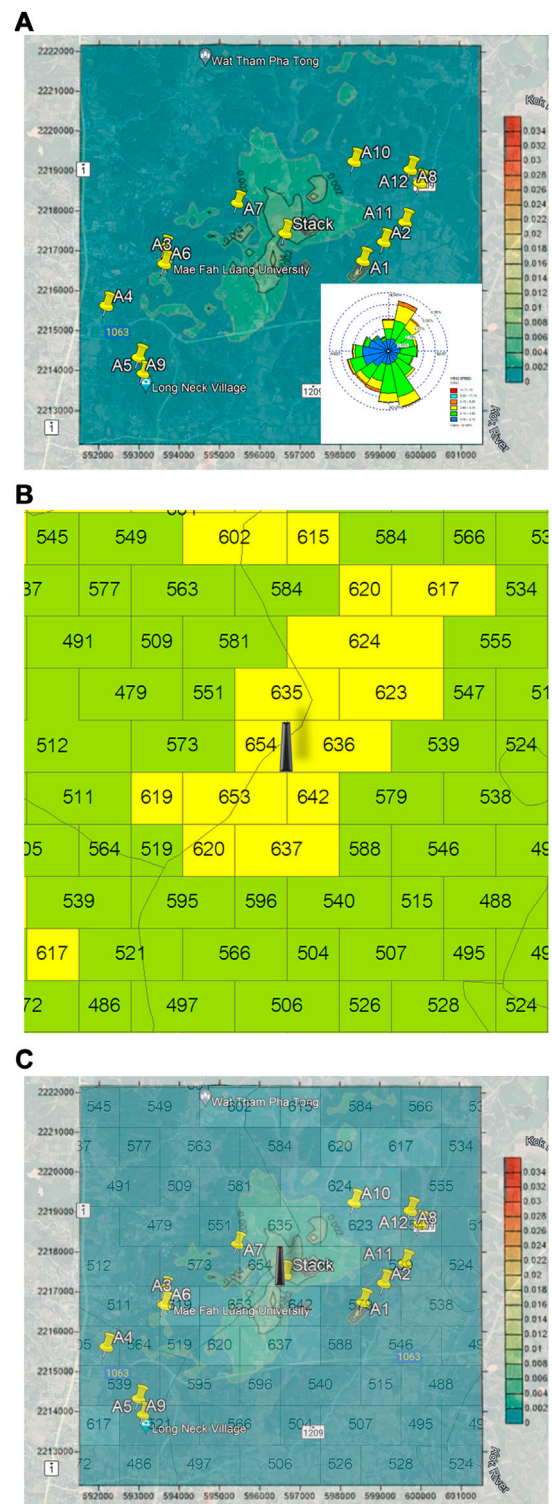

FIGURE 5
Dispersions of simulated PM$_{2.5}$ concentrations (μg/m^3) from the infectious waste incineration and MAIAC-AOD. **(A)** Annual average PM$_{2.5}$ concentration by AERMOD. **(B)** MAIAC-AOD 1 km resolution. **(C)** MAIAC-AOD overlaid on the average PM$_{2.5}$ concentration in 2020.

FIGURE 6
Dispersions of simulated PM$_{2.5}$ concentrations (µg/m^3) from the infectious waste incineration and MAIAC–AOD. **(A)** Annual average PM$_{2.5}$ concentration by AERMOD. **(B)** MAIAC–AOD 1 km resolution. **(C)** MAIAC–AOD overlaid on the average PM$_{2.5}$ concentration in 2021.

incineration, with the average annual PM$_{2.5}$ concentrations that were simulated by the AERMOD. Furthermore, between 2019, 2020, and 2021, the correlation between the predicted PM$_{2.5}$ by MAIAC-AOD and the simulated PM$_{2.5}$ concentrations by AERMOD was 0.7630, 0.7607, and 0.6504, respectively.

4 Discussion

The prediction of the air pollution dispersion from the infectious waste incinerator was performed using the AERMOD model. Although SO$_2$ and NO$_x$ were spread up to 1 km from the stack, the concentration did not exceed the national permissible limits. The predicted PM$_{2.5}$ by MAIAC-AOD was compared with the PM$_{2.5}$ simulated by AERMOD. The correlation between them was 0.7630, 0.7607, and 0.6504 for 2019, 2020, and 2021, respectively. According to the results, some areas have high AOD values, which indicates that sources other than infectious waste incinerators may also be causing the presence of PM$_{2.5}$. In Jiangsu Province, China, occurrence frequencies of MAIAC-AOD were found to be between 0.3 and 0.5, indicating the possibility of an atmosphere that was turbid as a result of human activities that increased emissions (Wang et al., 2021). Our study indicates that the MAIAC values in the 10 km^2 area around the infectious waste incinerator ranged from 0.51 to 0.88, which is significantly higher than the values found in previous studies, showing that this area was closer to the emission source. It was found that there was a consistent distribution trend between them, and this trend showed great potential for a thorough human exposure assessment at the community level [30. According to this study, the daily MAIAC-AOD can be employed as a preliminary monitoring tool to determine the risk area of exposure and the level of particulate matter. The MAIAC-AOD was daily and continuously both spatial and temporal, which was contrary to the normal monitoring period for stack emission monitoring of infectious waste that takes place at least twice a year. Therefore, it would be interesting to incorporate the AERMOD model or other air modeling with the daily MAIAC-AOD in the future to validate or cross-check the distribution of air pollution from other stationary emission sources or even the effect of transboundary air pollution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

SN contributed to the conception and design of the study, organized the database, and performed the statistical analysis. AH wrote the first draft of the manuscript and all sections of the
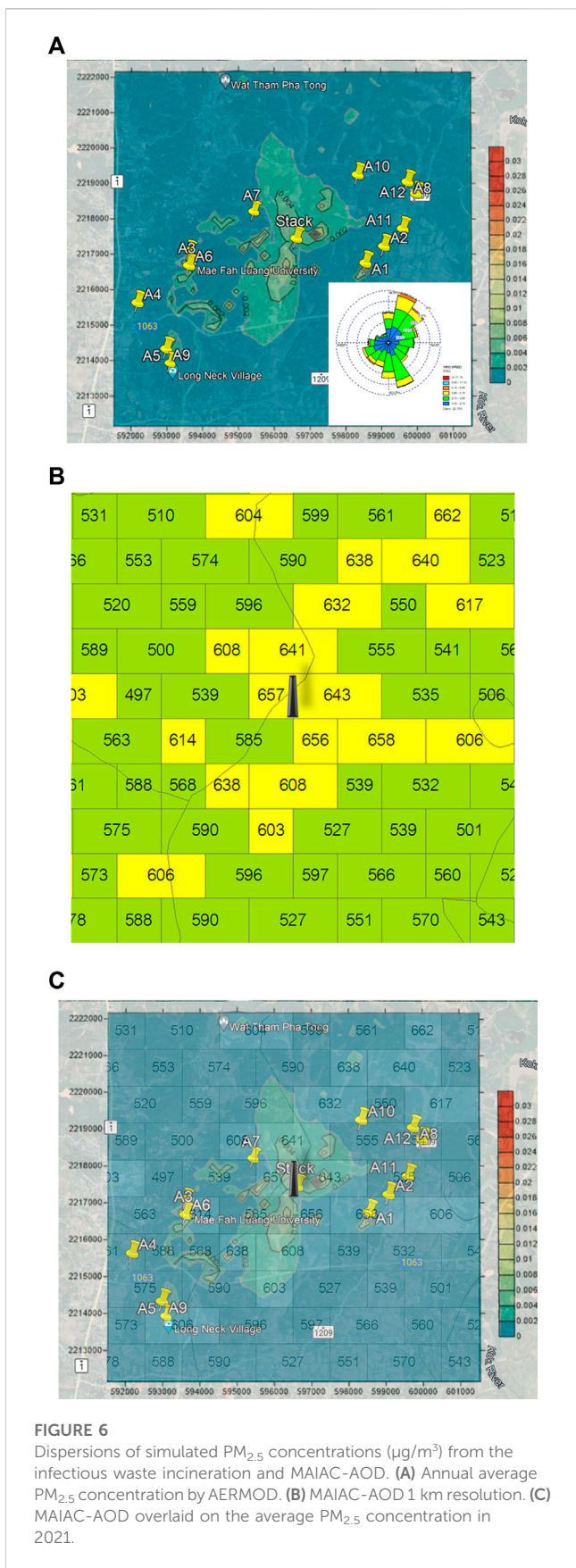
manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1240705/full#supplementary-material

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