Thai Environmental Engineering Journal Vol. 39 No. 2 (2025) : 73-83
www.eeat.or.th

Long-Term Analysis of $PM_{2.5}$ Concentrations and Seasonal Variation in Bangkok and Chiang Mai, Thailand: Impacts of COVID-19 Lockdowns and Fire Control Measures

Vineeth Vijayan[1], Supandee Maneelok[2] and Nantaporn Noosai[3*]

[1]Department of Mechanical and Mechatronics Engineering, Faculty of Engineering,
Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand
[2]Department of Occupational Health and Safety, Faculty of Health and Sports Science,
Thaksin University, Phatthalung 93210, Thailand
[3*]Department of Civil and Environmental Engineering, Faculty of Engineering,
Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand
[*]E-mail : nantaporn.no@psu.ac.th

Article History; *Received: 13 June 2025, Accepted: 27 August 2025, Published: 28 August 2025*

Abstract

An analysis of ten years of daily 24-h $PM_{2.5}$ data (2015–2024) from Thailand's Pollution Control Department at Bangkok (59T) and Chiang Mai (36T) reveals strong but distinct seasonality: Bangkok peaks in December–February with secondary formation and urban sources, whereas Chiang Mai exhibits pronounced February–April haze consistent with biomass burning. Two policy "experiments" were evaluated. During Bangkok's COVID-19 Wave-1 (22 Mar–31 May 2020), the window mean declined from a 2017–2019 baseline of 20.00 to 17.01 µg m^{-3} ($\Delta = -2.99$ µg m^{-3}; −14.9%), a statistically significant reduction of small-to-moderate magnitude (permutation p = 0.0036; Cohen's d = −0.39); two-way ANOVA showed a significant group effect, and daily exceedances of the 24-h standard (37.5 µg m^{-3}) fell from 3.3% to 0%. In Chiang Mai, January–April 2022 (first year of burning control) decreased from 54.2 to 29.5 µg m^{-3} versus 2019 ($\Delta = -24.7$ µg m^{-3}; −45.5%), a large, statistically significant reduction (permutation p = 0.0001; Cohen's d = −0.89), with significant group, month, and interaction terms; exceedances ≥37.5 µg m^{-3} dropped from 63.3% to 31.7%. NASA FIRMS hotspots concurrently decreased sharply in February–April 2022, corroborating reduced fire activity. Annual means show a steady decline in Bangkok (≈16.4 µg m^{-3} in 2024) and policy-sensitive variability in Chiang Mai; under the current Thai annual standard (15 µg m^{-3}), neither city achieves compliance. The combined ground-satellite evidence indicates that sustained, region-specific measures—traffic/precursor controls in Bangkok and consistent burning management in the North—are required to meet tightened standards.

Keywords : $PM_{2.5}$; Bangkok; Chiang Mai; biomass burning; COVID-19 lockdown; FIRMS; air quality standards; policy evaluation

Introduction

$PM_{2.5}$ is recognized as one of the most harmful air pollutants because fine particles penetrate deeply into the respiratory system and are linked to multiple adverse health outcomes [1]. In Thailand, concentrations often exceed national standards during the dry season, reflecting marked seasonality in regional emissions and meteorology [2, 3]. In 2022, Thailand strengthened its standards to 37.5 $\mu g\ m^{-3}$ for the 24-hour limit and 15 $\mu g\ m^{-3}$ for the annual limit, a policy change relevant for interpreting recent trends [3]. Health assessments continue to indicate substantial public-health burdens where annual means exceed 15 $\mu g\ m^{-3}$ [4]. In Bangkok, source apportionment and process studies identify traffic emissions and secondary with intermittent roles for industry and construction; boundary-layer dynamics can sustain elevated $PM_{2.5}$ during stagnant conditions [5-8]. In Chiang Mai and the northern region, multiple lines of evidence attribute first-quarter haze primarily to open biomass burning and transboundary transport; chemical markers and oxidative-potential assays corroborate biomass-burning dominance during smoke episodes [9-12].

Policy interventions offer natural experiments. Several Bangkok studies report $PM_{2.5}$ reductions during COVID-19 restrictions, although magnitudes vary with window and meteorology [13, 14]. In the North, authorities moved toward regulated burning and operational tools such as FireD; peer-reviewed evaluations are emerging, which motivates pairing hotspot data with ground $PM_{2.5}$ for empirical assessment [15-17].

Against this context, Bangkok and Chiang Mai are analyzed as contrasting cases. Daily 24-hour observations from station 59T (Bangkok) and station 36T (Chiang Mai) for 2015–2024 are used because they provide the most complete records in their urban cores; siting and representativeness are detailed in the Methodology. Because burning is episodic and spatially heterogeneous, ground measurements are complemented with NASA EOSDIS LANCE FIRMS (MODIS/VIIRS) active-fire detections for January to April to contextualize the 2022 burning-control enforcement in Chiang Mai [17]. The study characterizes seasonal and interannual variability at both sites, evaluates Bangkok's COVID-19 Wave-1 window (22 March to 31 May 2020) relative to a 2017–2019 baseline, compares Chiang Mai conditions in January to April of 2019 and 2022 using ground $PM_{2.5}$ with FIRMS hotspot distributions, and assesses compliance relative to the revised Thai standards (37.5 $\mu g\ m^{-3}$ for 24-hour and 15 $\mu g\ m^{-3}$ for annual).

Methodology

Study sites and data:

Two contrasting Thai settings were analyzed: Bangkok (urban, traffic/industry dominated) and Chiang Mai (biomass-burning influenced). Ground $PM_{2.5}$ came from Thailand's Pollution Control Department (PCD) as daily 24-h averages for 2015–2024. The primary monitors were Bangkok 59T and Chiang Mai 36T, selected for record continuity, central siting, and use in official reporting. Station metadata appear in Table 1; locations in Figure 1.

Table 1 Monitoring station metadata

Station ID	City	Station name	Latitude	Longitude	District	Province
59T	Bangkok	The Government Public Relations Department	13.7831	100.5404	Khet Phaya Thai	Bangkok
36T	Chiang Mai	Yupparaj Wittayalai School	18.7909	98.9900	Mueang	Chiang Mai

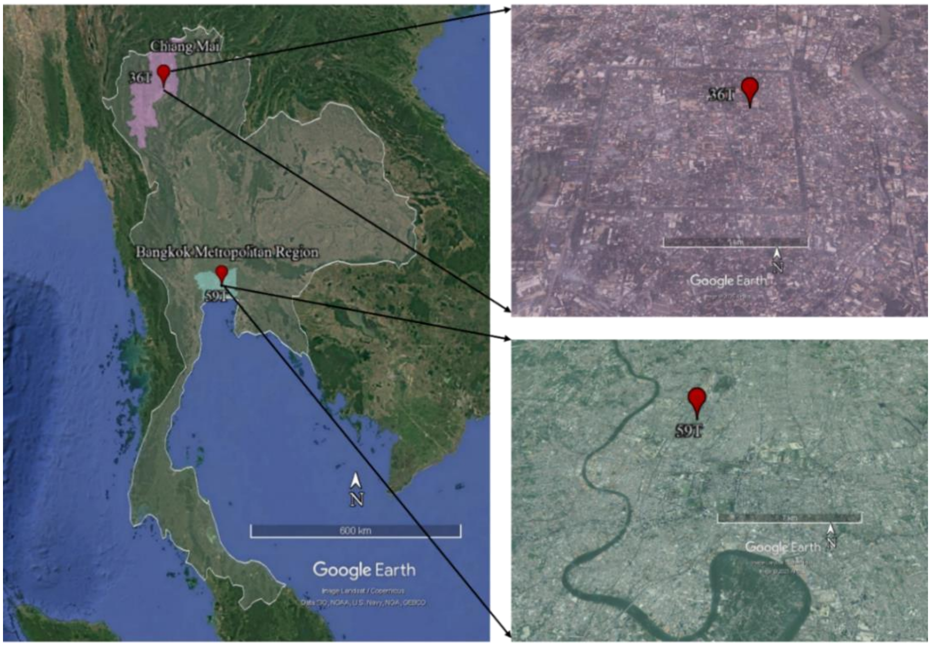

Figure 1 Map of monitoring stations 59T (Bangkok) and 36T (Chiang Mai)

Data and windows

Daily 24-h $PM_{2.5}$ (2015–2024) from Thailand PCD were analyzed at Bangkok 59T and Chiang Mai 36T, selected for long, continuous records and urban-core representativeness (see station table and map). Intervention windows were (i) Bangkok COVID-19 Wave-1: 22 Mar–31 May 2020 vs a 2017–2019 baseline restricted to the same dates; and (ii) Chiang Mai burning control: January–April 2022 vs January–April 2019. NASA EOSDIS LANCE FIRMS (MODIS/VIIRS) daily hotspot counts were aggregated over Chiang Mai for January –April 2019 vs 2022.

Metrics and inference

Seasonality (2015–2024) was summarized by monthly boxplots and monthly tables (mean, median, IQR, n, and daily exceedances $\geq$37.5 µg m^{-3}—Thai 24-h standard). For policy windows, group differences in daily means were tested with two-sided permutation tests (e.g., 20,000 shuffles; report mean difference, 95% CI, and Cohen's d). Two-way ANOVA (Group × Month) tested overall and month-specific effects for Bangkok (Mar–May) and Chiang Mai (Jan–Apr). Annual compliance used yearly means compared against the Thai annual standard of 15 µg m^{-3} (revised 2022). FIRMS corroboration used grouped monthly boxplots (2019 vs 2022) with dashed red lines for 2022 medians and month-wise permutation tests on daily hotspot counts. Cohen's d quantifies the standardized mean difference (about 0.2 small, 0.5 medium, 0.8 large). The sign indicates the direction of change. The permutation *p* value is the probability, under the null hypothesis of no group effect, of obtaining a difference as large as or larger than the observed difference after random shuffling of group labels. Smaller *p* values indicate stronger evidence for a real difference.

Processing and software

Dates were parsed to daily means; non-numeric/NaT rows were dropped; no imputation or meteorological normalization was applied. Analyses used Python (pandas, numpy, matplotlib, statsmodels).

Limitations

No meteorological normalization was applied; interannual differences may reflect both emission/activity changes and weather. FIRMS detections depend on satellite overpass, clouds, and detection thresholds and are interpreted as activity indicators, not emission fluxes.

Results and Discussions

Seasonal Patterns and Yearly Trends

Figure 2 (Bangkok, 59T) shows monthly boxplots of daily 24-h $PM_{2.5}$ for 2015–2024 with summary statistics in Table 2. The Chiang Mai results appear in Figure 3 (36T) with statistics in Table 3.

Both cities exhibit a strong seasonal cycle (dry-season highs, wet-season lows). Exceedance analyses below reference the Thai 24-hour $PM_{2.5}$ standard of 37.5 µg m^{-3} and are applied to daily values; counts of days ≥ 37.5 µg m^{-3} indicate short-term exposure pressure.

Bangkok (59T). $PM_{2.5}$ peaks in Jan–Feb (means ≈ 30–31 µg/m³) and Dec (≈ 28 µg m^{-3}), and falls to ≈ 11–12 µg/m³ in Jun–Aug. Exceedances of the 37.5 µg m^{-3}daily standard are concentrated in the cool-dry months: Jan 28% (78/276), Feb 31% (70/225), Mar 11% (28/249), Apr 10% (29/280), Dec 16% (50/308); they are rare elsewhere (May 0.6%, Jun–Aug 0%, Sep 1.7%, Oct 3.2%, Nov 6.0%).

Chiang Mai (36T). A pronounced haze season dominates Feb–Apr (means ≈ 45, 74, 61 µg m^{-3}). Daily exceedances of 37.5 µg m^{-3} are very persistent in this period: Jan 28% (84/298), Feb 65% (184/282), Mar 88% (268/304), Apr 73% (219/298), then drop sharply (May 15.8%) and are essentially zero in Jun–Oct (≤0.7%), with small upticks in Nov 0.4% (1/265) and Dec 4.3% (13/302).

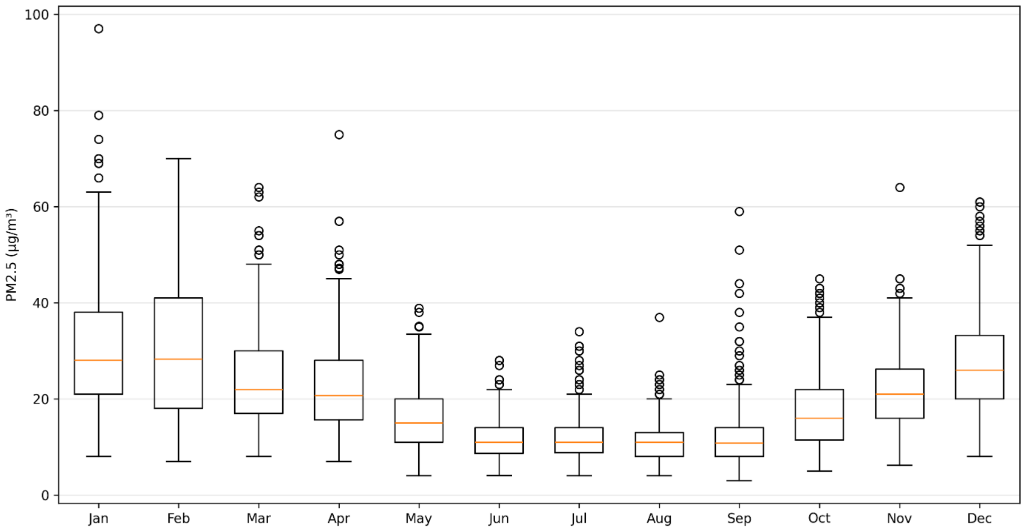

Figure 2 Bangkok (59T) $PM_{2.5}$ monthly boxplots (2015–2024). Boxes: IQR; line: median; whiskers: 1.5×IQR; points: outliers

Table 2 Bangkok (59T) monthly statistics (2015–2024): mean, median, IQR, exceedance days (≥ 37.5 µg m^{-3}), n

Month	Mean	Median	IQR	Exceed days ≥ 37.5 µg m^{-3}	n	Month	Mean	Median	IQR	Exceed days ≥ 37.5 µg m^{-3}	n
Jan	31.3	28	17	78	276	Jul	12.1	11	5.2	0	294
Feb	30.4	28.3	23	70	225	Aug	11.4	11	5	0	301
Mar	24.5	22	13	28	249	Sep	12.4	10.8	6	5	298
Apr	22.9	20.7	12.3	29	280	Oct	17.6	16	10.5	10	308
May	15.9	15	9	2	309	Nov	22.1	21	10.1	17	283
Jun	11.9	11	5.4	0	298	Dec	27.5	26	13.2	50	308

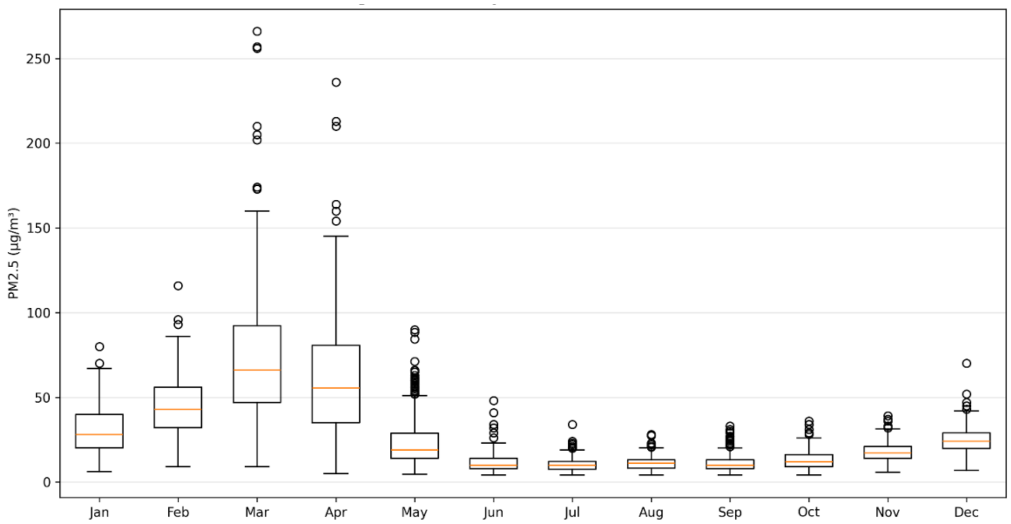

Figure 3 Chiang Mai (36T) $PM_{2.5}$ monthly boxplots (2015–2024). Boxes: IQR; line: median; whiskers: 1.5×IQR; points: outliers

Table 3 Chiang Mai (36T) monthly statistics (2015–2024): mean, median, IQR, exceedance days (≥ 37.5 µg m^{-3}), n

Month	Mean	Median	IQR	Exceed days ≥ 37.5 µg m^{-3}	n	Month	Mean	Median	IQR	Exceed days ≥ 37.5 µg m^{-3}	n
Jan	30.7	28	19.6	84	298	Jul	10.5	10	4.6	0	303
Feb	45.1	43	23.9	184	282	Aug	11.4	11	4.9	0	304
Mar	73.7	66	45.2	268	304	Sep	11	10	5	0	296
Apr	60.9	55.5	45.8	219	298	Oct	13.2	12	7.1	0	275
May	23.8	19	14.9	48	304	Nov	17.8	17	7	1	265
Jun	11.5	10	6	2	294	Dec	24.3	24	9.1	13	302

Both sites exhibit seasonality, but the signal is much more coherent in Chiang Mai. $PM_{2.5}$ rises sharply and persists through February to April, consistent with the burning season, then collapses in the monsoon months. Bangkok, in contrast, shows only a modest cool-season elevation, mainly in December to February, and a wide day to day spread across the broader dry season from November to April without a stable intra-seasonal pattern. This variability reflects overlapping and episodic influences such as weekday traffic intensity, construction and industrial activity, stagnant boundary-layer conditions, and occasional regional smoke intrusions, superimposed on the rain-season cleansing that drives the May to October minima. In summary, the absence of a consistent pattern during the dry season indicates that seasonal averages can mask short episodes of high exposure. This finding supports the need for real-time monitoring and targeted episodic control measures, alongside seasonal policy planning.

COVID-19 Lockdown Effects in Bangkok

To assess the impact of pandemic-related restrictions on $PM_{2.5}$ concentration, Figure 4 compares daily $PM_{2.5}$ concentrations at station 59T during the strictest COVID-19 Wave 1 lockdown period (March 22–May 31, 2020) against a three-year pre-pandemic baseline matched to the same calendar days (2017–2019). Table 4 reports the statistical analysis. During the restriction window 22 March–31 May 2020, daily $PM_{2.5}$ decreased from a 2017–2019 baseline mean of 20.00 to 17.01 μg m^{-3} (−2.99 μg m^{-3}, −14.9%; permutation p = 0.0036, 95% CI −4.71 to −1.24; Cohen's d = −0.39). Cohen's d = −0.39 indicates a small-to-moderate reduction in 2020 relative to the 2017–2019 baseline; the negative sign indicates lower 2020 values. The permutation p value of 0.0036 means that, if there were truly no group difference, a shift of this size would be very unlikely, supporting a genuine lockdown-period reduction. A two-way ANOVA (group by month) indicated significant effects of group (F = 8.80, p = 0.003) and month (F = 5.44, p = 0.005), with a non-significant interaction (p = 0.207), implying a broadly consistent reduction across March–May.

The proportion of days at or above 37.5 μg m^{-3} declined from 7/213 (3.3%) in the baseline to 0/71 (0%) in 2020, with the clearest visual shift in May, consistent with the onset of early-monsoon cleansing. The results indicate a moderate, statistically robust improvement during Wave-1, while remaining dry-season variability points to continuing influences of background and secondary formation processes in Bangkok.

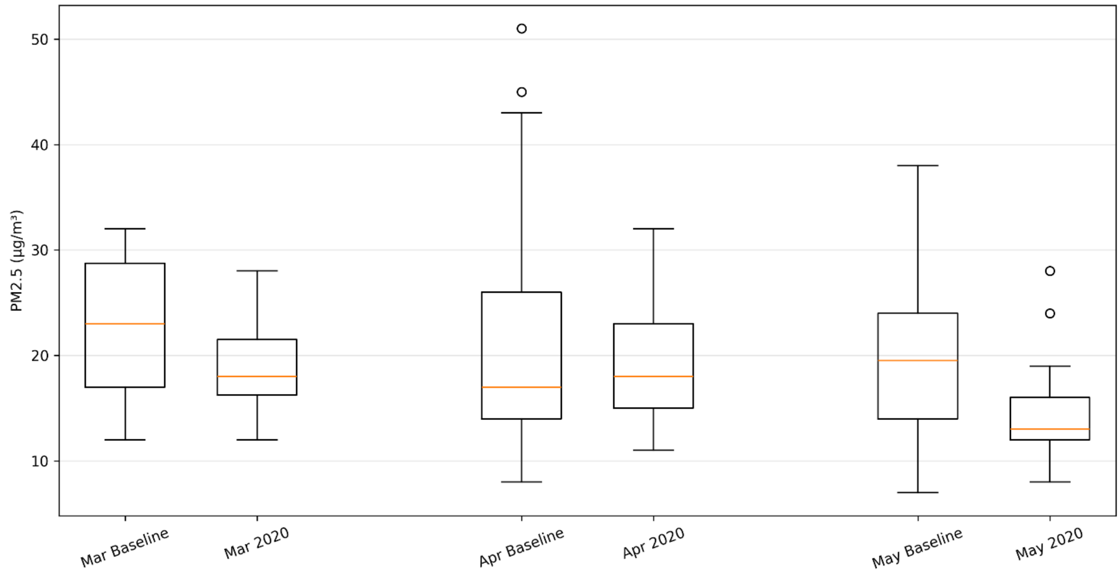

Figure 4 Bangkok (59T): Lockdown window (Mar 22–May 31) boxplots comparing Baseline (2017–2019) vs 2020

Table 4 Bangkok (59T) — COVID-19 Wave-1 restriction window (22 Mar–31 May 2020) vs baseline (2017–2019): summary metrics and two-way ANOVA

Window-level summary	**Baseline (2017–2019)**	**2020**	**Change (2020−Base)**	**Percent change**	**95% CI (μg m^{-3})**	**Cohen's d**	**Exceedance days ≥37.5 μg m^{-3} (base → 2020)**
Mean $PM_{2.5}$ (μg/m³)	20.00	17.01	−2.99	−14.9%	[−4.71, −1.24]	−0.39	**7 → 0 (3.3% → 0.0%**; n=213 → 71)
Two-way ANOVA (Group×Month)				**sum_sq**	**df**	**F**	**p (PR>F)**
Group (baseline vs 2020)				496.091	1.0	8.803	0.003
Month (Mar, Apr, May)				613.408	2.0	5.443	0.005
Group×Month				178.827	2.0	1.587	0.207
Residual				15158.751	269.0	—	—

Fire Control Measures in Chiang Mai

To evaluate the first year of burning control enforcement, Figure 5 compares January to April 2022 with the pre regulation season in 2019, and Table 5 reports the statistical analysis result. For January–April, $PM_{2.5}$ declined from 54.2 in 2019 to 29.5 µg m^{-3} in 2022 (Δ = −24.7 µg m^{-3}, −45.5%; permutation p = 0.0001, 95% CI −32.1 to −17.9; Cohen's d = −0.89). Cohen's d = −0.89 indicates a large reduction in 2022 relative to 2019; the negative sign indicates lower 2022 values. The permutation p value of 0.0001 indicates that such a decrease would be extremely unlikely under the null hypothesis of no difference. A two-way ANOVA showed significant group, month, and group×month effects (all $p < 0.001$), with the largest decreases in March–April, matching the core haze season. Using the 24-hour standard (37.5 µg m^{-3}), exceedance days decreased from 76/120 (63.3%) in 2019 to 38/120 (31.7%) in 2022. Consistent with these averages, the 2022 boxplots are lower and less dispersed in all four months, indicating both reduced central tendency and fewer extreme smoke days.

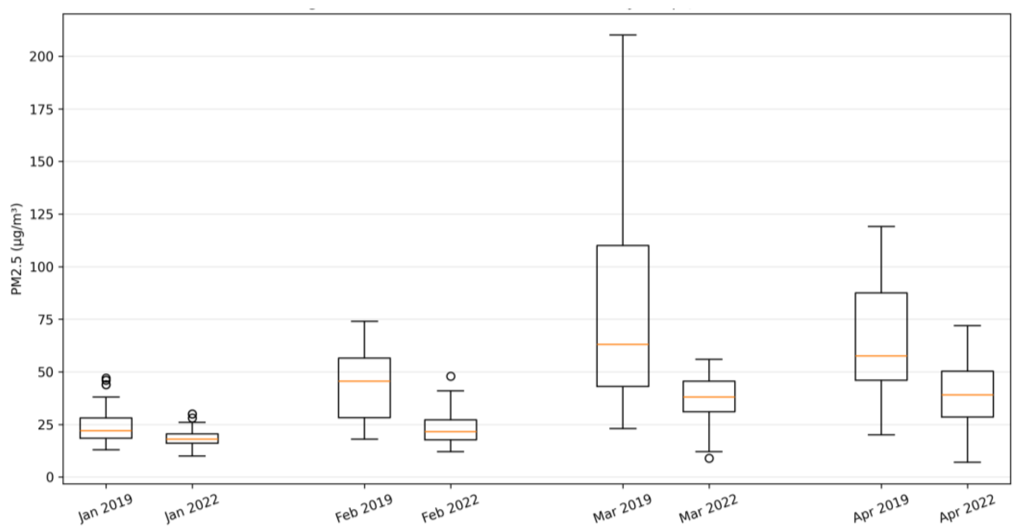

Figure 5 Chiang Mai (36T): Jan–Apr boxplots comparing 2019 vs 2022 during burning-control enforcement

Table 5 Chiang Mai (36T) — Burning-control season (Jan–Apr) 2022 vs 2019: summary metrics and two-way ANOVA

Window-level summary	**Baseline (2017–2019)**	**2020**	**Change (2020−Base)**	**Percent change**	**95% CI (µg/m³)**	**Cohen's d**	**Exceedance days ≥37.5 µg/m³ (base → 2020)**
Mean $PM_{2.5}$ (µg/m³)	20.00	17.01	−2.99	−14.9%	[−4.71, −1.24]	−0.39	**76 → 38** (63.3% → 31.7%)
Two-way ANOVA (Group×Month)				**sum_sq**	**df**	**F**	**p (PR>F)**
Group (baseline vs 2020)				496.091	1.0	8.803	0.003
Month (Mar, Apr, May)				613.408	2.0	5.443	0.005
Group×Month				178.827	2.0	1.587	0.207
Residual				15158.751	269.0	—	—

To verify that the 2019→2022 reduction in Chiang Mai $PM_{2.5}$ coincided with less open burning rather than only meteorological variability, a parallel analysis used NASA EOSDIS LANCE FIRMS active-fire detections. Daily hotspot counts were aggregated for January–April and compared between 2019 (pre-regulation) and 2022 (first enforcement year). The systematically lower and tighter 2022 distributions in February–April can be observed in Figure 6. Table 6 summarizes the month-wise differences in daily means with permutation p-values (20,000 shuffles). Month-wise permutation tests on daily hotspot counts yielded $p < 0.001$ in February–April, indicating the 2019-2022 reductions are highly unlikely under the null of no change in fire activity, aligning with the ground-level $PM_{2.5}$ decreases during the main haze months. The large and statistically significant decreases in February–April align with the ground-level $PM_{2.5}$ declines and indicate materially fewer or smaller fires during the core haze months in 2022. The January increase in hotspots alongside lower $PM_{2.5}$ suggests timing or dispersion differences (for example, changes in wind, mixing depth, fuel moisture, or burn size) that can decouple hotspot counts from surface concentrations early in the season. Taken together, the FIRMS evidence corroborates the interpretation that burning-control enforcement in 2022 reduced smoke load during the main haze period.

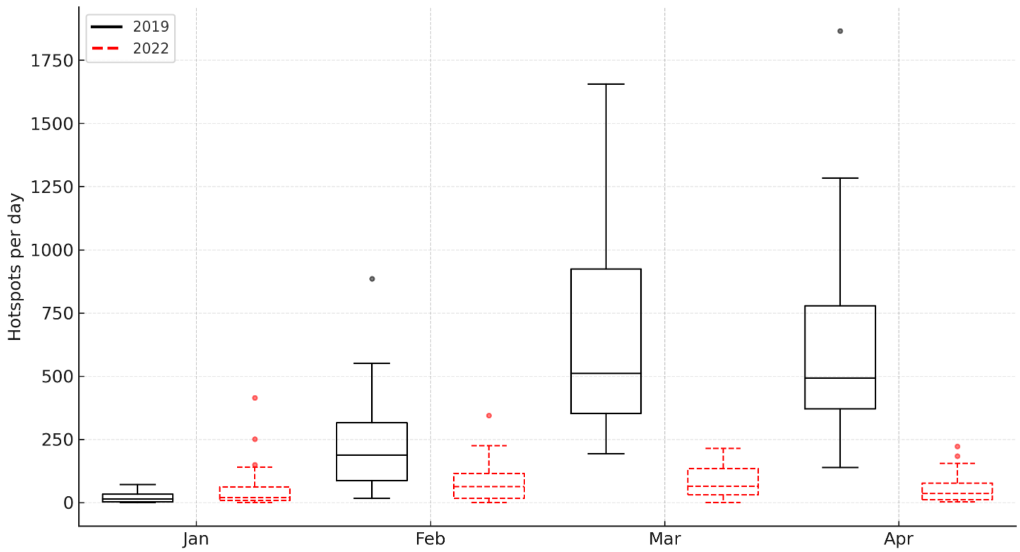

Figure 6 NASA FIRMS daily hotspot counts for Chiang Mai (Jan–Apr), grouped boxplots comparing 2019 and 2022 on a single axis. The dashed red line marks each month's 2022 median. Distributions in Feb–Apr 2022 are markedly lower and less dispersed than in 2019

Table 6 Month-wise FIRMS daily hotspot means for 2019 and 2022, differences (2022−2019), and permutation test p-values. Significant reductions in Feb–Apr support attribution of the $PM_{2.5}$ decrease to reduced burning activity

Month	Mean2019	Mean2022	Diff(2022-2019)	p_perm
Jan	22.552	59.759	37.207	$p = 0.014$
Feb	229.464	84.593	-144.872	$p < 0.001$
Mar	688.387	86.69	-601.697	$p < 0.001$
Apr	618.633	57.6	-561.033	$p < 0.001$

Yearly Average Analysis

Figure 7 summarizes decade-long annual means for Bangkok (59T) and Chiang Mai (36T) against Thailand's annual $PM_{2.5}$ standards (25 µg m^{-3} prior to June 2022; 15 µg m^{-3} since). The purpose of this analysis is to distill the many daily and seasonal fluctuations into a policy-relevant trajectory that can be compared directly with the national benchmarks and contrasted across the two cities. Bangkok shows a gradual decline from a local peak around 2017 (~24.9 µg m^{-3}) to ~16.4 µg m^{-3} in 2024 (≈−34%), with a small rebound in 2023. Chiang Mai exhibits much larger interannual variability governed by the burning season: a drop from ~30.3 µg m^{-3} (2019) to ~19.3 µg m^{-3} (2022) (≈−36%) coincident with burning-control enforcement, followed by a sharp rebound to ~32.8 µg m^{-3} (2023) and a partial easing in 2024 (~27.6 µg m^{-3}). Relative to the former 25 µg m^{-3} annual standard, Bangkok is below the limit in all years shown, whereas Chiang Mai exceeds it in most years except 2017 and 2022.

Under the current 15 µg m^{-3} annual standard, neither city meets the annual benchmark in any year, underscoring that, despite improvements, additional structural controls are required—especially for Chiang Mai, where year-to-year swings track the intensity of biomass-burning seasons. As annual means can mask short, severe episodes, these trends should be interpreted alongside the monthly distributions presented earlier, which show that Bangkok's exceedances cluster in Dec–Feb, while Chiang Mai's concentrations surge during Feb–Apr.

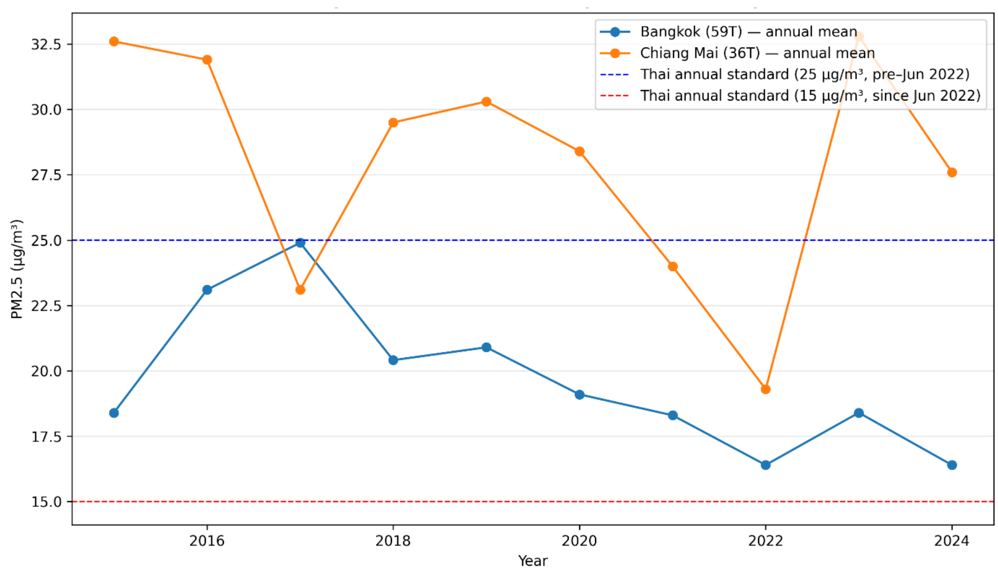

Figure 7 Annual average $PM_{2.5}$ at Bangkok (59T) and Chiang Mai (36T), 2015–2024. Dashed lines show Thai annual standards (25 µg m^{-3} pre-June 2022; 15 µg m^{-3} since)

Conclusions

From 2015–2024, both Bangkok (59T) and Chiang Mai (36T) show clear seasonality; Bangkok peaks in Dec–Feb and eases in Jun–Aug, while Chiang Mai has a stronger Feb–Apr haze pulse driven by burning. Interventions yielded different magnitudes: Bangkok's Wave-1 restrictions (22 Mar–31 May 2020) produced a moderate decline (−14.9% in the window) and eliminated daily exceedances ≥37.5 µg/m³ in that period; Chiang Mai's 2022 burning control delivered a large reduction (−45.5% Jan–Apr) and halved exceedance frequency. Annual means confirm a steady decline in Bangkok and policy-sensitive variability in Chiang Mai; under the current 15 µg/m³ annual standard, neither city achieves compliance. Policy priorities therefore differ: sustained control of traffic/precursor emissions for Bangkok, and consistent burning management with regional coordination for Chiang Mai.

References

[1] World Health Organization (WHO). 2021. Global Air Quality Guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: WHO.

[2] Pollution Control Department (PCD), Thailand. 2023. Thailand's Air Quality Management Framework (slides announcing the 2022 $PM_{2.5}$ standards: 24-h 37.5 µg m^{-3}; annual 15 µg m^{-3}), 30 May 2023, EANET Workshop.

[3] Bran, S. H., Macatangay, R., Chotamonsak, C., Chantara, S. and Surapipith, V. 2024. Understanding the seasonal dynamics of surface $PM_{2.5}$ mass distribution and source contributions over Thailand. Atmospheric Environment. 331: 120613.

[4] Air Quality Life Index (AQLI). 2024. Thailand Fact Sheet 2024. Chicago: Energy Policy Institute at the University of Chicago (EPIC).

[5] Rattanapotanan, T., Thongyen, T., Bualert, S., Choomanee, P., Suwattiga, P., Rungrattanaubon, T., Utavong, T., Phupijit, J. and Changplaiy, N. 2023. Secondary sources of $PM_{2.5}$ based on the vertical distribution of organic carbon, elemental carbon and water-soluble ions in Bangkok. Environmental Advances. 11: 100337.

[6] Ratanavalachai, T. and Trivitayanurak, W. 2023. Application of a $PM_{2.5}$ dispersion model in the Bangkok central business district for air quality management. Frontiers in Environmental Science. 11: 1237366.

[7] Ahmad, M., Manjantrarat, T., Rattanawongsa, W., Muensri, P., Saenmuangchin, R., Klamchuen, A., Aueviriyavit, S., Sukrak, K., Kangwansupamonkon, W. and Panyametheekul, S. 2022. Chemical composition, sources, and health risk assessment of $PM_{2.5}$ and PM_{10} in urban sites of Bangkok, Thailand. International Journal of Environmental Research and Public Health. 19(21): 14281.

[8] Archer, D., Bhatpuria, D. Nikam, J. and Taneepanichskul, N. 2024. Particulate matter pollution in central Bangkok: assessing outdoor workers' perceptions and exposure. Cities & Health. 1-19.

[9] Chansuebsri, S., Kolar, P., Kraisitnitikul, P., Kantarawilawan, N., Yabueng, N., Wiriya, W., Thepnuan, D. and Chantara, S. 2024. Chemical composition and origins of $PM_{2.5}$ in Chiang Mai (Thailand) by integrated source apportionment and potential source areas. Atmospheric Environment. 318: 120192.

[10] Ponsawansong, P., Prapamontol, T., Rerkasem, K., Chantara, S., Tantrakarnapa, K., Kawichai, S., Li, G., Fang, C., Pan, X., and Zhang, Y. 2023. Sources of $PM_{2.5}$ oxidative potential during haze and non-haze seasons in Chiang Mai, Thailand. Aerosol and Air Quality Research. 23(10): 230030.

[11] Suriyawong, P., Chuetor, S., Samae, H., Piriyakarnsakul, S., Amin, M., Furuuchi, M., Hata, M., Inerb, M. and Phairuang, W. 2023. Airborne particulate matter from biomass burning in Thailand: Recent issues, challenges, and options. Heliyon. 9(3): e14261.

[12] Inlaung, K., Chotamonsak, C., Macatangay, R. and Surapipith, V. 2024. Assessment of transboundary $PM_{2.5}$ from biomass burning in Northern Thailand using the WRF-Chem model. Toxics. 12(7): 462.

[13] Dejchanchaiwong, R. and Tekasakul, P. 2021. Effects of coronavirus induced city lockdown on $PM_{2.5}$ and gaseous pollutant concentrations in Bangkok. Aerosol and Air Quality Research. 21: 200418.

[14] Sanghatawatana, P., Thaithatkul, P., Anuchitchanchai, O., Liang, J. and Chalermpong, S. 2023. The effect of COVID-19 lockdown on particulate matters concentration: Case of land use regression difference modeling in Bangkok, Thailand. City and Environment Interactions. 20: 100125.

[15] AP News. 2024. As Thailand gasps through another haze season, researchers hope a fire-charting app can help. June 18, 2024.

[16] ABC News (Australia). Thailand seeks pollution solutions as fires exacerbate haze; FireD described. June 23, 2024.

[17] NASA Earthdata (EOSDIS LANCE). 2025. Fire Information for Resource Management System (FIRMS): Overview and Data Access. Greenbelt, MD: NASA.