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The role of monsoon dynamics in $PM_{2.5}$ concentration during the 2023–2024 El Niño event in Southeast Asia: a public health concern

Peran Dinamika Monsun terhadap Konsentrasi $PM_{2.5}$ selama Peristiwa El Niño 2023–2024 di Asia Tenggara: Sebuah Isu Kesehatan Masyarakat

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ABSTRACT

Background: *El Niño and positive Indian Ocean Dipole (IOD) events can disrupt monsoon circulation and increase air pollution exposure in Southeast Asia, particularly PM2.5, which poses significant public health risks.*
Objective: *This study aimed to analyze PM2.5 exposure during the 2023–2024 El Niño period and assess its potential public health risks in Southeast Asia.*
Methods: *Daily PM2.5 concentrations in major Southeast Asian capitals during the 2023–2024 El Niño period were analyzed to evaluate temporal variability, exceedances of WHO and national standards, and potential transboundary pollution using Spearman correlation analysis.*
Results: *Jakarta and Hanoi showed the highest daily median PM2.5 concentrations, exceeding 100 µg/m3. However, exceedances of WHO and national air quality standards occurred in almost all ASEAN capitals. Strong positive correlations were observed between Yangon and Vientiane ($r = 0.753$, $p < 0.01$), Vientiane and Bangkok ($r = 0.695$, $p < 0.01$), and Yangon and Bangkok ($r = 0.670$, $p < 0.01$), likely due to shared continental and monsoonal influences. In contrast, weaker correlations were found among maritime cities such as Jakarta, Singapore, and Kuala Lumpur because of variable sea–land circulation and tropical convection. Elevated PM2.5 concentrations during El Niño may increase respiratory and cardiovascular health risks.*
Conclusion: *PM2.5 concentrations during the 2023–2024 El Niño period exceeded WHO and national standards in most Southeast Asian capitals, highlighting the need for cross-border mitigation strategies and integrated early warning systems to protect public health.*

Keywords: *el niño, $PM_{2.5}$, public health, Southeast Asia, transboundary pollution*

ABSTRAK

Latar Belakang: Fenomena El Niño dan positive Indian Ocean Dipole (IOD) dapat mengganggu sirkulasi monsun dan meningkatkan paparan polusi udara di Asia Tenggara, khususnya PM2.5, yang berisiko terhadap kesehatan masyarakat.

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Tujuan: Penelitian ini bertujuan menganalisis paparan PM2.5 selama periode El Niño 2023–2024 serta menilai potensi risikonya terhadap kesehatan masyarakat di Asia Tenggara.
Metode: Konsentrasi harian PM2.5 di ibu kota negara-negara utama Asia Tenggara selama periode El Niño 2023–2024 dianalisis untuk menilai variasi temporal, pelampauan baku mutu WHO dan nasional, serta potensi polusi lintas batas menggunakan analisis korelasi Spearman.
Hasil: Jakarta dan Hanoi menunjukkan median harian PM2.5 tertinggi, melebihi 100 µg/m3. Namun, pelampauan baku mutu WHO dan nasional terjadi di hampir seluruh ibu kota ASEAN. Korelasi positif kuat ditemukan antara Yangon dan Vientiane ($r = 0{,}753$; $p < 0{,}01$), Vientiane dan Bangkok ($r = 0{,}695$; $p < 0{,}01$), serta Yangon dan Bangkok ($r = 0{,}670$; $p < 0{,}01$), yang dipengaruhi oleh kesamaan daratan kontinental dan sirkulasi monsun. Sebaliknya, kota maritim seperti Jakarta, Singapura, dan Kuala Lumpur menunjukkan korelasi yang lebih lemah akibat variasi sirkulasi laut-darat dan konveksi tropis. Peningkatan PM2.5 selama El Niño berpotensi meningkatkan risiko gangguan pernapasan dan kardiovaskular.
Kesimpulan: Konsentrasi PM2.5 selama periode El Niño 2023–2024 melampaui standar WHO dan nasional di sebagian besar ibu kota Asia Tenggara, sehingga diperlukan strategi mitigasi lintas batas dan sistem peringatan dini terintegrasi untuk melindungi kesehatan masyarakat.

Kata kunci: Asia Tenggara, *el niño,* kesehatan masyarakat, $PM_{2.5}$, pencemaran lintas batas

INTRODUCTION

The Asian monsoon is one of the major climate systems influencing atmospheric conditions across the region, and its variability can affect environmental conditions that are closely linked to public health.[1] In Southeast Asia, it plays a critical role in determining air quality, particularly during El Niño episodes.[2] Another ocean–atmosphere phenomenon, the Indian Ocean Dipole (IOD), can further exacerbate unfavorable atmospheric conditions. The IOD occurs when there is a contrast in sea surface temperatures across the western and eastern Indian Ocean, which modify regional weather patterns.[3,4] A positive IOD phase typically leads to drier conditions in Southeast Asia, increasing the potential for air pollutant accumulation. Among these pollutants, fine particulate matter ($PM_{2.5}$) is of particular concern because it is strongly linked to respiratory and cardiovascular health problems, especially in densely populated urban areas. During severe haze episodes, daily $PM_{2.5}$ concentrations can reach extremely high levels, ranging from approximately 78 to over 200 µg/m³, far exceeding international air quality guidelines. [5–7] Globally, exposure to ambient $PM_{2.5}$ contributed to approximately 4.9 million premature deaths in 2023 and accounts for a substantial proportion of the global disease burden related to air pollution. The health burden is particularly pronounced in low- and middle-income countries, where nearly 87% of $PM_{2.5}$-related deaths occur. Southeast Asia is among the regions experiencing high health impacts, with an estimated mortality rate of around 78 deaths per 100,000 population attributable to long-term $PM_{2.5}$ exposure.[8] Prolonged stagnant air during such events can trap pollutants for extended periods, amplifying the transboundary air pollution problem.

Emissions from transportation and industrial sectors, mainly through exhaust gases and particulates, remain the dominant sources of air pollution.[9,10] However, climate anomalies such as El Niño and positive IOD events can worsen existing air quality, posing serious implications for public health.[11] Numerous epidemiological studies have demonstrated that elevated $PM_{2.5}$ concentrations are associated with increased risks of

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hospital admissions, respiratory illnesses, cardiovascular diseases, and premature mortality.[12] Recent large-scale cohort analyses have reported that long-term exposure to $PM_{2.5}$ significantly increases the risk of cardiovascular disease and premature mortality across diverse populations worldwide.[13] Similarly, global epidemiological assessments have confirmed that even relatively low concentrations of $PM_{2.5}$ are associated with increased risks of cardiopulmonary diseases and all-cause mortality, especially for vulnerable populations.[14]

Previous studies have primarily focused on identifying emission sources, such as transportation, industrial activities, and biomass burning, during El Niño episodes, but fewer have examined how large-scale atmospheric mechanisms modify pollution dynamics. In East Asia, particularly southern China and Hong Kong, El Niño tends to weaken the East Asian monsoon and alter circulation patterns, producing wetter and windier conditions that improve air quality through enhanced dispersion and wet deposition. In contrast, El Niño has the opposite impact in Southeast Asia, where suppressed rainfall and prolonged drought intensify pollution levels. Reduced convection and weaker boundary-layer mixing limit vertical dispersion, allowing locally emitted particulates from transportation, industry, and households to accumulate near the surface. Lower humidity and stagnant air masses also slow removal processes such as wet deposition, while altered wind circulation can trap pollutants in urban basins or transport smoke plumes across borders.[15–17]

Despite these advances, integrated regional-scale evidence linking climate anomalies, PM2.5 dynamics, and public health implications across Southeast Asian cities remains limited. Most studies are city-specific or focus primarily on emission sources, with limited attention to temporal variability and transboundary pollution during extreme climate events. To address this gap, this study provides a multi-city assessment of PM2.5 dynamics during the 2023–2024 El Niño event, integrating temporal variability, exceedance analysis, and inter-city correlations. This study further aims to analyze PM2.5 exposure during El Niño events and assess its potential public health risks in Southeast Asia.

METHODS

Study design

This study employed a descriptive time-series analysis using secondary air quality data to examine the temporal dynamics of PM2.5 concentrations during the 2023–2024 El Niño period in Southeast Asia. The study period covered July 1, 2023, to May 30, 2024.

Data source and sampling procedure

Daily PM2.5 concentration data were collected from ambient air quality monitoring stations located in seven major Southeast Asian cities (Bangkok, Singapore, Hanoi, Jakarta, Yangon, Kuala Lumpur, and Vientiane). These cities were selected based on the following inclusion criteria: (1) major metropolitan areas representing key urban centers in Southeast Asia, (2) presence of substantial anthropogenic emission sources, particularly from transportation and industrial activities, and (3) availability of continuous and publicly accessible air quality monitoring data. These criteria ensured comparability across cities and representation of urban air pollution dynamics.

Air quality data were obtained from the U.S. Embassy Air Quality Monitoring Program via the World Air Quality Index platform (www.aqicn.org). The monitoring stations are located at U.S. embassy or consulate sites and use Air Quality Monitoring Systems

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(AQMS) equipped with reference-grade instruments based on U.S. Environmental Protection Agency methods. Each dataset represents a 24-hour average PM2.5 concentration (µg/m³) derived from hourly observations.

Variables of the study

The study variables included daily PM2.5 concentration (µg/m³) and monthly average PM2.5 levels. These values were also compared with reference standards, including the World Health Organization (WHO) 24-hour air quality guideline (15 µg/m³) and national ambient air quality standards of each country.

Measurement and instruments

PM2.5 concentrations were measured using Air Quality Monitoring Systems (AQMS) operated at U.S. embassy or consulate monitoring stations. These systems use reference-grade instruments aligned with U.S. EPA standards for fine particulate matter measurement.

National daily thresholds applied in this study were: 37.5 µg/m³ (Bangkok and Singapore), 50 µg/m³ (Hanoi and Vientiane), 55 µg/m³ (Jakarta), 25 µg/m³ (Yangon), and 35 µg/m³ (Kuala Lumpur).

Data collection

Daily PM2.5 data were compiled from hourly measurements. Records with incomplete daily observations were excluded. Missing data were handled using case-wise exclusion, and extreme values were verified against original monitoring records to ensure validity. Monthly averages were calculated from daily values to identify seasonal patterns across the seven cities.

Ethical considerations

This study used publicly available secondary air quality data and did not involve human subjects, personal data, or identifiable information. Therefore, formal ethical approval was not required according to institutional guidelines.

Data analysis

Descriptive statistical analysis was used to summarize daily and monthly PM2.5 concentrations and to describe temporal patterns during the study period. Spearman's rank correlation analysis was applied to assess associations between PM2.5 concentrations across the seven cities to identify potential transboundary pollution patterns and regional air pollution dynamics. Statistical significance was set at $p < 0.05$. All analyses were performed using Microsoft Excel and Minitab software licensed to Institut Teknologi Bandung, Indonesia.

RESULTS

Based on the analysis of daily $PM_{2.5}$ concentrations, substantial spatial and temporal variations were observed across seven major cities in Southeast Asia (Figure 1). Jakarta and Hanoi recorded the highest median concentrations, both exceeding 100 µg/m^3. In fact, the maximum daily $PM_{2.5}$ concentration in Hanoi reached 238 µg/m^3. This indicates very severe air pollution during the study period. In contrast, Singapore and Kuala Lumpur showed lower median concentrations (around 40–48.5 µg/m^3) and narrower IQRs. Consequently, air conditions were more stable and generally cleaner than those in other cities. Based on the analysis of monthly averages, $PM_{2.5}$ concentrations in seven major Southeast Asian cities showed strong temporal variations that are in line with monsoon dynamics during the 2023–2024 El Niño event (Figure 2).

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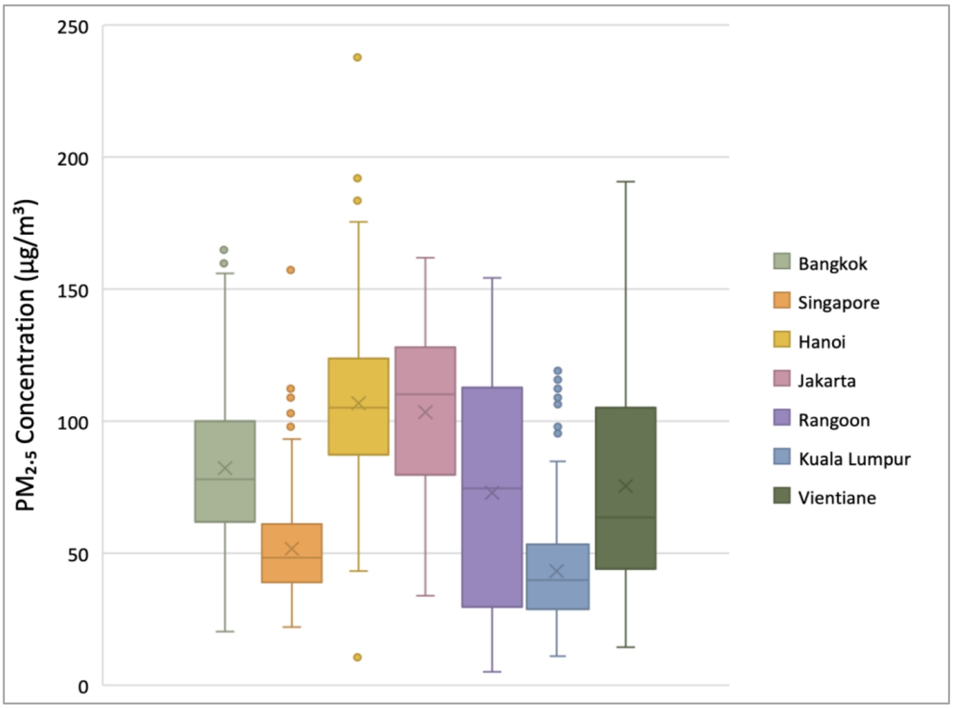

Figure 1. Daily Statistical Distribution (Boxplot) of $PM_{2.5}$ **Concentrations in Seven Southeast Asian Cities During the 2023/2024 El Niño Period**

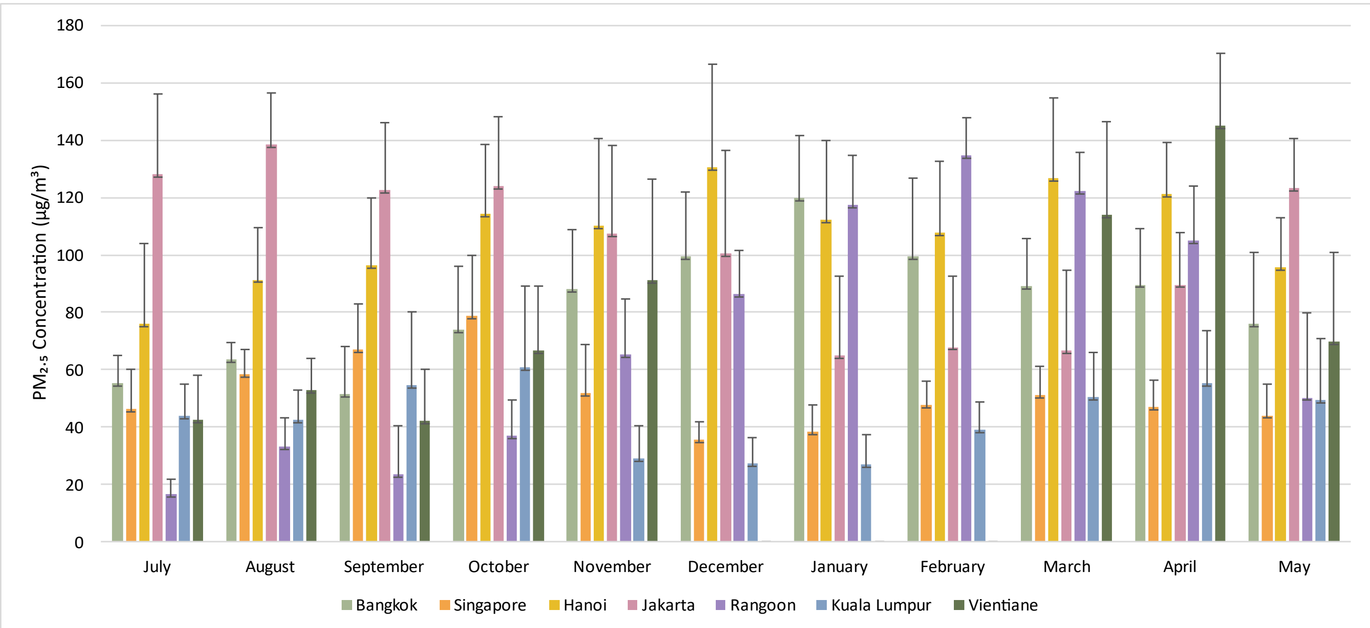

Figure 2. Monthly Variation of $PM_{2.5}$ **Concentration (±SD) in Seven Southeast Asian Cities During the 2023–2024 El Niño Event**

The frequency of days with $PM_{2.5}$ concentrations exceeding air quality thresholds indicates chronic pollution across nearly all major Southeast Asian cities (Figure 3). During the 2023–2024 El Niño period, all cities exceeded the WHO daily guideline on

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more than 90% of days, reaching 100% in Bangkok, Singapore, and Jakarta—meaning that no days met WHO standards in these cities.

Figure 4 shows the Spearman correlation between daily $PM_{2.5}$ concentrations in seven major ASEAN cities during the 2023/2024 El Niño period. Red shows a strong positive correlation, while blue indicates a weak or negative correlation. A strong positive correlation was seen between Yangon and Vientiane (r = 0.753, p < 0.01), Vientiane and Bangkok (r = 0.695, p < 0.01), and Yangon and Bangkok (r = 0.67, p < 0.01).

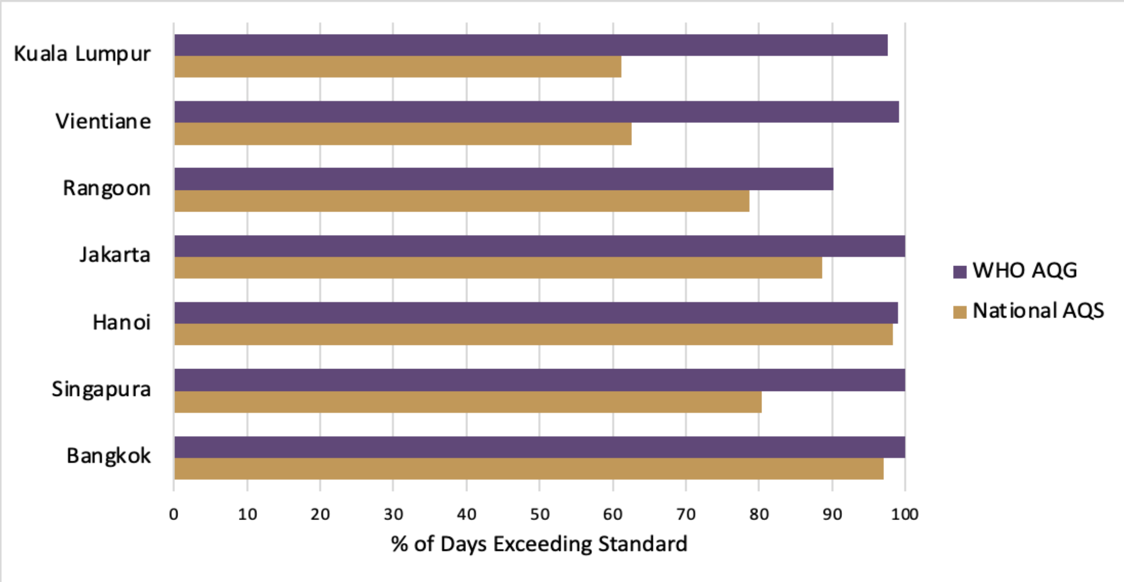
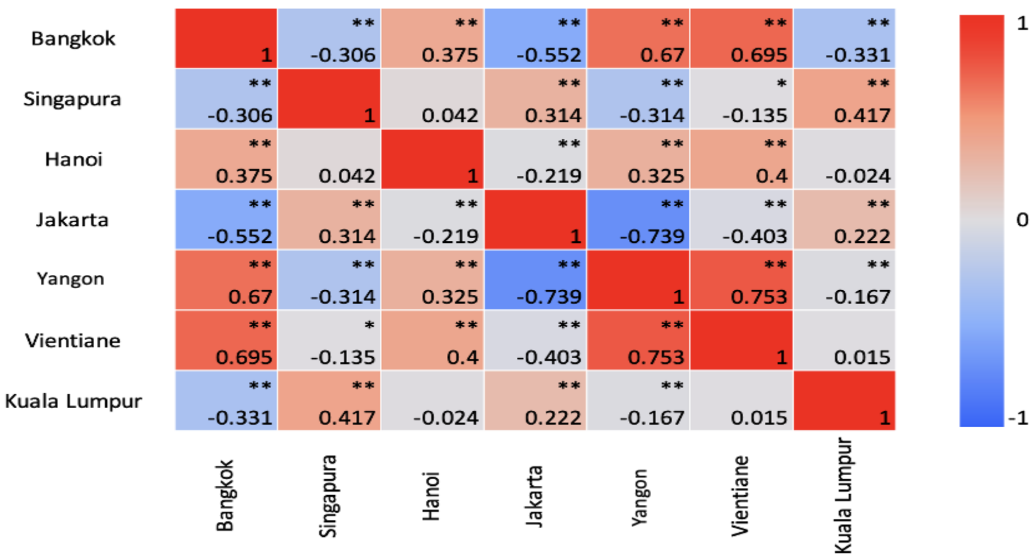


Figure 3. Percentage of Days Exceeding National and WHO $PM_{2.5}$ Standards During El Niño



	Bangkok	Singapura	Hanoi	Jakarta	Yangon	Vientiane	Kuala Lumpur
Bangkok	1	** -0.306	** 0.375	** -0.552	** 0.67	** 0.695	** -0.331
Singapura	** -0.306	1	0.042	** 0.314	** -0.314	* -0.135	** 0.417
Hanoi	** 0.375	0.042	1	** -0.219	** 0.325	** 0.4	-0.024
Jakarta	** -0.552	** 0.314	** -0.219	1	** -0.739	** -0.403	** 0.222
Yangon	** 0.67	** -0.314	** 0.325	** -0.739	1	** 0.753	** -0.167
Vientiane	** 0.695	* -0.135	** 0.4	** -0.403	** 0.753	1	0.015
Kuala Lumpur	** -0.331	** 0.417	-0.024	** 0.222	** -0.167	0.015	1

Figure 4. Spearman's correlation matrix of daily $PM_{2.5}$ concentrations among seven ASEAN cities during the 2023–2024 El Niño period. The asterisk indicates the level of statistical significance, i.e. p < 0.01 (**) and p < 0.05 (*)

DISCUSSION

During the 2023 El Niño event, anomalously higher surface temperatures and lower relative humidity were observed across parts of Southeast Asia, particularly in the

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southern region of the Indonesian Maritime Continent (IMC). Elevated temperatures can enhance photochemical reactions and secondary aerosol formation, while reduced humidity and rainfall limit wet deposition processes, allowing particulate matter to persist longer in the atmosphere and increasing potential human exposure. Reduced rainfall and drier atmospheric conditions limit the natural removal of airborne particles, allowing particulate matter to persist longer in the air and increasing potential human exposure. In contrast, cities in the northern region of the IMC, such as Kuala Lumpur and Singapore, continued to receive convective activity associated with the warming of the South China Sea, which helps disperse pollutants and maintain relatively lower $PM_{2.5}$ concentrations.[26] In addition, regional wind circulation during the El Niño period can facilitate the transport of pollutants across national boundaries, showing the influence of transboundary air pollution within the Southeast Asian region. However, in the case of Hanoi, the city is located in the Red River Delta, a region characterized by flat topography, which tends to limit natural air circulation and can promote pollutant accumulation in densely populated areas.[27] Under normal conditions, the region often experiences cold air intrusions (cold waves) from southern China during winter, which play an important role in improving atmospheric ventilation and reducing pollution buildup.[28] However, during the El Niño phase, the frequency and intensity of cold waves in East Asia, including those reaching Northern Vietnam, tend to decrease, resulting in more stagnant air in the lower atmosphere. Such stagnant atmospheric conditions can facilitate the accumulation of fine particulate matter near the surface, thereby increasing population exposure to harmful air pollution.[29]

An increase in $PM_{2.5}$ concentrations begins to be observed during the weakening phase of the southwest monsoon in August and peaks between October and December, coinciding with the maximum phase of El Niño and the transition to the northeastern monsoon.[30] During this period, air humidity decreases sharply, rainfall decreases, and atmospheric conditions become more stable, thus facilitating the accumulation of fine particles in the atmosphere.[31] Such stagnant atmospheric conditions can substantially increase population exposure to particulate pollution. Previous epidemiological studies have shown that $PM_{2.5}$ is associated with a measurable rise in hospital admissions for respiratory and cardiovascular diseases.[32] Notably, after the peak of El Niño, $PM_{2.5}$ concentrations remained high in some mainland cities such as Yangon and Vientiane until March–April. At this time, biomass burning activities from agricultural land, forests, and shrublands, reached maximum intensity in mainland Southeast Asia. Emissions from these sources can be transported over long distances under favorable meteorological conditions, contributing to elevated $PM_{2.5}$ levels in downwind urban areas and highlighting the significance of transboundary pollution in the region. The combination of dry and stable atmospheric conditions driven by monsoon dynamics and increased emissions from biomass burning resulted in persistently high $PM_{2.5}$ concentrations even after the main phase of El Niño had ended.[33]

When assessed against national air quality standards, exceedance rates remained high, particularly in Bangkok (97%), Hanoi (98%), and Jakarta (89%), suggesting that even the more lenient national limits were frequently surpassed. These proportions are considerably higher than those reported in earlier multi-year analyses, in which Southeast Asian cities recorded around 90% of days above the WHO guideline and less than 60% above national standards.[34] Frequent exceedances of air quality standards indicate that large urban populations may experience prolonged exposure to harmful particulate pollution, potentially increasing the burden of respiratory and cardiovascular diseases.[35]

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The statistical analysis using Spearman's correlation further supports the presence of regional-scale pollution dynamics. Strong and significant positive correlations were observed between Yangon–Vientiane ($r = 0.753$, $p < 0.01$), Vientiane–Bangkok ($r = 0.695$, $p < 0.01$), and Yangon–Bangkok ($r = 0.67$, $p < 0.01$), indicating that PM2.5 concentrations in these mainland Southeast Asian cities tend to increase and decrease simultaneously. This finding suggests the influence of shared meteorological conditions and transboundary pollution processes, including regional wind circulation, atmospheric boundary layer stability, and biomass burning emissions. The observed synchronization of $PM_{2.5}$ levels across several mainland cities further supports the presence of transboundary air pollution driven by regional atmospheric processes. This indicates simultaneous pollution dynamics, most likely influenced by regional meteorological factors such as wind circulation, atmospheric boundary layer stability, and cross-border smoke transport in mainland Indochina. Similar patterns of covariance have also been reported in previous El Niño events, when widespread biomass burning and stagnant air masses exacerbated haze in the Mekong subregion.[36] However, some cities located on the maritime continent, such as Jakarta, Singapore, and Kuala Lumpur, show relatively weaker $PM_{2.5}$ correlations. This can be attributed to more complex sea–land circulation patterns, local winds (sea-onshore winds), and tropical convection activity, which produce greater variability in daily pollution levels.[37]

Public Health Considerations

Although transport and industrial activities are generally recognized as the main sources of urban air pollution, these findings suggest that the patterns and intensity of $PM_{2.5}$ in Southeast Asian cities during 2023–2024 are not only controlled by local emissions, but also by regional climate anomalies. For example, in Jakarta, $PM_{2.5}$ is mostly affected by vehicle and industrial emissions (43%-46% for each sector).[38,39] Similarly, in Kuala Lumpur, $PM_{2.5}$ is largely attributed to motor vehicles (35%),[40] while dry conditions and poor ventilation during El Niño exacerbate the accumulation of pollutants. However, public transport policies, such as the Mass Rapid Transit (MRT) system, have been shown to reduce $PM_{2.5}$ concentrations and provide co-benefits for public health.[41] In comparison, Singapore's air quality is even better due to more stringent industrial emission controls and comprehensive nationally monitored vehicle pollution management.[42] These kinds of regulations are particularly important for mitigating $PM_{2.5}$ spikes during climate anomalies like El Niño.

The extreme $PM_{2.5}$ concentrations observed pose substantial risks to population health across Southeast Asia. Exposure levels exceeding thresholds have been shown to increase the likelihood of mortality, respiratory and heart-related health impacts, including worsening of asthma, stroke, chronic obstructive pulmonary disease (COPD), and ischemic heart disease.[35] These spikes in pollution disproportionately affect vulnerable populations, especially children, the elderly, and those already managing chronic illnesses.[43]

The spatial heterogeneity of pollution patterns also implies unequal health risks. The strong $PM_{2.5}$ correlations among Bangkok, Vientiane, and Yangon suggest regional haze transport over mainland Indochina, while the asynchronous patterns in other cities indicate locally driven exposure dynamics. These distinctions highlight that public health preparedness measures must be regionally tailored, reflecting both local emission sources and broader atmospheric behavior. Although ASEAN has made efforts to adjust its institutional mechanisms through gradual changes and initiatives such as the Haze-Free Roadmap,[44] additional mitigation policies are needed, particularly in anticipation of

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El Niño episodes and other monsoon events, such as positive IOD, that can affect air quality.

To mitigate future health impacts, urgent action is needed to shift towards preventive, climate-informed public health strategies. Key steps include strengthening collaboration among environmental, meteorological, and health authorities, as well as integrating real-time air quality data into health systems. Evidence from previous studies shows that early warning systems combining air quality monitoring and meteorological forecasting can significantly reduce exposure and health risks, particularly among vulnerable populations (e.g., elderly and children).[45]

In a broader policy context, the findings of this study emphasize the need to integrate air quality management with climate adaptation frameworks in Southeast Asia. Since El Niño and IOD episodes are recurring features of the regional climate system, their combined influence on air pollution must be explicitly considered in health and environmental planning. National and city-level policies should prioritize not only emission reductions but also enhancing adaptive capacity. For instance, integrated policies that combine emission control with climate adaptation (such as cleaner energy transitions and climate-resilient urban planning) have demonstrated measurable reductions in $PM_{2.5}$-related health burdens.[46] This approach will ensure that public health systems are better equipped to anticipate and mitigate the health impacts of climate-driven pollution extremes. Ultimately, reducing health risks from $PM_{2.5}$ in an era of intensified climate variability requires an integrated, evidence-based approach that bridges environmental science, public health, and climate policy.

This study has limitations that should be acknowledged. The observations were limited to major urban centers, representing city-level exposure rather than the broader regional or rural conditions. Consequently, the results may not fully capture intra-urban variability or population exposure in suburban and peri-urban areas. Future studies should integrate higher-resolution ground and satellite observations to better represent spatial disparities and strengthen the linkage between atmospheric dynamics and health outcomes across Southeast Asia.

CONCLUSION

The cities of Jakarta and Hanoi recorded the highest median concentrations, exceeding 100 µg/m^3, indicating very severe levels of air pollution. Temporally, $PM_{2.5}$ concentrations increase from August, reaching a peak in October–December during the maximum phase of El Niño and the transition to the northeastern monsoon. Even after the peak of El Niño, some mainland cities such as Vientiane and Yangon still recorded high concentrations through March-April due to widespread biomass burning in the dry season.

Most cities show very high levels of exceedance of the WHO threshold, with some such as Bangkok, Jakarta, and Singapore recording 100% days exceeding safe limits. The strong correlation between Bangkok, Yangon, and Vientiane shows the dynamics of cross-border pollution in mainland Indochina, while maritime cities are more influenced by local circulation and tropical convection.

In terms of public health, exposure to this extreme $PM_{2.5}$ risks increasing cases of respiratory and cardiovascular diseases such as asthma, COPD, stroke, and ischemic heart disease, especially in children, the elderly, and people with chronic diseases. Therefore, emission control and climate adaptation policies must be strengthened. The integration between air quality management and climate adaptation planning is essential, including cross-sectoral collaboration between environmental, meteorological and health agencies. An evidence-based approach that combines atmospheric science, public

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health, and climate policy is key to reducing health risks from $PM_{2.5}$ amid increasing regional climate variability.

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REFERENCES

1. Payus CM, Syazni MSN, Sentian J. Extended air pollution index (API) as tool of sustainable indicator in the air quality assessment: El-Nino events with climate change driven. *Heliyon*. 2022;8(3). https://doi.org/10.1016/j.heliyon.2022.e09157
2. Nguyen LSP, Chang JHW, Griffith SM, et al. Trans-boundary air pollution in a Southeast Asian megacity: Case studies of the synoptic meteorological mechanisms and impacts on air quality. *Atmos Pollut Res*. 2022;13(4):101366. https://doi.org/10.1016/j.apr.2022.101366
3. Fan Y, Li J, Zhu S, Li H, Zhou B. Trends and variabilities of precipitation and temperature extremes over Southeast Asia during 1981–2017. *Meteorology and Atmospheric Physics*. 2022;134(4):78. https://doi.org/10.1007/s00703-022-00913-6
4. Nurdiati S, Sopaheluwakan A, Septiawan P. Joint pattern analysis of forest fire and drought indicators in Southeast Asia associated with ENSO and IOD. *Atmosphere (Basel)*. 2022;13(8):1198. https://doi.org/10.3390/atmos13081198
5. Alahmad B, Khraishah H, Althalji K, Borchert W, Al-Mulla F, Koutrakis P. Connections between air pollution, climate change, and cardiovascular health. *Canadian Journal of Cardiology*. 2023;39(9):1182-1190. https://doi.org/10.1016/j.cjca.2023.03.025
6. Ustinaviciene R, Venclovienė J, Luksiene D, et al. Impact of Ambient Air Pollution with $PM_{2.5}$ on Stroke Occurrence: Data from Kaunas (Lithuania) Stroke Register (2010–2022). *Atmosphere (Basel)*. 2024;15(11):1327. https://doi.org/10.3390/atmos15111327
7. Othman M, Latif MT, Hamid, HHA, Uning R, Khumsaeng T, Phairuang W, Lung SCC. Spatial–temporal variability and health impact of particulate matter during a 2019–2020 biomass burning event in Southeast Asia. *Scientific reports*. 2022;12(1): 7630. https://doi.org/10.1038/s41598-022-11409-z
8. Health Effects Institute. *State of Global Air 2025. A Report on Air Pollution and Its Role in the World's Leading Causes of Death*. 2025. https://www.stateofglobalair.org/resources/report/state-global-air-report-2025
9. Bikis A. Urban air pollution and greenness in relation to public health. *J Environ Public Health*. 2023;2023(1):8516622. https://doi.org/10.1155/2023/8516622
10. Lestari P, Arrohman MK, Damayanti S, Klimont Z. Emissions and spatial distribution of air pollutants from anthropogenic sources in Jakarta. *Atmos Pollut Res*. 2022;13(9):101521. https://doi.org/10.1016/j.apr.2022.101521
11. Haines A, Lam HCY. El Niño and health in an era of unprecedented climate change. *The Lancet*. 2023;402(10415):1811-1813. https://doi.org/10.1016/s0140-6736(23)01664-1
12. Sharma S, Chandra M, Kota SH. Health effects associated with $PM_{2.5}$: A systematic review. *Curr Pollut Rep*. 2020;6(4):345-367. https://doi.org/10.1007/s40726-020-00155-3
13. Burnett R, Chen H, Szyszkowicz M, et al. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences*. 2018;115(38):9592-9597. https://doi.org/10.1021/acs.est.0c01764.s001
14. Cohen AJ, Brauer M, Burnett R, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The lancet*. 2017;389(10082):1907-1918. https://doi.org/10.1289/isee.2014.o-308

https://doi.org/10.34011/juriskesbdg.v18i1.3252

Vol 18 No 1, Mei 2026
e-ISSN: 2579-8103
p-ISSN:1979-8253

15. Yim SHL, Hou X, Guo J, Yang Y. Contribution of local emissions and transboundary air pollution to air quality in Hong Kong during El Niño-Southern Oscillation and heatwaves. *Atmos Res*. 2019;218:50-58. https://doi.org/10.1016/j.atmosres.2018.10.021
16. Lee BPYH, Davies ZG, Struebig MJ. Smoke pollution disrupted biodiversity during the 2015 El Niño fires in Southeast Asia. *Environmental Research Letters*. 2017;12(9):94022. https://doi.org/10.1088/1748-9326/aa87ed
17. Hayasaka H, Sepriando A. Severe air pollution due to peat fires during 2015 super El Niño in Central Kalimantan, Indonesia. *Land-atmospheric research applications in South and Southeast Asia*. Published online 2018:129-142. https://doi.org/10.1007/978-3-319-67474-2_7
18. UNOCHA. *Asia and the Pacific: El Niño in Review (2023-2024)* . 2024. https://www.unocha.org/publications/report/afghanistan/asia-and-pacific-el-nino-review-2023-2024-10-may-2024
19. Abdullah S, Mansor AA, Napi NNLM, et al. Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. *Sci Total Environ*. 2020;729:139022. https://doi.org/10.1016/j.scitotenv.2020.139022
20. Laoin P. Ministry monitoring air quality as pollution levels rise. Vientiane Times; 2020. Available from: https://www.vientianetimes.org.la/freeContent/FreeConten_Ministry_32.php
21. Dominutti, X Mari, JL Jaffrezo, VTN Dinh, S Chifflet, C Guigue, L Guyomarc'h, CT Vu. Disentangling fine particles (PM2.5) composition in Hanoi, Vietnam: Emission sources and oxidative potential Science of the Total Environment, 2024. Sci Total Environ. 2024;923: 171466. https://doi.org/10.1016/j.scitotenv.2024.171466
22. Vongruang P, Suppoung K, Kirtsaeng S, Prueksakorn K, Thao PTB, Pimonsree S. Development of meteorological criteria for classifying PM2.5 risk in a coastal industrial province in Thailand. Aerosol Air Qual Res. 2024;24(10):230321. https://doi.org/10.4209/aaqr.230321
23. PP No.22. Peraturan Pemerintah Republik Indonesia Nomor 22 tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup. Kementerian Sekretariat Negara Republik Indonesia; 2021. Available from: https://peraturan.bpk.go.id/Details/161852/pp-no-22-tahun-2021
24. Myanmar Govenrment. Myanmar National Environmental Quality (Emission) Guideliness. 2015. https://www.myanmar-responsiblebusiness.org/pdf/2015-12-29-National-Environmental-Quality_Emission_Guidelines_en.pdf
25. MSE Singapore. Clean Air | Ministry of Sustainability and the Environment. 2025. https://www.mse.gov.sg/policies/clean-air/
26. Zehri S, Yulihastin E, Marpaung F, et al. Diverse impact of 2023 El Niño on weather patterns over the Indonesian Maritime Continent. *Journal of Southern Hemisphere Earth Systems Science* . 2025;75(2). https://doi.org/10.1071/es25005
27. Nguyen THH, Wang G, Chen W, et al. Risk Assessment and Management Strategy of Coastal Erosion in the Red River Delta, Vietnam. *Land 2025, Vol 14, Page 1247*. 2025;14(6):1247. https://doi.org/10.3390/land14061247
28. Abdillah MR, Kanno Y, Iwasaki T, Matsumoto J. Cold surge pathways in east Asia and their tropical impacts. *J Clim*. 2021;34(1):157-170. https://doi.org/10.1175/jcli-d-20-0552.1
29. Nguyen DN. Effects of ENSO on cold - air activities and tropical cyclones in Vietnam. *Vietnam Journal of Science, Technology and Engineering*. 2017;59(2):88-91. https://doi.org/10.31276/vjste.59(2).88

https://doi.org/10.34011/juriskesbdg.v18i1.3252

Vol 18 No 1, Mei 2026
e-ISSN: 2579-8103
p-ISSN:1979-8253

30. Naidin S, Sentian J, Adnan FAF, Herman F, Mohd Hashim SR. Decade-Long Analysis: Unravelling the Spatio-Temporal Dynamics of PM10 Concentrations in Malaysian Borneo. *Aerosol Air Qual Res*. 2024;24(2):230176. https://doi.org/10.4209/aaqr.230176
31. Hassan Bran S, Macatangay R, Chotamonsak C, Chantara S, Surapipith V. Understanding the seasonal dynamics of surface $PM_{2.5}$ mass distribution and source contributions over Thailand. *Atmos Environ*. 2024;331:120613. https://doi.org/10.1016/j.atmosenv.2024.120613
32. Atkinson RW, Kang S, Anderson HR, Mills IC, Walton HA. Epidemiological time series studies of $PM_{2.5}$ and daily mortality and hospital admissions: a systematic review and meta-analysis. *Thorax*. 2014;69(7):660-665. https://doi.org/10.1289/isee.2016.3648
33. Yin S, Wang X, Zhang X, Guo M, Miura M, Xiao Y. Influence of biomass burning on local air pollution in mainland Southeast Asia from 2001 to 2016. *Environmental Pollution*. 2019;254:112949. https://doi.org/10.1016/j.envpol.2019.07.117
34. Wasi'ah NR, Iriana W, Qonita S. IOP Conference Series: Earth and Environmental Science Comparison of Fine Particulate Matter ($PM_{2.5}$) in Urban Areas Southeast Asia in Compliance with WHO Guidelines. In: 2025. https://doi.org/10.1088/1755-1315/1448/1/012009
35. Wan Mahiyuddin WR, Ismail R, Mohammad Sham N, Ahmad NI, Nik Hassan NMN. Cardiovascular and respiratory health effects of fine particulate matters ($PM_{2.5}$): a review on time series studies. *Atmosphere (Basel)*. 2023;14(5):856. https://doi.org/10.3390/atmos14050856
36. Nguyen HD, Bang HQ, Quan NH, Quang NX, Duong TA. Effect of Biomass Burnings on Population Exposure and Health Impact at the End of 2019 Dry Season in Southeast Asia. *Atmosphere 2024, Vol 15, Page 1280*. 2024;15(11):1280. https://doi.org/10.20944/preprints202407.1425.v1
37. Wei Y, Pu Z. Diurnal cycle of precipitation and near-surface atmospheric conditions over the maritime continent: land–sea contrast and impacts of ambient winds in cloud-permitting simulations. *Clim Dyn*. 2022;58(9):2421-2449. https://doi.org/10.1007/s00382-021-06012-3
38. Lestari P, Arrohman MK, Damayanti S, Klimont Z. Emissions and spatial distribution of air pollutants from anthropogenic sources in Jakarta. *Atmos Pollut Res*. 2022;13(9):101521. https://doi.org/10.1016/j.apr.2022.101521
39. Lestari P, Damayanti S, Arrohman MK. Emission Inventory of Pollutants (CO, SO_2, $PM_{2.5}$, and NO_X) In Jakarta Indonesia. *IOP Conf Ser Earth Environ Sci*. 2020;489(1):012014. https://doi.org/10.1088/1755-1315/489/1/012014
40. Rahman SA, Hamzah MS, Elias MS, et al. A long term study on characterization and source apportionment of particulate pollution in Klang Valley, Kuala Lumpur. *Aerosol Air Qual Res*. 2015;15(6):2291-2304. https://doi.org/10.4209/aaqr.2015.03.0188
41. Kwan SC, Tainio M, Woodcock J, Hashim JH. Health co-benefits in mortality avoidance from implementation of the mass rapid transit (MRT) system in Kuala Lumpur, Malaysia. *Rev Environ Health*. 2016;31(1):179-183. https://doi.org/10.1515/reveh-2015-0038
42. Molina LT, Velasco E, Retama A, Zavala M. Experience from Integrated Air Quality Management in the Mexico City Metropolitan Area and Singapore. *Atmosphere 2019, Vol 10, Page 512*. 2019;10(9):512. https://doi.org/10.3390/atmos10090512
43. Amnuaylojaroen T, Parasin N. Pathogenesis of $PM_{2.5}$-related disorders in different age groups: children, adults, and the elderly. *Epigenomes*. 2024;8(2):13. https://doi.org/10.3390/epigenomes8020013

https://doi.org/10.34011/juriskesbdg.v18i1.3252

Vol 18 No 1, Mei 2026
e-ISSN: 2579-8103
p-ISSN:1979-8253

44. Charusombat P. ASEAN cooperation on transboundary haze pollution: The perspective of institutional incremental change. *Journal of Environmental Information Science*. 2023;2022(2):1-12. https://doi.org/10.11492/ceispapersen.2022.2_1
45. Landrigan P J, Fuller , Acosta NJ, Adeyi O, Arnold R, Baldé AB, Zhong M. The Lancet Commission on pollution and health. *The lancet*. 2018; 391(10119), 462-512 https://doi.org/10.1016/s0140-6736(17)32345-0
46. Lelieveld J, Klingmüller K, Pozzer A, Burnett RT, Haines A, Ramanathan,V. Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences*. 2019; 116(15), 7192-7197. https://doi.org/10.1073/pnas.1819989116