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Spatial and Temporal Variability of $PM_{2.5}$ and PM_{10} in Malaysia: A Comparative Analysis of Selangor and Kelantan (2021–2023)

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ABSTRACT

Particulate matter (PM_{10} and $PM_{2.5}$) remains a critical air quality and public health concern in Malaysia, yet recent comparative analyses across states with contrasting development profiles remain limited. This study examines the spatial and temporal variability of PM concentrations in Selangor and Kelantan from 2021 to 2023, representing highly urbanised-industrial and less-developed regions, respectively. Secondary daily data from seven Continuous Ambient Air Quality Monitoring Stations were analysed using descriptive statistics, non-parametric tests, and compliance assessment against Malaysian Ambient Air Quality Standards (MAAQS 2020) and World Health Organization (WHO 2021) guidelines. Results indicate that Selangor consistently recorded higher mean concentrations than Kelantan, with PM_{10} and $PM_{2.5}$ levels approximately 17% and 36% greater, respectively. A notable post-pandemic increase in pollution was observed in 2023, with sharper rises in Kelantan, suggesting greater responsiveness to episodic emission influences. Both states exhibited a high $PM_{2.5}/PM_{10}$ ratio (~0.7), indicating a substantial contribution of fine particles, commonly associated with combustion-related processes across differing regional contexts. While all stations complied with national PM_{10} limits, approximately 90% exceeded the $PM_{2.5}$ standard, and universal non-compliance was observed against WHO guidelines, highlighting potential public health concerns. These findings suggest that fine particulate pollution is a pervasive issue across both developed and less-developed regions, likely influenced by combustion-related sources rather than solely by urban-industrial intensity. The study highlights a critical regulatory gap in current air quality management and underscores the need for consideration of stricter $PM_{2.5}$ control strategies, enhanced monitoring coverage, and closer alignment with health-based international standards.

1. Introduction

Air pollution remains one of the most pressing environmental and public health challenges globally [1,2] with particulate matter (PM), particularly fine particles ($PM_{2.5}$), recognised as a major contributor to premature mortality and morbidity. Due to their small aerodynamic diameter, $PM_{2.5}$ particles can penetrate deep into the respiratory system and enter the bloodstream leading to

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cardiovascular and respiratory diseases, as consistently reported in epidemiological studies, particularly in relation to long-term exposure to fine particulate matter [3]. Coarser particles (PM_{10}), while less penetrative, are also associated with adverse health outcomes, particularly affecting the upper respiratory tract and contributing to chronic respiratory conditions [4]. The growing body of evidence linking particulate pollution to adverse health outcomes underscores the need for effective monitoring and regulatory control [5].

In Malaysia, rapid urbanisation, industrialisation, and increasing vehicular emissions have significantly influenced ambient air quality [6,7], particularly in urban-industrial regions. Selangor, located within the Klang Valley, represents one of the most developed and densely populated regions in the country, characterised by high traffic density, industrial activities, and continuous urban expansion [8]. In contrast, Kelantan, situated on the east coast of Peninsular Malaysia, is generally less industrialised and exhibits more rural land use characteristics, despite the presence of urban centres such as Kota Bharu [9]. This contrast provides an important opportunity to examine how differing development intensities and land use patterns influence particulate matter concentrations across regions.

Malaysia's air quality management is guided by the Malaysian Ambient Air Quality Standards (MAAQS), which establish permissible limits for key pollutants, including PM_{10} and $PM_{2.5}$. However, these national standards are less stringent compared to the World Health Organization (WHO) [10,11] Air Quality Guidelines, raising concerns regarding their adequacy in protecting public health. Previous studies have indicated that particulate matter concentrations in Malaysia frequently exceed recommended health-based thresholds, particularly during pollution episodes such as transboundary haze and dry seasonal conditions [8,12]. Moreover, $PM_{2.5}$ has been identified as a dominant contributor to air pollution exposure in urban environments, with strong associations to combustion-related sources such as vehicular emissions and biomass burning [5].

Particulate matter concentrations in Malaysia are influenced by a combination of local emission sources and regional atmospheric processes [6,13]. Localised factors such as traffic density, industrial emissions, and domestic activities contribute to elevated pollution levels, particularly in urban-industrial areas [14]. At the same time, meteorological conditions, including monsoon cycles, rainfall patterns, and wind dynamics, play a significant role in the dispersion and accumulation of pollutants [8]. Seasonal variations are especially pronounced, with higher concentrations often observed during the Southwest Monsoon due to drier conditions and increased transboundary haze from biomass burning in neighbouring regions [12].

Despite extensive monitoring by the Department of Environment (DOE) through the Continuous Ambient Air Quality Monitoring System (CAQMS), existing research has largely focused on single locations, short-term analyses, or specific pollution events. Comparative, multi-year studies that examine spatial and temporal variations across states with differing socio-economic and land use characteristics remain limited [4]. In particular, there is a lack of recent studies integrating post-pandemic air quality dynamics, where changes in human activity patterns may have influenced pollution trends. Furthermore, limited attention has been given to evaluating particulate matter levels against both national and international standards to assess the extent of regulatory adequacy and potential public health implications.

This study addresses these gaps by investigating the spatial and temporal variability of PM_{10} and $PM_{2.5}$ concentrations in Selangor and Kelantan over a three-year period (2021–2023), using data obtained from the DOE's CAQMS network. By comparing a highly urbanised-industrial state with a less-developed counterpart, this research aims to provide a clearer understanding of how land use, development intensity, and temporal factors shape particulate pollution patterns. In addition, the study evaluates compliance with MAAQS and WHO guidelines to assess the effectiveness of current regulatory frameworks.

The findings are expected to contribute to the growing body of knowledge on air quality in Malaysia by highlighting the dominance of fine particulate matter across different regional contexts and identifying critical gaps in current air quality management strategies. More importantly, this study provides evidence to support the need for stricter $PM_{2.5}$ control measures, improved monitoring coverage, and greater alignment with health-based international standards.

2. Methodology

2.1 Study Area

This study focuses on two states in Peninsular Malaysia, Selangor and Kelantan, selected to represent contrasting levels of urbanisation, industrialisation, and land use characteristics. Selangor, located within the Klang Valley on the west coast, is one of the most economically developed regions in Malaysia, characterised by dense population, extensive industrial activities, and high traffic volume [8]. In contrast, Kelantan, situated on the east coast, is relatively less industrialised, with a higher proportion of rural land use despite the presence of urban centres such as Kota Bharu [9]. This contrast enables a comparative assessment of particulate pollution under differing socio-economic and environmental conditions.

2.2 Data Source and Study Period

Secondary air quality data were obtained from the Department of Environment (DOE) Malaysia through the Continuous Ambient Air Quality Monitoring System (CAQMS), which provides validated daily measurements of key pollutants. The dataset comprised daily concentrations of PM_{10} and $PM_{2.5}$ from January 2021 to December 2023, covering a three-year period that captures recent air quality trends, including post-pandemic recovery phases.

2.3 Monitoring Stations and Land Use Classification

A total of seven monitoring stations were selected based on data availability, completeness, and representation of different land use categories. Five stations were located in Selangor and two in Kelantan. The stations were classified according to DOE land use categories, including urban, suburban, and industrial environments. This classification allows for the assessment of spatial variation in particulate matter concentrations across different environmental settings.

2.4 Data Preprocessing and Quality Control

The dataset underwent a structured preprocessing procedure to ensure reliability and consistency. As the data were sourced from DOE's CAQMS network, initial quality assurance and quality control (QA/QC) procedures, including instrument calibration and validation, had already been implemented. Additional screening was conducted to address missing values, invalid measurements, and outliers.

To ensure representativeness, monthly averages were calculated only when data completeness exceeded 75%, in line with standard practices for air quality time series analysis [15]. Extreme values identified through the interquartile range (IQR) method were retained when associated with real environmental events such as haze episodes, as these represent genuine pollution conditions rather than measurement errors. Overall data completeness exceeded 99%, ensuring robustness of the dataset.

2.5 Statistical Analysis

Data analysis was performed using a combination of descriptive and inferential statistical methods.

2.5.1 Descriptive analysis

Summary statistics, including mean, median, standard deviation, minimum, and maximum values, were calculated for PM_{10} and $PM_{2.5}$ concentrations at daily, monthly, and annual levels. These metrics provide an overall characterisation of particulate matter concentrations across the study area.

2.5.2 Temporal trend analysis

Temporal variations were assessed using annual and seasonal comparisons. Trends over the study period were evaluated to identify changes in pollution levels, including potential post-pandemic effects. Seasonal variability was analysed in relation to Malaysia's monsoon cycles, which influence pollutant dispersion and accumulation [8,14].

2.5.3 Spatial and comparative analysis

Spatial differences in particulate matter concentrations between Selangor and Kelantan were assessed using non-parametric statistical tests due to deviations from normality in the dataset. The Mann–Whitney U test was applied to compare inter-state differences, while the Kruskal–Wallis test was used to evaluate variations across land use categories. These methods are appropriate for environmental datasets that do not meet parametric assumptions [16].

2.5.4 $PM_{2.5}/PM_{10}$ ratio analysis

The ratio of $PM_{2.5}$ to PM_{10} was calculated to assess the relative contribution of fine particles to total particulate matter. This indicator provides insights into dominant emission sources, with higher ratios typically associated with combustion-related processes [5].

2.5.5 Compliance assessment

Compliance with air quality standards was evaluated by comparing annual mean concentrations against the Malaysian Ambient Air Quality Standards (MAAQS 2020) and the World Health Organization (WHO 2021) Air Quality Guidelines. This assessment enables evaluation of both regulatory compliance and potential public health implications.

3. Results

3.1 Overview of Particulate Matter Concentrations

Particulate matter concentrations exhibited clear spatial variation between Selangor and Kelantan over the study period (2021–2023). As summarised in Table 1, Selangor consistently recorded higher mean concentrations for both PM_{10} (52.3 µg/m³) and $PM_{2.5}$ (36.4 µg/m³) compared to Kelantan (44.7 µg/m³ and 26.8 µg/m³, respectively). This represents approximately 17% higher PM_{10} and 36% higher $PM_{2.5}$ concentrations in Selangor, reflecting the influence of urbanisation, industrial activities, and traffic emissions [6,7].

Table 1
Descriptive statistics of PM_{10} and $PM_{2.5}$

State	Pollutant	Mean (µg/m³)	Median (µg/m³)	Min (µg/m³)	Max (µg/m³)	SD
Selangor	PM_{10}	52.3	50.1	18.0	142.0	21.5
Selangor	$PM_{2.5}$	36.4	34.8	10.5	98.2	15.7
Kelantan	PM_{10}	44.7	42.9	15.2	121.6	19.3
Kelantan	$PM_{2.5}$	26.8	25.4	8.1	76.5	13.2

The distribution of mean concentrations is further illustrated in Figure 1, which shows a consistent elevation in particulate levels across Selangor relative to Kelantan. In addition to higher mean values, Selangor also recorded greater maximum concentrations (Table 1), indicating more intense pollution episodes, particularly in industrialised areas.

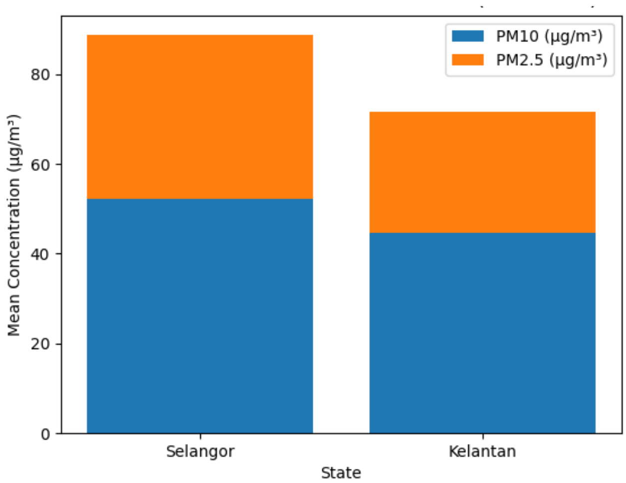

Fig. 1. Mean concentrations of PM_{10} and $PM_{2.5}$ in Selangor and Kelantan

3.2 Dominance of Fine Particulate Matter

The ratio of $PM_{2.5}$ to PM_{10} provides insight into the relative contribution of fine particles. As presented in Table 2, both states exhibited consistently high ratios, with mean values of 0.70 in Selangor and 0.72 in Kelantan. These results indicate that fine particles accounted for approximately 70% of total particulate matter in both regions.

Table 2
$PM_{2.5}/PM_{10}$ Ratio

State	Mean Ratio	Interpretation
Selangor	0.70	High contribution of fine particles
Kelantan	0.72	High contribution of fine particles

Despite substantial differences in development intensity, the similarity in ratios suggests that fine particulate pollution is a widespread regional issue rather than being confined to highly urbanised areas. This pattern suggests the influence of combustion-related sources [5], including vehicular emissions and biomass burning, across both states.

3.3 Temporal Trends and Post-Pandemic Rebound

Temporal analysis revealed notable changes in particulate matter concentrations over the study period. As shown in Table 3, both states experienced relatively stable or slightly declining concentrations between 2021 and 2022, followed by a marked increase in 2023.

Table 3
Annual mean concentrations and percentage change

State	Year	PM_{10} (μg/m³)	% Change	$PM_{2.5}$ (μg/m³)	% Change
Selangor	2021	50.2	–	34.8	–
	2022	49.1	-2.2%	33.5	-3.7%
	2023	55.2	+12.5%	36.9	+10.1%
Kelantan	2021	42.3	–	25.1	–
	2022	41.5	-1.9%	24.5	-2.4%
	2023	48.6	+17.1%	29.4	+20.0%

In Selangor, PM_{10} increased from 49.1 μg/m³ in 2022 to 55.2 μg/m³ in 2023 (+12.5%), while $PM_{2.5}$ rose from 33.5 μg/m³ to 36.9 μg/m³ (+10.1%). In contrast, Kelantan exhibited sharper increases, with PM_{10} rising from 41.5 μg/m³ to 48.6 μg/m³ (+17.1%) and $PM_{2.5}$ from 24.5 μg/m³ to 29.4 μg/m³ (+20.0%).

The steeper increase observed in Kelantan suggests greater responsiveness to episodic emission influences and environmental variability. Overall, the upward trend in 2023 is consistent with a post-pandemic rebound in anthropogenic activities [14], including transportation and economic operations.

3.4 Seasonal Variability and Monsoon Influence

Seasonal patterns of particulate matter concentrations are presented in Figure 2, which demonstrates clear variability aligned with Malaysia's monsoon cycles. Lower concentrations were consistently observed during the Northeast Monsoon (November–March), likely due to increased rainfall and enhanced pollutant removal through wet deposition.

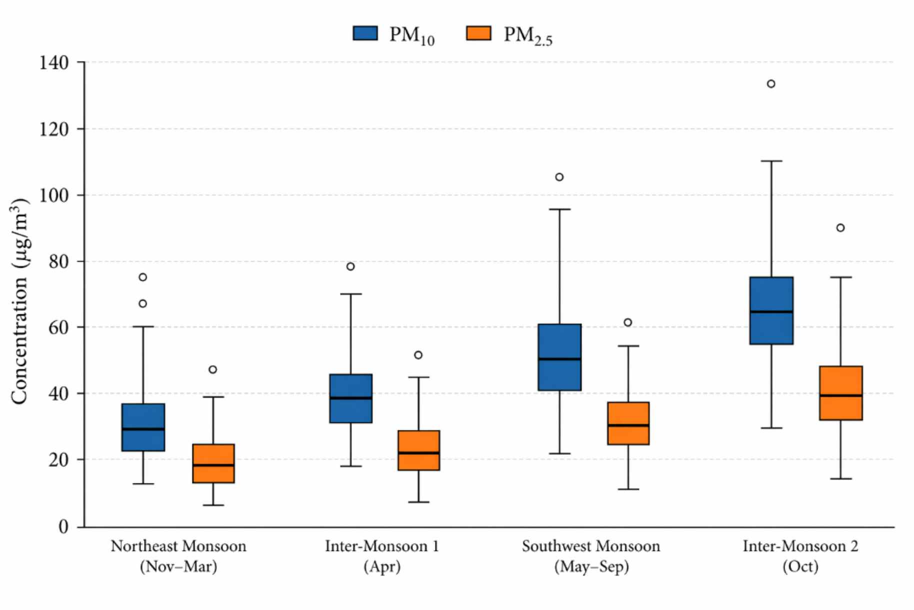

Fig. 2. Seasonal variation of PM_{10} and $PM_{2.5}$ concentrations across monsoon periods

Conversely, higher concentrations were recorded during the Southwest Monsoon (May–September) and inter-monsoon periods, characterised by drier conditions and reduced atmospheric dispersion. Peak concentrations were observed during inter-monsoon months, particularly in October 2023, coinciding with regional haze events.

These findings highlight the significant influence of meteorological conditions on air quality [6,13], with predictable seasonal peaks indicating potential windows for targeted intervention strategies.

3.5 Spatial Variation and Interstate Differences

Statistical comparisons between states, as presented in Table 4, confirmed significant differences in particulate matter concentrations. The Mann–Whitney U test indicated that Selangor had significantly higher PM_{10} ($p = 0.003$) and $PM_{2.5}$ ($p = 0.034$) concentrations compared to Kelantan.

The stronger statistical significance observed for PM_{10} suggests that coarse particulate matter is more sensitive to spatial factors such as urbanisation and industrial activity. In contrast, $PM_{2.5}$ exhibited less pronounced spatial differentiation, supporting the earlier observation that fine particulate matter is influenced by broader regional processes rather than localised sources alone.

Table 4
Statistical comparison between states

Pollutant	Test Used	p-value	Interpretation
PM_{10}	Mann–Whitney U	0.003	Significant difference
$PM_{2.5}$	Mann–Whitney U	0.034	Significant difference

3.6 Influence of Land Use

The influence of land use on particulate matter concentrations was examined across urban, suburban, and industrial categories. Descriptive patterns indicated that industrial areas recorded the highest mean concentrations, followed by urban and suburban areas for $PM_{2.5}$, while PM_{10} showed a similar but less distinct gradient.

However, statistical analysis using the Kruskal–Wallis test did not reveal significant differences across land use categories. This may be attributed to the limited number of monitoring stations within each category, which reduces statistical power. Nevertheless, the observed trends remain consistent with expected emission patterns, where industrial and traffic-related activities contribute to elevated particulate levels.

3.7 Identification of Pollution Hotspots

Station-level analysis identified distinct pollution hotspots within the study area. The Klang monitoring station (CA21B), representing an industrial setting, recorded the highest mean concentrations for both PM_{10} and $PM_{2.5}$ across the study period. This is consistent with its proximity to industrial zones, port activities, and high traffic density.

In contrast, suburban stations such as Kuala Selangor recorded the lowest concentrations. Notably, even lower-intensity areas in Selangor exhibited higher pollution levels than some sites in Kelantan, suggesting that regional development intensity exerts a stronger influence on air quality than local land use classification alone.

3.8 Compliance with Air Quality Standards

Compliance with air quality standards is illustrated in Figure 3. All monitoring stations met the Malaysian Ambient Air Quality Standards (MAAQS 2020) for PM_{10}, indicating effective control of coarse particulate matter.

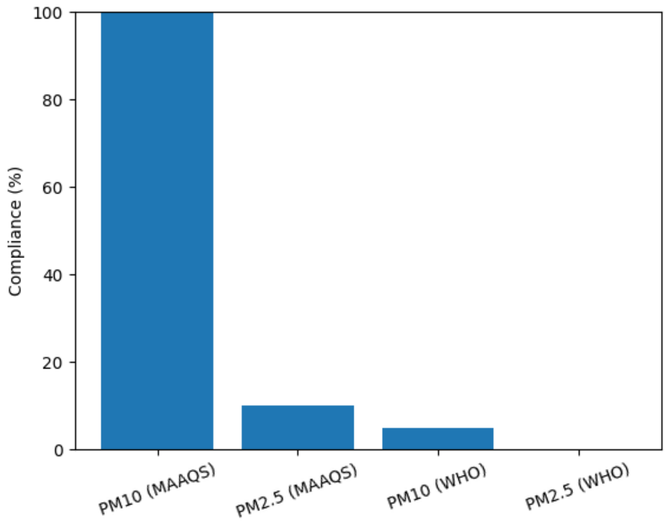

Fig. 3. Compliance status of PM_{10} and $PM_{2.5}$ concentrations against MAAQS and WHO guidelines

In contrast, $PM_{2.5}$ showed substantial non-compliance, with approximately 90% of observations exceeding the national standard. The situation is more critical when evaluated against WHO (2021) guidelines, where all stations exceeded the $PM_{2.5}$ limit and the majority exceeded PM_{10} thresholds.

This divergence highlights a critical gap between regulatory compliance and health-based standards, suggesting that current national limits may not adequately protect public health, particularly in relation to fine particulate exposure.

3.9 Interstate Disparities and the Role of Urbanisation

This study demonstrates clear interstate disparities in particulate matter concentrations, with Selangor consistently exhibiting higher levels of PM_{10} and $PM_{2.5}$ compared to Kelantan. This finding aligns with previous studies that associate elevated particulate concentrations with urbanisation, industrial activity, and traffic density [8,14]. As one of Malaysia's most developed regions, Selangor is characterised by dense transportation networks, industrial zones, and continuous urban expansion, all of which contribute to sustained emission loads.

However, the magnitude of the difference observed in this study suggests that the relationship between urbanisation and particulate pollution is not merely linear. While Selangor recorded higher overall concentrations, Kelantan exhibited comparable variability and sharper temporal increases, particularly in 2023. This indicates that less-developed regions are not insulated from air pollution risks and may, in fact, be more vulnerable to episodic events such as biomass burning or regional haze [12]. These findings challenge the conventional assumption that particulate pollution is predominantly an urban problem and instead highlight its broader regional dimension.

3.10 Dominance of Fine Particulate Matter Across Regions

A key finding of this study is the consistently high $PM_{2.5}/PM_{10}$ ratio (~0.7) observed in both Selangor and Kelantan. This indicates that fine particles account for the majority of particulate mass, regardless of regional development level. Such dominance of $PM_{2.5}$ is typically associated with combustion-related sources, including vehicular emissions, industrial processes, and biomass burning [5].

Importantly, the similarity in ratios between the two states suggests that fine particulate pollution is not confined to highly urbanised or industrialised areas. Instead, it reflects the influence of widespread and diffuse emission sources operating at both local and regional scales. This is consistent with evidence that $PM_{2.5}$ can be transported over long distances [17] and is less dependent on immediate proximity to emission sources compared to coarse particles [3].

From a public health perspective, this finding is particularly concerning. $PM_{2.5}$ is known to penetrate deep into the lungs and bloodstream, contributing to cardiovascular and respiratory diseases as widely reported in epidemiological studies on long-term $PM_{2.5}$ exposure. The dominance of fine particles across both study regions therefore suggests that population exposure to harmful pollutants is more pervasive than previously assumed, extending beyond urban-industrial hotspots.

3.11 Post-Pandemic Rebound and Anthropogenic Influence

The temporal trends observed in this study reveal a clear increase in particulate matter concentrations in 2023 following relatively stable levels in 2022. This pattern is likely associated with the resumption of anthropogenic activities following pandemic-related restrictions, reinforcing the strong link between anthropogenic activity and air quality [14].

Interestingly, the increase was more pronounced in Kelantan than in Selangor, suggesting that less-developed regions may exhibit greater sensitivity to changes in emission intensity. This could be due to a combination of factors, including limited pollution control infrastructure, reliance on biomass burning, and lower baseline emissions that amplify relative changes. Such findings highlight the need to consider not only absolute pollution levels but also responsiveness to socio-economic changes when assessing regional air quality dynamics.

3.12 Seasonal Dynamics and Regional Influences

Seasonal variation in particulate matter concentrations closely followed Malaysia's monsoon patterns, with lower concentrations during the Northeast Monsoon and higher levels during the Southwest Monsoon and inter-monsoon periods. These findings are consistent with previous studies that emphasise the role of meteorological conditions in influencing pollutant dispersion and accumulation [8].

The occurrence of peak concentrations during inter-monsoon periods, particularly in October 2023, suggests a strong influence of regional transboundary haze events, often associated with biomass burning in neighbouring countries [12]. This highlights the limitations of localised air quality management strategies, as a significant proportion of particulate pollution originates from sources beyond national boundaries.

Consequently, effective air quality management in Malaysia requires not only domestic emission control but also regional cooperation and transboundary pollution governance within the Southeast Asian context.

3.13 Land Use and Localised Emission Sources

Although descriptive patterns indicated higher particulate concentrations in industrial and urban areas, statistical analysis did not reveal significant differences across land use categories. This may be attributed to the limited number of monitoring stations, which constrains statistical power. Nevertheless, the observed gradients are consistent with established emission patterns, where industrial activities and vehicular traffic contribute significantly to particulate matter levels [4].

More importantly, the lack of strong statistical differentiation reinforces the earlier finding that fine particulate pollution is influenced by regional processes rather than purely localised sources. This suggests that land use classification alone may be insufficient to explain spatial variability in $PM_{2.5}$ concentrations, particularly in regions affected by transboundary pollution and atmospheric transport.

3.14 Regulatory Implications and the MAAQS–WHO Gap

One of the most critical findings of this study is the discrepancy between compliance with national standards and alignment with international health-based guidelines. While all monitoring stations complied with the Malaysian Ambient Air Quality Standards (MAAQS) for PM_{10}, the majority exceeded the $PM_{2.5}$ standard, and all exceeded WHO (2021) guideline values.

This divergence highlights a structural limitation in Malaysia's air quality regulatory framework. Compliance with MAAQS does not necessarily equate to adequate protection of public health, particularly in relation to fine particulate matter. Similar concerns have been raised in previous studies, which indicate that current national standards may underestimate the health risks associated with long-term $PM_{2.5}$ exposure [5].

The findings therefore underscore the need for a paradigm shift in air quality management, from compliance-based regulation towards health-based standards. This includes revising national thresholds, prioritising $PM_{2.5}$ control, and integrating epidemiological evidence into policy development.

3.15 Implications for Air Quality Management

The results of this study have several important implications for air quality management in Malaysia. First, the dominance of $PM_{2.5}$ highlights the need for targeted control strategies focusing on combustion-related emissions, including vehicular exhaust, industrial processes, and open burning. Second, the observed post-pandemic rebound emphasises the importance of sustainable urban planning and transport policies to mitigate future pollution increases.

Third, the influence of seasonal and transboundary factors suggests that national efforts must be complemented by regional cooperation mechanisms, particularly within ASEAN frameworks. Finally, the identified regulatory gap calls for alignment with WHO guidelines to ensure that air quality standards are truly protective of public health.

4. Conclusions

This study reveals significant spatial and temporal variability of PM_{10} and $PM_{2.5}$ in Malaysia, with higher concentrations in Selangor but notable variability and post-pandemic increases in Kelantan. The high $PM_{2.5}/PM_{10}$ ratio (~0.7) indicates the dominance of combustion-related sources across both regions. Despite compliance with PM_{10} standards, widespread exceedance of $PM_{2.5}$ especially against WHO guidelines that highlights a critical gap in health protection. These findings support the need for stricter $PM_{2.5}$ control and improved regulatory alignment.

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