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Characteristics and Seasonal Variations of Size-Segregated Particulate Matter at Industrial, Traffic, and Residential Sites in Southern Vietnam

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ABSTRACT

Particulate matter (PM) was investigated at industrial (ID), traffic-influenced (TF), and residential (RE) sites in Ho Chi Minh City and Bien Hoa, Dong Nai, southern Vietnam during 2023–2025. Five size fractions were collected using an Ambient Nano-Sampler during approximately 120-h events, conducted twice monthly at TF and monthly at ID and RE on staggered dates. Meteorological variables were matched to the collection windows. Mean PM concentrations were generally higher in the dry season, and ID generally exhibited the highest mean levels. The 2.5–10 µm fraction was the largest individual bin, contributing approximately 27–34% of collected PM mass. The >10 µm share was higher in the rainy season (19–26%) than in the dry season (17–21%). Inter-fraction correlations varied across sites, while meteorological associations were interpreted as exploratory and did not establish source contributions or causal mechanisms. These findings provide a local baseline for size-resolved PM monitoring under tropical conditions.

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1. Introduction

Air pollution has become one of the most serious environmental issues worldwide, particularly in developing countries experiencing rapid urbanization and industrialization [1]. Among various air pollutants, particulate matter (PM) is considered one of the most important air pollutants because particle size strongly influences atmospheric behavior, deposition, and adverse health effects [2]. Coarse particles (2.5–10 µm), were reported to cause irritation of the upper respiratory tract, whereas fine and submicrometer particles, such as PM2.5 and PM1.0, are capable of penetrating into the lower respiratory tract and increasing the risk of respiratory diseases, cardiovascular diseases, stroke, and lung cancer [3]. According to the World Health Organization (WHO), fine particulate air pollution has been recognized as one of the leading causes of premature mortality worldwide [1].

In recent years, rapid industrialization, increasing traffic activity, and intensive urban construction have contributed substantially to particulate emissions in many large cities. Industrial production, fossil-fuel combustion, freight transportation, and construction activities are important anthropogenic sources of airborne particulate matter [2]. In particular, industrial areas were often characterized by high concentrations of factories and production lines, resulting in substantial particulate emissions from fuel combustion, material processing, and equipment operation processes [4]. Meanwhile, traffic areas were strongly influenced by vehicle exhaust emissions, tire wear, road dust resuspension, and prolonged traffic congestion [5]. In residential areas, although direct emissions were relatively lower, air quality was still affected by household activities, construction processes, and the transport of pollutants from surrounding areas [6], [7]. In addition, atmospheric particles of different sizes originate from different sources and exhibit distinct atmospheric behaviors. Coarse particles are commonly associated with mechanical processes such as soil and road-dust resuspension, construction activities, and non-exhaust traffic emissions, whereas fine particles are more strongly associated with combustion processes and secondary aerosol formation [7]. Recent studies demonstrated that $PM_{2.5}$ could remain suspended in the atmosphere for extended periods and be transported over long distances, thereby increasing population

exposure risks [4], [8]. Furthermore, meteorological factors such as temperature, humidity, wind speed, and rainfall were found to significantly influence the distribution and concentration of airborne particulate matter [9]–[11].

In Vietnam, many urban and industrial areas have experienced deteriorating air quality, particularly in regions with high traffic density and intensive industrial activities [10]. However, studies simultaneously evaluating multi-size particulate matter concentrations in areas with different emission characteristics, such as industrial, traffic, and residential areas, have remained limited. Comparisons of size-resolved PM concentrations among areas with different dominant emission characteristics are needed to better understand spatial and seasonal variability in particulate pollution [2]. Related Southern Vietnam studies have examined PM-bound elements, potential sources, respiratory deposition, and health risks [10]–[12]. The present study focuses on gravimetric PM size distributions, seasonal contrasts across three contrasting settings, and associations with meteorological conditions. Therefore, this study aimed to (1) characterize the concentrations and size distributions of particulate matter at ID, TF, and RE sites; (2) examine seasonal differences between the rainy and dry seasons; and (3) evaluate the relationships between particle-size fractions and meteorological parameters.

2. Materials and Methods

2.1. Sampling locations

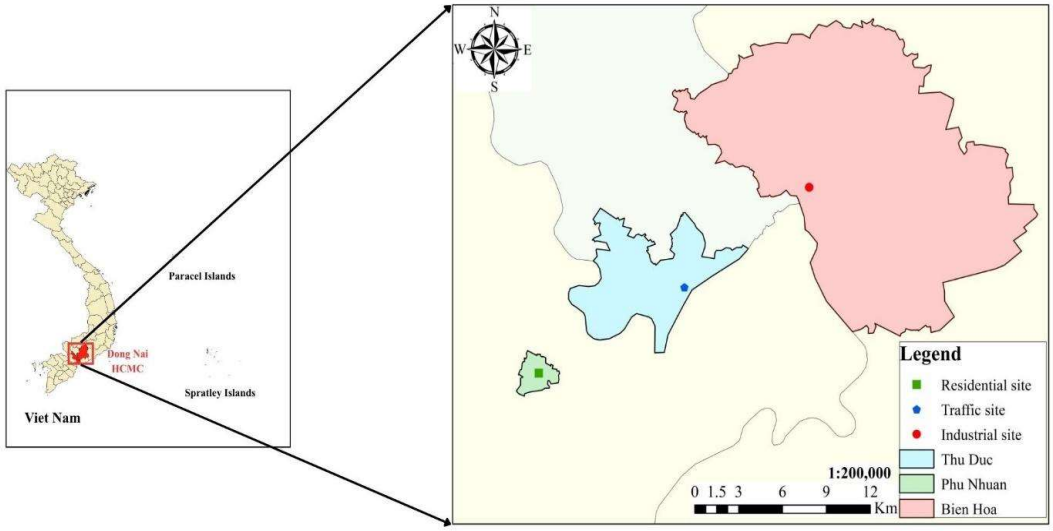


Figure 1. *Map of sampling location.*

The sampling locations are shown in Figure 1 which include the ID site was located on the fourth floor of a building adjacent to Bien Hoa 2 Industrial Park (Dong Nai province). The surrounding area contained numerous factories and industrial-processing facilities and was therefore selected to represent an industrially influenced environment [12]. The second sampling site was located on the 13th floor of the central building at Ho Chi Minh City University of Technology and Engineering. This site was situated at the intersection of two major roads within a densely populated urban area with high traffic density. Because the site was adjacent to major roads with high traffic density and no major industrial facilities were identified nearby, it was classified as a TF site. The third sampling site was established at a three-story residential building located in a residential area of Phu Nhuan District. The surrounding area mainly consisted of residential houses without industrial zones or major roads; accordingly, this location was classified as a RE site. Sampling locations were selected to receive mixed ambient air from surrounding activities, with unobstructed airflow and without immediate dominance by a single nearby emission source. Sampling elevations followed the available building conditions at each location.

Sampling was conducted over site-specific monitoring periods. At the TF site, 23 sampling events were conducted between July 2023 and June 2025, covering 24 months. At the ID site, 12 events were

conducted between July 2023 and June 2024, covering 12 months. At the RE site, nine events were conducted between July 2024 and June 2025, also covering 12 months. A total of 44 sampling events were recorded across the three sites. Sampling dates were staggered across locations, and each event integrated approximately five days (120 h), yielding five particle-size fractions. Each event at a given site constituted one observational unit. Meteorological variables were summarized over the corresponding collection windows. Differences in monitoring periods and temporal coverage were considered when interpreting comparisons among sites. The sampling period was divided into the rainy season (May to October) and the dry season (November to April). Meteorological parameters, including temperature, relative humidity, wind direction, rainfall, and wind speed, were obtained from the meteorological stations nearest to the respective sampling sites and recorded throughout the sampling period. For the ID sampling site, meteorological data were obtained from the Bien Hoa Meteorological Station, whereas data for the RE and TF sampling sites were obtained from the Tan Son Nhat Meteorological Station. Meteorological variables were averaged over the same approximately 120-h windows as the corresponding PM samples, rather than represented by instantaneous measurements. Because sampling was staggered across sites, the meteorological records matched to TF and RE could differ even though both sites used the same station.

2.2. Sample collection

Size-fractionated particulate matter was collected using an Ambient Nano-Sampler (ANS), following the configuration described by Hau et al. [12]. The sampler comprised four impactor stages collecting the >10, 2.5–10, 1–2.5, and 0.5–1 μm fractions, followed by a backup filter collecting particles <0.5 μm. Quartz-fiber collection filters were used. The sampler operated at a nominal flow rate of 40 L min^{-1}, maintained by a 350-W air pump and monitored using a flow meter (Sibata). Samples were collected twice per month at TF and once per month at ID and RE, with sampling conducted in rotation rather than simultaneously across the three sites. Each collection event integrated approximately 120 h. One event at one site constituted one observation; the five size fractions collected during that event were not independent replicate events. Before sampling, the sampler components were sonicated for 5 min and rinsed with high-purity ethanol.

Quartz-fiber filters were preheated at 450°C for 4 h. Before and after sampling, filters were conditioned for 24 h at 20–25°C and relative humidity below 40%, and repeatedly weighed under these controlled conditions until stable readings were obtained. The balance displayed mass to five decimal places in grams, corresponding to a readability of 0.00001 g (0.01 mg or 10 μg). An ionizing blower was used to neutralize electrostatic charges before weighing. Blank filters accompanied each filter-preparation and sampling batch and were processed and weighed in the same manner as sample filters. Blank mass changes were used for background correction; according to the laboratory observations, most blanks showed no discernible mass change at the balance readability. PM mass concentrations were determined from the blank-corrected filter mass gains and the sampled air volumes.

2.3. Statistical analysis

Statistical analyses were performed using SPSS (version 20), and correlation matrices were visualized using Origin (2026). Descriptive statistics were calculated by PM metric, site, and season. Each sampling event was treated as one observation, and samples from different sites were not treated as paired because collection dates were staggered. Spearman's rank correlations (r_s) were used to explore associations between PM fractions and meteorological variables matched to the collection windows. Correlations were interpreted as exploratory associations because multiple comparisons and shared seasonal variation may influence the results. Statistical significance was evaluated at $p < 0.05$.

3. Results and Discussion

3.1. Concentrations and seasonal variability of different-sized particulate matter

Figure 2 summarizes cumulative PM concentrations by site and season. Mean concentrations were generally lower in the rainy season than in the dry season. This pattern is consistent with a possible contribution from wet scavenging, although seasonal contrasts alone do not isolate the effect of rainfall.

Rainfall-associated reductions in $PM_{2.5}$ have also been reported elsewhere [13]. Relative humidity may affect particle growth and removal, but these mechanisms were not measured directly in this study. Seasonal mean $PM_{2.5}$ concentrations at all three sites were above 15 µg m^{-3}, and dry-season PM_{10} at ID was approximately 1.2 times 45 µg m^{-3}, as shown in Figure 2. These WHO 24-h guideline values [1] are used only as contextual benchmarks: the present samples integrate approximately 120 h and cannot establish daily exceedance frequencies or formal guideline attainment. The measurements characterize ambient concentrations rather than personal exposure.

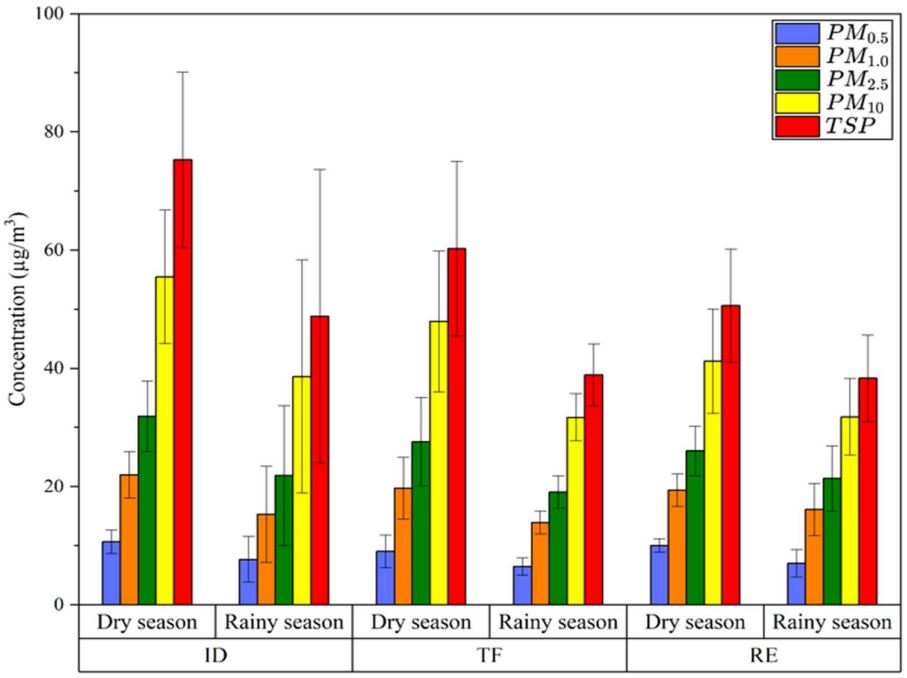


***Figure 2**. Mean concentrations of different particle-size fractions at ID, TF, and RE sites during the rainy and dry seasons. Error bars represent SD.*

Mean PM concentrations were generally highest at ID (Figure 2). Industrial combustion, material handling, mechanical processing, construction, and resuspended dust are plausible contributors in this setting, but the present mass measurements cannot quantify their individual contributions. TF had higher PM_{10} and TSP than RE in both seasons. In contrast, the TF–RE comparison for fine PM depended on particle size and season: dry-season $PM_{2.5}$ at TF was slightly higher than at RE, whereas rainy-season $PM_{2.5}$ was lower at TF. $PM_{0.5}$ and PM_1 were lower at TF than at RE in both seasons. These descriptive contrasts should not be interpreted as statistically significant without the corresponding tests. Fine-particle concentrations at RE may reflect mixed local and regional influences, including cooking, nearby traffic, secondary formation, and transport. Building morphology and sampling elevation may also influence the comparison, but their effects were not quantified. The site labels therefore describe surrounding land-use settings rather than isolated emission sources.

3.2. Seasonal distribution of particulate matter by particle size

Figure 3a shows variability in size-fractionated PM concentrations across sampling events. Concentrations generally tended to be higher in the dry season. Where means exceeded medians, the distributions were positively skewed, indicating occasional high concentrations rather than directly identifying emission events. The 2.5–10 µm fraction showed substantial variability, whereas the smaller fractions generally occupied narrower absolute concentration ranges. These distributional differences do not by themselves establish mechanical or combustion sources. Seasonal differences may reflect both emissions and meteorological conditions, including rainfall-associated removal [14], [15].

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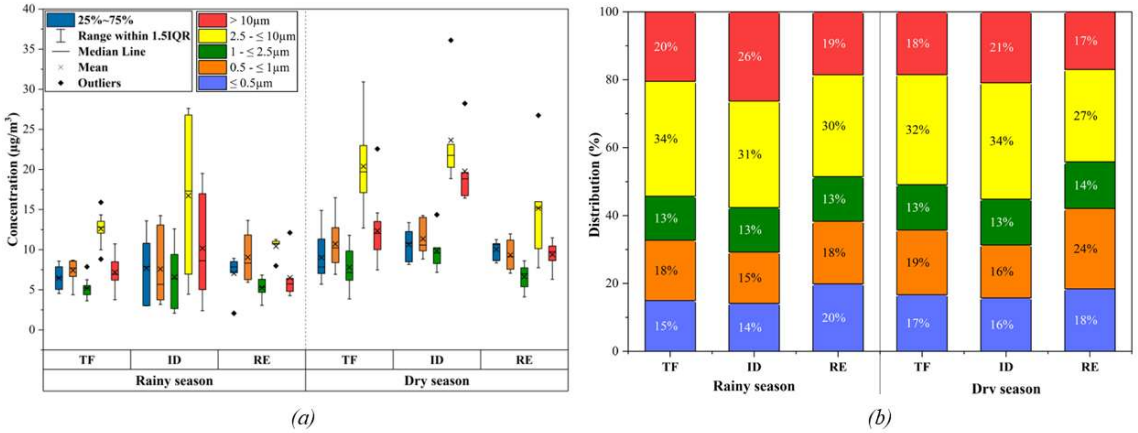


Figure 3. *Seasonal concentrations (a) and size distributions (b) of particulate matter at the industrial (ID), traffic (TF), and residential (RE) sites.*

Figure 3b shows the relative mass contribution of each size fraction. The 2.5–10 μm fraction was the largest individual bin, accounting for approximately 27–34% of collected PM mass; it did not constitute a majority of the total mass. The 1–2.5 μm fraction contributed approximately 13–14% across sites and seasons. The >10 μm mass share was higher in the rainy season than in the dry season: 20% versus 18% at TF, 26% versus 21% at ID, and 19% versus 17% at RE. These percentages describe relative contributions, not absolute concentrations. A larger seasonal share can coexist with a lower absolute concentration if other fractions or total PM decrease more strongly. The percentage differences therefore cannot alone establish size-selective scavenging or enhanced resuspension.

3.3. Correlations between meteorological parameters and size-segregated particulate matter

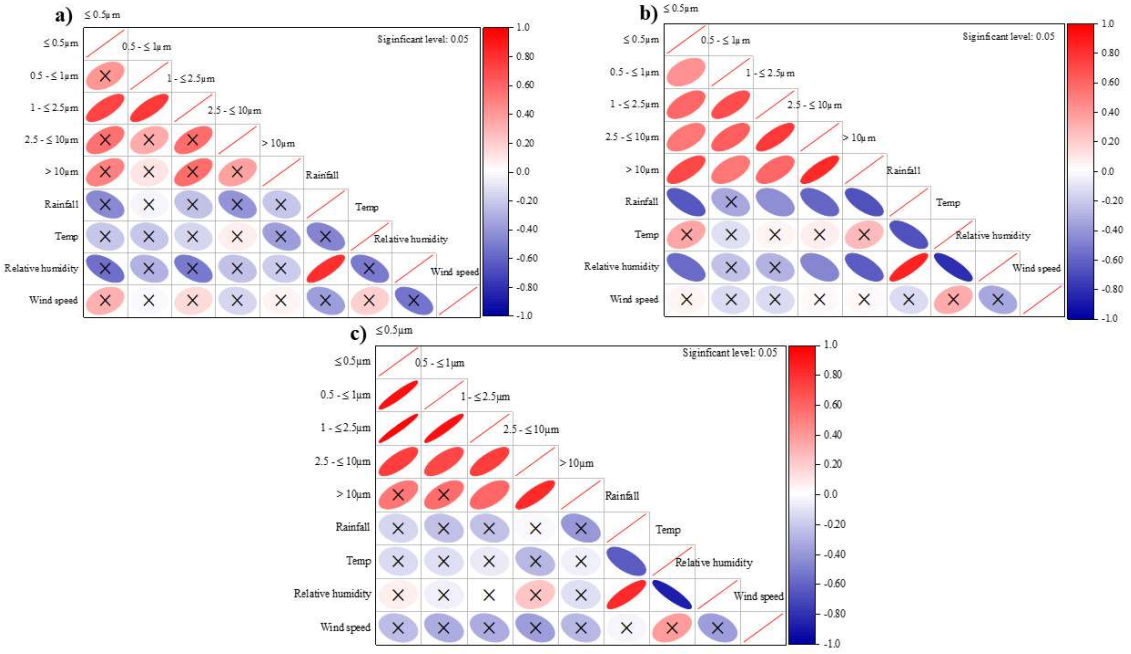


Figure 4. *Spearman correlation matrices among size-segregated PM fractions and meteorological parameters at (a) RE, (b) TF, and (c) ID. The color scale indicates the direction and magnitude of the coefficients. Relative humidity is expressed as a percentage.*

Figure 4 shows distinct correlation patterns among the particle-size fractions and meteorological parameters at the RE, TF, and ID sites. Overall, positive correlations were observed among most

particle-size fractions, although their strengths differed considerably among the three sampling sites. At the RE site (Figure 4a), correlations among the fine particle fractions were generally positive but varied in strength. The strongest relationships were observed between the ≤0.5 and 1–2.5 µm fractions and between the 0.5–1 and 1–2.5 µm fractions, with correlation coefficients of approximately r_s = 0.7–0.9. In contrast, correlations involving the coarse fractions (2.5–10 µm and >10 µm) were weaker, generally r_s < 0.4, and several were not statistically significant ($p > 0.05$). These relatively weak intercorrelations suggest that coarse and fine particles at the RE site may not vary synchronously and may be influenced by different local or regional sources. Particulate matter in residential environments can originate from a combination of household activities, cooking emissions, local traffic, construction-related dust, and transported aerosols. Similar observations have been reported in complex urban environments where PM concentrations are simultaneously influenced by several independent sources [16].

A markedly different pattern was observed at the TF site (Figure 4b), where the particle-size fractions exhibited consistently strong positive intercorrelations. Correlation coefficients among the fine fractions were approximately r_s = 0.7–0.9, while correlations involving the 2.5–10 µm and >10 µm fractions were also moderate to strong, generally around r_s = 0.5–0.8. Most of these relationships were statistically significant ($p < 0.05$). The strong synchronous variation among particle-size fractions suggests that particles of different sizes at the TF site were influenced by common or temporally concurrent processes. Traffic-related environments are affected not only by exhaust emissions but also by brake and tire wear, road-dust resuspension, and mechanical abrasion, which can simultaneously contribute particles across a broad size range. However, common meteorological forcing and shared seasonality can also produce synchronous variation; the correlations do not establish a common traffic source.

At the ID site (Figure 4c), very strong positive correlations were observed among the finer particle fractions. In particular, correlations among the ≤0.5, 0.5–1, and 1–2.5 µm fractions were approximately r_s = 0.8–0.95, indicating highly synchronous variation in fine-particle concentrations. The 2.5–10 µm fraction also showed moderate-to-strong positive correlations with the fine fractions, with r approximately 0.6–0.8. In contrast, correlations involving the >10 µm fraction were generally weaker, approximately r_s = 0.3–0.5, and several relationships were not statistically significant. Interestingly, the strongest relationship involving the >10 µm fraction was observed with the 2.5–10 µm fraction, with an approximate correlation coefficient of $r_s \approx 0.8$, suggesting that these two coarse fractions may share similar mechanical or resuspension-related processes. The weaker associations between very coarse particles and fine particles indicate that their temporal variations may be partly controlled by different processes. This pattern may be consistent with differing controls on coarse and fine particles, but correlation alone does not distinguish source contributions or physical mechanisms.

Regarding meteorological conditions, rainfall showed predominantly negative correlations with particulate-matter concentrations at all three sampling sites (Figure 4). At the RE site, correlations between rainfall and the different particle-size fractions were generally weak to moderate, approximately r_s = −0.2 to −0.5, and most were not statistically significant. At the TF site, however, rainfall exhibited considerably stronger negative correlations with PM, particularly for the fine and intermediate particle fractions, with coefficients of approximately r_s = −0.5 to −0.8. At the ID site, negative relationships were also observed, generally ranging from approximately r_s = −0.3 to −0.5. These negative associations may be consistent with the scavenging of atmospheric particles by precipitation through below-cloud and in-cloud removal processes. Rainfall can therefore reduce airborne PM concentrations through wet deposition, although the magnitude of this effect depends on rainfall intensity, duration, particle size, and local emission conditions [13], [17].

Wind-speed correlations with PM were generally weak to moderate and predominantly negative, with several relationships not statistically significant (Figure 4). The observed tendencies may be consistent with dispersion and dilution, but they do not establish a uniform wind effect across sites. Wind may also promote surface-dust resuspension. Accordingly, the present correlations cannot separate dispersion from resuspension or quantify their net contributions.

Temperature exhibited weaker and less consistent relationships with PM concentrations. At the RE site, temperature was generally negatively correlated with the fine particle fractions, with approximate values of r = −0.2 to −0.4, whereas weak positive or near-zero correlations were observed for some

coarse fractions. Similar weak and variable relationships were found at the TF and ID sites. Temperature can influence particulate matter through several mechanisms, including changes in atmospheric mixing, boundary-layer height, gas–particle partitioning, and rates of atmospheric chemical reactions. Higher temperatures may promote vertical atmospheric mixing and consequently reduce near-surface PM concentrations, but they may also modify aerosol formation through changes in gas–particle equilibrium and photochemical activity [18]. Consequently, the overall effect of temperature on PM concentrations is strongly dependent on local atmospheric and emission conditions [2].

Relative humidity also exhibited site-dependent relationships with PM concentrations. At the RE site, relative humidity was predominantly negatively correlated with the particle-size fractions, with coefficients of approximately $r_s = -0.3$ to -0.6, whereas weaker and more variable correlations occurred at the TF and ID sites. In addition, rainfall and relative humidity showed strong positive correlations at all sites, approximately $r_s = 0.7–0.9$, while temperature and humidity were generally strongly negatively correlated, particularly at the TF and ID sites (r_s approximately -0.7 to -0.9). These meteorological relationships reflect the seasonal climatic characteristics of the study region. Relative humidity can influence particulate concentrations through competing processes. Increased humidity promotes hygroscopic growth, increasing particle diameter and mass, while high-humidity conditions may also facilitate aqueous-phase reactions and secondary aerosol formation [19]. Conversely, high humidity frequently accompanies rainfall, which enhances wet removal of atmospheric particles. Therefore, the observed relationship between relative humidity and PM concentration may reflect competing contributions from hygroscopic growth, secondary aerosol formation, and wet deposition rather than a single controlling mechanism.

Overall, the matrices suggest site-dependent temporal covariation among PM fractions and meteorological variables. Stronger positive inter-fraction relationships were evident at TF and ID, while wind relationships were generally weak or statistically inconclusive. Shared seasonality, staggered sampling, and the number of comparisons limit causal interpretation. These results should therefore be interpreted as exploratory rather than as source apportionment or evidence of specific controlling mechanisms.

4. Conclusion

This study provides site-specific evidence of seasonal and size-dependent PM variability in Ho Chi Minh City and Bien Hoa, Dong Nai. Mean concentrations were generally higher during the dry season, and ID generally showed the highest mean levels. The 2.5–10 µm fraction was the largest individual size bin, contributing approximately 27–34% of total collected mass. The >10 µm fraction had a higher relative share in the rainy season, which should be distinguished from its absolute concentration. Inter-fraction correlations and meteorological associations varied by site and were interpreted as exploratory because shared seasonality and sampling design may influence these relationships. The findings provide a local baseline for further monitoring without attributing PM to individual sources.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used AI-assisted tools for English language editing. The authors reviewed, revised, and approved all content and take full responsibility for the final manuscript.

Data Availability Statement

Event-level gravimetric PM data and matched meteorological summaries supporting this study are available from the corresponding author upon reasonable request.

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