

Article

Seasonal and Diurnal Variation of Carbonaceous Components in PM_{0.1} Collected at Phnom Penh City, Cambodia

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Abstract

This study examines the seasonal and diurnal variations in ultrafine particles (PM_{0.1}) and their carbonaceous components (OC and EC), collected at the Institute of Technology of Cambodia in Phnom Penh. Sampling was conducted over 14 consecutive days in September 2024 (during the wet season) and February 2025 (during the dry season). The average mass concentration of PM_{0.1} in February (8.5 µg/m³; range: 3.9–11.3 µg/m³) was approximately three times greater than that in September, driven by a corresponding increase in OC concentration. Conversely, average EC concentrations remained almost stable across both seasons, indicating consistent local emission sources. Total carbonaceous compounds (OC + EC) constitute approximately 50% of the PM_{0.1} mass in both seasons. Primary organic carbon (POC) concentration increases almost four times in February compared to September. Secondary organic carbon (SOC) concentrations were significantly elevated during February daytime (1.4 ± 1.0 µg/m³), indicating active photochemical formation. Backward trajectory analysis and satellite hotspot data revealed that September air masses originated from maritime sources without significant local burning influences, while February pollution events were likely influenced by short-range transboundary transport from biomass-burning areas across the Cambodia–Vietnam border.

Keywords: carbonaceous components; ultrafine particles; diurnal pattern; size-segregated PM; secondary formation

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1. Introduction

Air pollution is ubiquitous, posing environmental and public health risks worldwide. Cambodia is one of the developing countries in Southeast Asia, currently facing environmental challenges due to rapid population growth and development across all sectors, leading to increased infrastructure, a rising number of vehicles, and waste generation. Phnom Penh, the only capital city, is especially susceptible to these challenges. The population of Phnom Penh is increasing in line with large-scale urban development,

reaching and attracting more citizens from other provinces due to its economic importance, abundant employment opportunities, and educational institutions. The total population in Phnom Penh city reached 2.28 million in 2019 [1]. In 2021, the number of newly registered vehicles in Phnom Penh was 506,226. Of these, motor vehicles accounted for more than 85% of the total vehicles, while the other 12% and about 3% were represented by light and heavy vehicles, respectively [2]. In 2015, the emissions of particulate pollutants ($PM_{2.5}$, PM_{10} , BC, and OC) were found to be dominated by the residential sector, with at least 40% of national total emissions, followed by waste burning, which contributed between 25 and 30% of national total emissions [3]. In many studies, vehicular transportation has been reported to be an important primary source of pollution in urban areas [4,5]. Like many other agricultural-based countries in Southeast Asia, Cambodia generates massive amounts of agricultural residue after harvesting, often burned in the field before the next crop cycle due to the approach being fast and cheap; it contributes substantially to haze formation, further exacerbating regional air pollution [6–9]. About 10 million tons of rice straws are produced, of which about 30% are burned [9]. In addition to open burning of crop residue, residential open burning of solid waste, the use of biofuel for cooking, and industrial activities have also intensified major emission production, contributing to air quality deterioration [3]. On the other hand, these anthropogenic emissions, combined with the changes in meteorological conditions such as boundary layer height, temperature inversion, and humidity, likely reflect the diurnal variation in atmospheric aerosols and secondary formation in local areas [5,10,11].

According to time-resolved $PM_{2.5}$ data reported by the Ministry of Environment in Cambodia to the regional platform of the Acid Deposition Monitoring Network in East Asia (EANET, <https://www.eanet.asia>, accessed on 03 August 2025), the seasonal and diurnal variations were significantly observed. $PM_{2.5}$ usually increases in the dry season, spanning from November to April. The daily average $PM_{2.5}$ concentration, especially in the dry season, almost reached the Cambodian national standard of $50 \mu\text{g}/\text{m}^3$. The indication is suspected with a major contribution from seasonal crop residue burning, which is consistent with increased spread-out hotspot numbers during this season [1]. However, the distinct meteorological effects and local characteristics are still scarcely discussed. Furthermore, based on the same data source, the diurnal variation was observed by the peak of $PM_{2.5}$ during nighttime from around 6 pm to midnight. In contrast, a data collection survey by JICA showed that the total traffic volume had only two peaks during rush hour: in the morning (7:00–8:00) and in the evening (17:00–18:00) [2]. This suggests contributions from various local sources to the diurnal variation rather than traffic activities after sunset. Based on historical estimation in Cambodia by [3], OC accounts for approximately 45% of $PM_{2.5}$, which is dominated by the residential sector, followed by waste burning and transport sectors. However, the monitoring and projection data from these undertakings in Cambodia were considered insufficient to correctly describe the real situation of air pollution and thus hindered the effective air quality management. Therefore, the temporal track of particulate matter (PM) and its chemical composition is crucial to understanding the distinct emission sources (local and long-range transportation) and formation mechanisms of air pollutants.

PM plays a significant role in atmospheric chemistry, visibility reduction, and climate forcing through its interactions with solar radiation and cloud formation processes [12]. Ultrafine particles or nanoparticles (UFPs), known as $PM_{0.1}$, are classified by their aerodynamic diameter of less than $0.1 \mu\text{m}$. Although it is still less regulated for the health impact benchmark, $PM_{0.1}$ is recognized as extremely hazardous and an important inhalable subset of PM, capable of entering the bloodstream and damaging organs [13,14]. Based on a study with the International Committee of Radiological Protection (ICRP) model, $PM_{0.1}$ was found to exhibit higher deposition efficiencies reaching up to 50% in the alveolar

region and approximately 30% in the tracheobronchial regions, while coarser PM shows lower efficiency [15,16]. On the other hand, PM_{0.1} particles are said to be freshly or directly emitted from various combustion sources, including vehicle engine combustion, industrial fossil fuel combustion, residential biofuel or waste burning, biomass burning, or forest fire [17,18]. They can also be newly formed in the atmosphere from precursor gases, such as H₂SO₄, NH₃, and some VOCs [18]. Hence, the generated key components can be primarily in gas or particulate form, including elemental carbon, organic, and inorganic compounds. Over time, in complex atmospheric conditions, these smaller particles can accumulate mass through condensation and coagulation, then grow into larger particles, significantly increasing the mass of PM_{2.5} [17]. However, the primary influence of characteristics of PM_{0.1} usually arises from local sources [19]. To our understanding, the knowledge of precise effects, sources, and movement associated with PM_{0.1} is still limited. Therefore, extending the detailed study to mass-based PM_{0.1} and its major components provides an insightful understanding and scientific basis for source analysis and formation mechanisms toward broader PM fractions, especially PM_{2.5}.

Carbonaceous components such as elemental carbon (EC) and organic carbon (OC) are identified as substantial components of PM, especially PM_{0.1} or PM_{2.5}. EC often comes from primary anthropogenic sources of incomplete combustion of coal, oil, gasoline, and other biomass materials, and does not undergo chemical transformations [19]. EC is generally generated in the form of soot or black carbon, which has light-absorption ability. Diesel exhaust has been identified as the major source of EC in developed countries [20]. EC is usually regarded as a direct indicator of air pollution caused by transportation [20,21]. OC is not only emitted directly from anthropogenic and biogenic sources (primary OC, POC) but is also formed within the atmosphere through gas-to-particle conversion of volatile organic compounds or photochemical reactions (secondary OC, SOC). Therefore, OC can be classified into two types: primary organic carbon (POC) and secondary organic carbon (SOC) [19,20]. In terms of environmental and health effects, EC possesses a strong capability of absorbing solar radiation and is considered to play an important role in global climate change, as it causes positive radiative forcing. It is the second most important component of global warming, after CO₂, while OC is mainly a scattering medium and exerts a negative climate forcing influence [19,20]. Therefore, understanding the characteristics of carbonaceous components is necessary to analyze PM_{0.1} sources toward air pollution control. Time-resolved OC and EC data also provide a better understanding of the dynamics of SOA formation, because emissions and atmospheric processes of pollutants are dynamic on the time scale of minutes to hours [22]. Due to the distinctive characteristics of OC and EC, numerous studies have reported the mass ratios of OC to EC (OC/EC) to interpret the emission sources and transformation characteristics of carbonaceous aerosol [19]. For example, the OC/EC ratio ranges from 1.2 to 1.3 for transportation emission, 1.6–2.3 for industrial activity, and 3.9–4.2 for biomass burning [11]. Similarly, [23] stated that OC/EC of 1.5 arises from motor vehicle emissions, 2.7 from coal burning, and 4.1 from wood burning. A study by [24] shows a higher value of the OC/EC ratio of 6.7, indicating the emissions from Japanese crop burning. In addition, [19] reported OC/EC ratios of 1–4.2 account for motorcycle exhaust, 2.5–10.5 for residential coal burning, 3.8–13.2 for biomass burning, 4.3–7.7 for cooking activities [25], and 5.67 for rice straw field [26]. However, the diesel consumption is always reported with the lowest ratio of 0.06–0.8 [27].

Through investigations in other countries, such as Thailand, Vietnam, or Myanmar, which share a border with Cambodia and have similar situations, serious contamination issues were detected at great distances from the collection sites [26,28,29]. In Cambodia, previous studies [1,30] indicate a great effect of transboundary transport on the Phnom Penh site, while detailed information on the concentration levels and local source

characteristics remains limited. While recent studies have provided valuable foundational data on $PM_{0.1}$ in Cambodia, such as the long-term weekly sampling by [1] and the one-week dry-season continuous observation by [30], detailed high-resolution comparisons across contrasting meteorological extremes remain scarce. To build upon these works, this study conducts a 14-day, consecutive, 12 h (day/night) sampling campaign in both the peak wet and dry seasons to deeply elucidate the seasonal and diurnal dynamics of $PM_{0.1}$ carbonaceous components in Phnom Penh over a diurnal cycle (daytime: 6:00–18:00; nighttime: 18:00–6:00) during two consecutive seasons, September 2024 (wet season) and February 2025 (dry season). The specific objectives are to (1) inform the temporal variability of mass-based size-segregated PM down to $PM_{0.1}$ in Cambodia, (2) quantify the seasonal and diurnal carbonaceous components (OC, EC) associated with $PM_{0.1}$, and (3) discuss their sources based on carbonaceous components with their molecular diagnostic ratios. In addition, the meteorological data, air mass trajectory, and the distribution of hotspots obtained from satellite images were also taken into account to evaluate the possible influences of long-range transportation and local effects.

2. Materials and Methods

2.1. Site Description

The sampling location is situated in the Tuol Kouk district, which is classified as one of the residential and commercial areas in Phnom Penh (Figure 1). The samplers were installed on the rooftop of a three-story building, approximately 12 m above ground level (AGL), at the Institute of Technology of Cambodia (ITC). ITC is located next to two main roads: Russian Federation Boulevard and Mohasenapramuk Kim Il Sung Boulevard, near the railway and surrounded by residential buildings, universities, offices, restaurants, cafeterias, and street food vendors. It can be considered one of the dynamic areas leading to active transportation in local and cross-border areas. Cambodia's meteorology is characterized by two distinct monsoon cycles: the wet southwest monsoon (May–October) brings heavy rainfall and high humidity. In contrast, the dry northeast monsoon (November–April) brings sunnier, drier weather. The climate is tropical and humid year-round, with high temperatures (peaking around 35 °C in April) and high humidity. Air temperature remains relatively constant throughout the year, with the highest average humidity in the wetter months (approaching 90%). The coolest months of the year tend to be from October to December; although temperatures during these months are relatively low for Cambodia, they remain mild by global standards, with average temperatures hovering around 24–26 °C. Based on the sampling record, most of the sampling days in September were marked by rain for several hours during the day.

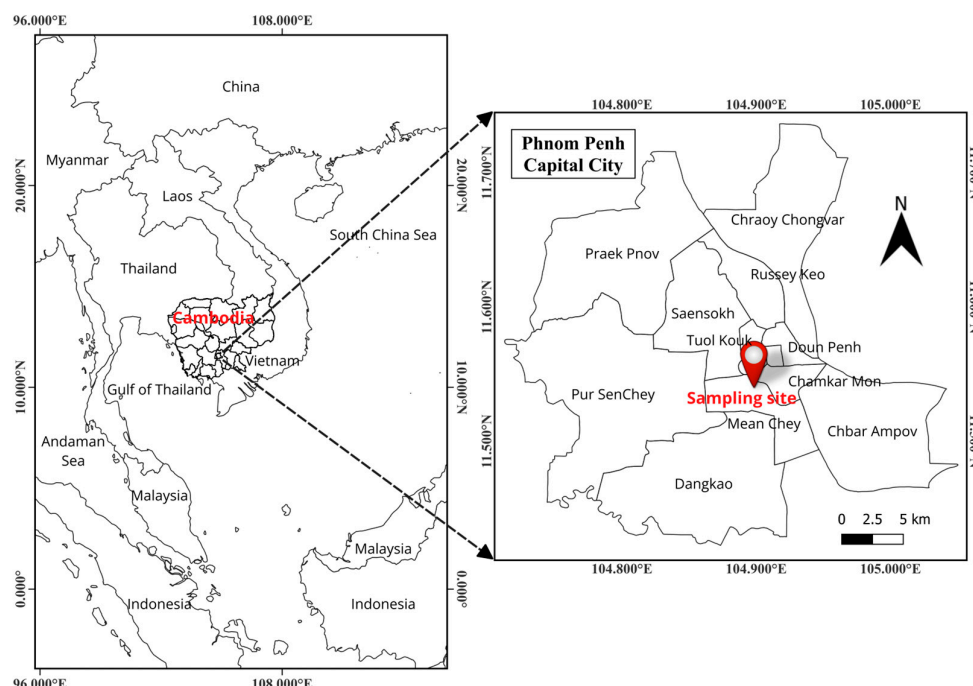


Figure 1. Sampling site at the Institute of Technology of Cambodia (ITC) in Phnom Penh, Cambodia (11.570° N, 104.898° E).

2.2. PM Samples and Meteorological Data Collection

To ensure the physical stability of the ultrafine PM mass under the high-pressure drops of the cascade impactor (20–30 kPa), this study concurrently operated two parallel samplers: one equipped with a Teflon-coated glass fiber (TXF, Pallflex TX40HI20-WW, Pall Corp., CT, USA) filter for highly stable gravimetric measurements, and the other with a standard quartz fiber (QFF, Pallflex 2500 QAT-UP, Pall Corp., CT, USA) filter, which is essential for the high-temperature thermal-optical carbon analysis. This parallel sampling approach minimizes mass measurement uncertainties while allowing for robust OC and EC quantification [31]. The filters before and after sampling were weighed using a microbalance (Sartorius Cubis MSU2.7S-000-DF, Sartorius AG, Göttingen, Germany) under conditions of constant temperature (21.5 ± 1.5 °C) and relative humidity ($35 \pm 5\%$). To ensure the stability and accuracy of the weighing, filters were conditioned for 48 h before weighing. QFF filters were used for carbonaceous components (OC and EC) analysis. To remove potential organic contaminants and residual moisture, QFF was pre-baked for 1 h at 350 °C before sampling [29,32]. All filters were individually wrapped in aluminum foil and a plastic bag before and after sampling. The methodology was conducted following the protocol of the Ministry of Environment of Japan [32].

The ANS operates at a nominal flow rate of 40 L/min. To remove larger particles before isolating the ultrafine fraction, the sampler is configured with a 4-stage cascade impactor upstream, with cut-off aerodynamic diameters of 10 μm , 2.5 μm , 1 μm , and 0.5 μm . The filters placed on these impaction plates do not function as filtration media; rather, they are specifically placed to prevent particle bounce and re-entrainment. Following the impactor stages, the ANS is equipped with inertial filters (IF) consisting of webbed stainless-steel fibers, which capture particles within the 0.1–0.5 μm range. Particles passing through this stage ($\text{PM}_{0.1}$) are subsequently captured by the final backup filter. This backup filter functions as the actual filtration stage and is firmly secured with a Teflon ring to completely prevent bypass leakage from the outer circumference.

The volumetric airflow was measured and adjusted to 40 L/min by connecting a rotameter to the inlet of the ANS at the immediate start and end of each daytime and nighttime cycle. At these times, the pressure drop across the entire sampler was also recorded using a vacuum gauge installed downstream. During the actual sampling period, the rotameter was removed. As a strict quality-control measure, any sampling run showing a flow rate deviation greater than $\pm 5\%$ between the initial and final rotameter readings was to be excluded from subsequent chemical analysis. However, over the entire sampling campaign, no sampled cycles exceeded this operational threshold.

The sampling was conducted for approximately 11–12 h, characterized by distinct daytime (6:00–18:00 local time) and nighttime (18:00–6:00 local time) during two intensive measurement periods: 2–15 September 2024 (wet season), and 17 February–2 March 2025 (dry season). A total of 28 daytime–nighttime sample pairs and six field blank samples were collected during the sampling period in both seasons. The collected filters were stored at $-20\text{ }^{\circ}\text{C}$ after sampling for further analysis.

To investigate the influence of meteorology on PM levels, real-time meteorological data were collected from the Air Quality Monitoring System (AQMS, Horiba Ltd., Kyoto, Japan). This AQMS sensor is installed on the rooftop of building A (16m above ground level) at the Institute of Technology of Cambodia. The real-time wind speed (WS, m/s), wind direction (WD, degrees), and precipitation intensity (PI, l/m²/h) data were obtained and converted into 12 h averages following the sampling timeframe.

2.3. Carbonaceous Components Analysis

Carbonaceous components on QFF were analyzed by a thermal/optical carbon analyzer (Sunset Laboratory Inc., Tigard, Oregon (OR), USA) with the Interagency Monitoring of Protected Visual Environments-Thermal/Optical Reflectance (IMPROVE-TOR) method. A sample of 1 cm² (1 cm $\times$ 1 cm) was punched from a QFF of the PM_{0.1} fraction and inserted into a carbon analyzer through a sample boat. Inside the analyzer, the sample was heated at temperatures of 120, 250, 450, and 550 $^{\circ}\text{C}$ to produce four organic carbon fractions (OC₁, OC₂, OC₃, and OC₄), respectively, in a non-oxidizing helium atmosphere, as well as three elemental carbon fractions (EC₁, EC₂, and EC₃) at 550, 700, and 800 $^{\circ}\text{C}$, respectively, in an oxidizing atmosphere of 2% O₂/98% He. At the same time, pyrolyzed OC (Pyrol OC) is produced in the inert atmosphere, which decreases the reflected light to correct for charred OC [33]. Therefore, OC was finally defined as OC₁ + OC₂ + OC₃ + OC₄ + Pyrol OC, EC was defined as EC₁ + EC₂ + EC₃ – Pyrol OC. The detection limit of OC and EC in this study was 0.9 $\mu\text{g}/\text{cm}^2$ and $1.7 \times 10^{-4} \mu\text{g}/\text{cm}^2$, respectively, obtained by three times the standard deviation of six measurements of the sucrose standard. The subtraction of OC and EC in the blank from the collected samples was also applied to avoid the potential contamination during transportation or storage.

2.4. Primary and Secondary Organic Aerosol Estimation

Due to the complex and changeable form of OC, the direct separation and quantification of primary organic carbon (POC) and secondary organic carbon (SOC) are challenging. Therefore, the EC tracer method was employed [22,34,35]. This method utilizes EC as a conservative tracer for primary combustion, under the assumption that Elemental Carbon (EC) and Primary Organic Carbon (POC) share the same emission sources. This approach suggests that samples having a low OC/EC ratio contain almost exclusively primary carbonaceous compounds [22]. Because absolute primary emission compositions cannot be strictly defined using limited ambient data, the EC tracer method is utilized semi-quantitatively in this study to evaluate the relative temporal variations in POC and SOC rather than their absolute values.

The total measured Organic Carbon (OC) is defined as the sum of its primary and secondary fractions [22]:

$$OC_{total} = POC + SOC \quad (1)$$

where POC represents primary organic carbon, and SOC represents secondary organic carbon. The POC concentration is estimated based on the measured EC and the characteristic primary emission ratio $(OC/EC)_{pri}$ as follows:

$$POC = (OC/EC)_{pri} \times EC + OC_{non-comb} \quad (2)$$

Here, $(OC/EC)_{pri}$ is the ratio representing local primary combustion sources (e.g., vehicular exhaust and biomass burning), and $OC_{non-comb}$ is a constant representing the contribution of organic carbon from non-combustion sources, such as biogenic emissions. Subsequently, the SOC fraction is calculated by subtracting the estimated POC from the total OC:

$$SOC = OC_{total} - POC \quad (3)$$

The accurate estimation of secondary organic carbon (SOC) via the EC tracer method is fundamentally dependent on the selection of a representative primary $(OC/EC)_{pri}$ ratio. In this study, the $(OC/EC)_{pri}$ ratio was determined by linear regression, and the uncertainty was quantified using 95% confidence intervals based on the standard error of the slope.

2.5. Determination of $(OC/EC)_{pri}$

Initially, a comparative analysis of the $(OC/EC)_{pri}$ slopes was conducted across different months representing distinct seasons and diurnal periods (day and night) using the lowest 10% of observed ratios for each period. As a result, the high confidence intervals were observed, leading to mathematically wide 95% confidence intervals due to the high critical t-value at low degrees of freedom. Therefore, a sensitivity analysis with the 20th percentile was then performed to determine the optimal percentile threshold for isolating primary emissions within a linear regression model forced through the origin. This excluded intercept approach was chosen to reflect the physical reality of the ultrafine fraction, where the absence of elemental carbon (EC) typically corresponds to a near-zero concentration of combustion-derived organic carbon. Finally, the use of the 20th percentile threshold and a forced-zero linear regression model provided the most stable statistical results, with R^2 values consistently at 0.99 and minimized 95% confidence intervals. Table 1 shows the comparison of $(OC/EC)_{pri}$ calculation using 10% and 20% threshold of the data collected intensively during September 2024 and February 2025.

Table 1. Sensitivity analysis and $(OC/EC)_{pri}$ calculation using 10% and 20% threshold of the data collected intensively during September 2024 and February 2025 at the Institute of Technology of Cambodia (ITC).

Daily Samples	Sample (N)	Threshold (%)	n	Forced Zero (Without Intercept)			With Intercept			
				Slope $(OC/EC)_{pri}$	R^2	95% CI	Slope $(OC/EC)_{pri}$	Intercept	R^2	95% CI
Sep (day + night)	28	10	3	1.71	0.98	3.10	1.36	0.20	0.77	9.44
		20	6	1.92	0.97	0.47	1.27	0.32	0.70	1.15
Feb (day + night)	28	10	3	4.65	0.99	5.94	1.43	2.67	0.23	33.25
		20	6	4.91	0.99	0.69	0.64	3.44	0.03	5.05

2.6. Backward Trajectory and Hotspot Number Observation

To investigate the source and transport pathways of the airborne particles arriving at the sampling site, backward trajectories were calculated using the final run of GDAS one-degree NOAA ARL Archived Data from the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (<https://www.ready.noaa.gov/HYSPLIT.php>, last access: 16 February 2026). The 72 h backward trajectories were preliminarily simulated, but air masses were predominantly maritime without major emission sources in the open ocean, suggesting clean air beyond that timeframe. Thus, the trajectory was limited to 24 h when the air mass crossed the coastline and entered the local region. The 24 h backward trajectories were calculated using the model vertical velocity at 500 m above ground level. The starting time of these trajectories was simulated at 11:00 UTC (18:00 ICT) for daytime (red line) and 23:00 UTC (6:00 ICT the next day) for nighttime (black line) across sampling periods. The hotspot numbers were obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) with a spatial resolution of 375 m, via the Fire Information for Resource Management System (FIRMS) (<https://firms.modaps.eosdis.nasa.gov/download/>, last access: 12 January 2026). The fire spots were also visualized in distinct daytime and nighttime. Trajectory-hotspot intersections were calculated and visualized using QGIS Geographic Information System (3.34.1-Prizren).

2.7. Statistical Analysis

Correlation analysis was performed using R (version 4.5.0) with the following packages: dplyr (v1.2.1), Hmisc (v5.2.5), and openxlsx (v4.2.8.1). Pearson correlation coefficients were calculated to examine linear relationships between variables across different temporal conditions (day/night) and monthly periods. The calculated correlations were interpreted as follows: very high positive (0.9–1.0), high positive (0.7–0.9), moderate positive (0.5–0.7), low positive (0.3–0.5), and negligible (0.0–0.3) correlations, as adopted from [36]. The statistical significance was determined using the following criteria: *** $p < 0.001$ (highly significant), ** $p < 0.01$ (very significant), * $p < 0.05$ (significant).

Statistical differences in $PM_{0.1}$ mass and chemical component concentrations (OC and EC) between sampling months (September vs. February) and diurnal periods (Daytime vs. nighttime) were evaluated using a two-sample t -test assuming unequal variances (Welch's t -test). The unequal-variance assumption was selected to account for the inherent meteorological and emission variability between sampling periods. All statistical calculations were performed in Microsoft Excel LTSC Professional Plus 2021, and a p -value of less than 0.05 ($p < 0.05$) was considered statistically significant.

3. Results

3.1. Seasonal and Diurnal Variation in PM Size Distribution

Figure 2a,b illustrate the temporal variation in size-segregated PM mass concentrations and their fractional contributions, respectively, collected at the Institute of Technology of Cambodia in September 2024 (wet season) and February 2025 (dry season) campaigns.

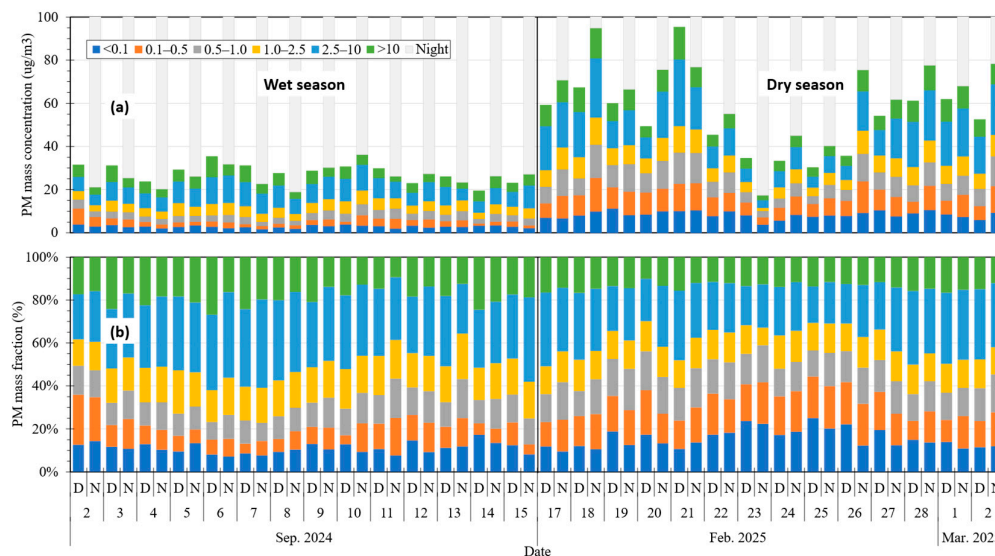


Figure 2. Seasonal and diurnal variation in size-resolved (a) PM mass concentrations and (b) PM mass fractions at the Institute of Technology of Cambodia in Phnom Penh, Cambodia.

As shown in Figure 2a, total PM mass concentrations were markedly higher during February 2025 (dry season) than during September 2024 (wet season), with values approximately three times greater than those in September. In September, total PM concentrations were suppressed, averaging $<30 \mu\text{g}/\text{m}^3$, while in February they almost reached $100 \mu\text{g}/\text{m}^3$ on some days. This seasonal contrast is likely driven by reduced wet scavenging during the dry season, increased biomass-burning activities, and shallower planetary boundary layer heights that promote pollutant accumulation near the surface. Within the dry season, notable day-to-day variability was observed, with several daytime spikes, particularly around 19 February and 26 February, suggesting episodic influence from trans-boundary transport events rather than a steady-state local emission background.

Regarding the size distribution (Figure 2b), $\text{PM}_{2.5-10}$ was the single largest contributing fraction, accounting for approximately 32% of total PM mass on average in September, followed by $\text{PM}_{>10}$ (18%), suggesting a persistent contribution from mechanical resuspension and coarse-mode aerosols. Similarly, in February, the $\text{PM}_{2.5-10}$ accounted for 26% of the total PM, followed by the fine-mode aerosols ($\text{PM}_{<1.0}$). $\text{PM}_{0.1-0.5}$ fraction contributed approximately 16%, followed closely by $\text{PM}_{<0.1}$ (15.6%) and $\text{PM}_{0.5-1.0}$ (15.3%). This relatively even distribution across size ranges suggests a mixed aerosol population driven by both mechanical generation (coarse) and combustion processes (fine and ultrafine). The fine and submicron fractions ($\text{PM}_{0.1-1.0}$) collectively accounted for approximately 47% of total PM mass, indicating active combustion-derived aerosol loading from traffic and biomass burning during the dry season.

Notably, the $\text{PM}_{0.1}$ fraction contributed approximately an average of 11% (range 7–15%) of total PM in September, slightly higher than in February (16%; range: 10–25%) during the dry season. The consistently elevated $\text{PM}_{0.1}$ fraction during the dry season, despite the simultaneous increase across all size fractions, suggests that ultrafine particle sources, particularly incomplete combustion from traffic and biomass burning, were disproportionately active during this period. A discernible diurnal pattern is also apparent in the fractional contributions: the ultrafine and fine fractions ($\text{PM}_{<1.0}$) tended to constitute a larger proportion of total PM during daytime compared to nighttime, especially in September, when coarser fractions became relatively more dominant. This diurnal shift likely reflects daytime photochemical new particle formation and active traffic-related combustion emissions, contrasted with nocturnal boundary-layer compression that preferentially

retains larger, mechanically generated particles near the surface. However, the nocturnal peak is often observed in February, suggesting the importance of primary emission or meteorological influences during the absence of sunlight.

3.2. Seasonal and Diurnal Variation of Carbonaceous Components Associated with $PM_{0.1}$

Figure 3a–d show the temporal variations in mass concentrations of carbon components (OC and EC) associated with $PM_{0.1}$ collected in Phnom Penh, Cambodia, including the OC/EC ratio of measured and estimated (OC/EC)_{pri}.

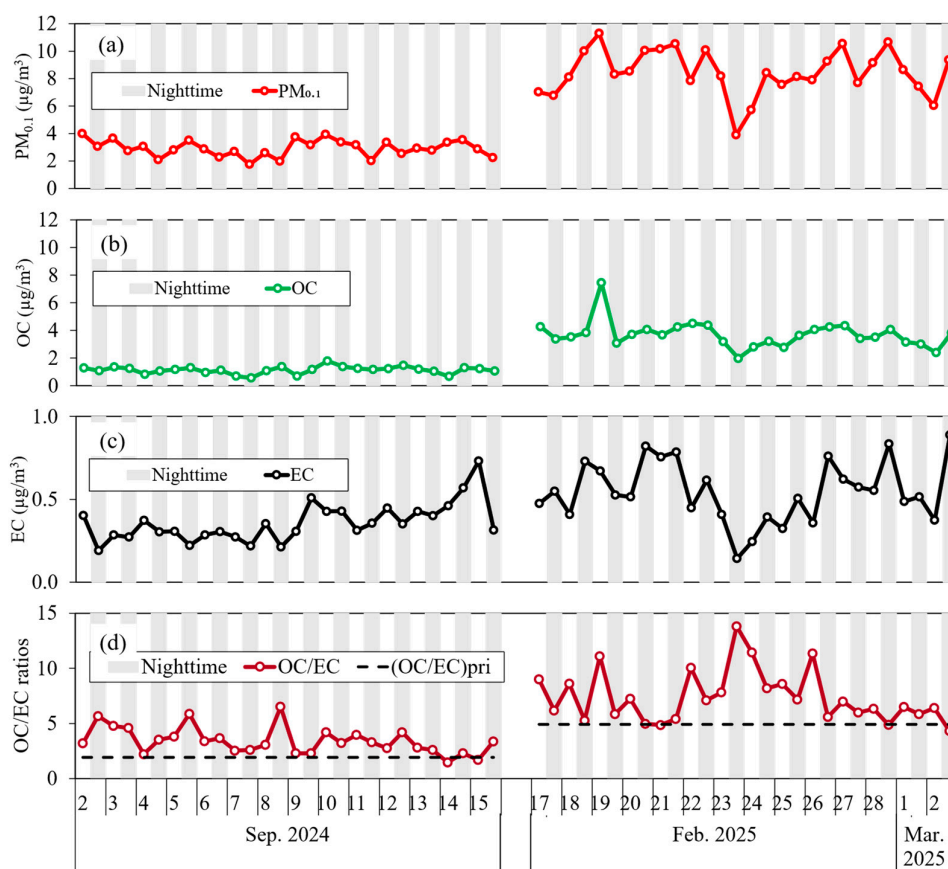


Figure 3. Seasonal and diurnal mass concentration of (a) $PM_{0.1}$ and its key components: (b) OC, (c) EC collected at the Institute of Technology of Cambodia (ITC), with respective measured and estimated primary (d) OC/EC ratios.

Corresponding to the total PM mentioned above, $PM_{0.1}$ in February was approximately three times higher than that in September ($p < 0.05$). In September, the average $PM_{0.1}$ concentration was $3.2 \pm 0.5 \mu\text{g}/\text{m}^3$ during the day and $2.6 \pm 0.6 \mu\text{g}/\text{m}^3$ at night, while in February, these values were $8.3 \pm 1.6 \mu\text{g}/\text{m}^3$ and $8.6 \pm 1.8 \mu\text{g}/\text{m}^3$ during the day and night, respectively. OC concentrations also increased with an intensity consistent with $PM_{0.1}$ in February compared to September ($p < 0.05$), while EC increased modestly (1.25 times) but disproportionately less than OC and $PM_{0.1}$. On the other hand, diurnal variation was significant for all measured components in February ($p < 0.05$), except OC. The average concentration of OC in September was $1.1 \pm 0.3 \mu\text{g}/\text{m}^3$ during the day and $1.2 \pm 0.2 \mu\text{g}/\text{m}^3$ at night (Table S1). In February, the average OC concentrations were $3.8 \pm 1.2 \mu\text{g}/\text{m}^3$ and $3.6 \pm 0.6 \mu\text{g}/\text{m}^3$ during the day and at night, respectively. Moreover, the average EC concentrations during day and night in September were $0.4 \pm 0.1 \mu\text{g}/\text{m}^3$ and $0.3 \pm 0.1 \mu\text{g}/\text{m}^3$, respectively. The average EC concentration was slightly increased compared to

those in September, $0.5 \pm 0.1 \mu\text{g}/\text{m}^3$ and $0.6 \pm 0.2 \mu\text{g}/\text{m}^3$ during the day and night, respectively.

The maximum concentration of $\text{PM}_{0.1}$ was $11.3 \mu\text{g}/\text{m}^3$ observed on the daytime of 19 February 2025 (Table S1). On the same day, OC also peaked with a concentration of $7.5 \mu\text{g}/\text{m}^3$. In contrast, on 23 February 2025, at night, $\text{PM}_{0.1}$ was observed to have the lowest value ($3.9 \mu\text{g}/\text{m}^3$) compared to the other days in February. Accordingly, OC and EC also decreased to the lowest concentration of $2.0 \mu\text{g}/\text{m}^3$ and $0.1 \mu\text{g}/\text{m}^3$, respectively. This significant decrease was observed with the occurrence of precipitation, so that wet deposition was suspected.

The diurnal distribution of $\text{PM}_{0.1}$ concentrations exhibited a distinct seasonal reversal: daytime concentrations were dominant on 85% of days during observation in September, whereas nighttime concentrations were higher on 64% of days in February. Similarly, EC had a clearer nocturnal peak in February compared to September ($p < 0.05$). However, OC showed an unclear diurnal pattern across the observation period ($p > 0.05$). This behavior can be governed by seasonal meteorological shifts or localized primary emissions.

The temporal variability of OC/EC ratios is shown in Figure 3d. The OC/EC ratio in February showed higher values, about three times greater than those in September, consistent with the substantial increase in OC and slight variability of EC. As mentioned in Section 1, the OC/EC ratio has been roughly used to distinguish sources such as vehicle emissions, biomass burning, industrial activities, or power plants. The average of the OC/EC ratio was 3.0 ± 1.0 during the day and 3.8 ± 1.4 at night in September. In February, the OC/EC ratio was 8.3 ± 2.1 and 6.5 ± 2.4 during the day and night, respectively. Because ambient OC/EC ratios are heavily influenced by the mixing of various primary sources and the formation of SOC (which adds pure organic mass), directly matching ambient ratios to specific source emission profiles is inherently limited. However, the dramatic seasonal tripling of the ambient OC/EC ratio from September to February serves as a strong qualitative indicator of a shift in atmospheric regimes. Supported by our trajectory and hotspot data, this elevated ratio in the dry season qualitatively suggests a massive influx of OC-rich primary emissions, such as transboundary biomass burning, coupled with potentially enhanced secondary formation.

Figure 4a–d show the fractions of OC and EC in $\text{PM}_{0.1}$ during the day and night in September and February. As a result, the total of both OC and EC accounted for approximately 50% of the $\text{PM}_{0.1}$ mass. This indicates the major contribution of carbonaceous compounds to $\text{PM}_{0.1}$ mass. In September, OC accounted for 34% of $\text{PM}_{0.1}$ mass during the daytime and 44% at night. Similarly, it accounted for 46% during the daytime and 42% at nighttime in February. On the other hand, EC contributed fairly 12% of $\text{PM}_{0.1}$ mass during the day and 13% at night in September. However, the EC fraction of $\text{PM}_{0.1}$ mass in February was about 6% and 7% of its $\text{PM}_{0.1}$ mass during the day and night, respectively. Despite the high concentration of OC in February, its fraction in $\text{PM}_{0.1}$ also shows a consistently high value. This suggests that the substantial organic and other related sources contributed to the $\text{PM}_{0.1}$ level during this period. Notably, the OC fraction in $\text{PM}_{0.1}$ was higher during the night than during the day in September. This may suggest that OC-related emissions in the local area were elevated during nighttime or were subject to delayed emission.

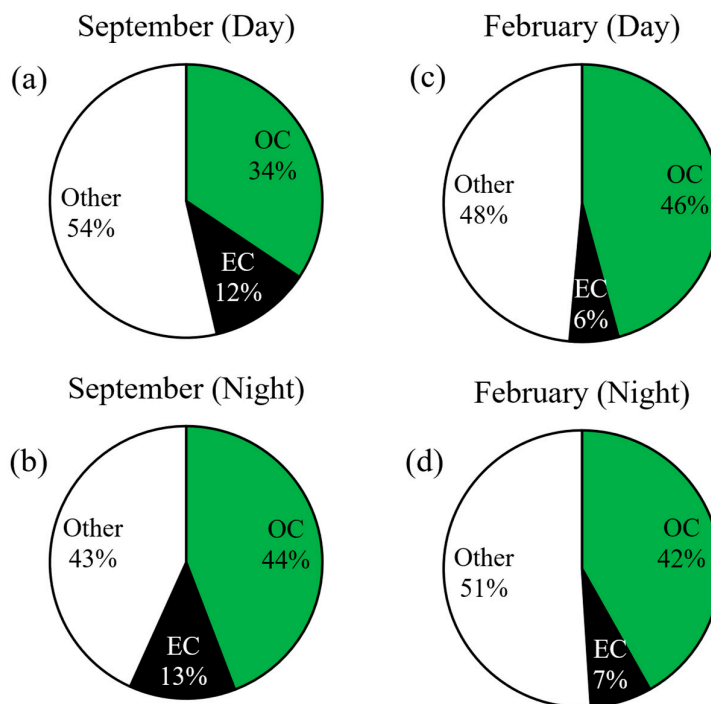


Figure 4. Composition fraction of OC and EC in $PM_{0.1}$ collected at the Institute of Technology of Cambodia in Phnom Penh, Cambodia: (a) September 2024 at daytime, (b) September 2024 at nighttime, (c) February 2025 at daytime, (d) February 2025 at nighttime.

The correlation coefficient between $PM_{0.1}$, OC, and EC is shown in Table S2. OC and $PM_{0.1}$ show a stronger correlation in February than in September, with an R value of 0.38 ($p > 0.05$) < 0.47 ($p > 0.05$) < 0.64 ($p < 0.05$) < 0.91 ($p < 0.001$) for Sep (Day) < Sep (Night) < Feb (Day) < Feb (Night), respectively. Regarding EC and $PM_{0.1}$, it also showed a similar correlation pattern (R: Sep (Day) < Sep (Night) < Feb (Night) < Feb (Day) with the value of 0.00 ($p > 0.05$) < 0.48 ($p > 0.05$) < 0.86 ($p < 0.001$) < 0.88 ($p < 0.001$). This indicates the important movement of OC and EC together with $PM_{0.1}$ in February. However, the correlation coefficient between OC and EC was strongly significant during the night in February ($R = 0.90$, $p < 0.001$). This suggests that OC and EC may share common emission sources, especially at night in February. In contrast, a weak correlation of OC and EC in September likely showed that both components were not emitted at the same time or from a predominant single source.

3.3. Estimation of Primary and Secondary Organic Carbon (POC and SOC)

Figure 5 illustrates the temporal variability of primary and secondary organic carbon (POC and SOC) in $PM_{0.1}$ collected during September (wet season) and February (dry season) at the Institute of Technology of Cambodia. POC and SOC were estimated based on the $(OC/EC)_{pri}$ of 1.92 for the dataset in September and 4.91 for those in February.

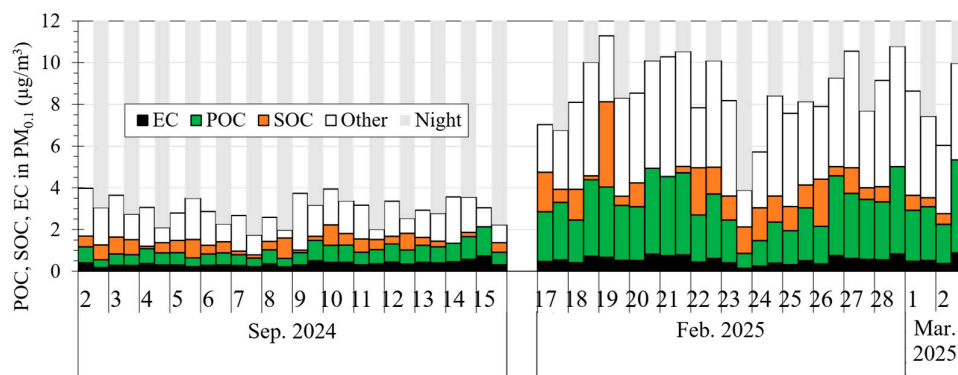


Figure 5. Seasonal and diurnal variations in primary and secondary organic carbon (POC and SOC) in PM_{0.1} collected at the Institute of Technology of Cambodia.

As a result, POC showed a dominant fraction of OC concentration and had a consistent seasonal shift, with a higher value in February than in September ($p < 0.05$). The average POC was $0.7 \pm 0.2 \mu\text{g}/\text{m}^3$ and $0.6 \pm 0.2 \mu\text{g}/\text{m}^3$ on September day and at night, respectively (Table S1). In February, POC was $2.4 \pm 0.7 \mu\text{g}/\text{m}^3$ during the day and $3.1 \pm 1.0 \mu\text{g}/\text{m}^3$ during the night. While the diurnal variation in POC was unclear in September ($p > 0.05$), it often showed higher values at night in February ($p < 0.05$). Notably, the POC/OC ratio showed a comparable mean value, ranging from 0.6 to 0.8 across the observation period. Moreover, the average concentrations of SOC in September were $0.4 \pm 0.3 \mu\text{g}/\text{m}^3$ during daytime and $0.5 \pm 0.3 \mu\text{g}/\text{m}^3$ during nighttime. In February, during the day and night, respectively, the average concentration of SOC was $1.4 \pm 1.0 \mu\text{g}/\text{m}^3$ and $0.6 \pm 0.5 \mu\text{g}/\text{m}^3$. Based on the average value, SOC in September was comparable between day and nighttime ($p > 0.05$), while that in February at daytime was more than two times higher than at nighttime ($p < 0.05$).

Interestingly, the calculated SOC concentrations in September showed comparable values between night and daytime, with no statistically significant diurnal difference ($p > 0.05$). This apparent persistence or slight enhancement of SOC at night may be related to continued secondary formation, but it could also be an artifact of the EC tracer method if nighttime primary emission sources (such as localized burning) shift the true primary OC/EC ratio. Because bulk carbon analysis cannot definitively distinguish between nocturnal secondary formation and primary emission shifts, further investigations using source-specific molecular organic tracers are required to elucidate the exact nocturnal aerosol dynamics in the wet season.

3.4. Meteorological Information

Figure 6 presents the 12 h average meteorological parameters, including wind speed (WS), wind direction (WD), and precipitation intensity (PI) that were monitored at the Institute of Technology of Cambodia in September (wet season) and February (dry season).

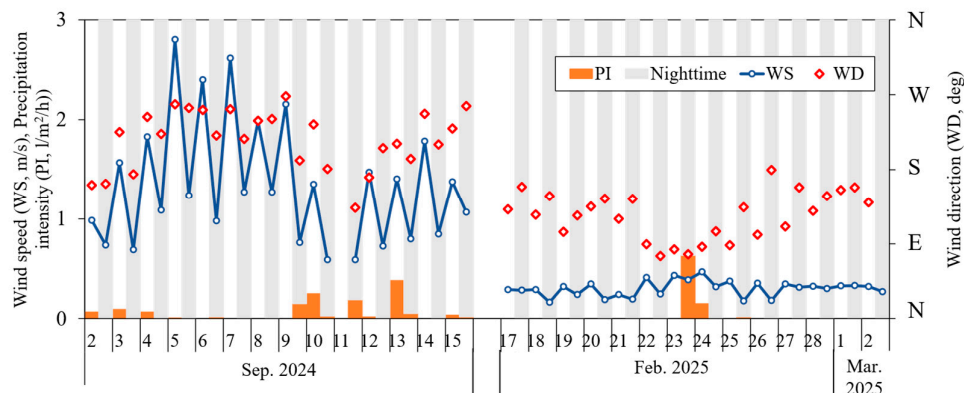


Figure 6. The 12 h average of meteorological data: wind speed (WS, m/s), wind direction (WD, deg), and precipitation intensity (PI, l/m²/h) monitored by AQMS at the Institute of Technology of Cambodia.

In September, wind speeds were notably higher and more variable, ranging from approximately 0.6 to 2.8 m/s on average, with a distinct alternating pattern between daytime and nighttime periods. The diurnal pattern showed a clear peak during the daytime compared to nighttime. Wind directions were predominantly from the south to southwest, consistent with the prevailing southwest monsoon during the wet season. Precipitation events were observed on several days, with intensities reaching up to approximately 0.4 L/m²/h. These rainfall occurrences are consistent with wet scavenging effects that may have contributed to the reduced PM_{0.1} concentrations.

Unlike in September, wind speeds in February were considerably lower and more stable, generally remaining below 0.5 m/s throughout the campaign. Wind speed during the day showed slightly higher values than at night and was almost stable from the end of February until the end of the campaign. Wind directions shifted predominantly to the northeast and southeast, reflecting the influence of the dry northeast monsoon. As in the middle of the dry season, precipitation was almost absent in February, except on 23 and 24 February when the average precipitation intensity reached 0.6 L/m²/h, even higher than that observed in September. The combination of low wind speeds and the absence of rainfall created stagnant atmospheric conditions that suppressed pollutant dispersion, favoring the accumulation of PM_{0.1} and its carbonaceous components near the surface. These conditions, together with the shallower nocturnal boundary layer, are consistent with the elevated PM_{0.1} concentrations and the nighttime-dominant diurnal pattern observed during the dry season.

3.5. Trajectory and Hotspot Observation

To identify the potential source regions influencing PM_{0.1} concentrations at the sampling site, 24 h backward trajectories were computed using the NOAA HYSPLIT model for each sampling period: September 2024 (Figures S1) and February 2025 (Figure S2). During the September 2024 campaign (wet season), air masses predominantly originated from the southwest/south (mean wind direction: $216.8^\circ \pm 35.5^\circ$), consistent with the southwest monsoon, transporting relatively cleaner marine air from the Gulf of Thailand and the Indian Ocean toward Phnom Penh. In contrast, during the February 2025 campaign (dry season), trajectories indicated air mass transport primarily from the east to northeast (mean wind direction: $125.0^\circ \pm 28.6^\circ$), passing over regions with active biomass burning as evidenced by the 48 h fire spot data. The convergence of long-range transport from fire-affected areas with the prevailing dry season meteorological conditions, characterized by significantly lower wind speeds (mean 0.3 ± 0.1 m/s vs. 1.3 ± 0.6 m/s in September) and

negligible precipitation, likely contributed to the substantially elevated $PM_{0.1}$, OC, and EC concentrations observed in February 2025 relative to September 2024.

4. Discussion

$PM_{0.1}$ mass concentrations in February (range 3.9–11.3 $\mu\text{g}/\text{m}^3$) are significantly higher than in September (mostly between 1.7 and 4.0 $\mu\text{g}/\text{m}^3$). Although some rainfall occurred during the September sampling, it did not result in a significant reduction in $PM_{0.1}$ concentrations, as well as their carbonaceous components. It might be due to the low intensity of precipitation (mean $< 0.5 \text{ L}/\text{m}^2/\text{h}$), which is likely insufficient to trigger significant wet deposition of ultrafine particles ($PM_{0.1}$). On the other hand, the rain might soak in the waste or unwanted materials, leading to unfavorable conditions for open burning. Another important reason might be the non-harvest season, so that agricultural burning was almost non-existent. The difference between daytime and nighttime source contributions to $PM_{0.1}$ concentrations reflects the mix of sources around the sampling locations. Because the total OC+EC mass is relatively constant day/night, the $PM_{0.1}$ diurnal shift is driven by unanalyzed fractions, and the exact mechanism cannot be determined without further inorganic analysis.

Conversely, the dry season (February) lacked precipitation entirely, shifting the diurnal control to boundary-layer dynamics and atmospheric ventilation. During February nights, the complete loss of solar radiation coupled with consistently low nocturnal wind speeds compressed the mixing volume near the surface. This mechanical stagnation trapped ongoing local traffic emissions and transboundary agricultural plumes near ground level, which may drive the nighttime accumulation of primary organic carbon (POC) during the dry period.

The 24 h trajectories indicate that the air mass crosses the coastline and enters the local region (Figures S2 and S3). In September, backward trajectories indicated that air masses predominantly originated from the Gulf of Thailand. However, no hotspots were observed in the transport pathway during this month. The lack of trajectory-hotspot intersection, combined with the maritime nature of the air, suggests that the transboundary effect was not a primary contributor to $PM_{0.1}$ during this period, leaving local emissions as the dominant source. In the dry period (February), hotspot numbers were found to be dense in the north and northeast parts of Cambodia. In contrast, the trajectories usually travel from the eastern and southern parts across the Cambodia–Vietnam border. This provides corroborating evidence that the observed spikes in $PM_{0.1}$ and carbonaceous components were likely driven by short-range transboundary transport from nearby burning areas, rather than long-range transport from distant countries.

Despite the increase in $PM_{0.1}$ and OC concentrations in February, EC showed minimal variation across the observation period. EC is an important indicator of primary pollutants emitted mainly from vehicular fossil fuel combustion. On the other hand, EC can also be emitted during the combustion of biomass, waste/plastic, as well as firewood [8]. EC would therefore be expected to increase alongside $PM_{0.1}$; however, the relatively constant EC throughout the observation period likely reflects the commonality of local activities throughout the year, especially traffic volume or residential burning activities.

Although local combustion sources may remain relatively stable year-round, EC concentrations showed a modest yet statistically significant increase ($\sim 1.25\times$) in the dry season. This slight elevation can be partially attributed to meteorological stagnation, such as lower wind speeds ($0.3 \pm 0.1 \text{ m/s}$ in February vs. $1.3 \pm 0.6 \text{ m/s}$ in September), which traps local emissions. However, this EC increment is disproportionately smaller compared to the 3.4-fold rise in OC. We hypothesize that this notable divergence is primarily driven by the seasonal influx of regional biomass-burning plumes, which are typically characterized by high OC/EC ratios as suggested by our trajectory and hotspot analysis, along with

potentially enhanced secondary organic aerosol (SOC) formation under dry-season conditions. Furthermore, it should be noted as a limitation that EC determined by the thermal-optical method may carry charring artifacts.

5. Conclusions

This study successfully characterized the seasonal and diurnal variations in ultrafine particles (PM_{0.1}) and their carbonaceous components (OC and EC) in Phnom Penh, Cambodia, providing critical baseline data for an understudied metropolitan area in Southeast Asia. The total mass concentration of PM_{0.1} exhibited a distinct seasonal pattern, with a concentration in February ($8.5 \pm 1.7 \mu\text{g}/\text{m}^3$) being approximately three times higher than that in September (wet season). This substantial increase was predominantly driven by a matching threefold rise in OC concentrations, whereas EC concentrations slightly fluctuated: $0.4 \pm 0.1 \mu\text{g}/\text{m}^3$ (September) and $0.5 \pm 0.2 \mu\text{g}/\text{m}^3$ (February). The steady baseline of EC suggests a consistent year-round contribution from local urban sources. On average, the total carbonaceous fraction (OC + EC) constituted roughly half of the PM_{0.1} total mass. Diurnal variations and EC tracer analysis revealed that secondary organic carbon (SOC) concentrations increased during the daytime in February ($1.4 \pm 1.0 \mu\text{g}/\text{m}^3$), pointing to intensive photochemical oxidation under favorable dry-season meteorological conditions. Furthermore, backward trajectory modeling combined with satellite hotspot analysis demonstrated that while the wet season was dominated by clean maritime air masses, the elevated PM_{0.1} and OC spikes in the dry season were likely influenced by short-range trans-boundary transport from biomass-burning areas across the Cambodia–Vietnam border.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/atmos17070646/s1>. Figure S1. The 24-h backward trajectories and 48-h fire spots from 2–15 September 2024 (S1–S14) were obtained at the Institute of Technology of Cambodia (ITC); Figure S2. The 24-h backward trajectories and 48-h fire spots from February 17 to 2 March 2025 (F1–F14) were obtained at the Institute of Technology of Cambodia (ITC); Table S1. Average PM_{0.1}, OC, and EC mass concentrations (mean $\pm$ standard deviation (S.D.)) collected during daytime and nighttime in September 2024 and February 2025 in Phnom Penh; Table S2. Correlation coefficient between PM_{0.1}, OC, and EC collected in September 2024 and February 2025 at the Institute of Technology of Cambodia in Phnom Penh; Table S3. Seasonal variation of PM_{0.1} mass and carbonaceous components collected at the Institute of Technology of Cambodia in Phnom Penh; Table S4. Diurnal concentrations and *t*-test parameters for PM_{0.1} chemical components.

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Conflicts of Interest: Author Pengsreng Ngoun is an employee of the Japan International Cooperation Agency (JICA). The funder had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the articles. The paper reflects the views of the scientists and not the funding agency. The remaining authors declare no conflicts of interest.

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