Seasonal characterization of gaseous air pollutants in Phnom Penh, Cambodia

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Abstract. Phnom Penh, the rapidly urbanized capital city of Cambodia, faces significant challenges from air pollution. Air pollutants, including gaseous compounds such as nitric oxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), ozone (O_3), and carbon monoxide (CO), impact public health and can serve as indicators of direct emission sources that may vary seasonally. This study characterized the seasonal variability of these gases over three months in the rainy (August–October, 2024) and dry (January–March, 2025) seasons in Phnom Penh. In the rainy season, NO, NO_2, and NO_x exhibited higher concentration, while O_3 levels were elevated in dry season. These patterns suggest seasonal differences in dominant emission sources between vehicular emissions and biomass burning, as well as distinct atmospheric chemical processes. CO concentrations remained relatively stable across seasons. Meteorological factors, including precipitation and temperature, displayed limited influence on these gaseous pollutant levels, whereas wind speed showed weak correlations. Diurnal patterns revealed morning and evening peaks in NO, NO_2, NO_x, and CO associated with rush hours, while ozone peaked in the afternoon, corresponding to peak sunlight intensity.

1 Introduction

Many cities worldwide, particularly in developing countries, are still facing major environmental problems, among which air pollution is one of the most serious [1]. Phnom Penh, the capital city of Cambodia, is no exception. With its ongoing urban development, increasing traffic volume, expanding construction activities, and rising energy consumption, air pollution has become a major concern for everyday life in the city [2]. Air pollutants include both gaseous pollutants and particulate components. Among the gaseous pollutants, nitrogen oxides (NO, NO_2, and collectively NO_x) and carbon monoxide (CO) serve as indicators of direct emissions from sources, as well as the precursors to secondary pollutants formed through atmospheric chemical reactions, such as ozone (O_3) and other particulate components [3].

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NO, NO_2, and NO_x are primarily emitted from high-temperature combustion processes, including vehicle exhaust and industrial activities, and they play key roles as precursors in the formation of ozone (O_3) and secondary particulate matter [3, 4]. Ozone, a photochemical secondary pollutant, is known to cause respiratory illnesses and contribute to crop damage [5]. Carbon monoxide (CO), mainly emitted from the incomplete combustion of carbonaceous fuels, poses serious health hazards due to its ability to reduce oxygen delivery in the body [3]. The concentrations of these gases often display distinct seasonal patterns driven by variability in meteorological conditions, emission activities, and atmospheric chemistry [6].

Understanding the characteristics of these gaseous pollutants is crucial for addressing the current knowledge gap regarding the seasonal air quality dynamics in Phnom Penh and for developing effective air quality management and public health protection strategies. Therefore, this study aims to characterize the seasonal variation of gaseous air pollutants, NO, NO_2, NO_x, O_3, and CO, in Phnom Penh by analyzing average daily and hourly concentrations during both the dry and rainy seasons in relation to some meteorological parameters.

2 Methodology

2.1 Study area

Phnom Penh is the capital city of Cambodia, serving as the center of economic, political, and industrial activities [7]. It is located in the south-central region of the country, lying at the confluence of the Mekong, Tonle Sap, and Bassac rivers (**Figure 1**). Phnom Penh has a tropical climate characterized by two distinct seasons— a monsoon-driven rainy season lasting from May to October, and a dry season from November to April [8]. With its rapid population growth and increasing economic activity, Phnom Penh is experiencing increased energy consumption, a rising number of private vehicles, and accelerated infrastructure development, all of which contribute to the growing environmental pressure in the city [7]. In this study, the air quality monitoring site was situated at the Institute of Technology of Cambodia (ITC), located near the center of Phnom Penh, and surrounded by commercial areas and major vehicular traffic routes, including trains, cars, and motorbikes.

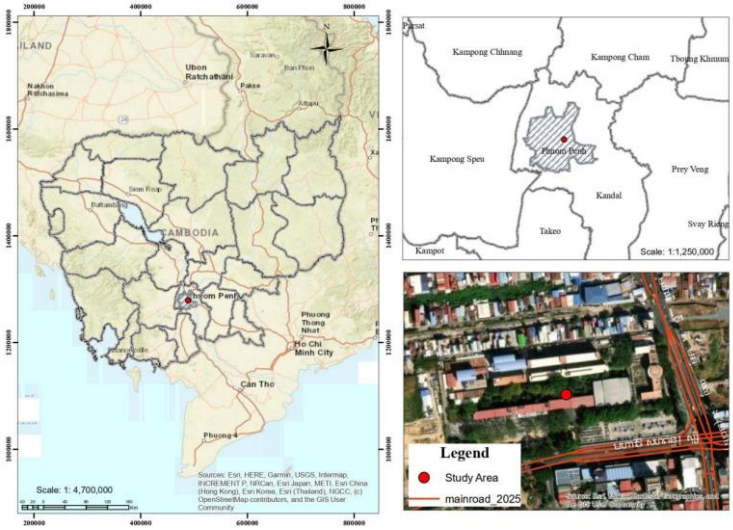

Fig.1. Location of sampling site (ITC), Phnom Penh city, Cambodia.

2.2 Data collection and analysis

The monitoring of gaseous air pollutants in this study was conducted using an Air Quality Monitoring Station (AQMS-1560, HORIBA, Japan), installed on the 4th floor and connected to the rooftop of Building A at ITC. The monitoring period covered three months in the rainy season (from August to October, 2024) and another three months in the dry season (from January to March, 2025). The AQMS provides continuous measurement of key air pollutants, including particulate matter and gaseous pollutants; however, in this study, only five major gases (NO, NO_2, NO_x, O_3, and CO) were reported. Hourly average concentrations of each gas were recorded and downloaded from the AQMS for the monitoring period. Daily average concentrations of each gas were calculated and analyzed to identify characteristic patterns of gaseous air pollutants during the two seasons in Phnom Penh, Cambodia.

Meteorological parameters, including temperature (T), precipitation (Prcp.), and wind speed (Ws), as daily averages corresponding to the monitoring period, were acquired from the open-access weather website, Meteostat (https://meteostat.net/en/). Pearson's correlation coefficient (r) was used to measure the strength and direction of the relationship between each gas pollutant with meteorological parameter. The value ranges of r were categorized as follows: $|r| < 0.4$, little to no meaningful correlation; $0.4 \leq |r| < 0.6$, weak; $0.6 \leq |r| < 0.8$, moderate; $0.8 \leq |r| < 0.9$, strong; and $|r| \geq 0.9$, very strong. A significance level of $p < 0.05$ was used to assess the statistical significance of the correlation.

3 Results and Discussion

3.1 Seasonal variation of each gaseous pollutant

Table 1 summarizes the three-month averages of the daily average concentrations of five gaseous air pollutants (NO, NO_2, NO_x, O_3 and CO) in the rainy and dry seasons in Phnom Penh, Cambodia. Nitrogen-related gases, including NO, NO_2, and NO_x, exhibited significantly higher average concentrations during the rainy season (2.4 ± 2.0 ppb, 9.6 ± 3.3 ppb, and 12.0 ± 4.7 ppb, respectively) compared with the dry season (0.4 ± 0.8 ppb, 6.8 ± 3.4 ppb, and 7.3 ± 3.9 ppb, respectively). Interestingly, carbon monoxide (CO) concentrations remained nearly constant between the rainy (0.6 ± 0.1 ppm) and dry (0.6 ± 0.2 ppm) seasons. Ozone concentrations were higher in the dry season (21.9 ± 6.9 ppb) than in the rainy season (11.9 ± 4.7 ppb). This is considered to be due to stronger sunlight and drier atmospheric conditions in the dry season, which enhance photochemical reactions [5].

The seasonal pattern of the NO_x/CO ratio can serve as an indicator for explaining seasonal differences in emission sources. Vehicle emissions involve high-temperature combustion, whereas biomass burning occurs at lower temperatures than internal combustion and involves incomplete combustion. As a result, vehicle exhaust produces more NO_x and less CO compared with biomass burning, leading to a higher NO_x/CO ratio than that associated with biomass-burning emissions [9]. In Phnom Penh, the NO_x/CO ratio tended to be higher in the rainy season and lower in the dry season. Considering that open burning and forest fires frequently occur in Cambodia's rural and forested areas during the dry season and can influence air quality in and around Phnom Penh, the lower NO_x/CO ratio observed in the dry season is consistent with this influence [10]. In addition, the frequent cloud cover observed during the rainy season reduces solar radiation, suppressing ozone formation and consequently allowing nitrogen oxides to accumulate more easily. This may be another possible reason for the higher NO_x/CO ratio during the rainy season.

Table 1. Average concentrations of each gaseous air pollutant across Rainy and Dry seasons.

Season	NO (ppb)	NO_2 (ppb)	NO_x (ppb)	O_3 (ppb)	CO (ppm)
Rainy	**2.4 ± 2.0**	**9.6 ± 3.3**	**12.0 ± 4.7**	11.9 ± 4.7	0.6 ± 0.1
Dry	0.4 ± 0.8	6.8 ± 3.4	7.3 ± 3.9	**21.9 ± 6.9**	**0.6 ± 0.2**

3.2 Correlations of daily variations of each gas to meteorological conditions

Figure 2 depicts the daily average values of meteorological parameters, including precipitation, wind speed, and temperature along with the daily average concentrations of each gaseous pollutant during August to October in the rainy season and January to March in the dry season in Phnom Penh city. In the rainy season, frequent rainfall events occurred; however, no clear influence pattern was observed on the concentrations of the gases. Correlation coefficients between precipitation and each gas showed insignificant relationships (n = 85; r = 0.06, −0.12, −0.06, 0.05, and 0.03, respectively, for NO, NO_2, NO_x, O_3, and CO, with all p-values > 0.05) (**Table 2**). Similarly, in the dry season, despite less precipitation, no significant correlations with the gases were found (n = 84; r = 0.02, 0.14, 0.13, −0.14, and −0.14, respectively, for NO, NO_2, NO_x, O_3, and CO). These results suggest that the washout effect of precipitation may have limited impact on these gaseous pollutants during the monitoring period.

Wind speed in the rainy season, showed a statistically significant weak negative correlation with O_3 (n = 92; r = −0.44; p < 0.01) (**Table 2**), and no correlation with other gases such as NO, NO_2, NO_x, and CO. In contrast, in the dry season, wind speed showed statistically significant weak negative correlations with NO_2, NO_x, and CO (n = 90; r = −0.40, −0.40, and −0.53, respectively; all p < 0.01), yet it had no meaningful correlation with O_3 (n = 90; r = 0.29; p < 0.01) (**Table 2**). This indicated that higher ozone concentrations in the rainy season were associated with lower wind speed, as evident in October of the rainy season (**Figure 2**); yet it appeared to have no effect on ozone concentrations during the dry season. Rather, in the dry season, temperature tended to show a statistically significant moderate negative correlation with O_3 concentration (n = 90; r = −0.67; p < 0.01) (**Table 2**).

Table 2. Correlations of gaseous air pollutants and meteorological conditions in rainy and dry seasons.

Season	Meteorological parameters	Gaseous air Pollutants				
		NO	**NO_2**	**NO_x**	**O_3**	**CO**
Rainy	**Prcp. (mm)** *(n=85)*	0.06	−0.12	−0.06	0.05	0.03
	Ws (m/s) *(n=92)*	**0.32****	0.10	0.20	**−0.44****	−0.19
	T (°C) *(n=92)*	0.11	**0.25***	**0.22***	0.02	**−0.24***
Dry	**Prcp. (mm)** *(n=84)*	0.02	0.14	0.13	−0.14	−0.14
	Ws (m/s) *(n=90)*	**−0.27****	**−0.40****	**−0.40****	**0.29****	**−0.53****
	T (°C) *(n=90)*	**0.25***	**0.30****	**0.31****	**−0.67****	0.02

Prcp., precipitation; Ws, wind speed; T, temperature; n, sample size.
**p* < 0.05, ***p* < 0.01.

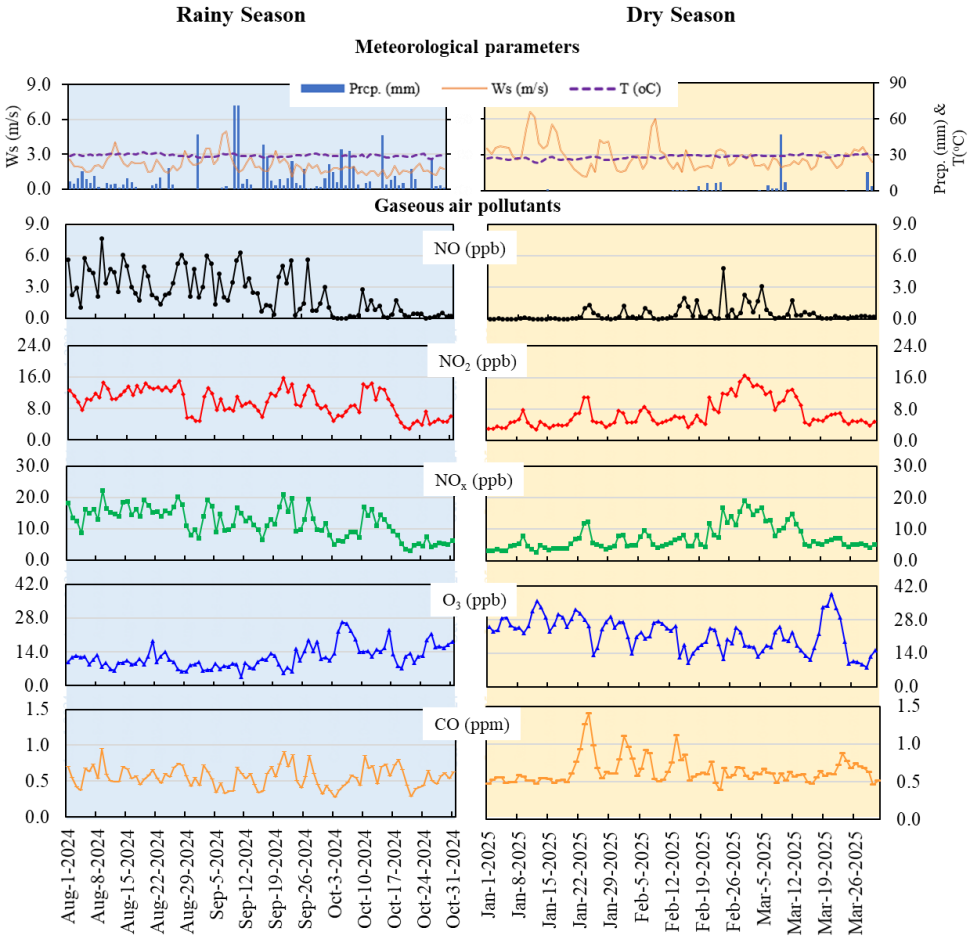

Fig.2. Daily average values and concentrations of meteorological parameters and each gas across 3 months of the rainy and dry seasons in Phnom Penh city.

3.3 Diurnal variation of each gaseous pollutant

Figure 3 illustrates the diurnal variations in NO, NO_2, NO_x, O_3, and CO concentrations during the rainy and dry seasons in Phnom Penh. The average hourly concentrations of NO, NO_2, NO_x and CO exhibited two peaks throughout the day, occurring in the morning and evening in both seasons. During the rainy season, the morning peaks for these gases were observed between 6:00 and 8:00, while evening peaks occurred between 17:00 and 21:00. Similarly, in the dry season, morning peaks occurred from 7:00 to 9:00, with evening peaks extending from 18:00 to nearly 22:00. These peak periods correspond to typical rush hours, characterized by increased vehicular emissions, contributing to the high emissions of these primary pollutants [11].

Ozone concentrations, in contrast, showed only a single peak in both seasons, primarily during the afternoon. The ozone peak in the rainy season occurred around 12:00, while in the dry season, it peaked later, between 14:00 and 15:00. This pattern aligns with the role of solar radiation, which drives photochemical reactions responsible for ozone formation during daylight hours, with stronger radiation during the dry season promoting higher ozone levels in the afternoon [11].

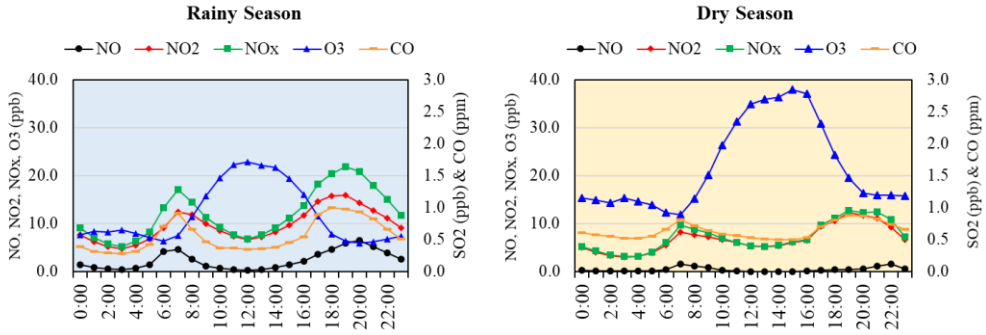

Fig. 3. Average hourly concentration of each gaseous air pollutants of the two seasons

4 Conclusion

This study highlights significant seasonal and diurnal variations in gaseous air pollutant concentrations in Phnom Penh, driven by complex interactions between emission sources and meteorological conditions. Higher levels of nitrogen-related gases (NO, NO_2, and NO_x) during the rainy season and increased ozone (O_3) concentrations during the dry season reflect distinct atmospheric chemistry influenced by sunlight and human activities such as vehicular emissions and biomass burning. Carbon monoxide (CO) concentrations remained relatively stable across seasons. Daily meteorological parameters such as precipitation and temperature had limited or no significant influence on these gaseous pollutants during both seasons, except for temperature in the dry season, which showed a moderate negative correlation with ozone. Wind speed tended to have statistically significant weak correlations with most gases, with an opposite pattern for O_3 between the rainy and dry seasons. Diurnal variation patterns revealed morning and evening peaks in nitrogen oxides and CO concentrations, corresponding to increased vehicular emissions during rush hours. Ozone exhibited a single afternoon peak, which may be linked to higher solar radiation in the afternoon time. These findings emphasize the need for season-specific air quality management strategies that target major pollution sources while accounting for climatic influences in Phnom Penh. To better characterize the variation patterns of gaseous pollutants, additional meteorological parameters such as solar radiation, wind direction, and humidity should be incorporated in future analyses, and hourly measurements of these variables should be used to more precisely elucidate their influences on pollutant characteristics in Phnom Penh, Cambodia.

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