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Short communication

Temporal Variations of $PM_{2.5}$ and Its Meteorological Determinants in an Urban Background Site of Butuan City, Philippines

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High levels of air pollution have been linked to global health and environmental issues for more than half a century. Particulate matter (PM), specifically fine particles with a diameter of 2.5 micrometers or less, known as the $PM_{2.5}$, degrades air quality and has been widely associated with adverse effects on the human respiratory system (Xing *et al.,* 2016; Feng *et al.,* 2016; Sharma *et al.,* 2020; Krittanawong *et al.,* 2023). To evaluate its environmental and health impacts, studies on the characterization and temporal variations have been conducted (Betito *et al.,* 2025; Hilario *et al.,* 2020). Additionally, several studies have investigated the relationships between $PM_{2.5}$ concentration and meteorological parameters, such as wind speed, temperature, relative humidity, and precipitation, revealing that these parameters can significantly influence particulate dispersion and accumulation (Yang *et al.,* 2017; Chen *et al.,* 2016). Even studies on vertical profiling of air pollutants are also increasing (Dubey *et al.,* 2022; Nyayapathi *et al.,* 2025). Hence, understanding the trends, cycles, and location-specific characteristics of PM2.5, as well as the influence of meteorology, is crucial for providing a better assessment of health impacts and for developing effective mitigation strategies for air quality management and policy (Cholianawati *et al.,* 2024).

Although several studies have been conducted, the understanding of $PM_{2.5}$ dynamics in urban background areas of medium-sized cities in the Philippines remains limited. Particularly, local sources such as vehicular emissions, residential activities, and vegetation cover may interact with meteorological conditions to shape temporal trends. Examining the weekly and monthly variations of $PM_{2.5}$ and their meteorological determinants in such settings is essential for identifying critical periods of high exposure, understanding pollutant behavior, and informing air quality management strategies tailored to local conditions. Therefore, the present study aims to analyze the temporal variations of $PM_{2.5}$ in an urban-background area of Butuan City, Philippines, and to evaluate the influence of key meteorological factors on its concentration patterns. Wherein findings are useful for evaluating future health risk assessment in a dense and traffic-heavy city center, and for shaping relevant policies.

Study area and data

The $PM_{2.5}$ concentration data used in this study were obtained from the Department of Environment and Natural Resources – Caraga region (DENR-Caraga). The air quality monitoring station is located within the CARBDP motor pool compound, Barangay Doongan, Butuan City, at the following geographic coordinates: 8.954990°N, 125.526790°E. Meteorological parameters were acquired from Open-Meteo, an open-source weather API that offers high-resolution reanalysis datasets (Zippenfenig, 2023; Hersbach *et al.,* 2023). The meteorological data included daily records of key meteorological factors such as temperature, precipitation, wind speed, shortwave radiation, relative humidity, cloud cover, and soil moisture. The data covered the period from January 1, 2022, to December 31, 2024, and was recorded at a daily temporal resolution.

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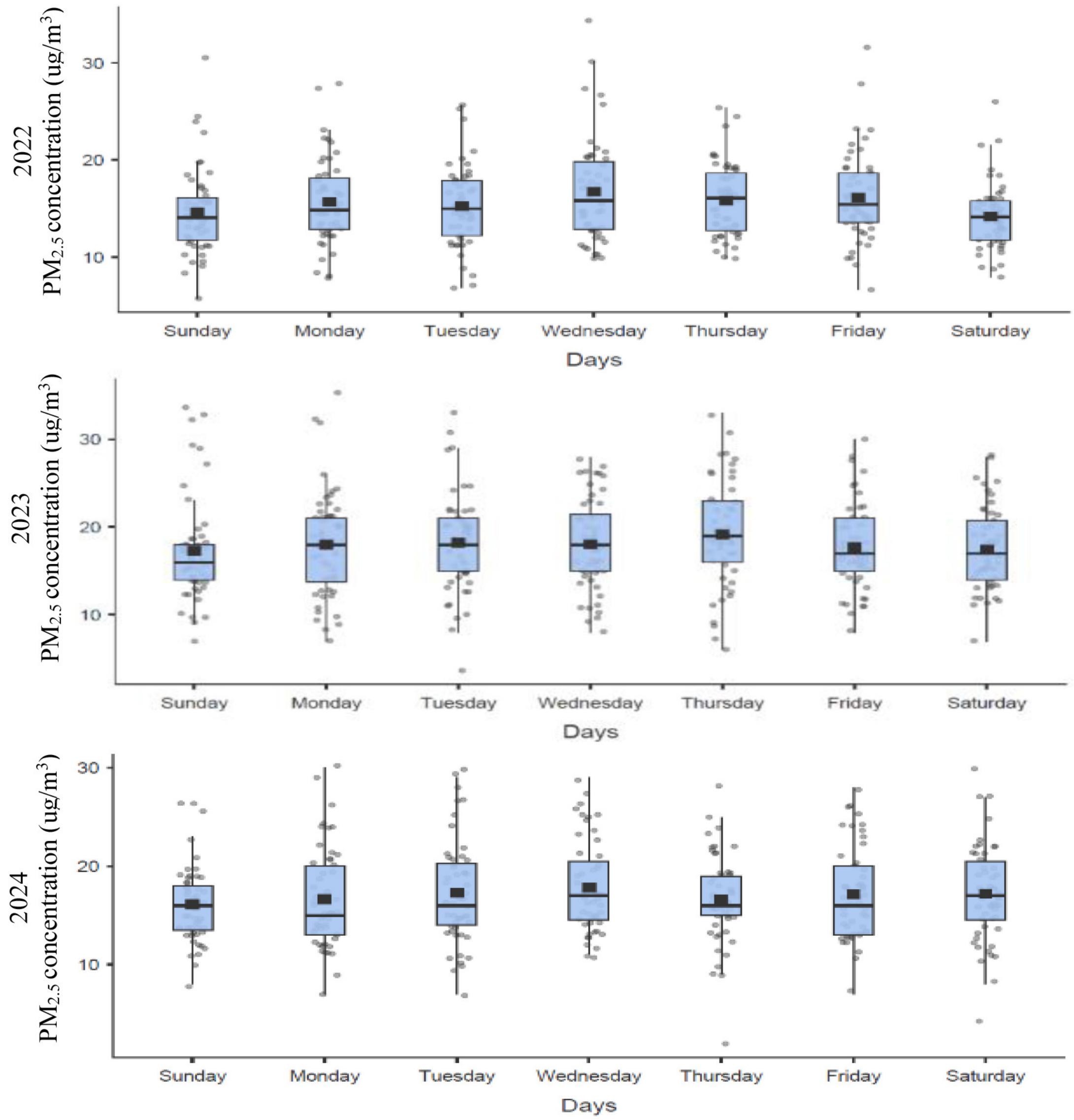

Fig. 1: Weekly variations in $PM_{2.5}$ concentrations (ug/m³) for the years 2022-2024.

$PM_{2.5}$ weekly variation

$PM_{2.5}$ concentration across the week is likely to appear fairly similar, with small variations for the year 2022-2023 (Fig. 1). In 2022, midweek (Monday to Friday) $PM_{2.5}$ levels are relatively stable and slightly higher than on weekends (Saturday to Sunday). This pattern suggests that human activities on midweek do not substantially affect $PM_{2.5}$ levels. Thus, the area does not exhibit a strong weekly cycle, as commonly observed in traffic sites of larger cities, where PM levels peak on weekdays and decline on weekends due to vehicle emissions. Across the years, the consistency of the weekly pattern suggests that local emission-driven sources and activity rhythms within the compound are typical rather than exceptional events.

Fig. 2 shows the monthly PM2.5 concentrations from 2022 to 2024. Clear temporal and inter-annual variations in air quality are observed. Generally moderate and stable PM2.5 levels were observed in 2022, ranging from 12.56 to 17.89 µg/m³, with relatively low variability across months. In contrast, substantially higher concentrations in almost all months, peaking in October at 23.26 µg/m³ were recorded in 2023, the highest value observed during the three-year period. The greatest variability was also exhibited, particularly in July (SD = 8.31), indicating episodic pollution events or unstable atmospheric conditions.

Meanwhile, the 2024 data show PM2.5 values falling between those of 2022 and 2023. The month of September (19.07 µg/m³) and November (20.02 µg/m³) is observed to approach similar elevated levels recorded in 2023, while mid-year months (April–June) remained comparatively lower. In general, 2023 emerged as the most polluted year, characterized by sustained high PM2.5 levels and greater fluctuations, whereas 2022 appeared the cleanest air quality profile.

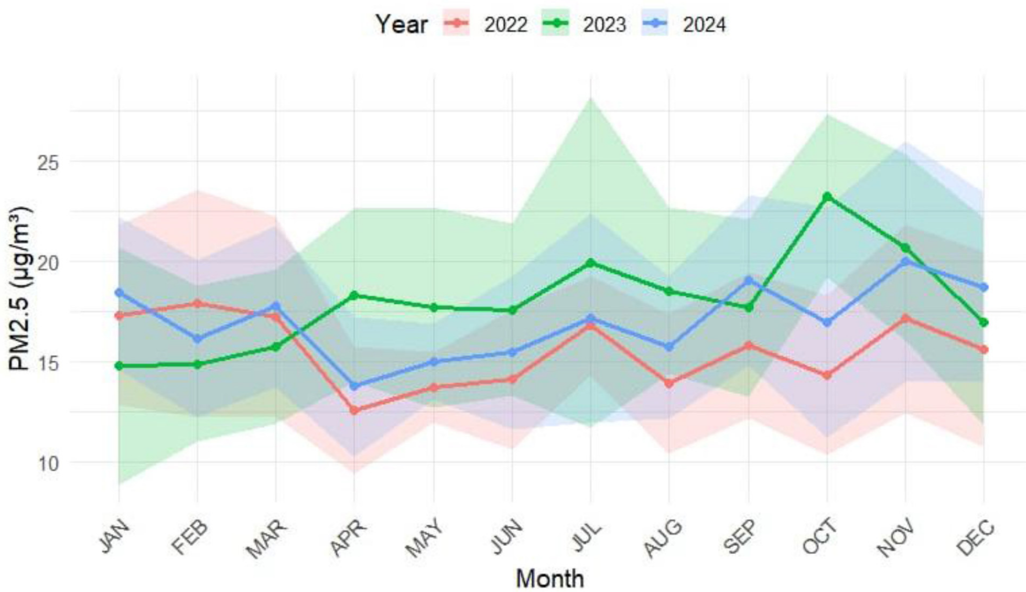

Fig. 2: Monthly averaged $PM_{2.5}$ concentrations (ug/m^3) for the years 2022-2024.

Table 1: Correlation matrix of $PM_{2.5}$ concentration and meteorological parameters

Variable	Precip.	Cloud	RH	Soil M.	PM2.5	ET0	Shortwave	Temp max	App. temp	Wind	App. mean
Precip.	1.00	0.34	0.50	0.31	-0.20	-0.40	-0.36	-0.41	-0.29	-0.19	-0.22
Cloud	0.34	1.00	0.55	0.36	-0.09	-0.55	-0.51	-0.51	-0.44	-0.25	-0.26
RH	0.50	0.55	1.00	0.71	-0.09	-0.71	-0.57	-0.82	-0.60	-0.52	-0.49
Soil M.	0.31	0.36	0.71	1.00	-0.04	-0.49	-0.36	-0.65	-0.47	-0.49	-0.48
PM2.5	-0.20	-0.09	-0.09	-0.04	1.00	0.06	0.07	0.05	0.05	0.03	0.18
ET0	-0.40	-0.55	-0.71	-0.49	0.06	1.00	0.88	0.84	0.81	0.38	0.41
Shortwave	-0.36	-0.51	-0.57	-0.36	0.07	0.88	1.00	0.74	0.76	0.29	0.32
Temp max	-0.41	-0.51	-0.82	-0.65	0.05	0.84	0.74	1.00	0.91	0.37	0.58
App. temp	-0.29	-0.44	-0.60	-0.47	0.05	0.81	0.76	0.91	1.00	0.16	0.59
Wind	-0.19	-0.25	-0.52	-0.49	0.03	0.38	0.29	0.37	0.16	1.00	0.41
App. mean	-0.22	-0.26	-0.49	-0.48	0.18	0.41	0.32	0.58	0.59	0.41	1.00

Note. Values are Pearson correlation coefficients (r). Abbreviations: Precip. = precipitation; RH = relative humidity; Soil M. = soil moisture; PM2.5 = fine particulate matter ≤2.5 µm; ET0 = evapotranspiration; Shortwave = shortwave radiation; Temp max = maximum temperature; App. temp = apparent temperature; App. mean = mean apparent temperature. The table reproduces the coefficients shown in the original correlation-matrix figure and uses no colour coding.

Relationship between $PM_{2.5}$ and Meteorological Parameters

Linear relationships between $PM_{2.5}$ concentration and several meteorological parameters in the present study are presented in Table 1. A very weak to slightly negligible correlation can be observed in most meteorological parameters. A positive correlation exists between $PM_{2.5}$ and evapotranspiration, shortwave radiation, wind, and temperature. It is negatively correlated with soil moisture, precipitation, and cloud cover. The result is inconsistent with the mechanisms in an urban site, where $PM_{2.5}$ is negatively correlated with wind, temperature, relative humidity, and precipitation (Chen *et al.,* 2016). The positive correlation between $PM_{2.5}$ and temperature suggests that higher temperatures may enhance secondary aerosol formation or promote atmospheric stagnation, leading to increased particulate concentrations.

Meanwhile, a positive correlation with wind speed suggests that wind may be transporting pollutants from external sources and resuspending particulates within the area, thereby increasing their concentration. Thus, this area is not influenced by the traffic-dense city, where wind usually helps disperse PM2.5 rather than increasing it. The results are considered reliable because the air quality monitoring station is situated within a government compound with open space and surrounding trees, despite being relatively close to a roadway. Therefore, the influence of meteorological factors on $PM_{2.5}$ varies across different regions and is highly site-specific, often resulting in inconsistent or even contradictory relationships by regions (Tai *et al.,* 2010; Krishnaveni *et al*., 2024).

The baseline data in this study will be useful for future studies, such as assessing the impact on crop production and evaluating health risks associated with higher concentrations, particularly in areas with high traffic volumes. However, the present study is limited to only one station, the urban background site, because no air quality monitoring system has been installed in other areas. Overall, the findings of this study provide valuable baseline information that can be used by other regions with similar environmental conditions and monitoring limitations. By demonstrating how $PM_{2.5}$ levels respond to local meteorological factors and urban activity patterns, the study offers a scientific basis for comparative assessments and supports evidence-based policymaking.

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Authorship contribution: **Grethyl C. Jamero:** Investigation, Data visualization and analysis, Writing original draft, Review editing; **Rey Marc T. Cumba:** Data cleaning and analysis, Review, Editing; **Jerico D. Catipay:** Data visualization and analysis; **Roxan Jimenez and Kenneth Albert Arcamo:** Data collection.

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