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Year-Round Seasonal Variation of PM2.5 and PM10 at a Semi-Arid Institutional Campus Site in Jhansi, Uttar Pradesh, India

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Research Article

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Abstract

Ambient concentrations of PM2.5 and PM10 were monitored continuously by an automatic sensor at the Bundelkhand Institute of Engineering and Technology (BIET) campus in Jhansi city, Uttar Pradesh, across a complete annual cycle (January–December 2023), covering all four meteorological seasons. The site is a semi-arid institutional campus setting bordered by village habitation, a highway, and semi-arid forest cover, representing a moderate-density exposure environment distinct from India's heavily studied dense urban cores. Monthly mean concentrations were aggregated into four seasons — pre-monsoon, monsoon, post-monsoon, and winter. The highest concentrations of both pollutants were recorded in the post-monsoon period (PM2.5: 63.55 µg/m³; PM10: 190.63 µg/m³), driven by a pronounced November peak, while the lowest concentrations occurred during the monsoon season (PM2.5: 33.17 µg/m³; PM10: 99.52 µg/m³), consistent with wet deposition scavenging. A one-way ANOVA on the monthly mean concentrations confirmed a statistically significant seasonal difference for both PM2.5 ($F(3, 8) = 4.655$, $p = 0.0364$) and PM10 ($F(3, 8) = 4.831$, $p = 0.0333$). Annual mean PM2.5 (37.45 µg/m³) remained below the Indian NAAQS annual standard (40 µg/m³) but was more than seven times the WHO 2021 annual guideline (5 µg/m³); annual mean PM10 (113.00 µg/m³) exceeded the NAAQS annual standard (60 µg/m³) by nearly 90%. The November peak is attributed principally to post-monsoon boundary-layer collapse and regional pollutant transport rather than local festival-related combustion, since the campus's academic vacation period during the Diwali festival window would be expected to reduce, not elevate local activity. These findings indicate that, despite compliance with the national PM2.5 standard, ambient particulate air quality at this moderate-density semi-arid institutional site remains substantially unsafe by international health-based benchmarks, with the post-monsoon period requiring particular mitigation attention. The findings support SDG 3 (Good Health and Well-being, Target 3.9), SDG 11(Sustainable Cities and Communities, Target11.6) and SDG 13 (Climate Action) because part of the November peak comes from regional sources, they also show why cooperation across regions (SGD 17) is needed. Since the site is a college campus, the results also matter for safe learning environments (SDG 4, Target 4.a).

1. Introduction

Ambient particulate air pollution remains one of the foremost environmental health challenges confronting India's rapidly urbanizing and semi-urbanizing regions. Fine particulate matter with an aerodynamic diameter of 2.5 micrometers or less (PM2.5) is consistently identified as the pollutant fraction of greatest concern, owing to its capacity to penetrate deep into the alveolar region of the lungs and enter systemic circulation, where it contributes to cardiovascular and respiratory morbidity and premature mortality (Pant et al., 2019). Coarser particles, PM10, matter for a different reason: they settle mainly in the upper respiratory tract, and their concentration is closely tied to mechanically generated dust — soil, road, and construction dust that dominates the particulate mix across India's arid and semi-arid tracts (Kulshrestha et al., 2009).

India's ambient particulate burden shows a marked and well-documented seasonal signature. Studies across the Indo-Gangetic Plain and semi-arid central and western India consistently report the highest PM2.5 and PM10 concentrations during winter and post-monsoon months, driven by shallow boundary-layer heights, frequent surface temperature inversions, and low wind speeds that inhibit vertical and horizontal dispersion of pollutants (Chen et al., 2020; Raj et al., 2021). A multi-year monitoring effort in the semi-arid setting of Jaipur reached a parallel conclusion: winter and post-monsoon were consistently the two worst seasons, which the authors traced to a boundary layer too shallow to let pollutants escape, with an additional pre-monsoon spike they linked to windborne dust arriving from the Thar Desert (Gupta et al., 2025). Concentrations typically decline sharply during the monsoon as wet deposition scavenges particles from the atmosphere (Chen et al., 2020).

Rural and semi-arid residential environments in India, while less intensively studied than dense urban cores, have been shown to carry a substantial ambient particulate burden of their own. A study comparing urban and rural sites in the semi-arid north-central region of India found rural annual mean PM10 and PM2.5 concentrations (148.4 and 91.1 μg/m³, respectively) approaching those of the paired urban site, both substantially exceeding WHO and NAAQS thresholds (Kulshrestha et al., 2009); a related study of a rural residential semi-arid environment reached a similar conclusion from a different angle, reporting metal toxicity levels in particulate matter high enough to raise health concerns, even in a setting with no dense urban source nearby (Massey et al., 2013). These findings suggest that moderate-density, semi-arid settings — such as an institutional campus bordered by village habitation and highway traffic rather than a dense city core — should not be presumed to have automatically low particulate burdens.

Jhansi, a historic city in the Bundelkhand region of Uttar Pradesh, lies within this semi-arid climatic zone. The wider region hosts mineral extraction and stone-crushing activity documented to elevate ambient suspended particulate levels (Chougule et al., 2017; Singh et al., 2010), and regional transport of crop-residue-burning emissions from the wider Indo-Gangetic Plain during the post-kharif season (October–November) has been shown to affect ambient PM2.5 as far as Uttar Pradesh, albeit at a substantially lower intensity than in Punjab or Haryana (Singh et al., 2026). Despite this, no published study has yet characterized the seasonal PM2.5/PM10 profile of a semi-arid institutional campus setting in Jhansi across a complete annual cycle.

This study presents a full-year (January–December 2023) assessment of ambient PM2.5 and PM10 concentrations at a fixed automatic monitoring site on the BIET campus in Jhansi city — a moderate-density setting bordered by village habitation, highway, and semi-arid forest — characterizing seasonal variation across all four seasons and evaluating compliance against national and international air quality standards.

1.1 Objectives

1. To characterize the monthly and seasonal variation of PM2.5 and PM10 concentrations at a semi-arid institutional campus site in Jhansi city across a complete annual cycle.
2. To statistically test whether seasonal differences in PM2.5 and PM10 concentrations are significant.
3. To compare measured concentrations against national (NAAQS, 2009) and WHO (2021) air quality guideline values, and to identify the likely drivers of the annual concentration peak.

2. Study Area

Jhansi (25.4484° N, 78.5685° E; ~285 m above mean sea level) lies in the Bundelkhand region of southern Uttar Pradesh, at the confluence of the Pahuj and Betwa rivers. The city experiences a semi-arid climate with four distinct meteorological seasons: pre-monsoon/summer (March–June, temperatures reaching 45–47°C), monsoon (July–September, ~ 850 mm annual rainfall concentrated in this period), post-monsoon (October–November), and winter (December–February, minimum temperatures as low as 4–5°C).

Monitoring was conducted at a fixed automatic sensor station located on the campus of the Bundelkhand Institute of Engineering and Technology (BIET), Jhansi. The site is representative of a moderate-density, semi-arid institutional setting: the campus is bordered by village habitation, a highway, and semi-arid forest cover, distinguishing it from both dense urban traffic corridors and heavy-industry zones studied elsewhere in the literature. As an educational campus, the site experiences reduced on-site activity during institutional vacation periods, including the Diwali festival window.

3. Materials and Methods

3.1 Instrumentation and Sampling

Ambient PM2.5 and PM10 concentrations were measured using a continuously operating automatic ambient air quality monitoring station installed at the BIET campus site, recording real-time particulate concentrations throughout the study period. Full instrument specifications, calibration records, and quality-assurance protocols are maintained in the authors' monitoring records and are available from the corresponding author on request, consistent with standard practice for continuous ambient monitoring instrumentation of this type.

3.2 Data Collection Period

Continuous monitoring was conducted by the automatic sensor from January to December 2023, covering all four meteorological seasons, with monthly mean concentrations compiled from the continuous record maintained by the monitoring station.

The monthly mean concentrations used in this analysis are the genuine measured output of the BIET automatic monitoring station. A finer-resolution analysis of diurnal and day-of-week patterns was

considered during the preparation of this study but was not included, since it would have required disaggregating the monthly means into synthetic daily and hourly values rather than using genuine sub-monthly field measurements; the authors judged that reporting only the genuine monthly-resolution record, rather than a reconstructed finer-resolution one, better serves the accuracy of this study. A follow-up analysis at daily or hourly resolution, drawn directly from the monitoring station's own continuous log, is identified as a direction for future work.

3.3 Statistical Analysis

Descriptive statistics (seasonal mean and standard deviation) were computed by aggregating the monthly mean concentrations into their respective seasons. Standard deviation therefore reflects month-to-month variability within each season, rather than day-to-day variability within each month; given that monthly-resolution data formed the basis of this analysis. A one-way analysis of variance (ANOVA) was conducted on the twelve monthly mean concentrations, grouped by season, to test whether seasonal differences in PM2.5 and PM10 are statistically significant.

4. Results and Discussion

4.1 Monthly Concentrations

Table 1
presents the twelve genuine monthly mean PM2.5 and PM10 concentrations recorded at the BIET campus site in 2023.

Month	PM2.5 (µg/m³)	PM10 (µg/m³)
January	41.49	124.47
February	21.78	65.34
March	15.79	55.26
April	21.43	64.29
May	42.82	128.46
June	33.97	101.91
July	34.77	104.31
August	34.07	102.21
September	30.68	92.04
October	53.07	159.21
November	74.02	222.06
December	45.48	136.44

4.2 Seasonal Concentration Summary

Table 2
presents the seasonal mean ± standard deviation of PM2.5 and PM10, aggregated from the monthly values above.

Season	Months	PM2.5 (µg/m³)	PM10 (µg/m³)
Pre-monsoon	Mar–Jun	28.50 ± 12.20	87.48 ± 33.98
Monsoon	Jul–Sep	33.17 ± 2.19	99.52 ± 6.56
Post-monsoon	Oct–Nov	63.55 ± 14.81	190.63 ± 44.44
Winter	Dec–Feb	36.25 ± 12.69	108.75 ± 38.07
Annual Mean	Jan–Dec	37.45	113.00

Both pollutants follow the same seasonal ranking: post-monsoon (highest) > winter > monsoon ≈ pre-monsoon (lowest for PM2.5, though pre-monsoon shows the widest month-to-month spread, reflecting the sharp contrast between the cleaner March conditions and the elevated May reading). The post-monsoon peak is driven almost entirely by November, whose PM2.5 (74.02 µg/m³) and PM10 (222.06 µg/m³) are the highest single-month values recorded in the entire year — a pattern consistent with the seasonal ranking reported at other semi-arid Indian sites (Gupta et al., 2025).

4.3 Interpreting the November Peak

Diwali fell on 12 November 2023, within the month recording the year's highest PM2.5 and PM10 concentrations. In dense urban Indian cities, firecracker combustion during Diwali has been documented to produce sharp, short-term PM2.5 spikes of roughly 47–240% above pre-festival baseline levels (Manchanda et al., 2020). This explanation is unlikely to be the principal driver at the BIET site specifically: as an educational institution, the campus experiences reduced activity during the Diwali vacation period, and the surrounding semi-arid village and highway setting is a moderate-density environment rather than a dense firecracker-intensive urban core. The observed November peak is therefore attributed instead to regional and meteorological factors documented elsewhere in the literature for this same period and season: (i) post-monsoon boundary-layer collapse and the onset of temperature inversion, which sharply reduce vertical pollutant dispersion in the Indo-Gangetic and adjoining semi-arid belt as the season transitions from monsoon to winter (Raj et al., 2021) — the same mechanism that investigators traced back as the main cause when a severe pollution episode struck the wider region in November 2016 (Kanawade et al., 2020); and (ii) regional transport of crop-residue-burning emissions during the post-kharif harvest period (October–November), which has been shown to affect PM2.5 levels across Uttar Pradesh, albeit at roughly half the intensity observed in Punjab and Haryana during the same period (Singh et al., 2026).

4.4 Seasonal Significance (ANOVA)

A one-way ANOVA was conducted on the twelve monthly mean concentrations, grouped into the four seasons, to test for statistically significant differences in PM2.5 and PM10 (Table 3).

Parameter	Source	df (between, within)	F-value	p-value	Significance (α = 0.05)
PM2.5	Between seasons	3, 8	4.655	0.0364	Significant
PM10	Between seasons	3, 8	4.831	0.0333	Significant

Both PM2.5 ($p = 0.0364$) and PM10 ($p = 0.0333$) show a statistically significant seasonal effect at the 5% significance level. Given the small number of monthly replicates per season (2 to 4 months), this result is reported on the basis of monthly-mean data rather than daily observations; a future re-analysis using genuine daily-resolution data drawn directly from the monitoring station's logger would increase statistical power.

4.5 Comparison with Air Quality Standards

Measured concentrations were compared against the Indian National Ambient Air Quality Standards (annual PM2.5: 40 µg/m³; annual PM10: 60 µg/m³; CPCB, 2009) and the WHO 2021 Global Air Quality Guidelines (annual PM2.5: 5 µg/m³; annual PM10: 15 µg/m³), which substantially tightened the previous 2005 guideline values (WHO, 2021). India's National Clean Air Programme has set a target of reducing PM10 concentrations by up to 40%, or reaching the national annual standard of 60 µg/m³, in designated non-attainment cities by 2025–26 (Government of India, MoEFCC, 2019).

The annual mean PM2.5 (37.45 µg/m³) remained just below the Indian NAAQS annual standard (40 µg/m³) but exceeded the WHO 2021 guideline (5 µg/m³) by a factor of approximately 7.5. Annual mean PM10 (113.00 µg/m³) exceeded the NAAQS annual standard (60 µg/m³) by approximately 88%, and the WHO guideline (15 µg/m³) by a factor of approximately 7.5 — a magnitude of Exceedance comparable to that reported at other semi-arid Indian sites (Gupta et al., 2025). During the post-monsoon season specifically, monthly PM10 reached 222.06 µg/m³ in November, more than three-and-a-half times the annual NAAQS standard, indicating that annual compliance can mask serious short-term Exceedance during specific months — consistent with observations that a single annual average can understate the health-relevant burden of episodic peaks (Kanawade et al., 2020).

5. Conclusion

This study presents a full annual-cycle (2023) assessment of PM2.5 and PM10 at a moderate-density, semi-arid institutional campus site in Jhansi city. Both pollutants showed a consistent seasonal pattern, peaking in the post-monsoon period (driven by a pronounced November spike attributed to regional meteorological and transport factors rather than local festival combustion) and reaching their lowest levels during the monsoon. The seasonal difference was statistically significant for both PM2.5 and

PM10. While annual mean PM2.5 remained within the Indian NAAQS limit, annual mean PM10 exceeded the national standard, and both PM2.5 and PM10 substantially exceeded WHO 2021 guidelines throughout the year — indicating that national-standard compliance alone does not represent a safe air quality outcome. Given the regional contribution identified in the post-monsoon peak, mitigation would benefit from coordination beyond the city level, including regional crop-residue-burning management, alongside continued local monitoring.

Limitations

This study is based on monthly mean concentration data from a single fixed monitoring site; day-to-day and diurnal variability could not be characterized from the genuine data available for this analysis, and the reported standard deviations reflect month-to-month rather than day-to-day variability. The statistical power of the seasonal ANOVA is limited by the small number of monthly replicates per season (2–4 months). As a single-site study, this paper does not characterize spatial variation across Jhansi city. Gaseous pollutants (SO2, NO2, CO) measured at the same site are addressed in a companion paper of this research program rather than here.

Declarations

Funding statement: The authors did not receive any funding for this research. The work was carried out without grants, sponsorship or financial support from any public, commercial or non-profit organization. Please treat this as our funding declaration.

Ethical consent to participate and consent to publish: The study does not involve human participants, personal data or identifiable information. Therefore, ethics approval, consent to participate and consent to publish are not applicable.

Data Availability Statement: The monthly mean PM2.5 and PM10 concentrations that support the findings of this study are provided in full in Table1 of this article. The underlying continuous monitoring records from the BIET campus station are available from the corresponding author, Angita, on reasonable request.

Response to Technical Check

Manuscript title: Year-Round Seasonal Variation of $PM_{2.5}$ and PM_{10} at a Semi-Arid Institutional Campus Site in Jhansi, Uttar Pradesh, India

Dear Editorial Team,

Thank you for checking our manuscript and pointing out the items that needed attention. We have gone through each one and updated the manuscript and the submission system where needed. Our responses are below.

1. Corresponding author: we have named the corresponding author on the title page of the manuscript. It is Angita. **Name request:** Actually in Corresponding Author name only Angita and have no surname so add as Angita again in family name section.

2. Consistency of author names: We compared the names in the submission system against the manuscript and fixed the mismatches. Both now list the authors as Angita, Vinit Kumar and Ekta Panday.

3. Consistency of author order: The order differed between the two places, so we changed it to match. Both now follow this sequence: Angita, Vinit Kumar, and Ekta Panday.

4. Country in affiliations:

- Department of Regional & Environmental Studies, Bundelkhand University, Jhansi, Uttar Pradesh, India
- Applied Sciences Deaprtment,Bundelkhand Institute of Engineering & Technology, Jhansi, Uttar Pradesh, India

5. Clinical trial registration: This is an air-quality monitoring study and it is not a clinical trial, so clinical trial registration is not applicable.

We appreciate the careful check and the chance to correct these points. Please let us know if anything else is needed.

Yours sincerely,
Angita, Corresponding Author

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