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Comparative Assessment of Urban and Rural $PM_{2.5}$ Concentrations across Physiographic Regions of Nepal

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Abstract

The adverse health effects of exposure to ambient air pollution are well established; however, limited spatial coverage of regulatory monitoring networks constrains comprehensive assessment, particularly in regions with complex terrain. The increasing availability of low-cost sensors provides a promising approach to overcome these limitations. In this study, a network of TSI BlueSky low-cost $PM_{2.5}$ monitors was deployed to investigate the spatial and temporal variability of $PM_{2.5}$ concentrations across four physiographic regions of Nepal: Eastern Terai, Western Terai, Inner Terai, and Mid hills. The Eastern Terai consistently recorded the highest $PM_{2.5}$ concentrations, followed by Western Terai, with winter levels at several sites far exceeding both national standards and WHO air quality guidelines. $PM_{2.5}$ concentrations in the Inner Terai and Mid Hill regions were comparatively lower, though still of significant public health concern during winter months. A marked increase in $PM_{2.5}$ concentrations across the Terai belt immediately following the monsoon season indicates the influence of transboundary pollution, with elevated levels persisting throughout the winter period. A sharp rise in $PM_{2.5}$ concentrations across all study regions during April highlights the substantial contribution of forest fire activity to regional air quality degradation. Urban–rural paired site analysis revealed that $PM_{2.5}$ pollution is not exclusively an urban phenomenon, as rural sites such as Lumbini and Sauraha recorded concentrations equal to or exceeding those of their urban counterparts. Coefficient of Divergence analysis confirmed that industrially influenced sites display markedly distinct pollution signatures compared to proximate paired sites. These findings underscore the necessity for strengthened monitoring networks and regionally tailored mitigation strategies that account for local emissions, transboundary pollution, and topographic influences on $PM_{2.5}$ across Nepal.

Key words: *Air quality, spatio-temporal, variation, low-cost sensors, Terai*

Introduction

Air pollution has emerged as one of the most critical environmental and public health challenges worldwide. The adverse health effects associated with exposure to ambient air pollutants, particularly particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$), are well documented (Brook et al., 2010; Ostro et al., 2021; Thurston et al., 2021). Due to their small size, $PM_{2.5}$ particles can penetrate deep into the respiratory tract and enter the bloodstream, leading to respiratory and cardiovascular diseases and increasing the risk of premature mortality (Pope et al., 2002).

In Nepal, approximately 78% of the population lives areas where $PM_{2.5}$ concentrations exceed even the least stringent WHO Interim Target for healthy air quality (35 $\mu g/m^3$) (HEI, 2025). Household air pollution and ambient particulate matter pollution were ranked among the top three risk factors for tracheal, bronchus, and lung cancer in 2019 (Huang et al., 2024). Furthermore, the number of deaths from non-communicable diseases and lower respiratory infections attributable to $PM_{2.5}$ exposure was estimated at 48,881 (95% CI: 37,175–61,470) in 2019 (Dhital et al., 2024). Vehicular emissions, industrial activities, biomass burning, solid waste burning and forest fire have significantly contributed to the deterioration of air quality across Nepal (World Bank 2025).

Given the substantial health burden associated with $PM_{2.5}$ exposure, high-resolution spatial and temporal data are essential for accurately assessing pollution levels and related health risks (Huang et al., 2015). Spatio-temporal studies also provide critical insights into variations in air pollution across different geographic locations and time periods, enabling researchers and policymakers to better understand the influence of meteorological conditions, topography, emission sources, and human activities on air quality dynamics.

Assessing urban–rural differences in $PM_{2.5}$ variability is essential for developing targeted mitigation strategies and informing future air quality policies. Rural regions of Nepal have received comparatively limited research attention despite their vulnerability to transboundary pollution, household biomass combustion, agricultural residue burning, and dust transport. The lack of comprehensive rural air quality monitoring has created substantial gaps in understanding broader national patterns of air pollution exposure. In particular, the southern districts of Nepal are considered highly vulnerable because of their greater exposure to cross-border pollution transport from the Indo-Gangetic Plain (Shrestha et al., 2026). These regions have also been reported to experience the highest adult mortality burden attributable to $PM_{2.5}$ exposure in Nepal (Dhital et al., 2024).

Therefore, examining the spatio-temporal variation of air pollution across both urban and rural regions of Nepal is essential for developing a comprehensive understanding of the country's air quality dynamics. Although reducing population exposure to $PM_{2.5}$ should primarily focus on densely populated urban centers, assessing urban–rural differences in $PM_{2.5}$ variability is equally important for informing targeted mitigation strategies and guiding future air quality policy formulation. Understanding urban–rural differences and the key drivers of particulate matter pollution is critical for evaluating the effectiveness of environmental policies and ensuring equitable public health benefits (Song and Chen, 2025). However, comparative studies investigating $PM_{2.5}$ characteristics between urban and rural regions in Nepal remain limited. Such an approach can help identify regional disparities, improve pollution management strategies, and support evidence-based policymaking aimed at protecting public health and environmental sustainability throughout Nepal.

In this study, we use a network of TSI BlueSky low-cost $PM_{2.5}$ monitors to conduct a comparative assessment of ambient $PM_{2.5}$ concentrations Eastern Terai, Western Terai, Inner Terai, Mid hill and the valleys. We further compare the $PM_{2.5}$ variation in urban areas and their corresponding rural counterparts to better understand urban–rural pollution gradients and regional differences in air quality dynamics. In addition, this study evaluates the potential of affordable continuous monitoring systems for identifying pollution-prone areas and assessing their capability to capture spatio-temporal variability in $PM_{2.5}$ concentrations across diverse environmental settings. The findings are expected to support the development of more targeted and region-specific emission reduction and air quality management strategies in Nepal.

Materials and Methods

Study Area

Nepal covers a total area of 147,181 sq km, stretching approximately 885 km from east to west and 193 km from north to south. The country is marked by an exceptionally varied and complex landscape, where flat lowlands, steep hills, broad and deeply incised river valleys, and high snow-capped peaks all coexist within a remarkably compressed horizontal distance of around 250 km (Kshetri, 2023).It is situated between the Gangetic plains to the south and the Himalayan range to the north. Based on meteorological conditions, four climatic seasons prevail in Nepal are pre-monsoon (March–May), summer monsoon (June–September), post-monsoon (October–November), and winter (December–February) (GoN 2015). The summer monsoon season receives the highest proportion (~80%) of precipitation, while other seasons receive approximately 20% of the total precipitation (Talchabhadel et al., 2018). Pre-monsoon and monsoon winds are relatively strong and predominantly southwesterly. In the post-monsoon period, wind patterns shift and become calmer, transitioning from southwest to northeast. During winter, winds are generally weak and northerly to northeasterly, favoring the accumulation of both local and regional pollutants (Ramachandran & Rupakheti, 2021).

Sensors were installed in the Eastern Terai, Western Terai, Inner Terai, Mid hill and the valleys (Fig 1, Table 1). Terai is a continuation of the flat, fertile plains that comprise part of the Indo Gangetic Plain (IGP). Inner Terai Valleys of Nepal comprise several elongated river valleys in the Terai. Mid hills are a region of hills and mountains with valleys, gorges, and terraces, lying north of the Mahabharat range (Kshetri, 2023). Kathmandu and Pokhara represent the valleys of Mid hill while Hetauda and Surkhet are the valleys of Terai.

Nepal's topography plays a critical role in shaping regional air movement and pollution dispersion. The country's terrain transitions sharply from the flat, low-lying Terai plains in the south to steep hills and finally to the towering Himalayan range in the north. This dramatic altitudinal gradient, coupled with the east-west orientation of major mountain ranges and valleys, governs wind channeling, temperature inversions, and the vertical mixing of pollutants, particularly during winter when stable atmospheric conditions often suppress dispersion.

Sensor Networks

A calibrated network of TSI BlueSky units was used to monitor surface-level mass concentrations of $PM_{2.5}$ in $\mu g/m^3$ at different locations in Nepal every 15 minutes from June 2022 to April 2023.

Our analysis considered data from an average of 28 calibrated sensors in Kathmandu Valley (Table 1),

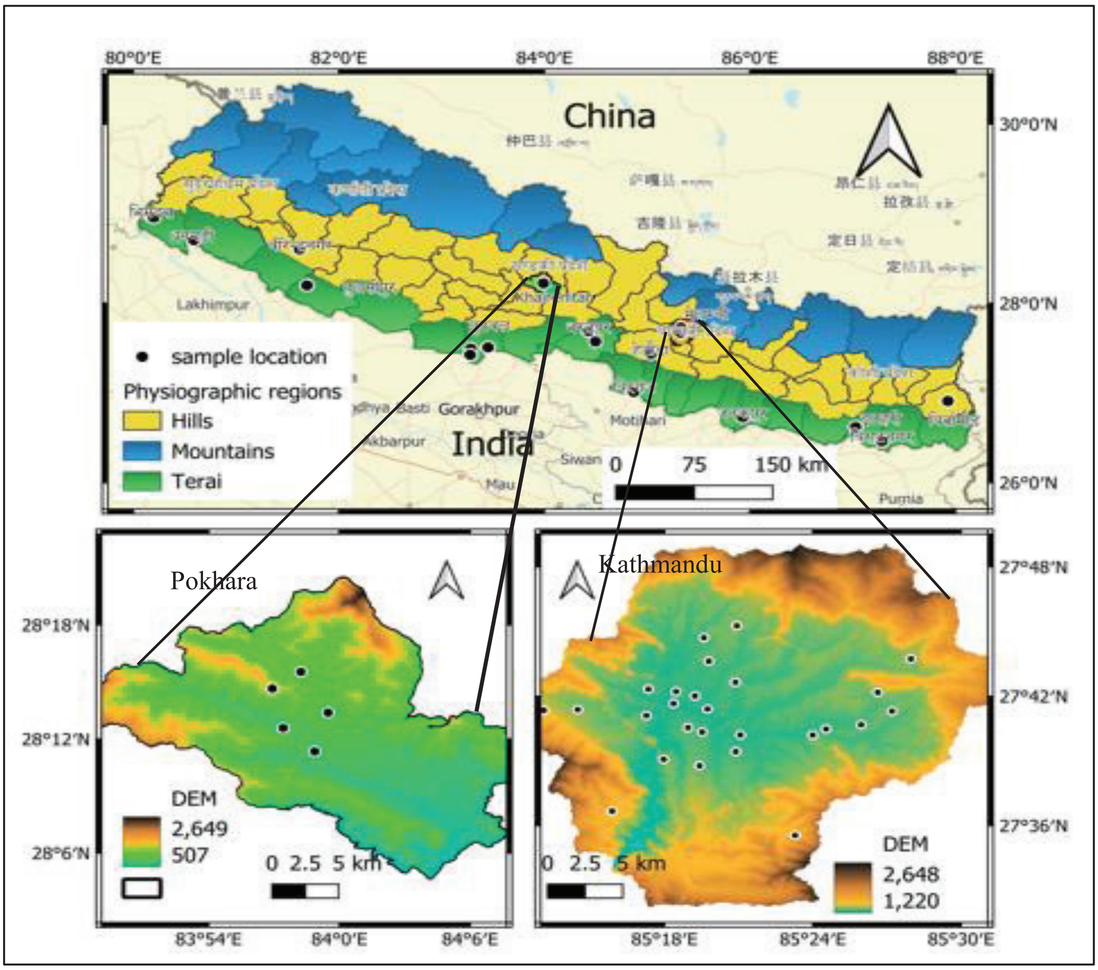

Figure 1: Sensor locations at different parts of Nepal

average of 5 sensors in Pokhara Valley (Table 1), 1 sensor each at Hetauda, Surkhet and Illam and 10 independent sensors in the Terai region (Table 1). Within the urban Terai, four sensors were paired with corresponding sensors at rural sites (Table 2) to evaluate both local and non-local influences on $PM_{2.5}$ concentrations. Because the paired urban and rural locations exhibit similar topographic and meteorological conditions, the sensors were matched under the assumption that urban emission sources exert minimal influence on the corresponding rural sites (Shrestha et al., 2026). Urban and rural sites were located within a 50 km radius, with sensors positioned at comparable elevations, and rural sites situated upwind of urban locations to minimize the influence of urban emissions on rural measurements. Detail method of the urban and rural pairing is explained in (Shrestha et al., 2026). This pairing strategy enabled subsequent assessment of non-local and transboundary pollution contributions in these regions (Shrestha et al., 2026). The urban and rural sites were considered according to Degree of Urbanization in Nepal (NSO, 2024) which followed Degree of Urbanization (DEGURBA) approach. DEGURBA classifies a country's territory along an urban–rural continuum into three mutually exclusive categories viz. cities, towns and suburbs, and rural areas, based on population size and density (EUROSTAT, 2021).

Instrumentation

We used TSI BlueSky sensors each weighing 0.35lb and dimensions of 6 (H) x 5.5 (W) x 4.5 (D). The sensors simultaneously measured PM_1, $PM_{2.5}$, PM_4 and PM_{10} mass concentrations, as well as temperature and relative humidity all in real-time. The TSI BlueSky sensor uses a sensirion SPS30 light scattering single particle counter. The aerosol mass concentrations are depicted from 0 to 1000 $\mu g/m^3$, with a measurement resolution of 1 $\mu g/m^3$ (TSI, 2023). The sensors are based on the light scattering principle, and a photodiode detector converts the scattered light to 105 a voltage pulse using advanced particle size binning to convert particle number to mass concentrations through proprietary algorithms (TSI, 2023). All data were collected at a temporal resolution of 15 min and stored in the microprocessor using Python scripts. The date and time were automatically synchronized.

Quality Assurance and Quality Control (QA/QC) of $PM_{2.5}$ Data

All sensors were collocated on the rooftop of the Central Department of Environmental Science (CDES), Kirtipur, Nepal. The coefficient of variation of $PM_{2.5}$ measurements obtained from replicate TSI BlueSky sensors ranged from 2% to 15%. The sensors were harmonized with each other. Harmonization was performed by applying sensor-specific correction factors, derived from three days of collocated measurements relative to the median concentration, to each sensor's readings. A detailed description of the calibration and harmonization procedure followed is provided in Shrestha et al. (2025). The TSI BlueSky monitors recorded raw $PM_{2.5}$ data at 15-minute intervals. For subsequent analyses, these data were aggregated to hourly averages. Measurements falling outside the sensor detection limits (d" 0 $\mu g/m^3$ or e" 1000 $\mu g/m^3$) were considered outliers and excluded. Only hourly averages with at least 75% data completeness were retained for further evaluation.

Time Series Analysis

Time series analysis involves examining data points that are gathered sequentially over a defined time span (Jose, 2022). The sites of sensor deployed were grouped into Eastern Terai, Western Terai, Inner Terai and Mid hill and the time series were compared within and between the groups. To study the regional contribution of $PM_{2.5}$ we visually inspected the time series to analyze high-pollution episodes along the time series.

Coefficient of Divergence

The spatial heterogeneity was also investigated for each component using Coefficient of Divergence (COD). A COD of zero indicates no difference between site concentration (homogeneous), whereas a COD greater than 0.2 is considered to indicate substantial spatial heterogeneity (Wilson et al., 2005).

$$COD_{jk} = \sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(\frac{x_{ij} - x_{ik}}{x_{ij} + x_{ik}}\right)^2}$$

Where x_{ij} and x_{ik} represent the mass concentration for time period i at sampling site j, k is the number of sites, and p is the number of observations (Krudysz et al., 2009).

Results and discussion

Comparative analysis of $PM_{2.5}$ at different region of Nepal

Figure 2 illustrated the time series variation of $PM_{2.5}$ in different regions of Nepal. A clear seasonal variation was observed all over Nepal. A gradual rise of $PM_{2.5}$ was observed after monsoon which peaked in winter. A gradual dip with the start of pre monsoon seized with the sudden rise in early April. Monsoon season had the lowest $PM_{2.5}$ concentrations across all regions across all regions, ranging from 7.8 ± 3.2 µg/m³ at Hetauda (Inner Terai) to 18.9 ± 12.5 µg/m³ at Dhangadhi (Western Terai). Most sites showed mean values between 10–19 µg/m³, below the NAAQS of 40 µg/m³ (Table 2). The relatively low concentrations during this period are attributed to wet scavenging by rainfall, increased atmospheric turbulence, and suppressed open biomass burning activity. A marked increase in $PM_{2.5}$ was observed in the post-monsoon season across all regions. Eastern Terai sites showed the sharpest rise, with Birgunj reaching 75.7 ± 49.7 µg/m³, Janakpur 70.1 ± 51.5 µg/m³, and Biratnagar 43.2 ± 27.5 µg/m³. In the Western Terai, Lumbini (74.2 ± 46.1 µg/m³) and Bhairahawa (63.7 ± 37.9 µg/m³) similarly recorded elevated levels. $PM_{2.5}$ concentration increased by 3.4 times at Eastern and Western Terai during post monsoon compared to monsoon. The increase was lower at Mid hill (2.2 times) and inner Terai (1.8 times). Recurring episodes of pollution at Terai during post monsoon season were claimed to be caused by transboundary air pollution originating with agricultural residue burning in the northwestern region of the IGP (Rupakheti et al., 2020). Such pollutants originated in IGP can also be transported to Kathmandu and higher elevations, mainly through the river valleys (Khanal et al., 2022).

Winter recorded the highest $PM_{2.5}$ concentrations across all sites. with the highest percentage of days exceeding NAAQS in the order of Eastern Terai (99%), Western Terai (93%), Mid hill (71%) and Inner Terai (47%). Janakpur recorded the highest concentration of 170.5 ± 80.9 µg/m³, followed by Birgunj at 154.0 ± 63.9 µg/m³ and Biratnagar at 131.8 ± 58.8 µg/m³ three to four times exceeding NAAQS 24-hour guideline value. The $PM_{2.5}$ concentration was 1.6 to two times the NAAQS at Bhimdutta (67.2 ± 23.21 µg/m³) and Lumbini (101.6 ± 33.1 µg/m³) in Western Terai. Mid Hill sites, while substantially lower, still recorded elevated concentrations at Kathmandu (53.6 ± 10.9 µg/m³), Bhaktapur (62.4 ± 15.8 µg/m³), and Pokhara (42.5 ± 11.4 µg/m³). Inner Terai sites such as Surkhet (30.7 ± 9.3 µg/m³) and Hetauda (39.3 ± 14.6 µg/m³) were comparatively better but still at levels of significant public health concern. It is noteworthy that winter data completeness was lower at some sites (e.g., Bhairahawa: 22%; Birgunj: 41%), which may introduce uncertainty into the reported averages and warrants caution in interpretation. Shrestha *et al* (2026) mentioned that the Terai was heavily influenced by regional pollution during winter. According to the study, non-fire sources (urban, industrial, or agricultural) from the probable source regions in Bihar and eastern Uttar Pradesh, India, likely contributed substantially to the pollution transported into Nepal during episodic events. Pre-monsoon concentrations were intermediate between post-monsoon and winter levels for most sites. There was a sharp increase of $PM_{2.5}$ during April at all the regions in Nepal. But the increase was highest at Pokhara, Hetauda and Bharatpur. The $PM_{2.5}$ concentration at April is increased by 52%, 33% and 29% at Pokhara, Hetauda and Bharatpur respectively (Table 2). One of the major contributors of $PM_{2.5}$ during April is likely to be forest fires, which are common in the region during this season. Kuikel et al (2024) found positive high correlation with statistical significance ($p<0.05$) of $PM_{2.5}$ with fire count. Nevertheless, Birgunj stood out with an exceptionally high mean of 113.9 ± 34.3 µg/m³, possibly reflecting long-range transport of dust and biomass burning aerosols from the Indo-Gangetic Plain.

The comparative analysis revealed that $PM_{2.5}$ concentrations were highest in the Eastern Terai, followed by the Western Terai, Mid hills, and Inner Terai, respectively. Within the Eastern Terai, $PM_{2.5}$ levels were broadly comparable across all study sites. In the Western Terai, locations situated farther east, namely Bhimdutta, Dhangadhi, and Kohalpur, exhibited relatively lower $PM_{2.5}$ concentrations. In the Mid hills, $PM_{2.5}$ concentrations were generally similar among sites. However, Pokhara was most affected by forest fire activity during April, whereas Illam experienced the least impact. The consistently low $PM_{2.5}$ levels observed during post-monsoon in Illam further suggest a weaker influence of regional pollution. During the winter season, the Inner Terai valleys, particularly Hetauda and Surkhet, recorded the lowest $PM_{2.5}$ concentrations compared with other regions. The observed spatial heterogeneity and seasonal dynamics of $PM_{2.5}$ highlight complex pollution processes, underscoring the need for more detailed, site-specific investigations.

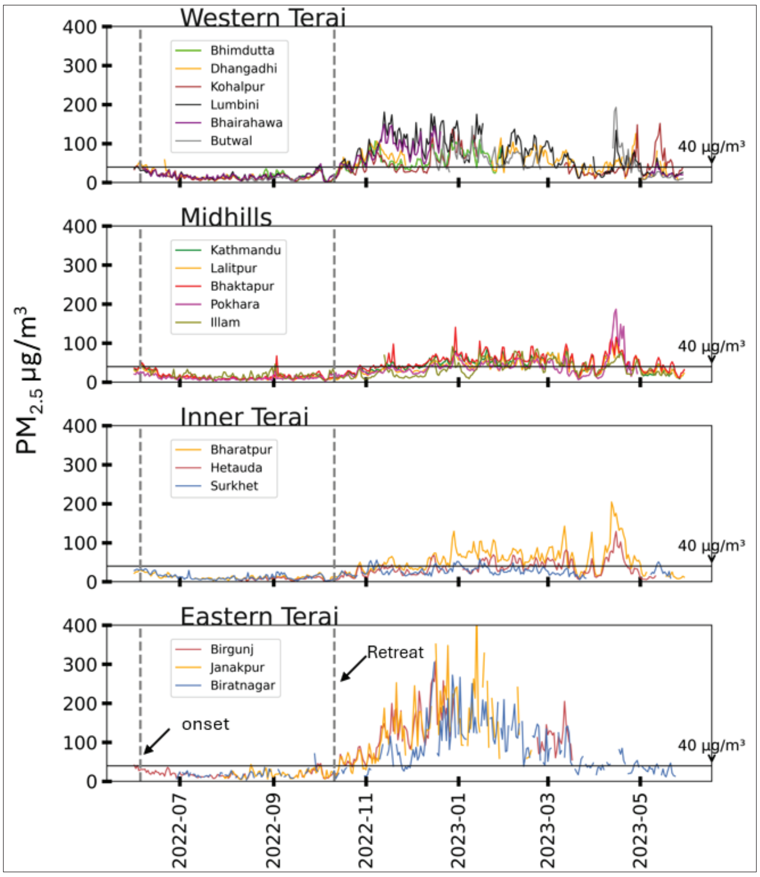

Figure 2: Time series of $PM_{2.5}$ at different regions of Nepal from June 2022 to May 2023. The vertical dashed line in the figure depicts the onset (June 5, 2022) and the retreat (October 11, 2023)of Monsoon .

Table 1: Seasonal variation of $PM_{2.5}$ in Different location of Nepal

Region	Site	$PM_{2.5}$ (µg/m^3)							
		Monsoon	data %	Post-monsoon	data %	Winter	data %	Pre-monsoon	data %
Western Terai	Bhimdutta	15.0 ± 7.5	100	43.0 ± 23.7	100	67.2 ± 23.2	100		
Western Terai	Dhangadhi	18.9 ± 12.5	70	62.3 ± 23.1	79	71.3 ± 21.7	41	42.1 ± 23.6	91
Western Terai	Kohalpur	15.4 ± 9.3	100	37.3 ± 20.5	100	66.9 ± 32.4	49	39.5 ± 28.5	88
Western Terai	Lumbini	17.4 ± 7.8	100	74.2 ± 46.1	100	101.6 ± 33.1	89	41.0 ± 23.8	96
Western Terai	Bhairahawa	16.0 ± 6.8	100	63.7 ± 37.9	100	91.6 ± 29.1	22	23.0 ± 9.1	26
Inner Terai	Surkhet	13.0 ± 7.9	100	21.5 ± 12.3	90	30.7 ± 9.3	100	22.3 ± 9.9	49
Inner Terai	Bharatpur	12.1 ± 6.3	90	29.3 ± 15.7	100	64.6 ± 20.2	100	60.9 ± 47.8	87
Inner Terai	Hetauda	7.8 ± 3.2	100	20.4 ± 12.0	100	39.3 ± 14.6	90	39.3 ± 28.1	87
Mid hill	Kathmandu	14.3 ± 8.5	100	26.3 ± 12.4	100	53.6 ± 10.9	100	42.4 ± 24.8	100
Mid hill	Lalitpur	12.7 ± 7.8	100	22.2 ± 10.3	100	45.3 ± 11.5	100	42.7 ± 23.0	100
Mid hill	Bhaktapur	16.1 ± 10.4	100	31.7 ± 16.5	100	62.4 ± 15.8	100	47.7 ± 24.9	89
Mid hill	Pokhara	10.6 ± 5.4	100	23.6 ± 8.8	100	$4_{2.5}$ ± 11.4	100	46.8 ± $4_{2.5}$	100
Mid hill	Illam	16.5 ± 7.9	94	17.6 ± 11.2	98	42.1 ± 20.5	100	38.4 ± 16.9	100
Eastern Terai	Birgunj	18.3 ± 8.5	80	75.7 ± 49.7	100	154.0 ± 63.9	41	113.9 ± 34.3	100
Eastern Terai	Janakpur	18.6 ± 9.0	100	70.1 ± 51.5	93	170.5 ± 80.9	70		
Eastern Terai	Biratnagar	18.3 ± 9.7	70	43.2 ± 27.5	56	131.8 ± 58.8	88	46.3 ± 29.4	81

*Kathmandu, Lalitpur, Bhaktapur and Pokhara represent the average data of the corresponding sites

Comparison of urban $PM_{2.5}$ with rural pair

As outlined in the methodology section, four of the sensors in the urban Terai was paired in the corresponding rural sites (Table 2) to assess both local and non-local contributions to ambient $PM_{2.5}$ levels. Figure 3 illustrates the comparative analysis of $PM_{2.5}$ concentration between urban–rural pairs across different sub-regions of the Terai.

At the Mahendranagar pair, $PM_{2.5}$ concentrations at the urban and rural sites were largely comparable. The COD value of less than 0.2 indicates a similarity in pollution sources between the two sites (Mukherjee et al., 2019), which can be attributed to their close geographical proximity, with the two stations being separated by only 2.8 km. Sauraha, designated as the rural pair of Bharatpur, recorded higher $PM_{2.5}$ concentrations during an episodic pollution event in April, and its seasonal comparative $PM_{2.5}$ also surpassed that of Bharatpur (Table 3). Nevertheless, the COD value remained below 0.2, suggesting that both sites were subjected to similar regional-scale pollution influences during study period. These findings challenge the widely held assumption that urban areas invariably experience higher ambient particulate matter concentrations than their rural counterparts.

In the Butwal–Lumbini pair, $PM_{2.5}$ concentrations at Lumbini frequently exceeded those recorded at Butwal. Although Lumbini was designated as the rural counterpart of Butwal, it is situated near several major industrial facilities, and has therefore been reclassified as an industrial reference site rather than a conventional rural monitoring location. Butwal, in contrast, is representative of a typical urban Terai environment characterized by the predominance of traffic and residential emission sources. The COD for the Butwal–Lumbini pair exceeded 0.2, indicating a substantial dissimilarity in pollution sources between the two sites. In the Biratnagar–Koshi Tappu pair, Biratnagar functions as Nepal's principal industrial hub, whereas Koshi Tappu is a designated wildlife reserve with minimal anthropogenic activity. Mean $PM_{2.5}$ was considerably lower at Koshi Tappu, and the COD value exceeded 0.2, providing clear evidence of divergent pollution source characteristics between the two locations.

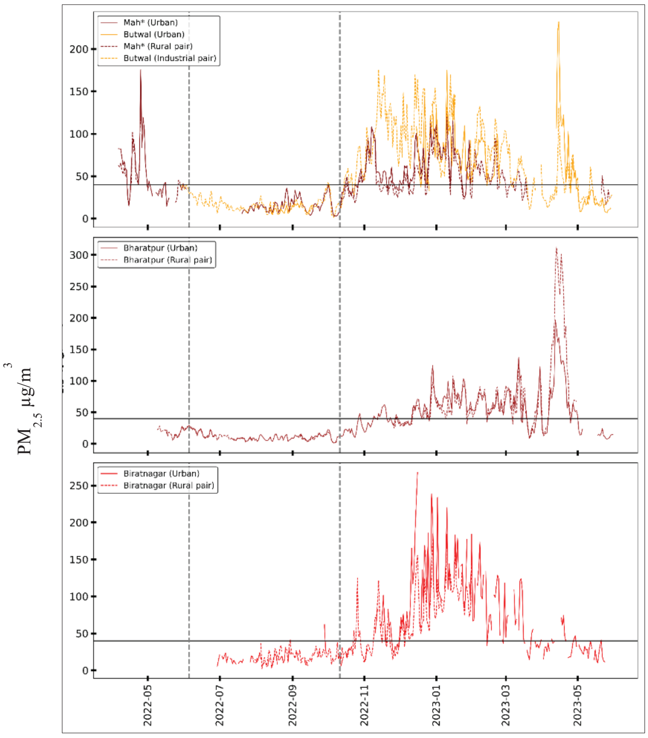

Figure 3: Comparison of $PM_{2.5}$ in the urban and rural settings of Nepal

Table 2: Urban and rural pair in Terai

Site Name	Region	District	Category	Land Use
Mah* urban (Bhimdutta)	Western Terai	Kanchanpur	Urban pair	Built area
Mah* rural	Western Terai	Kanchanpur	Rural pair of Bhimdutta	Open area
Butwal	Western Terai	Butwal	Urban pair	Built area
Lumbini	Western Terai	Rupandehi	Industrial pair of Butwal	Open area
Bharatpur	Inner Terai	Chitwan	Urban pair	Built area
Sauraha	Inner Terai	Chitwan	Rural pair of Bharatpur	Open area
Biratnagar	Eastern Terai	Sunsari	Urban pair	Built area
Koshi Tappu	Eastern Terai	Sunsari	Rural pair of Biratnagar	Open area

Mah* = Mahendranagar

Table 3: Coefficient of Divergence at rural and urban site of Terai

Site pair	Distance (km)	Count	Urban site	Mean	Rural site	Mean	COD
Mahendranagar pair	2.8	133	Urban Site	59.43	Rural site	52.14	0.1
Bharatpur Sauraha	15.2	256	Bharatpur	46.52	Sauraha	51.64	0.13
Butwal Lumbini	22.1	213	Butwal	42.28	Lumbini	58.53	0.28
Biratnagar Koshi Tappu	33.7	130	Biratnagar	77.84	Koshi Tappu	59.57	0.21

COD has been widely applied as a metric to quantify the spatial variability of $PM_{2.5}$ concentrations between paired monitoring sites (Mukherjee et al., 2019; Pinto et al., 2004). COD values below 0.2 observed at both the Mahendranagar and Bharatpur pairs indicate low spatial divergence in $PM_{2.5}$, implying similar source influences, most likely transboundary pollution at both the sites within each pair. Conversely, the industrial sites of Lumbini and Biratnagar exhibited markedly dissimilar pollution patterns relative to their respective paired sites, highlighting the significant and distinct contribution of industrial emission sources to local air quality at these locations.

Conclusion

This study presented a comprehensive seasonal and spatial assessment of $PM_{2.5}$ concentrations across multiple monitoring sites in Nepal, encompassing the Western Terai, Eastern Terai, Inner Terai, and Mid Hill regions. The findings consistently demonstrated pronounced seasonal variability in $PM_{2.5}$ levels, with the lowest concentrations recorded during the monsoon season and the highest during winter across all regions. The Eastern and Western Terai emerged as the most critically polluted sub-region, with winter $PM_{2.5}$ concentrations far exceeding both national standards and WHO air quality guidelines, underscoring the urgent need for targeted emission control interventions in this region.

The urban–rural paired analysis revealed that $PM_{2.5}$ pollution in the Terai is not exclusively an urban phenomenon. Sites such as Lumbini and Sauraha, despite being classified as rural or reference locations, recorded $PM_{2.5}$ concentrations equal to or exceeding those of their urban counterparts, highlighting the significant role of industrial emissions and regional transboundary pollution transport in shaping ambient air quality. COD analysis further confirmed that sites in close proximity or under the influence of similar regional emission sources exhibit low spatial divergence, whereas industrially influenced sites display markedly distinct pollution signatures.

Overall, the results of this study highlight the critical air quality challenges faced across Nepal, with particular severity in the Terai regions during winter and pre-monsoon seasons. The findings underscore the necessity for strengthened air quality monitoring networks, improved data continuity, and the development of tailored pollution mitigation strategies that account for the complex interplay of local emission sources, transboundary pollution, and meteorological and topographic influences on $PM_{2.5}$ levels across the country.

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Conflict of interest: The authors declare that they have no competing interests.

Data availability statement: The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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