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Anthropogenic Intensification and Emerging Air Pollution Patterns across the Western Himalaya: Multi-Year Spatiotemporal Case Study

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Abstract

Anthropogenic intensification is profoundly impacting air quality within vulnerable mountain ecosystems, yet the availability of long-term, high-resolution data from the Western Himalaya is strikingly limited. This study provides a detailed multi-year (2020-2024) spatiotemporal analysis of particulate matter (PM_{10} and $PM_{2.5}$), nitrogen oxides (NO_x), ammonia (NH_3), and ozone (O_3) concentrations across contrasting anthropogenic settings—specifically, tourist influx zones such as Dharamshala and industrial hotspots like Damtal in Himachal Pradesh, India. Key pollutants examined include Particulate Matter (PM_{10} and $PM_{2.5}$), and gaseous pollutants such as nitric oxide (NO_X), ammonia (NH_3), and O_3, analysed across four seasonal periods: December to February (winter), March to May (spring/summer), June to August (monsoon), and September to November (autumn). The findings of this study indicate that the accumulation of PM_{10} and $PM_{2.5}$ is higher in the low-altitude industrial area of Damtal due to emissions, particularly compared to higher altitudes during the winter season. In contrast, significant changes are observed in the enhancement of O_3 formation at higher-altitude Dharamshala during the summer season, which may be attributed to increased anthropogenic activity or photochemical processes. The lockdown period (2020) saw significant reductions in PM and gaseous pollutants (NO_2, NH_3, O_3), underscoring the impact of human activities on regional air quality. Additionally, altitude and forest cover significantly influenced pollutant distribution, with Dharamshala's higher elevation and dense forests contributing to better air quality compared to Damtal's lower elevation and sparse forestation, which led to elevated pollutant levels, except for ozone.

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INTRODUCTION

Over the past five decades, rapid urbanisation has led to a global shift toward city living, exacerbating environmental issues such as urban air pollution (Baldasano et al., 2003) [1]. . Air pollution is a major public health concern, contributing to over 30% of deaths from coronary heart disease and stroke, 17% from chronic obstructive pulmonary disease, and nearly 9% from lung cancer and respiratory infections globally (Mukta et al., 2020) [2]. According to the 2015 Global Burden of

Disease study, ambient particulate matter (PM) and household air pollution ranked as the 6th and 8th leading causes of Disability-adjusted life years (DALYs) worldwide. As per the World Health Organisation (WHO) report, 92% of the global population lives in polluted areas, which contribute to 11.6% of all deaths globally. Most alarmingly, 90% of these deaths occur in low- and middle-income countries (Barzeghar et al., 2020) [3].

Although urban centres drive economic growth, they face significant challenges including traffic congestion, inadequate infrastructure, and deteriorating environmental quality, especially in areas of water supply, waste management, and sanitation (Molina et al., 2019) [4]. Urban populations are constantly exposed to a variety of often undetectable pollutants, which present significant threats to both human health and ecosystems. Even minor fluctuations in pollutant levels can result in serious adverse effects (Syrek-Gerstenkorn et al., 2024) [5].

India has experienced substantial industrialisation and urbanisation over recent decades, significantly altering its economic and social framework. The proportion of the urban population has surged from 10.8% in 1901 to 31.2% according to the 2011 Census. The growth rate indicates that by 2031, over 600 million individuals, approximately 40% of the total population, will inhabit urban areas (Ram, 2018) [6]. While this transformation promotes growth; however, it simultaneously places significant pressure on resources and contributes to heightened levels of pollution. Over and rapid construction in large scale and industrialisation in India significantly contribute to ambient particulate matter, particularly $PM_{2.5}$ and PM_{10}, primarily from coal combustion, construction dust, and vehicular emissions. For instance, in the Delhi NCR region, industrial activities account for approximately 8–10% of $PM_{2.5}$ and PM_{10} levels, with major sources being brick kilns, power plants, and stone crushers. Nationally, over 60% of $PM_{2.5}$ exposure is linked to anthropogenic sources, including residential energy use and industrial combustion (Seth Block, 2018). By 2050, premature deaths linked to $PM_{2.5}$ are projected to increase by 24% compared to 2015 (Sharma & Mauzerall, 2022) [7]. India is one of the most populous countries in the world, facing a significant threat from air pollution. According to the World's Air Quality Report-2019, India hosts 21th rank of the world's 30 most polluted cities and ranks 5th globally for $PM_{2.5}$ levels (Bedi et al., 2020) [8].

Particulate matter (PM_{10}, $PM_{2.5}$), sulfur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2), lead (Pb), and carbon monoxide are identified as a (CO) six critical air pollutants by U.S. EPA: (Nautiyal *et al*., 2007) [9]. Aerosols, comprising fine particulate matter from both natural and anthropogenic sources, play a vital role in influencing the climate system and degrading air quality, impacting visibility and ecosystems (Mushtaq et al., 2023) [10]. Agricultural crop residue burning (ACRB), in India, is a significant seasonal contributor to aerosol levels (Awasthi et al., 2011) [11].

Smaller urban centres (population 150,000-1.5 million) and megacities in Asia confront issues with air quality, emphasizing the importance of better understanding localised effects and seasonal variations that remain under-researched (Dadhich et al., 2018) [12]. Himachal Pradesh, historically considered a low-pollution region in the Western Himalayas, is currently experiencing environmental challenges due to urban expansion, increased vehicle emissions, deforestation, and industrialization (Gupta et al., 2023; Mahtta [13]. Cities like Damtal and Dharamshala are experiencing rising pollution levels influenced by both human activities and natural factors. However, comprehensive data on long-term trends and spatial pollution patterns remain limited. In response to the growing concerns about air quality, this study is designed to provide valuable insights by thoroughly analysing the composition of airborne pollutants in the regions of Damtal and Dharamshala from 2020 to 2024. This study focuses on the annual variations (month-to-month variations) in key pollutants, including PM_{10}, $PM_{2.5}$, NH_3, NO_x, and O_3, as well as identifying the primary sources contributing to pollution levels.

MATERIAL AND METHODS

Study area

This study is conducted in Himachal Pradesh, Western Himalayas of India. The region features a climate that varies from semi-tropical to semi-arctic, depending on the altitude. Himachal Pradesh experiences three distinct seasons: summer (April to June), monsoon (July to September), and winter (October to March), all of which significantly impact its tourism-driven economy (Tripathi et al., 1993) [14].

As per the 2011 Census, 89% of the population resides in rural areas. Agriculture, primarily rainfed, accounting for 80% of cultivated land, contributes approximately 22% to the state's Gross Domestic Product (GDP) and employs about 70% of the workforce, with 88.86% of land holdings categorised as small or marginal (Chadha & Srivastava, 2022) [15]. Dharamshala (tourist hub) and Damtal (emerging industrial hub)-located in Kangra district, were selected for comparative analysis for this study (Table 1 and Figure 1).

The methodology for selecting monitoring sites, collecting air quality data, and identifying various pollutants in the atmosphere throughout different regions of Himachal Pradesh has been detailed, as illustrated in Figure 2.

Table 1. HPSPCB air quality selected monitoring stations.

Location	Monitoring station	Elevation	Latitude	Longitude
Dharamshala	Dari	1457 m	32.196019	76.337886
	Kotwali		32.220233	76.318637
Damtal	Damtal 1	360 m	32.218094	75.662329
	Damtal 2		32.226059	75.664411

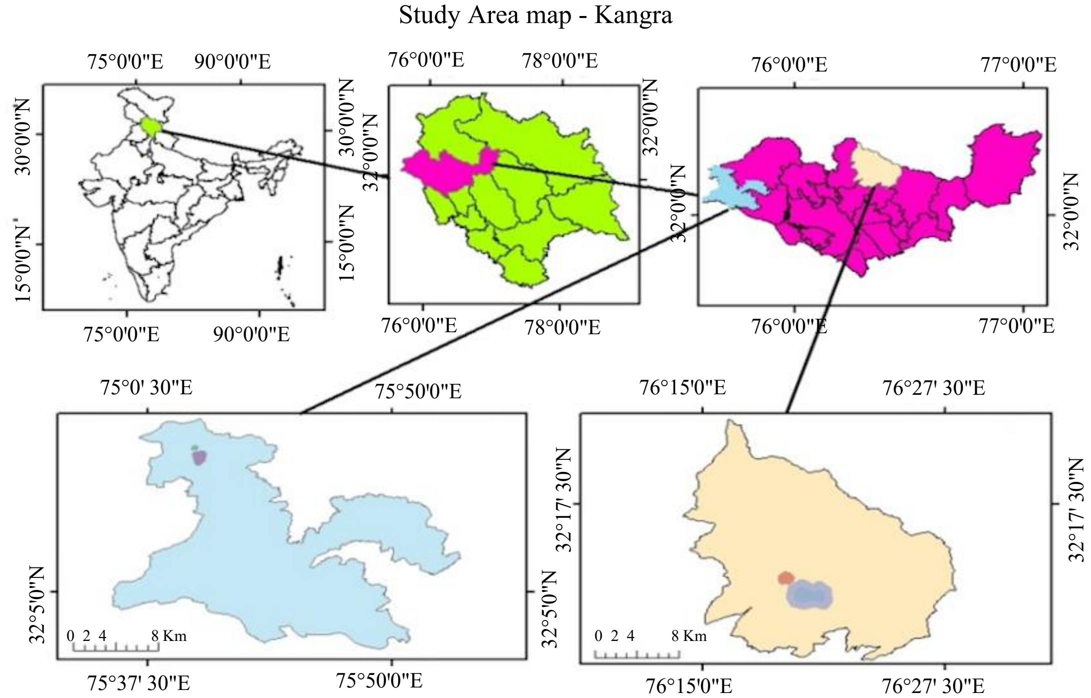

Figure 1. (a) State of Himachal Pradesh within map of India; (b) Kangra district highlighted within map of Himachal Pradesh; (c) Selected blocks in Kangra district: Dharamshala (yellow) and Indora (baby blue); (d) Study sites in Indora block: Damtal1 (violet) and Damtal2 (green); (e) Study sites in Dharamshala block: Kotwali (Blush pink) and Dari (Lavender blue).

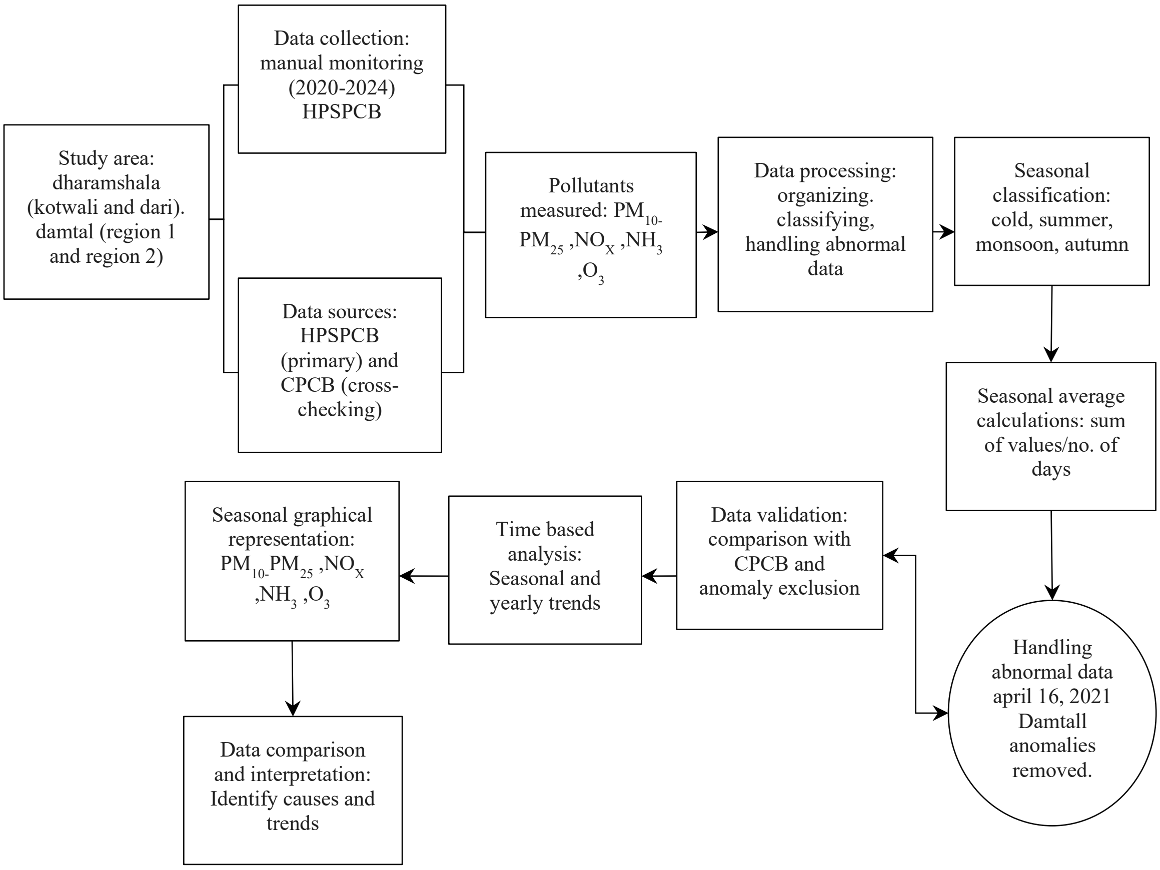

Figure 2. Schematic of methodological workflow.

RESULTS and DISCUSSION

Concentration of PM_{10}

In conducting a comprehensive seasonal assessment of PM_{10} concentrations from 2020 to 2024, significant spatial and temporal variability was identified across the regions of Kotwali, Dari, Damtal-1, and Damtal-2 (Table 2). The analysis revealed a pronounced and consistent regional pollution gradient, with mean PM_{10} levels ranked as follows: Damtal-2 > Damtal-1 > Dari > Kotwali. Specifically, Damtal-2 concentrations averaged approximately 25–35% higher than those observed in Kotwali, while Damtal-1 levels exceeded Kotwali by 15–25%, as depicted in Figure 3. It could be due to ambient temperatures and a shallow atmospheric boundary layer, restricted vertical dispersion, and trapping particulate matter at the surface. Low wind speeds and persistent low-pressure systems further hindered horizontal transport, increasing pollutant accumulation (Mukta et al., 2020) [2]. Increased emissions from diesel-powered vehicles, including direct emissions and wear from tyres, brakes, clutch plates and re-suspension of road dust, further contribute to high particulate levels (Dadhich et al., 2018) [12].

The monitoring data reveals a pronounced seasonal variation in PM_{10} concentrations across all sites studied. The winter season (D: December–February) is characterised by notably elevated PM_{10} levels, consistently surpassing those observed during the monsoon season (B: June–August) by approximately 30-50%. This increase can be attributed to several factors, including temperature inversions that trap pollutants near the surface, a reduction in boundary layer height, heightened biomass burning activities, and increased domestic fuel usage. Summer season (A: March–May) values were moderately elevated (≈ 10–20% higher than monsoon levels), likely due to dust resuspension and dry atmospheric conditions. (Figure 3). Moreover, Post-monsoon (C: September–November) showed transitional behavior, with concentrations gradually increasing toward winter maxima, which could be related to the use of Diwali firecrackers. Saxena *et al.* has already revealed that firecrackers show significant negative impact on the air quality in temporary manner (Saxena et al., 2022) [16].

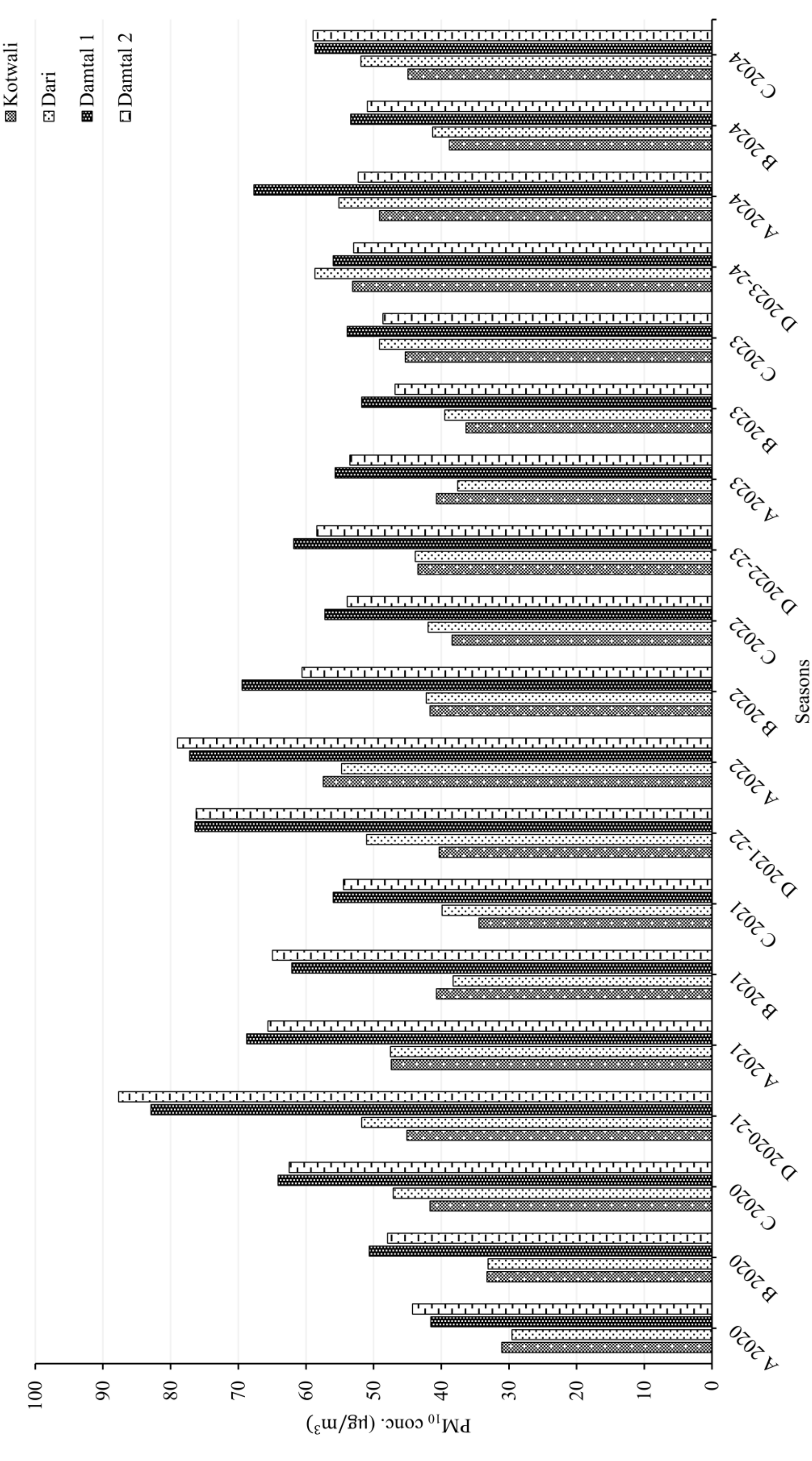

Figure 3. Seasonal variation of PM_{10} concentrations from 2020-2024 across Kotwali, Dari, Damtal-1 and Damtal-2. Here, A corresponds to March to May, B corresponds to June to August, C correspond to September to November, and D corresponds to December to February.

For instance, PM_{10} levels in Lucknow increased from 233 before Diwali to 558 on the night of Diwali (Saxena et al., 2022) [16]. In 15 Indian states, a nationwide investigation also found that PM_{10} increased during Diwali (Ghosh et al., 2024) [17]. Due to stable post-monsoon weather and firecracker lighting around Diwali, it is fair to assume that these factors contributed to the higher PM_{10} levels in September to November 2023.

A comprehensive year-on-year analysis reveals a significant increase in PM_{10} concentrations from 2020 to 2021, culminating in peak pollution levels observed during the winter months of 2021–2022, especially at Damtal sites, where values approached the upper end of the observed range (~75–90 µg m^{-3}). From 2022 to 2024, a moderate declining trend is evident, with reductions of approximately 5–15% across most monitoring locations. This decline may be attributable to improvements in emission control measures, alterations in local socio-economic activities, or variations in meteorological conditions. However, despite these modest reductions in recent years, winter PM_{10} levels remain persistently elevated, underscoring the ongoing challenges of seasonal air quality management. Notably, the relative consistency in site rankings over the five years indicates that local source contributions are the primary drivers of PM_{10} levels, overshadowing the influences of short-term meteorological fluctuations.

Concentration of $PM_{2.5}$

The analysis of site-wise seasonal and interannual variability from 2020 to 2024 reveals pronounced spatial heterogeneity in temporal behaviour (Table 3). Kotwali consistently demonstrates the lowest magnitudes and weakest seasonal variations, with minimal interannual variability and no predominant peak season. This subdued response indicates strong urban buffering influences, where ongoing baseline activity, infrastructural saturation, and land use regulations suppress fluctuations across seasons and years (Lu *et. al.,* 2021; Bhattarai *et. al*., 2024) [18, 19]. Conversely, Dari exhibits moderate seasonal modulation, with elevated values during Seasons C and D, suggesting heightened sensitivity to seasonal forcing typical of transitional urban-peri-urban environments (Amil *et. al.,* 2016) [20]. Nonetheless, interpretation at Dari is limited by missing data between Season C-2022 and Season A-2023, due to data unavailability-a common challenge in field-based monitoring during transition and post-monsoon periods (WMO, 2018) (Figure 4). Generally, $PM_{2.5}$ levels are also exacerbated during winter by fossil fuel and biomass combustion, particularly under unfavourable dispersion conditions (Xiao et al., 2018; Wang et al. 2015) [21, 22].

Damtal-1 exhibits a pronounced seasonal dependence, particularly evident during the latter part of the year, but it also demonstrates a significant plateau between Season B-2023 and Season C-2024. This short-term stability likely indicates a phase of localised equilibrium, influenced by consistent land-use practices, a lack of episodic disturbances, and relatively stable anthropogenic activities. Such patterns have been documented in peri-urban environments following a phase of infrastructural maturation (Amil *et. al*., 2016) [20]. In contrast, Damtal-2 consistently shows the highest values and largest seasonal amplitudes, displaying marked interannual variability, with a notable peak occurring in 2021, a subsequent decline in 2023, and a recovery in 2024 as depicted in Figure 4. This pattern underscores its greater sensitivity to seasonal drivers, enhanced post-monsoon effects, and external socio-environmental influences (Seto et al., 2012; Awasthi et al., 2011) [23, 11].

Overall, cross-site comparisons reveal a gradient from weather-vulnerable urban systems to highly responsive peri-urban environments, emphasizing that the observed trends arise from interactions between weather factors and site-specific urbanization, rather than from uniform regional pressures (Amil *et. al.,* 2016) [20].

Concentration of NO_x

As per the site-wise emission assessment study, the transport sector accounts for 60% of nitrogen oxides (NO_x) emissions, with cement manufacturing and open burning practices constituting the remaining significant sources in Himachal Pradesh (Mahtta, TERI, 2015 report; Syrek-Gerstenkorn et al., 2024) [24, 5].

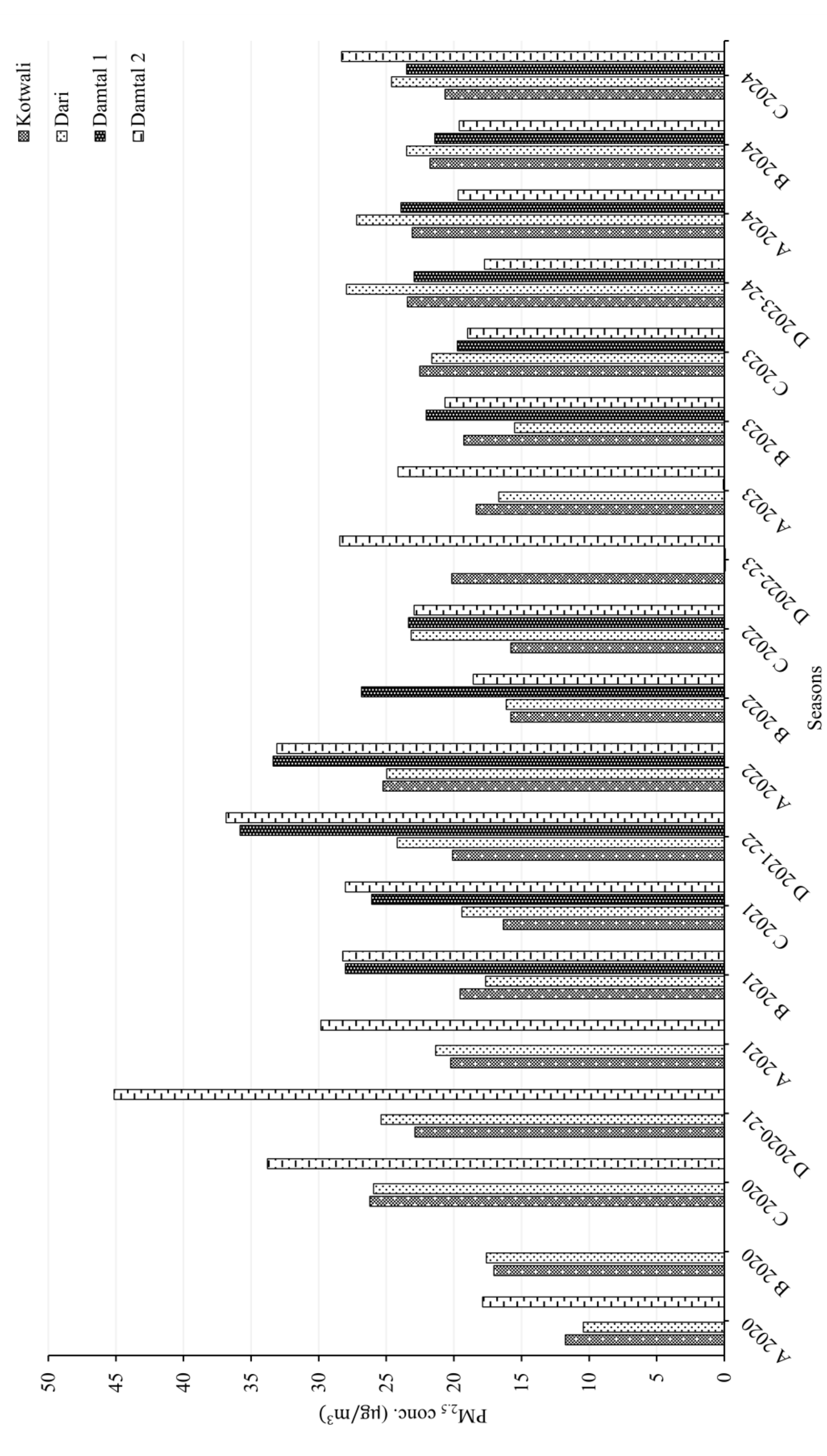

Figure 4. Seasonal variation of $PM_{2.5}$ concentrations from 2020–2024 across Kotwali, Dari, Damtal 1 and Damtal 2. Here, A corresponds to March to May, B corresponds to June to August, C correspond to September to November and D corresponds to December to February.

The analysis of NO_x concentrations in Kotwali, Dari, Damtal-1, and Damtal-2 from 2020 to 2024 indicates a notable evolution from significant spatial heterogeneity to a more uniform distribution over time (Table 4). In early 2020, elevated NO_x levels, particularly at Damtal-1 and Damtal-2, imply heightened localised emissions during that phase (≈7.4–8.5 μg/m^3). Following this initial period, the concentrations across all monitoring sites gradually converged within a narrow band of approximately 4.5–5.0 μg/m^3, exhibiting minimal seasonal or site-specific variability after 2021. This trend suggests a reduction in localised emission sources and a potential stabilisation of atmospheric NO_x levels in the region (Figure 5).

The observed decline and stabilisation pattern in nitrogen dioxide (NO_2) levels aligns with documented reductions linked to variations in traffic intensity, fuel usage, and persistent post-pandemic emission controls (Carslaw *et al*., 2011) [25]. Additionally, this trend reflects longer-term urban emission homogenization (Sharma et al., 2020) [26]. Overall, the dataset indicates that, while early observations were largely influenced by site-specific emission strengths, the implementation of regional-scale controls and a decrease in episodic activity have contributed to consistent NO_x levels across urban and peri-urban areas in recent years (Poulhès & Proulhac, 2022) [27]. This highlights the effectiveness of emission moderation and suggests a diminishing impact of localised seasonal factors.

Concentration of NH_3

Between 2020 and 2024, there was a significant and consistent increase in ammonia (NH_3) concentrations at the Kotwali, Dari, Damtal-1, and Damtal-2 monitoring sites, indicating a widespread enrichment of NH_3 in the region (Table 5). Year-over-year analysis revealed that all four sites exhibited progressively higher mean concentrations, with the most pronounced increases occurring during season D of each year. Seasonally, NH_3 levels were at their lowest during Season A, with concentrations ascending through Seasons B and C, ultimately peaking in Season D as shown in Figure 6. This pattern suggests a strong seasonal influence on ammonia dynamics, driven by temperature and flow-related processes. Enhanced organic nitrogen mineralisation and diminished nitrification rates under warmer temperatures and low-flow conditions are likely contributing factors to these observed trends (Bernot and Dodds, 2005) [28] (Figure 6). Spatially, Damtal-1 consistently recorded the highest NH_3 levels, followed by Dari and Damtal-2, with Kotwali persistently the lowest-differences that align with variable upstream anthropogenic pressures (intensive agriculture, livestock density, and wastewater inputs) known to elevate instream ammonia loads (Carey and Migliaccio, 2009) [29]. Year-wise comparisons show that the upward trajectory is most pronounced during Seasons C and D, suggesting cumulative nitrogen loading and potential legacy effects whereby past and sustained inputs continue to sustain elevated riverine NH_3 export (Cao *et al*., 2025) [30]. Collectively, the uniform seasonal pattern across sites-coupled with site-specific magnitude differences-implies that regional drivers and hydrological seasonality set the timing of NH_3 peaks while local land-use and point-source pressures determine their intensity; these combined trends heighten the risk of eutrophication and ammonia toxicity in receiving waters and therefore warrant targeted source-tracking and management of agricultural and wastewater inputs (Camargo and Alonso, 2006) [31].

Concentration of O_3

A seasonal analysis of O_3 concentration data from March 2020 to November 2024 in Kotwali, Dari, Damtal-1, and Damtal-2 shows strong seasonal variation (Table 6 and Figure 7). As expected in photochemical reactions, higher concentrations were always recorded during the warmer months (March to August), and lower concentrations were recorded during the cooler months. In terms of spatial variation, Kotwali and Damtal-2 showed the highest O_3 concentrations during the entire period, with maximum concentrations of about 2.0 μg/m^3 during March to August 2021. Damtal-1 showed moderate concentrations, while Dari showed the lowest concentrations, suggesting relatively lower precursor accumulation or possibly different dispersion properties. Analysis of the data suggests that summer and pre-monsoon seasons are conducive to higher ozone formation due to increased photolysis, higher temperatures, and longer sunlight periods. These factors enhance the reaction cycles of NO_x and VOCs.

Moreover, the relatively stable atmospheric conditions may also lead to accumulation of pollutants near the surface, thereby increasing episodic ozone formation. Year-wise analysis shows that there are minor variations in O_3 concentrations after 2022, but overall, the concentrations have been relatively stable during the five-year period. The highest site-specific concentration was recorded during March to August 2021, while the lowest concentration was recorded at Kotwali during March to May 2023 (approximately 1.03 $\mu g/m^3$). The stability of the spatial distribution over the years indicates that local precursor accumulation and site-specific emission properties are relatively more important than meteorological properties. In the Kangra district of Himachal Pradesh, ground-level ozone is a secondary pollutant, formed *via* intricate photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs). The primary sources of these precursors consist of both anthropogenic and biogenic origins. In urban areas such as Dharamshala and Palampur, vehicular emissions represent the predominant anthropogenic source, significantly contributing NO_x and VOCs through the combustion of fossil fuels. Additionally, seasonal biomass combustion, residential wood use, and small-scale industrial operations such as brick kilns further exacerbate the load of ozone precursors. Moreover, Kangra's expansive forest ecosystems release biogenic VOCs, including isoprene and monoterpenes (from pine trees). These compounds, when combined with anthropogenic NO_x and under conditions of elevated solar irradiance, facilitate enhanced ozone production. Meteorological factors, particularly during the summer months, elevate photolytic activity while restricting vertical dispersion, thereby exacerbating the incidence of ozone episodes in the region. In this study, O_3 concentrations were taken from HPSPCB manual monitoring stations, which report one daily value. For this reason, the analysis is based on daily mean concentration. Although the Indian NAAQS uses maximum 8-hours averages, the daily values provided by the monitoring network still give a reliable picture of seasonal patterns and difference between the study sites.

No significant long-term trend (increasing or decreasing) was detected across the study locations; however, the recurring seasonal peaks are primarily driven by higher summer temperatures, which enhance photochemical ozone formation. O_3 concentrations showed a positive correlation with temperature and an inverse relationship with NO_2 levels-higher O_3 levels coincided with reduced NO_2, and vice versa.

Site Characteristics and Air Quality Influences in Damtal and Dharamshala

Damtal, located at ~360 m above sea level in Himachal Pradesh, is a major industrial hub with numerous manufacturing units, including Varun Beverages, Dinesh Glass Industries, B7 Star Ceramic, and others. The region experiences heavy vehicular activity due to the transportation of raw materials and goods, leading to significant emissions from trucks, commercial vehicles, and public transport. Additionally, unpaved roads and congested marketplaces contribute to elevated levels of road dust and particulate matter (PM) pollution. These factors result in a high pollution load dominated by industrial and vehicular emissions. In contrast, Dharamshala (~1457 m above sea level) has a distinctly different emission profile. Kotwali, its commercial centre, has moderate pollution levels caused by traffic congestion and bus station activity. Emissions from both private and public transport are the main contributors. Dari, however, is primarily residential place, with minimal industrial activity and lower traffic density, resulting in comparatively better air quality.

The difference in forest cover between Damtal and Dharamshala also plays a key role in air quality profiles. Dharamshala has ~47.8% forest cover compared to Damtal's ~32.9%. Forested areas are known to reduce atmospheric pollutants via stomatal uptake of gases and interception of particulates on leaf surfaces. Additionally, trees direct impact particulate matter in the atmosphere by capturing and releasing particles (pollen), as well as the resuspension of particles from the plant's surface. High percentage tree cover areas, such as forest cover, will eliminate higher pollution and could result in more significant drops in the levels of air pollution in and around these places.

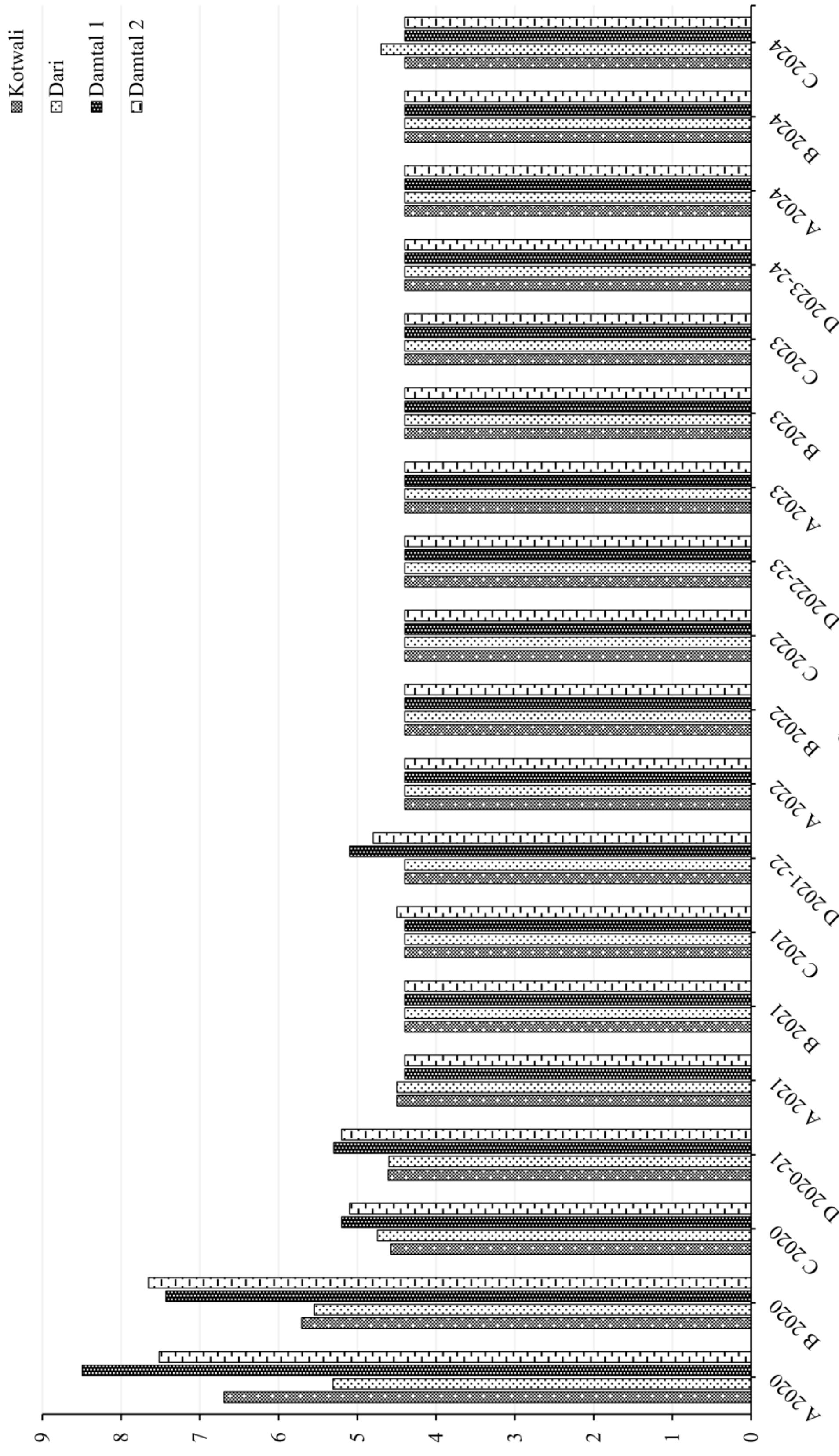

Figure 5. Seasonal variation of NO_X concentrations from 2020-2024 across Kotwali, Dari, Damtal 1 and Damtal2. Here, A corresponds to March to May, B corresponds to June to August, C correspond to September to November, and D corresponds to December to February.

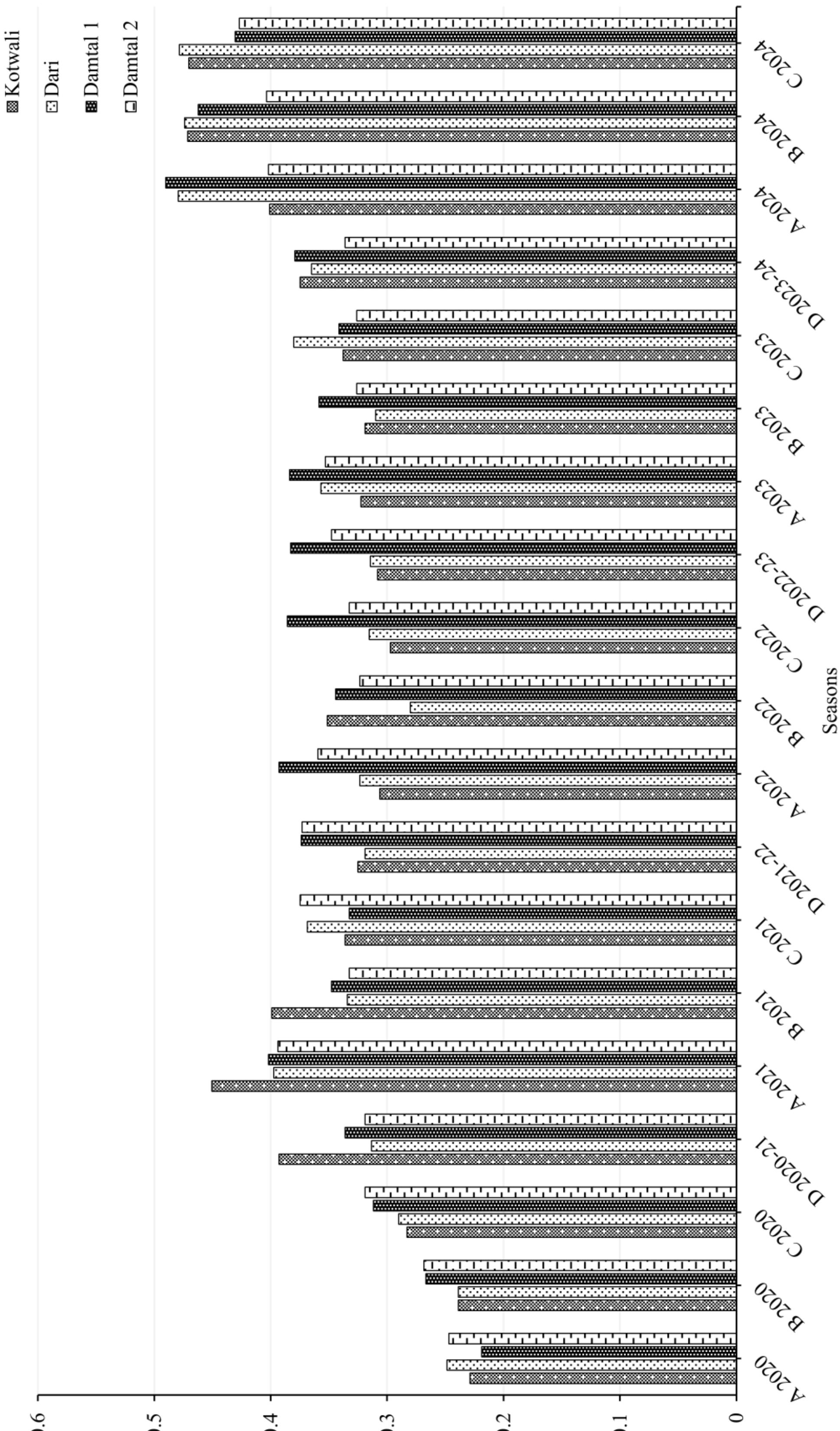

Figure 6. Seasonal variation of NH_3 concentrations from 2020-2024 across Kotwali, Dari, Damtal 1 and Damtal2. Here, A corresponds to March to May, B corresponds to June to August, C correspond to September to November, and D corresponds to December to February.

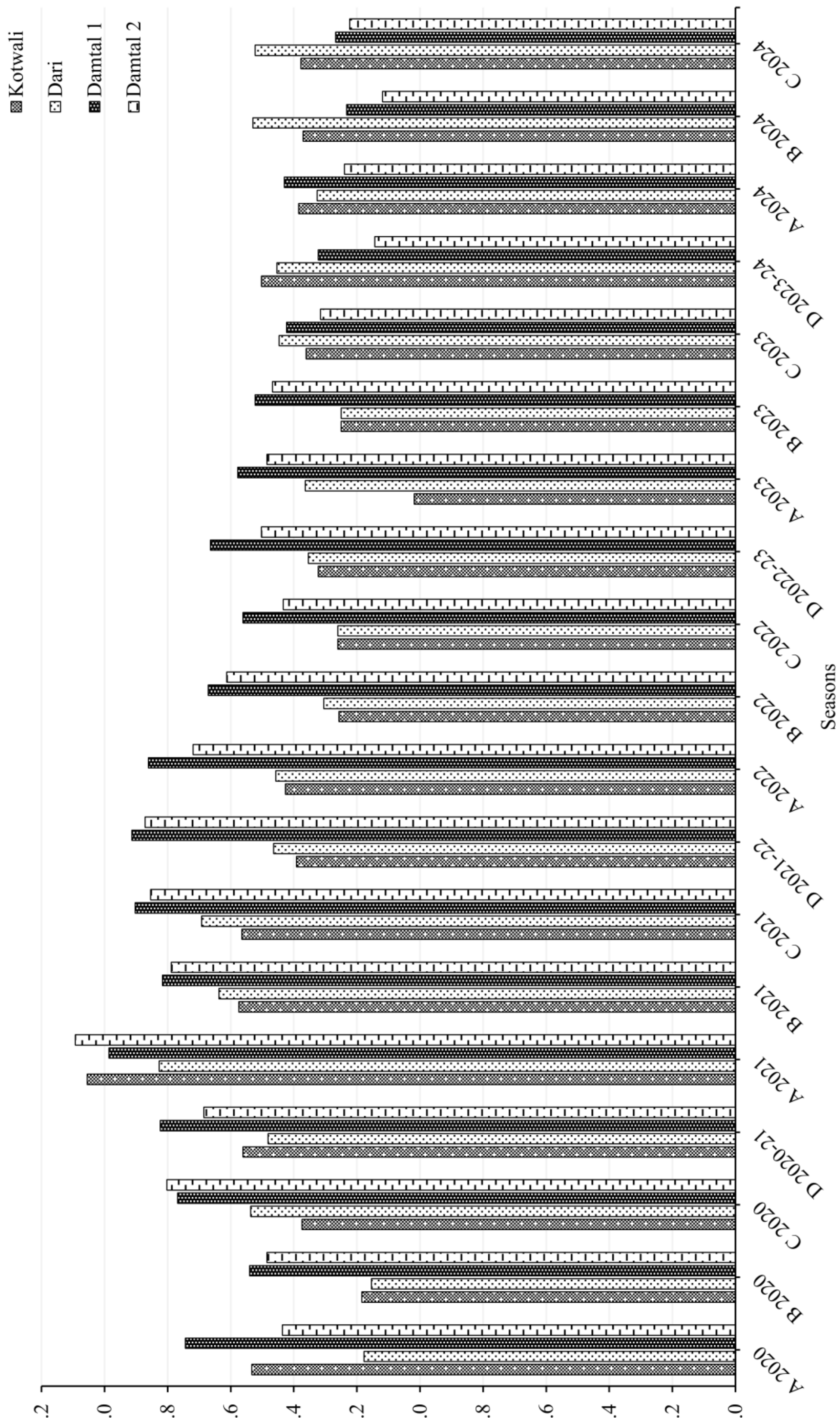

Figure 7. Seasonal variation of O_3 concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, and Damtal 2. Here, A corresponds to March to May, B corresponds to June to August, C corresponds to September to November, and D corresponds to December to February.

However, forested areas also a significant source of volatile organic compounds (VOCs), which can participate in photochemical reactions and lead to ozone formation, particularly under high solar radiation and warm conditions (Chen et al., 2022; Antonelli et al., 2020; Ma et al., 2022; Kroll et al., 2020) [32, 33, 34, 35]. Therefore, forests can simultaneously mitigate and contribute to atmospheric pollution depending on environmental conditions.

Topography and elevation further influence pollutant behaviour. Higher altitudes are associated with increased atmospheric dilution and dispersion, leading to generally lower PM concentrations (Roostaei et al., 2024) [36]. This is linked to the dilution effect in the atmosphere as altitude increases; air gets more mixed and dispersed, resulting in decreased concentration. But air transport and local emission sources can cause concentration to suddenly rise at higher altitudes. Lower mixing height and nighttime chemistry are probably the main factors affecting $PM_{2.5}$ concentration at lower elevations. Although most studies do not find a significant relationship, they do demonstrate that PM_{10} concentrations decrease with altitude. Because these are mostly created by physical activities like grinding, crushing, so due to the greater mass and size of these particles causes them to settle more quickly under gravity, which speeds up their clearance from the atmosphere. Previous studies discovered that the $PM_{2.5}/PM_{10}$ ration increased with altitude PM_{10}, suggesting that PM_{10} comprises larger particle size and mass, settles faster and decreases more significantly with altitude than $PM_{2.5}$, which remains suspended longer, resulting in an increasing $PM_{2.5}/PM_{10}$ ratio at higher elevations. NO_x levels also decrease with altitude as emissions from ground-based sources like vehicles are limited and vertical mixing is enhanced. However, in stable conditions with low mixing height, pollutants can be trapped near the surface, even at higher elevations (Li et al., 2020) [37]. Furthermore, elevated solar radiation at higher altitudes promotes ozone (O_3) formation via enhanced photochemical reactions, increasing O_3 concentrations despite lower NO_x levels. Despite having lower NO_x emissions than Damtal, Dharamshala had slightly higher O_3 levels. This could be explained by a NO_x-limited regime, in which ozone formation is facilitated by abundant biogenic VOCs from forest cover and increased sun radiation at higher elevations. Damtal, on the other hand, has a VOC-limited regime with excess NO_X, which restricts the formation of O_3 and also causes ozone depletion by reacting directly with O_3 and its precursors (Kroll et al., 2020) [35]. Ozone can also build up close to the surface due to stable atmospheric conditions and less vertical mixing at higher elevations. Surface ozone levels may be further enhanced by occasional stratospheric intrusions that have been documented in the Himalayan region (Moore & Semple, 2009) [37].

During the nationwide COVID-19 lockdown (March 24-May 31, 2020), anthropogenic emissions from transportation, tourism, and industry declined sharply. This led to significant reductions in PM_{10} and $PM_{2.5}$ levels, while gaseous pollutants like NO_x, SO_x, and NH_3 also showed marked decreases due to reduced industrial and vehicular activity (Chand et al., 2023) [39].

CONCLUSION

This study investigated air pollution trends in the Damtal and Dharamshala regions of Himachal Pradesh from 2020 to 2024, highlighting the influence of altitude, land use, and seasonal variability on air quality. Particulate matter (PM_{10} and $PM_{2.5}$) concentrations were generally higher at lower altitudes, such as in Damtal, due to limited atmospheric dispersion and the gravitational settling of larger particles. Similarly, nitrogen oxides (NO_x), primarily emitted from ground-level sources like vehicular traffic, also showed a decreasing trend with elevation. In contrast, elevated ozone (O_3) levels at higher altitudes, driven by increased solar radiation, photochemical activity, and occasional stratospheric intrusions, contributed to enhanced secondary formation of NO_x in areas like Dharamshala. Forest cover, which is more extensive in Dharamshala, played a mitigating role by capturing airborne particulates and absorbing gaseous pollutants through leaf stomata. Seasonal patterns were evident, with improved air quality during the summer due to enhanced atmospheric mixing, rainfall, and higher ventilation rates, excluding ozone, which increased with solar intensity. Winter months exhibited higher pollutant concentrations, largely attributed to biomass burning and restricted atmospheric dispersion. Notably, during the COVID-19 lockdown (March-May 2020), significant reductions were observed in both particulate and gaseous pollutants (PM_{10}, $PM_{2.5}$ NO_2, NH_3), corresponding with minimal anthropogenic activity. Overall, this study underscores the complex interplay of topography, vegetation, emission sources, and meteorological factors in shaping regional air quality dynamics. To improve air quality in these areas, strategies like stricter emission controls in winter, promotion of sustainable agricultural practices in summer are essential.

Declaration

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Authors' Contributions

Karishma Thakur: Writing-Original Draft; Neha Singh: Review and Editing; Nirmal Kumar Katiyar: Data Validation; Onkar Singh Nayal: Software and data curation, manuscript drafting; Maheshwar S. Thakur: Conceptualisation and supervision.

Ethical Compliance

This study was conducted following institutional and ethical research standards. All air quality data were obtained from publicly accessible government sources (HPSPCB and CPCB), and no human or animal subjects were involved.

Consent to Participate

Not Applicable

Consent to Publish

Not applicable.

Note

For this study, data were sourced from the Himachal Pradesh State Pollution Control Board (HPSPCB) and validated against Central Pollution Control Board (CPCB) records for accuracy.

Competing Interests

The authors declare that they have no competing interests.

Data Availability

The datasets generated and/or analysed during the current study are publicly available in the supporting information file and Microsoft excel file.

Table 2. Seasonal variation of PM_{10} concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, Damtal 2

Year	Season	Kotwali (μg/m^3)	Dari (μg/m^3)	Damtal1 (μg/m^3)	Damtal2 (μg/m^3)
2020	March 2020 to May 2020	31.09	29.52	41.46	44.75
	June20 to Aug 2020	33.22	33.05	50.39	48.06
	Sep 20 to Nov 20	41.41	47.13	63.64	62.91
2021	Dec 2020 to Feb 2021	44.88	51.694	82.628	87.617
	March 2021 to May 2021	47.11	47.78	68.7	65.535
	June21 to Aug 2021	40.5	38.9	62.057	65.323

	Sep 21 to Nov 21	34.31	40.28	55.862	54.558
2022	Dec 21 to Feb 2022	40.19	51.314	76.029	76.2
	March 2022 to May 2022	57.57	55.2	77.05	78.942
	June22 to Aug 2022	41.48	42.315	69.184	60.709
	Sep 22 to Nov 22	38.42	42.64	57.3	53.886
2023	Dec 22 to Feb 23	43.48	43.93	61.63	58.5
	March 23 to May 23	40.8387	37.967	55.21	53.63
	June 23 to Aug 23	36.218	39.8	51.3684	46.781
	Sep 23 to Nov 23	45.259	49.43	53.7	49.175
2024	Dec 23 to Feb 24	53.0625	59.114	55.857	53.147
	March 24 to May 24	49.42	55.029	67.13	52.593
	June 24 to Aug 24	38.692	41.4871	53.392	51.05
	Sep 24 to Nov 24	45	51.73	58.13	58.8095

Table 3. Seasonal variation of $PM_{2.5}$ concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, Damtal 2.

Year	Season	Kotwali (μG/M^3)	Dari (μG/M^3)	Damtal 1 (μG/M^3)	Damtal 2 (μG/M^3)
2020	March 20- May 20	13.18	11.48		19.8
	June20 - Aug 20	18.57	19.38		
	Sep 20 - Nov 20	28.86	28.6		37.33
2021	Dec 20 -Feb 21	25	27.75		49.814
	March 21-May 21	22.22	23.46		32.785
	June21 -Aug 21	21.61	19.631	31	30.896
	Sep 21 - Nov 21	18.15	21.5	28.8275	31.136
2022	Dec 21 - Feb 22	22.25	26.714	39.5588	40.6
	March 22 - May 22	28.06	27.676	36.8	36.392
	June22 - Aug 22	17.33	17.789	29.531	20.5
	Sep 22 - Nov 22	17.5	25.428	25.72	25.486
2023	Dec 22 - Feb 23	22.21			31.2
	March 23 - May 23	20.3	18.4782		26.807
	June 23 -Aug 23	21.23	17.16	24.4	22.87
	Sep 23 - Nov 23	24.5	23.847	21.76	20.717
2024	Dec 23 -Feb 24	25.67	30.736	25.5142	19.62
	March 24 -May 24	25.5	30	26.5	21.5312
	June 24 -Aug 24	23.9	25.63	23.678	21.606
	Sep 24 -Nov 24	22.58	27.06	25.896	31.06

Table 4. Seasonal variation of NO_X concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, Damtal 2.

Year	Season	Kotwali (μg/m^3)	Dari (μg/m^3)	Damtal 1 (μg/m^3)	Damtal 2 (μg/m^3)
2020	March 20- May 20	6.7	5.32	8.52	7.37
	June20 - Aug 20	5.72	5.57	7.42	7.51
	Sep 20 - Nov 20	4.56	4.76	5.15	5.05
2021	Dec 20 -Feb 21	4.6	4.6	5.0428	4.814
	March 21-May 21	4.6	4.6	4.5	4.5
	June21 -Aug 21	4.5	4.5	4.5	4.5
	Sep 21 - Nov 21	4.5	4.5	4.5	4.604
2022	Dec 21 - Feb 22	4.5	4.5	5.173	4.68

	March 22 - May 22	4.5	4.5	4.5	4.5
	June22 - Aug 22	4.5	4.5	4.5	4.48
	Sep 22 - Nov 22	4.5	4.5	4.5	4.5
2023	Dec 22 - Feb 23	4.5	4.5	4.5	4.5
	March 23 - May 23	4.5	4.5	4.5	4.5
	June 23 -Aug 23	4.5	4.5	4.5	4.5
	Sep 23 - Nov 23	4.5	4.5	4.5	4.5
2024	Dec 23 -Feb 24	4.5	4.5	4.5	4.485
	March 24 -May 24	4.5	4.5	4.483	4.5
	June 24 -Aug 24	4.5	4.5	4.5	4.5
	Sep 24 -Nov 24	4.5	4.9	4.5	4.5

Table 5. Seasonal variation of NH_3 concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, Damtal 2.

Year	Season	Kotwali (µg/m^3)	Dari (µg/m^3)	Damtal 1 (µg/m^3)	Damtal 2 (µg/m^3)
2020	March 20- May 20	0.23	0.25	0.22	0.25
	June20 - Aug 20	0.24	0.24	0.27	0.27
	Sep 20 - Nov 20	0.28	0.29	0.31	0.32
2021	Dec 20 -Feb 21	0.394	0.31	0.3342	0.317
	March 21-May 21	0.45	0.4	0.4	0.392
	June21 -Aug 21	0.4	0.3303	0.348	0.329
	Sep 21 - Nov 21	0.338	0.368	0.331	0.3767
2022	Dec 21 - Feb 22	0.3258	0.3171	0.376	0.373
	March 22 - May 22	0.306	0.3228	0.3916	0.362
	June22 - Aug 22	0.34827	0.2789	0.3447	0.325
	Sep 22 - Nov 22	0.2923	0.315	0.383	0.3318
2023	Dec 22 - Feb 23	0.306	0.315	0.3818	0.344
	March 23 - May 23	0.31935	0.356	0.3818	0.353
	June 23 -Aug 23	0.3156	0.3114	0.3578	0.325
	Sep 23 - Nov 23	0.337	0.376	0.343	0.325
2024	Dec 23 -Feb 24	0.375	0.3657	0.38	0.3352
	March 24 -May 24	0.4	0.477	0.5	0.4031
	June 24 -Aug 24	0.47	0.4717	0.4607	0.4075
	Sep 24 -Nov 24	0.47	0.48	0.43	0.4261

Table 6. Seasonal variation of O_3 concentrations from 2020-2024 across Kotwali, Dari, Damtal 1, Damtal 2.

Year	Season	Kotwali (µg/m^3)	Dari (µg/m^3)	Damtal 1 (µg/m^3)	Damtal 2 (µg/m^3)
2020	March 20- May 20	1.54	1.19	1.74	1.43
	June20 - Aug 20	1.18	1.16	1.54	1.49
	Sep 20 - Nov 20	1.37	1.54	1.77	1.82
2021	Dec 20 -Feb 21	1.57	1.4916	1.834	1.7088
	March 21-May 21	2.06	1.828	2	2.089
	June21 -Aug 21	1.584375	1.648	1.82	1.791
	Sep 21 - Nov 21	1.57	1.695	1.917	1.8581
2022	Dec 21 - Feb 22	1.393	1.471	1.926	1.87
	March 22 - May 22	1.43	1.464	1.86	1.717
	June22 - Aug 22	1.27	1.3131	1.673	1.619

	Sep 22 - Nov 22	1.26	1.264	1.55	1.43409
2023	Dec 22 - Feb 23	1.3212	1.354	1.657	1.502
	March 23 - May 23	1.0302	1.373	1.5818	1.486
	June 23 -Aug 23	1.2468	1.2514	1.5342	1.4781
	Sep 23 - Nov 23	1.374	1.441	1.426	1.315
2024	Dec 23 -Feb 24	1.5062	1.457	1.328	1.144
	March 24 -May 24	1.385	1.3323	1.436	1.2437
	June 24 -Aug 24	1.388	1.53	1.2464	1.12
	Sep 24 -Nov 24	1.38	1.524	1.27	1.219

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