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Government of Nepal
Ministry of Agriculture, Forests and Environment
Department of Environment
Babarmahal, Kathmandu, Nepal

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Editorial

It is our great pleasure to present **Volume XII of the Journal of Environment Sciences**, an annual publication of the Department of Environment. This volume continues our commitment to promoting scientific excellence, evidence-based environmental management, and information sharing through various relevant research in the field of environment. This edition comprises **eleven peer-reviewed research articles** contributed by researchers, academicians and environmental professionals. The articles address a broad spectrum of contemporary environmental issues under various major thematic areas such as **air pollution, environmental assessment, disaster risk management, solid waste assessment, climate change, biodiversity and environment policy**.

The Editorial Board sincerely acknowledges the dedication and valuable contributions of all authors who entrusted us with their research. We extend our heartfelt appreciation to the reviewers for their rigorous evaluations, constructive comments, and commitment to maintaining the scientific quality and integrity of this journal. We also thank the members of the Editorial Board as well as Mr. Sabit Deshar and Mr. Govinda Prasad Lamichhane from Department of Environment in helping us internally reviewing the article. Similarly, we also thank Ms. Nabina Maharjan, Ms. Sadikshya Wosti, Ms. Arati Shrestha, Ms. Pritika Pushpam and Ms. Manisha Ghimire for helping us with the reference formatting.

The views and interpretations expressed in the published articles are solely those of the respective authors and do not necessarily represent the official position or policies of the Department of Environment.

We hope that **Volume XII** will serve as a valuable reference for researchers, students, environmental professionals and policymakers working in the field of environment conservation. Also we hope to receive constructive feedback of our readers regarding the journal which will help to strengthen this publication each year.

Editorial Board

Journal of Environment Sciences

Volume XII

Department of Environment

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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 $\mu\text{g}/\text{m}^3$) (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),

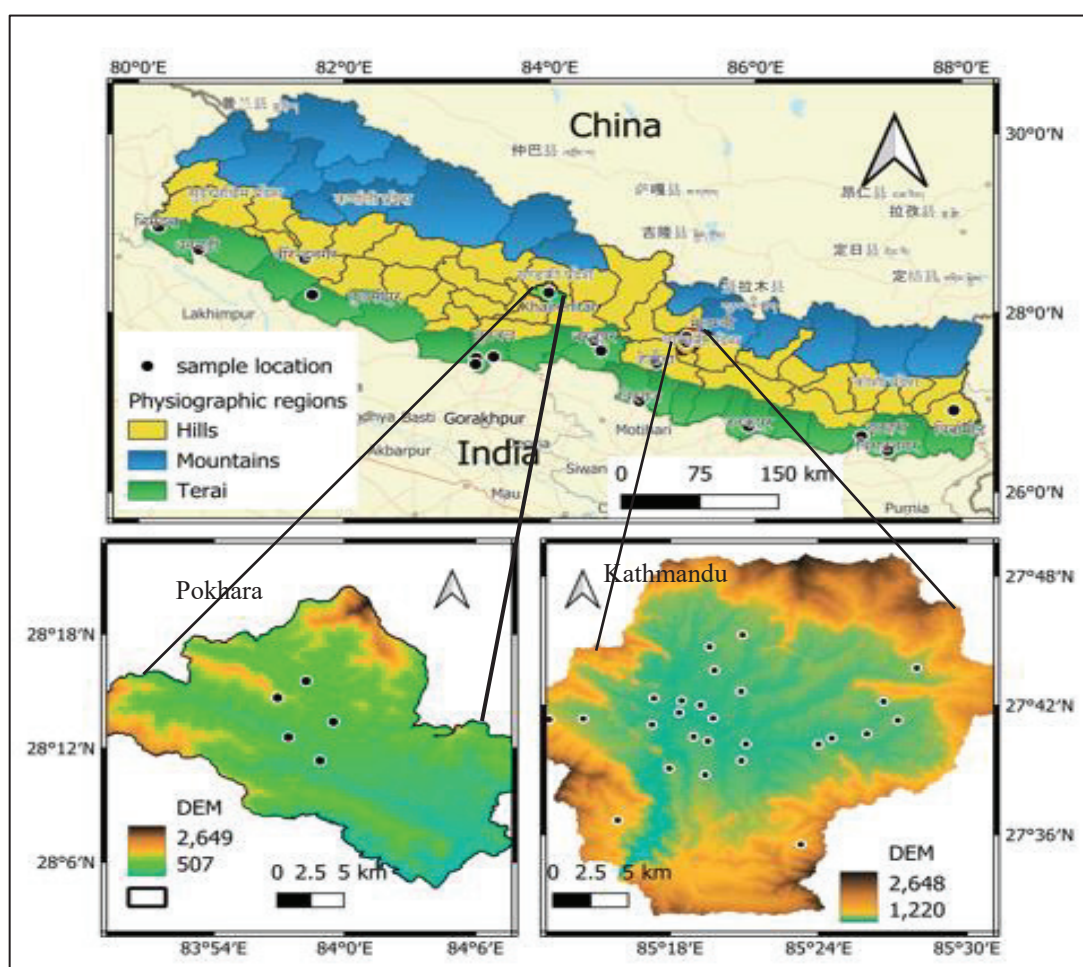


Figure 1: Sensor locations at different parts of Nepal

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 $7.8 \pm 3.2 \mu\text{g}/\text{m}^3$ at Hetauda (Inner Terai) to $18.9 \pm 12.5 \mu\text{g}/\text{m}^3$ at Dhangadhi (Western Terai). Most sites showed mean values between $10\text{--}19 \mu\text{g}/\text{m}^3$, below the NAAQS of $40 \mu\text{g}/\text{m}^3$ (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 $75.7 \pm 49.7 \mu\text{g}/\text{m}^3$, Janakpur $70.1 \pm 51.5 \mu\text{g}/\text{m}^3$, and Biratnagar $43.2 \pm 27.5 \mu\text{g}/\text{m}^3$. In the Western Terai, Lumbini ($74.2 \pm 46.1 \mu\text{g}/\text{m}^3$) and Bhairahawa ($63.7 \pm 37.9 \mu\text{g}/\text{m}^3$) 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 $170.5 \pm 80.9 \mu\text{g}/\text{m}^3$, followed by Birgunj at $154.0 \pm 63.9 \mu\text{g}/\text{m}^3$ and Biratnagar at $131.8 \pm 58.8 \mu\text{g}/\text{m}^3$ 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 ($67.2 \pm 23.21 \mu\text{g}/\text{m}^3$) and Lumbini ($101.6 \pm 33.1 \mu\text{g}/\text{m}^3$) in Western Terai. Mid Hill sites, while substantially lower, still recorded elevated concentrations at Kathmandu ($53.6 \pm 10.9 \mu\text{g}/\text{m}^3$), Bhaktapur ($62.4 \pm 15.8 \mu\text{g}/\text{m}^3$), and Pokhara ($42.5 \pm 11.4 \mu\text{g}/\text{m}^3$). Inner Terai sites such as Surkhet ($30.7 \pm 9.3 \mu\text{g}/\text{m}^3$) and Hetauda ($39.3 \pm 14.6 \mu\text{g}/\text{m}^3$) 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 $113.9 \pm 34.3 \mu\text{g}/\text{m}^3$, 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.

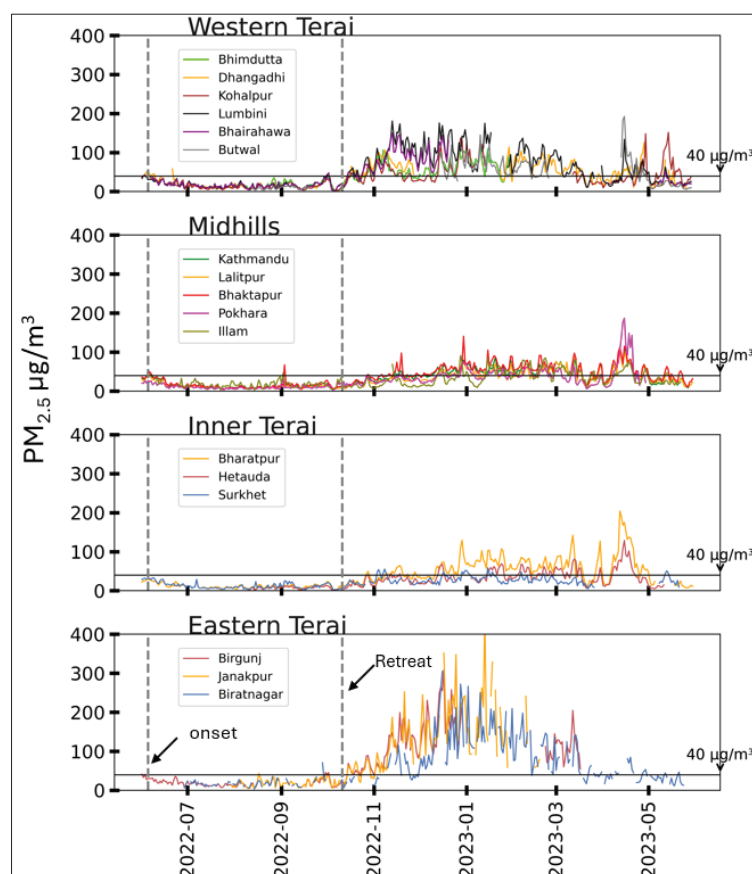


Figure 2: Time series of $PM_{2.5}$ at different regions of Nepal from June 2022 to May 2023. The vertical dashed line in the figure depicts the onset (June 5, 2022) and the retreat (October 11, 2023) of Monsoon.

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

Region	Site	$PM_{2.5}$ ($\mu g/m^3$)							
		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	$4_{2.5} \pm 11.4$	100	$46.8 \pm 4_{2.5}$	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.

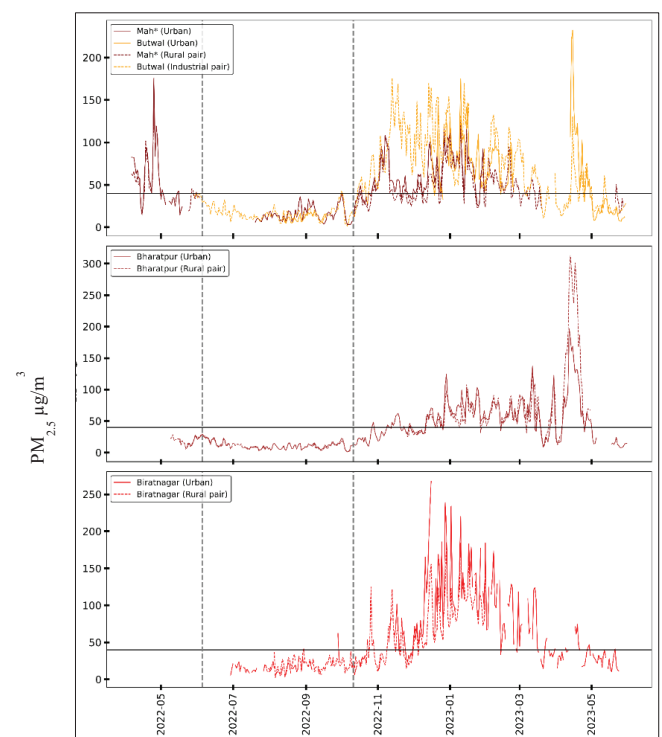


Figure 3: Comparison of PM_{2.5} in the urban and rural settings of Nepal

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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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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Spatiotemporal analysis of tropospheric NO₂ in Kathmandu Valley using TROPOMI satellite data

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Abstract

Kathmandu Valley faces severe air quality degradation driven by rapid urbanization, geographic constraints, and seasonal meteorological patterns. This study presents a systematic spatiotemporal characterization of tropospheric nitrogen dioxide (NO₂) across Kathmandu Valley, Nepal, using Sentinel-5 Precursor TROPospheric Monitoring Instrument (TROPOMI) satellite observations resampled to a 0.01° output grid spanning July 2018 to December 2024 (n = 78 monthly composites). Non-parametric trend detection methods — the Theil-Sen slope estimator and the Mann-Kendall test (with seasonal and pre-whitened variants as sensitivity checks) were applied to quantify temporal trends, seasonal decomposition was used to characterize intra-annual variability, and spatial analysis was conducted across five analytical zones to assess intra-valley concentration differences. The analysis identifies a marginally increasing trend of $+5.3 \times 10^{-7} \text{ mol m}^{-2} \text{ year}^{-1}$ across the full study period; however, this trend is not statistically significant at $\alpha = 0.05$ ($p \geq 0.05$; seasonal-MK $p = 0.41$, pre-whitened-MK $p = 0.36$). COVID-19 lockdown periods produced a modest reduction of approximately 4.5% with a 95% bootstrap CI of (−1.4, +9.9)%, indicating the reduction is not statistically significant at $\alpha = 0.05$ in NO₂ concentrations relative to equivalent months in non-lockdown years. Pronounced seasonal variability was observed, with pre-monsoon (March–May) concentrations approximately 14% higher than monsoon (June–September) levels, a pattern coincident with regional biomass burning due to forest fire and local brick kiln emissions but not by itself causally attributable to any single source. Significant intra-valley spatial heterogeneity was detected (Kruskal-Wallis $H = 23.4$, $p < 0.001$), with Kathmandu Metropolitan City recording the highest mean NO₂ concentration ($7.8 \times 10^{-5} \text{ mol m}^{-2}$, Z-score = +1.8), indicating a disproportionate pollution burden relative to other analytical zones. These findings establish a baseline for air quality monitoring in the valley and highlight the need for targeted emission reduction interventions in identified pollution hotspots.

Keywords: Nitrogen dioxide, TROPOMI, air quality, intra-urban variability, Kathmandu, mann-kendall, COVID-19

1. Introduction

Atmospheric pollution is a major environmental threat to human health and ecological systems in Nepal and around the world (Giri et al., 2023). Nitrogen dioxide is a significant criteria air pollutant primarily generated from fossil fuel combustion in the transportation and industrial sectors (Hassan et al., 2021; Jarvis et al., 2010). This toxic gas is a critical indicator of human activity and a major precursor to the formation of surface ozone and nitrate aerosols (Zhang et al., 2020). Exposure to high concentrations of nitrogen dioxide is linked to serious respiratory and cardiovascular illnesses and millions of premature deaths annually

(Virghileanu et al., 2020). Effective urban air quality management requires routine monitoring to detect and mitigate high concentrations of these contaminants (Öçer et al., 2024). The launch of the Sentinel 5 Precursor satellite with the Tropospheric Monitoring Instrument in 2017 has revolutionized the ability to monitor atmospheric composition (Veefkind et al., 2012). This sensor provides unprecedented accuracy and spatial resolution for mapping urban air pollution at a global scale (Tack et al., 2017).

South Asia is recognized as a global air pollution hotspot characterized by rapid urbanization and high population density (Upadhyay et al., 2022).

The central Himalayan region presents unique atmospheric challenges because its complex topography significantly influences the accumulation and transport of pollutants (Moore & Semple, 2021). Himalayan valleys are particularly vulnerable to pollutant trapping due to meteorological conditions such as temperature inversions and low wind speeds (Bhatta et al., 2024). Analysis of long-term satellite data shows a gradual increase in nitrogen dioxide levels across most regions of the Third Pole since 2005 (Sharma et al., 2023). Previous studies have used satellite observations to assess regional trends and identify the impact of economic growth on the atmospheric composition of mountainous regions (Sharma et al., 2023).

The Kathmandu Valley is one of the most severely impacted urban centers in the Himalayan region (Ishtiaque et al., 2017). Its bowl-shaped geography restricts air ventilation and leads to the accumulation of emissions from anthropogenic sources (Panday & Prinn, 2009; Kuikel et al., 2024). Rapid urban expansion and a surge in the number of vehicles have exacerbated local air quality issues (Gyawali et al., 2025). In Nepal inefficient residential combustion and industrial activities such as brick and cement production contribute significant pollutant loads to the atmosphere. Despite these challenges air quality monitoring in the region has been mostly limited to measuring particulate matter (Dhital et al., 2022). This focus on aerosols has created a significant knowledge gap regarding the spatiotemporal dynamics of gaseous pollutants like nitrogen dioxide (Gyawali et al., 2025).

Methodological advances in recent literature have demonstrated the utility of high-resolution satellite products for urban scale assessments (Prunet et al., 2020). The Google Earth Engine platform has facilitated the processing of large volumes of satellite data for spatiotemporal analysis (Öçer et al., 2024). Research conducted during the COVID 19 pandemic provided a rare opportunity to evaluate the relationship between reduced human activity and air quality improvements (Hassan et al., 2021). In the Kathmandu Valley the countrywide lockdown in 2020 resulted in a noticeable decrease in nitrogen dioxide concentrations (Dhital et al., 2022).

However, studies have also noted that natural events such as forest fires can mask the environmental benefits of anthropogenic emission reductions in the region (Upadhyay et al., 2022).

TROPOMI provides daily global coverage of tropospheric NO₂ column density at an unprecedented combination of spatial resolution and signal-to-noise ratio. Following the upgrade of 6 August 2019, the native ground pixel size is approximately 3.5 × 5.5 km² (Van Geffen et al., 2022). However, retrieval performance degrades in complex terrain because (i) the air mass factor (AMF) calculation assumes a priori vertical NO₂ profiles that may not match the strong boundary-layer trapping observed in mountain valleys; (ii) surface albedo over snow-covered Himalayan peaks introduces scene-specific uncertainty in the AMF (Hedelt et al., 2019); and (iii) cloud and aerosol contamination, even after standard quality filtering, can bias the column low by 10–30% (Van Geffen et al., 2022). Post-processing super-resolution approaches are an active research area but require ground-based prior information that is not currently available for Kathmandu Valley.

There are very few studies on medium-term spatiotemporal assessments of nitrogen dioxide for the Kathmandu Valley. Intra urban analysis is essential to identify pollution hotspots and understand the dynamics of local emissions (Gurung et al., 2017). Detailed investigations are needed to support targeted air quality interventions and evidence-based management in developing Himalayan cities (Upadhyay et al., 2022).

Several recent works have addressed aspects of Kathmandu Valley air quality. Mahapatra et al. (2019) used OMI (13 × 24 km native pixels) for the period 2005–2015 with WRF-Chem; Upadhyay et al. (2022) used OMI for a 2020 COVID-19 snapshot; Dhital et al. (2022) used OMI + ground-based PM for the 2020 dry/wet split; Bhatta et al. (2024) used TROPOMI for the 2019–2021 COVID impact window; and Gyawali et al. (2025) used TROPOMI for emission-source attribution. To my knowledge, this study provides the first comprehensive TROPOMI based assessment of NO₂ dynamics in the Kathmandu Valley using

a continuous 6.5-year dataset spanning the pre-COVID, lockdown, and recovery periods. The analysis integrates robust trend detection methods, including conventional and seasonal Mann Kendall approaches, evaluates COVID 19 impacts through same month comparisons, examines seasonal patterns and anomalies, and assesses spatial variability across five municipalities using a consistent analytical framework. This combination of long-term monitoring, statistical rigor, and spatial analysis offers a stronger baseline understanding of NO_2 variability in the Kathmandu Valley than previous studies.

This study addresses these gaps through comprehensive analysis of TROPOMI nitrogen dioxide data at 0.01° resampled output grid for Kathmandu Valley from 2018 to 2024. The objectives are to quantify spatiotemporal nitrogen dioxide patterns including seasonal cycles, inter annual trends, and COVID 19 impacts and to identify intra urban pollution gradients across five municipalities in core Kathmandu valley. Several limitations apply to this analysis. The lack of data availability for ground-based nitrogen dioxide

validation data limits direct accuracy assessment of satellite retrievals, although TROPOMI has demonstrated reliability in urban environments globally. Tropospheric column densities do not perfectly correspond to surface concentrations relevant for human exposure, as vertical mixing and boundary layer dynamics influence the relationship between integrated columns and ground level mixing ratios. Municipal scale aggregation uses approximate boundaries that may misclassify peripheral areas, and retrieval uncertainties related to surface albedo, cloud cover, and aerosol loading may introduce bias under local atmospheric conditions.

2. Materials and Methods

2.1 Study Area

Kathmandu Valley is located in central Nepal at the southern edge of the Himalayan range, approximately between 27.5°N and 27.8°N latitude and 85.2°E and 85.6°E longitude (Figure 1). The valley is at 1,300 to 1,400 meters elevation from sea level, while surrounding mountain ranges

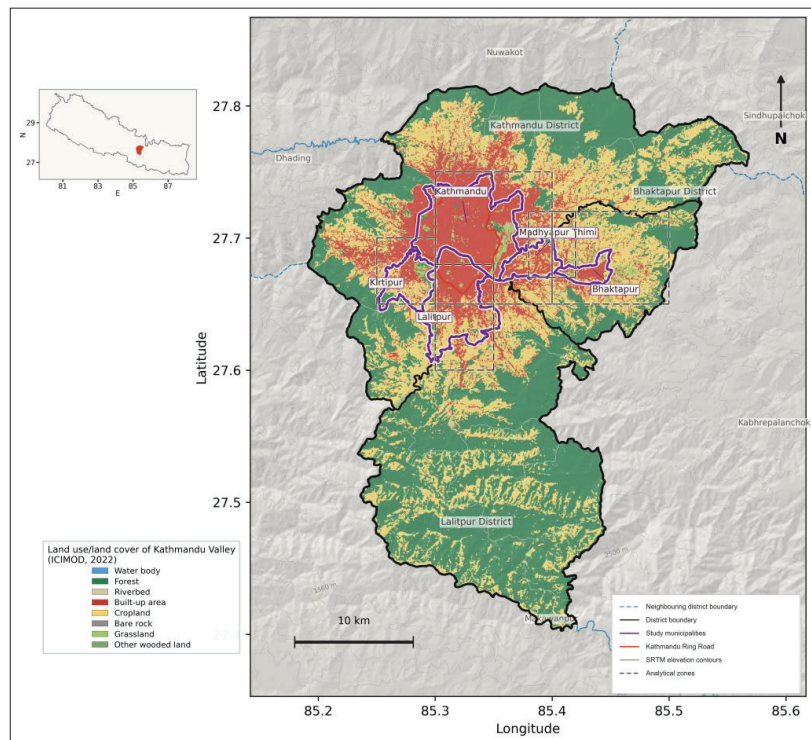


Figure 1: Study area map of Kathmandu Valley, Nepal, showing (a) location within Nepal (inset), (b) district boundaries (Kathmandu, Lalitpur, Bhaktapur), five study municipalities (purple outlines), Kathmandu Ring Road (red), SRTM elevation contours, analytical zones of the study and ICIMOD 2022 land use/land cover. Built-up areas (red) concentrate in the urban core, while forest and cropland dominate peripheral zones.

are above 2,700 meters which creates a bowl shaped topography that limits ventilation and traps atmospheric pollutants (Kitada & Regmi, 2003; Aryal et al., 2009). The valley experiences distinct seasonal meteorology that influences pollutant dispersion. Winter temperature inversions from December to February trap pollutants near the surface, while the summer monsoon from June to September scavenges pollutants through precipitation (Panday & Prinn, 2009; Shrestha et al., 2013). Weak prevailing winds and mountain valley circulations lead to frequent atmospheric stagnation, particularly during winter nights (Panday et al., 2009).

Rapid urbanization has made Kathmandu Valley the most densely populated region in Nepal, with over three million residents and extensive transportation networks (CBS, 2021; Ishtiaque et al., 2017). Major nitrogen dioxide emission sources include vehicular traffic, residential biomass and fossil fuel combustion, brick kilns, and small industries (Shrestha et al., 2013; Stockwell et al., 2016). Air quality in the valley ranks among the poorest in South Asia (Health Effects Institute, 2023), though previous research has focused primarily on particulate matter rather than nitrogen dioxide (Gurung & Bell, 2013; Mishra & Kulshrestha, 2021).

Kathmandu Valley encompasses five major municipalities, each with distinct urban and peri-urban characteristics that shape local atmospheric pollution patterns. Kathmandu Metropolitan City constitutes the commercial and administrative core of the valley, marked by high population density, an extensive road network, and concentrated economic activity. Lalitpur Sub-Metropolitan City exhibits mixed residential and industrial land use alongside historically significant settlements, while Bhaktapur Municipality retains a predominantly historical urban fabric, though suburban expansion along its periphery has accelerated in recent decades.

Kirtipur Municipality occupies the western peri-urban fringe, where elevated topography, university-centered development, and interspersed agricultural land produce a land use pattern distinct from the valley interior. Madhyapur Thimi Municipality

functions as a transitional zone between urban and rural land use, and its southern section contain a notable concentration of brick kilns, which represent a significant localized emission source.

Collectively, the enclosed basin topography, rapid urbanization, and diverse anthropogenic emission sources of the valley create conditions that are well-suited for satellite-based analysis of tropospheric NO₂. This study uses TROPOMI/Sentinel-5P retrievals to examine spatiotemporal variation in column NO₂ concentrations across these five municipalities. The valley is a particularly relevant study context given the limited availability of continuous ground-based air quality monitoring, which constrains the use of conventional in-situ approaches and strengthens the case for satellite-derived data as a primary analytical tool.

2.2 Satellite data acquisition and preprocessing

2.2.1 TROPOMI NO₂ data: Tropospheric NO₂ column density data were obtained from the Sentinel-5 Precursor (S5P) TROPOMI sensor, operational since July 2018 (Veefkind et al., 2012). The OFFL (Offline) Level-3 product (COPERNICUS/S5P/OFFL/L3_NO2), which provides superior data quality compared to Near Real-Time (NRTI) products (Van Geffen et al., 2022) was utilized. The product version used is OFFL processing baseline $\geq 02.04.00$, current as of mid-2024. The dataset spans July 2018 to December 2024 (6.5 years), showing pre-COVID baseline, pandemic disruption, and post-pandemic recovery periods.

The monthly median compositing prior to analysis was implemented to optimize computational efficiency and mitigate the 10,000-image indexing limitation inherent to Google Earth Engine Xee interface (Gorelick et al., 2017). For each month, the daily Level-2 granules to the study area were filtered, quality assurance screening (Section 2.2.3) was applied and the pixel-wise median NO₂ column density was computed. This aggregation reduced the dataset from approximately 2,300 daily images to 78 monthly composites, enabling rapid processing while preserving seasonal signals and reducing random noise. The median value was

chosen because it is less affected by unusual data points caused by temporary cloud cover or errors in the satellite measurements.

2.2.2 Spatial processing: Monthly composites were reprojected to WGS84 (EPSG:4326) at 0.01° spatial resolution (~1 km at the equator, ~0.9 km in Kathmandu) using bilinear interpolation. This resolution balances the native TROPOMI ground pixel dimensions (3.5 × 7 km at nadir) with the need to resolve intra-urban pollution gradients. Bilinear interpolation was selected because it preserves the continuity of the NO₂ field and reduces block artefacts during resampling, making it suitable for representing spatially continuous atmospheric variables. It is also the default resampling approach implemented in Google Earth Engine for atmospheric trace gas products (Gorelick et al., 2017) and has been widely applied in urban scale TROPOMI based air quality studies (Crippa et al., 2024; Ialongo et al., 2020). Data extraction was constrained to the Kathmandu Valley bounding box (85.25° – 85.55°E, 27.55° – 27.85°N), yielding

a 30 × 30-pixel grid. This analysis focuses on the central and eastern portions of Kathmandu Valley, encompassing the five municipalities that constitute the primary urban agglomeration (approximately 85.25°–85.55°E, 27.55°–27.85°N). The western portions of the valley and rural peripheral areas are not included in this analysis domain. The Xee Python interface enabled direct conversion from Google Earth Engine's Image Collection to Xarray Dataset format (Hoyer & Hamman, 2017), facilitating subsequent spatiotemporal analysis. The function `fast_time_slicing=True` was enabled to optimize temporal dimension indexing.

2.2.3 Quality assurance and cloud filtering: A multi-step QA pipeline (Table 1) is applied to each monthly composite prior to statistical analysis.

The L3 product already aggregates to a 0.05° grid prior to download; the 0.01° resampling is performed after the QA filtering and is a post-processing step.

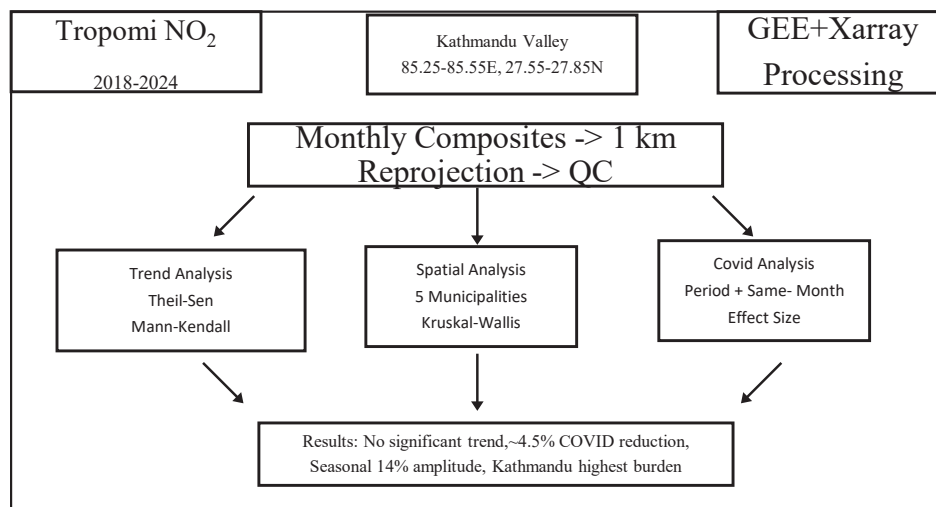


Figure 2: Methodological workflow of this study

Table 1: Quality assurance filtering summary for the TROPOMI NO₂ monthly composites

Step	Criterion	Reference
1	Pixels with 'qa_value < 0.75' are masked out	Recommended threshold for scientific use (Van Geffen et al., 2022)
2	Negative column values removed before monthly median computation	Retrieval failures over snow, clouds, or water bodies
3	Pixels with 'SolarZenithAngle > 70°' excluded	Limit low-light retrieval noise
4	Pixels with 'cloud_fraction > 0.3' excluded	Remove partially-cloudy scenes
5	Months with < 5 valid pixels within the valley bounding box discarded	None in this study - all 78 months retained

The following subsections describe each analytical component in detail, corresponding to the three parallel streams shown in Figure 2.

2.3 Temporal aggregation and trend analysis

2.3.1 Time series construction: Monthly spatial mean NO₂ concentrations were computed by averaging across all valid pixels within the study domain, producing a continuous time series from July 2018 to December 2024 (n=78 months). Missing values (<5% of record) were excluded from analysis.

2.3.2 Trend detection: Monthly median NO₂ concentrations were used for all trend analyses. Non-parametric statistical methods robust to non-normal distributions and outliers common in satellite-derived atmospheric composition data was employed (Hirsch et al., 1982). Using the Mann-Kendall test and Theil-Sen slope estimator together is standard practice in atmospheric and environmental trend analysis (Collaud Coen et al., 2020; Davtalab et al., 2023; Gocic & Trajkovic, 2013).

Theil-Sen Slope Estimator: A median-based pairwise slope calculation providing robust trend magnitude (Sen, 1968; Theil, 1950).

$$\beta = \text{median}\left(\frac{x_j - x_i}{t_j - t_i}\right) \forall i < j$$

where x represents NO₂ concentration and t represents time in decimal years. The 95% confidence interval was computed via Sen's method.

Mann-Kendall Test: A rank-based test for monotonic trend significance (Kendall, 1975; Mann, 1945)

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

where sgn is the sign function. The standardized test statistic Z was compared against critical values at $\alpha = 0.05$.

Monthly NO₂ time series from atmospheric composition products exhibit strong seasonality, which can bias significance estimates when applying the classic Mann Kendall test to raw data (Hirsch et al., 1982; Zhang & Zwiers, 2004). To address this limitation, two complementary robustness checks were applied. The Seasonal Mann Kendall approach performs trend detection within individual seasons and combines the resulting statistics into an overall trend estimate (Hirsch et al., 1982). The Pre whitened Mann Kendall approach removes lag one autocorrelation prior to applying the standard test to reduce the influence of temporal dependence (Collaud Coen et al., 2020; Zhang & Zwiers, 2004). Both approaches produce trend estimates consistent in magnitude and significance with the classic Mann Kendall results, while the classic form is retained as the primary reporting metric for consistency with prior studies and the seasonal and pre whitened results are presented as sensitivity checks. Trend analysis was conducted for the full study period (2018–2024) and seasons to maximize statistical power and minimize seasonal confounding. Sub-period trend analysis was performed for exploratory purposes only, given the strong seasonal variability (~14% amplitude) and short sub-period durations, these results should not be over-interpreted. Specific sub-period trend values are not reported to avoid misleading conclusions about directional changes during brief time windows.

2.4 COVID-19 impact assessment

The five distinct periods based on Nepal federal and provincial lockdown policies has been defined, illustrated in Table 2.

Table 2: COVID-19 study periods for impact assessment

Period	Dates	Description
Pre-COVID	July 2018–February 2020	Baseline anthropogenic activity
Lockdown 1	March 2020–July 2020	Strict nationwide lockdown (Phase I–III)
Transition	August 2020–March 2021	Phased reopening with intermittent restrictions
Lockdown 2	April 2021–May 2021	Second wave emergency restrictions
Recovery	June 2021–December 2024	Gradual normalization

Period differences were evaluated using the Kruskal-Wallis H-test, followed by pairwise Mann-Whitney U tests with Bonferroni correction for post-hoc comparisons. This avoids the normality assumption of one-way ANOVA and the equal-variance assumption of Tukey's HSD, both of which are unlikely to hold given the small sample sizes ($n = 2$ to 43) of the COVID period data. Effect sizes were quantified using Cohen's d (Cohen, 1988):

$$d = \frac{\bar{x}_1 - \bar{x}_2}{S_{pooled}}$$

Where, S_{pooled} represents the pooled standard deviation. Magnitude was interpreted as, small (0.2–0.5), medium (0.5–0.8), or large (>0.8).

In the same month comparison analysis, the Change (%) column represents the percentage reduction in NO_2 concentration during the lockdown period relative to the non-lockdown reference years, calculated as:

$$\% \text{ change} = \frac{\text{Other Years Mean} - \text{Lockdown time Mean}}{\text{Other Years Mean}} \times 100.$$

The 95% confidence interval of the reduction was obtained by non-parametric bootstrap (10,000 resamples), and the statistical significance of each monthly comparison was assessed using the Wilcoxon rank-sum (Mann-Whitney U) test.

2.5 Seasonal decomposition and anomaly detection

The additive seasonal decomposition to partition the monthly time series was applied into (Cleveland et al., 1990):

$$Y_t = T_t + R_t + S_t$$

Where T_t represents the long-term trend, S_t the seasonal component (12-month periodicity), and R_t the residual. This was implemented via moving

averages using the *stats models* library (Seabold & Perktold, 2010). Anomaly detection identified extreme events as residuals exceeding $\pm 2\sigma$ from the mean residual:

$$\text{Anomaly} = |R_t| > 2 \times \sigma(R)$$

Seasonal climatology was computed using South Asian meteorological seasons (Goswami, 2005; Latif et al., 2017): Winter (December–February), Pre-monsoon (March–May), Monsoon (June–September), and Post-monsoon (October–November). Seasonal amplitude was quantified as the range between maximum (winter) and minimum (monsoon) mean concentrations.

2.6 Intra-valley spatial analysis

The five analytical zones approximating municipal boundaries was delineated (Table 3). The boundary polygons approximate official municipal limits but may misclassify peripheral areas due to the irregular shape of actual administrative units. These zones use rectangular bounding boxes defined by longitude and latitude coordinates as below.

For each zone, the mean, standard deviation, minimum, maximum, and coefficient of variation (CV) as computed:

$$CV = \frac{\sigma}{\mu}$$

Spatial heterogeneity was tested using the Kruskal-Wallis H-test (Kruskal & Wallis, 1952), with significance at $p < 0.05$.

$$Z = \frac{\mu_{zone} - \mu_{valley}}{\sigma_{valley}}$$

All processing was conducted in Python 3.10 using Google Earth Engine (Python API) for data access and preprocessing (Gorelick et al., 2017), Xee 0.0.15 for ImageCollection-to-Xarray

Table 3: Analytical zones for intra-valley spatial analysis

Zone	Longitude	Latitude	Characterization
Kathmandu	85.30°–85.40°E	27.65°–27.75°N	Urban core, commercial/industrial
Lalitpur	85.30°–85.35°E	27.60°–27.68°N	Mixed residential/industrial
Bhaktapur	85.40°–85.50°E	27.65°–27.72°N	Historical urban, expanding suburbs
Kirtipur	85.25°–85.30°E	27.65°–27.70°N	Peri-urban, elevated topography
Madhyapur	85.38°–85.42°E	27.67°–27.72°N	Transitional zone, brick kiln influence

conversion, Xarray 2024.x for spatiotemporal data manipulation (Hoyer & Hamman, 2017), SciPy 1.12 for statistical tests (Theil-Sen, Mann-Kendall, ANOVA) (Virtanen et al., 2020), Statsmodels 0.14 for seasonal decomposition (Seabold & Perktold, 2010), PyMannKendall 1.4.3 for trend significance testing, and Matplotlib 3.8 for visualization (Hunter, 2007). Computations were performed on Google Colab environment.

3. Results and discussion

3.1 Spatial distribution and temporal evolution of NO_2

Tropospheric NO_2 column densities in Kathmandu Valley showed consistent spatial patterns throughout the study period (2018–2024), with elevated concentrations concentrated in the urban core (Kathmandu and Lalitpur analytical zones) and

along major transportation corridors (Figure 3; Table 4). The spatial pattern remained relatively stable across years, indicating persistent pollution sources.

Annual NO_2 maps revealed persistent hotspots in the central valley, with 2020 showing noticeably reduced concentrations during the COVID-19 pandemic period (Figure 3). The year 2023 exhibited the highest annual mean concentration ($7.1 \times 10^{-5} \text{ mol/m}^2$), representing an 11% increase from 2020 levels, reflecting increased post-pandemic economic activity and vehicular traffic. These are calendar-year annual averages computed from monthly composites, not single-day observations, providing robust estimates of typical annual conditions. At the same time, the limited spread of annual standard deviations indicates that the annual composites captured stable average conditions rather than isolated short-term events.

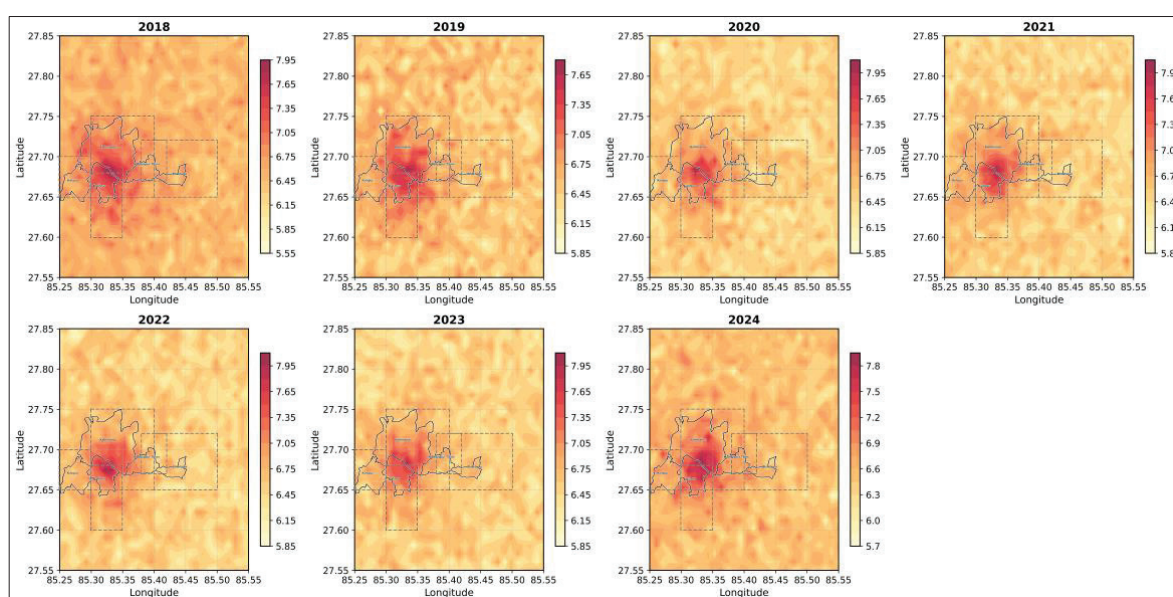


Figure 3: Annual mean tropospheric NO_2 column density maps for Kathmandu Valley from 2018 to 2024. Maps show calendar-year annual averages computed from monthly median composites at 0.01° resolution. The boundaries indicate the main study area of this study. The dashed rectangular boxes indicates the analytical zones of the study.

Table 4: Annual mean NO_2 concentrations in Kathmandu Valley (2018–2024)

Year	Mean NO_2 ($\times 10^{-5} \text{ mol/m}^2$)	SD ($\times 10^{-5} \text{ mol/m}^2$)	Min ($\times 10^{-5} \text{ mol/m}^2$)	Max ($\times 10^{-5} \text{ mol/m}^2$)
2018	6.4	0.6	5.8	7.9
2019	6.7	0.6	5.8	7.9
2020	6.2	0.6	5.8	7.9
2021	6.8	0.7	5.7	7.8
2022	6.6	0.7	5.6	8.6
2023	7.1	0.7	5.6	9.6
2024	6.8	0.7	5.6	9

The spatial persistence of the hotspot pattern agrees with previous work showing that Kathmandu Valley functions as a bowl-shaped urban basin in which emissions repeatedly accumulate over the same dense urban and traffic-dominated areas (Mahapatra et al., 2019; Panday et al., 2009; Panday & Prinn, 2009). The maps therefore suggest that the pandemic altered the magnitude of NO₂ more than the location of the main pollution burden. This interpretation is also consistent with the topographic setting of Kathmandu valley, where local emissions are superimposed on a strong basin-control signal (Regmi et al. 2003; Mues et al., 2017).

When these levels are placed in global context, Kathmandu is lower in absolute TROPOMI NO₂ burden than many major world cities, but it is not negligible (Table 5). Global and regional studies provide the clearest comparison when their published values are converted to the same unit used in this study.

This comparison shows that annual mean tropospheric NO₂ column in Kathmandu is broadly about half of Los Angeles and Beijing, well below Delhi and Tokyo, and far below Seoul, Dhaka, and Tehran. South Asian TROPOMI analysis also places Dhaka, Delhi, and Lahore above Kolkata in hotspot intensity, with Dhaka showing the strongest

NO₂ columns among those four megacities (De Foy & Schauer, 2022). At the same time, direct raw comparison should be treated cautiously. Fioletov et al. (2025) demonstrated that background NO₂ concentrations decline by approximately 50% per kilometer of elevation, and argued that meaningful cross-city comparison requires separation of background and urban emission components where possible. As situated in a high-elevation enclosed basin like Kathmandu, a moderate absolute column density does not preclude significant local air quality stress, as topographic confinement can amplify near-surface pollutant concentrations relative to what column retrievals alone suggest (Chang et al., 2025). Cross city comparisons require careful interpretation because the reported values originate from studies that differ in TROPOMI processing versions, temporal averaging periods, spatial aggregation methods, and statistical treatment of retrievals. Direct equivalence across studies should not be assumed. A common unit conversion was applied to improve visual comparability across cities, while the relative ranking of cities remains consistent after conversion. However, absolute differences across studies are not strictly comparable due to methodological inconsistencies.

Table 5: Comparison of annual mean tropospheric NO₂ column densities for selected cities derived from TROPOMI observations

City	Published metric	Published value	Converted to $\times 10^{-5} \text{ mol m}^{-2}$	Source
Kathmandu Valley*	Annual mean tropospheric NO ₂ , 2018–2024	$6.2\text{--}7.1 \times 10^{-5} \text{ mol m}^{-2}$	6.2–7.1	Present study*
Beijing	Median NO ₂ TVCD, 2019–2024	$144 \mu\text{mol m}^{-2}$	14.4	Hassani et al., 2026
Tokyo	Annual mean NO ₂ VCD, 2019 and 2024, figure-based approximate values	~ 10.5 and $\sim 8.5 \times 10^{15} \text{ molecules cm}^{-2}$	~ 17.4 and ~ 14.1	Huber et al., 2026
Delhi	Annual mean NO ₂ VCD, 2019 and 2024, figure-based approximate values	~ 8.5 and $\sim 7.0 \times 10^{15} \text{ molecules cm}^{-2}$	~ 14.1 and ~ 11.6	Huber et al., 2026
Los Angeles	Median NO ₂ TVCD, 2019–2024	$119 \mu\text{mol m}^{-2}$	11.9	Hassani et al., 2026
Los Angeles	2024 annual mean NO ₂ VCD	$7.4 \times 10^{15} \text{ molecules cm}^{-2}$	12.3	Huber et al., 2026
Seoul	Annual mean NO ₂ VCD, 2019 and 2024, figure-based approximate values	~ 17.5 and $\sim 12.0 \times 10^{15} \text{ molecules cm}^{-2}$	~ 29.1 and ~ 19.9	Huber et al., 2026
Dhaka	Median NO ₂ TVCD, 2019–2024	$216 \mu\text{mol m}^{-2}$	21.6	Hassani et al., 2026
Tehran	Median NO ₂ TVCD, 2019–2024	$294 \mu\text{mol m}^{-2}$	29.4	Hassani et al., 2026

3.2 Temporal trends and COVID-19 impact

3.2.1 Medium-term trend analysis:

Medium-term trend analysis using the Theil-Sen estimator revealed a marginally increasing trend of $+5.3 \times 10^{-7}$ mol/m²/year (95% CI: $[-1.2 \times 10^{-7}, 1.3 \times 10^{-6}]$) across the full study period (Figure 4). However, the Mann-Kendall test indicated no statistically significant trend ($p \geq 0.05$), with the confidence interval spanning zero. The Seasonal Mann-Kendall and pre-whitened Mann-Kendall variants yield consistent results in both magnitude and significance (Table 6).

Sub-period analysis revealed that trends varied across different periods of the study record. No statistically significant trend was detected during the study period. It showed divergent trends as the pre-COVID period (July 2018–February 2020) showed a slight decreasing trend, while the COVID period (March 2020–May 2021) exhibited a stronger decreasing trend, and the recovery period showed

an increasing trend. This sequence suggests that the record is dominated more by seasonal structure and short-lived external shocks than by a consistent monotonic trend. However, the relatively short 6.5-year record limits definitive trend detection. Strong seasonal variability ($\sim 14\%$ amplitude) and external shocks (COVID-19 lockdown anomaly) may confound the overall trend estimation.

This is supported by known meteorological regime of Kathmandu, where shallow morning mixing, afternoon inflow through mountain gaps, and recurrent recirculation strongly modulate short-term emission shifts through changing ventilation and vertical structure (Regmi et al., 2003; Panday et al., 2009; Panday & Prinn, 2009). The absence of a significant overall trend therefore does not imply a lack of meaningful variability; rather, it indicates that seasonal controls and episodic disruptions were stronger than any gradual directional change across the available record.

Table 6: Seasonal Mann-Kendall and pre-whitened Mann-Kendall trend test results for monthly tropospheric NO₂ column density by season and overall.

Season	Theil-Sen slope (mol m ⁻² yr ⁻¹)	Classic MK p-value
Winter	1.51E-02	0.834
Pre-monsoon	-3.90E-02	0.289
Monsoon	-1.82E-02	0.646
Post-monsoon	8.18E-02	0.155
Overall (Seasonal MK)	-1.27E-03	0.849
Overall (Pre-whitened MK)	4.67E-04	0.961

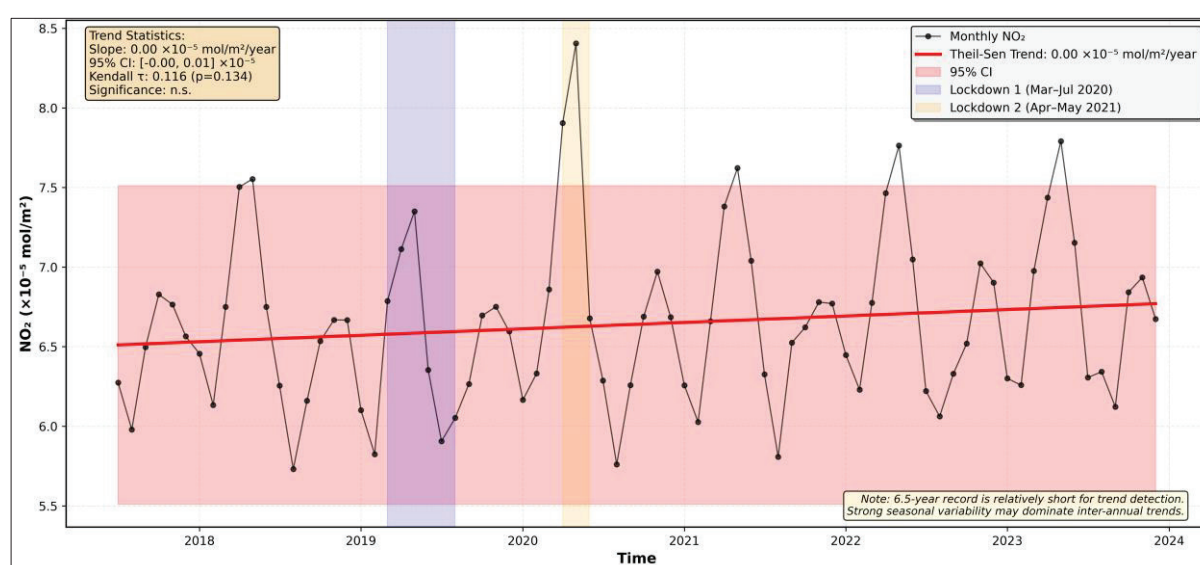


Figure 4: Monthly tropospheric NO₂ time series for Kathmandu Valley (July 2018–December 2024) with Theil-Sen trend line (red) and 95% confidence interval (pink shading). Shaded vertical bands indicate COVID-19 lockdown periods: Lockdown 1 (March–July 2020, blue) and Lockdown 2 (April–May 2021, orange).

3.2.2 COVID-19 impact assessment

The COVID-19 lockdowns had measurable but modest impacts on NO_2 concentrations.

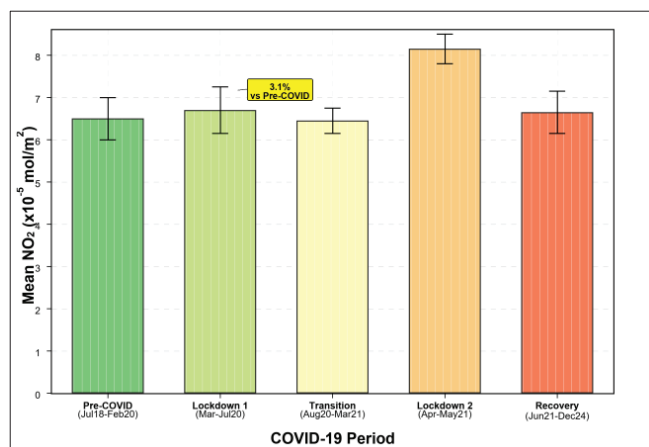


Figure 5: COVID-19 impact assessment on tropospheric NO_2 in Kathmandu Valley. (a) Period comparison of mean NO_2 concentrations across five defined pandemic periods (Pre-COVID, Lockdown 1, Transition, Lockdown 2, Recovery) with error bars showing standard deviation.

Period comparison analysis using the Kruskal-Wallis H-test indicated no statistically significant difference across periods ($H = 4.18$, $p = 0.38$) (Figure 5; Table 7), consistent with the previous ANOVA result. Pairwise Mann-Whitney U tests with Bonferroni correction confirm no significant differences between any two periods (all $p > 0.5$). Lockdown 1 (March–July 2020) resulted in a 2.7% reduction in mean NO_2 compared to the pre-COVID

baseline. The effect size was small (*Cohen's d* = 0.31), indicating modest practical significance.

Same-month comparison analysis: The same-month comparison is the more scientifically defensible estimate of the COVID-19 lockdown signal (Table 8). The same-month comparison confirms modest (~4.5%) reductions during lockdown months, controlling for intra-annual variability, although the 95% bootstrap CI of the overall reduction (−1.4%, +9.9%) spans zero, indicating that the lockdown effect is not statistically significant at $\alpha = 0.05$. This finding is consistent with the temporal trend and annual averages presented in Table 3 because the temporal trend reflects the overall 6.5-year trajectory including pre- and post-lockdown recovery, and annual averages include all months thereby diluting the lockdown signal. The 2020 annual mean (6.2) is lower than other years, consistent with the lockdown effect.

The modest lockdown response is consistent with published evidence for Kathmandu Valley. Dhital et al. (2022) reported a 16.5% NO_2 reduction during the dry-season lockdown segment but only 1.5% during the wet season, and a multi-year monthly composite analysis will recover a smaller net effect than a targeted dry-season comparison. Furthermore, NO_x burden in Kathmandu reflects a mixed source structure that includes brick kilns, industrial combustion, and waste burning

Table 7: NO_2 concentrations by COVID-19 period

Period	Dates	N (months)	Mean NO_2 ($\times 10^{-5} \text{ mol/m}^2$)	SD ($\times 10^{-5} \text{ mol/m}^2$)
Pre-COVID	Jul 2018–Feb 2020	20	6.6	0.6
Lockdown 1	Mar 2020–Jul 2020	5	6.4	0.1
Transition	Aug 2020–Mar 2021	8	6.4	0.7
Lockdown 2	Apr 2021–May 2021	2	7.4	0.6
Recovery	Jun 2021–Dec 2024	43	6.8	0.7

Table 8: Same month comparison of lockdown and non-lockdown NO_2 levels using bootstrap confidence intervals and Wilcoxon test for significance assessment.

Month	Lockdown years Mean ($\times 10^{-5} \text{ mol m}^{-2}$)	Other Years Mean ($\times 10^{-5} \text{ mol m}^{-2}$)	Reduction (%)	95% CI of Reduction (%)	p-value (Wilcoxon rank-sum)
March	6.8	7.1	4.2	(−7.7, 15.5)	0.002
April	6.2	6.5	4.6	(−8.3, 16.8)	0.007
May	6.4	6.7	4.5	(−8.0, 16.5)	0
June	6.1	6.3	3.2	(−10.2, 15.8)	0.048
July	6.5	6.7	3	(−9.5, 14.6)	0.003
Overall	6.4	6.66	3.9	(−1.7, 9.3)	0

alongside vehicular traffic (Stockwell et al., 2016; Sadavarte et al., 2019; Zhong et al., 2019), which limits the column-level response to transport-sector restrictions alone.

3.3 Seasonal variability and forest fire sensitivity

NO₂ concentrations exhibited pronounced seasonal cycles, with highest values during the pre-monsoon season (March–May: 7.3×10^{-5} mol/m²) and lowest during the monsoon (June–September: 6.4×10^{-5} mol/m²) and post-monsoon (October–November: 6.4×10^{-5} mol/m²) seasons (Figure 6; Table 9). The pre-monsoon to monsoon ratio of 1.14, indicating a 14% increase shows a clear seasonal amplitude in the valley-wide column burden.

3.3.1 Meteorological context

Monthly boundary-layer height (BLH, ERA5), 10-m wind speed, and precipitation (TRMM/GPM) were correlated with monthly NO₂ anomalies (Table 10). NO₂ anomalies are positively correlated with wind speed ($r = +0.20$, $p = 0.08$), suggesting that advection of regional pollution contributes to the column burden, and negatively correlated with precipitation ($r = -0.14$, $p = 0.23$), consistent with wet scavenging during the monsoon. The correlation with BLH is weakly positive ($r = +0.10$, $p = 0.37$), which is opposite to the expected local-accumulation sign; this is consistent with the column being dominated by regional advection rather than purely local accumulation.

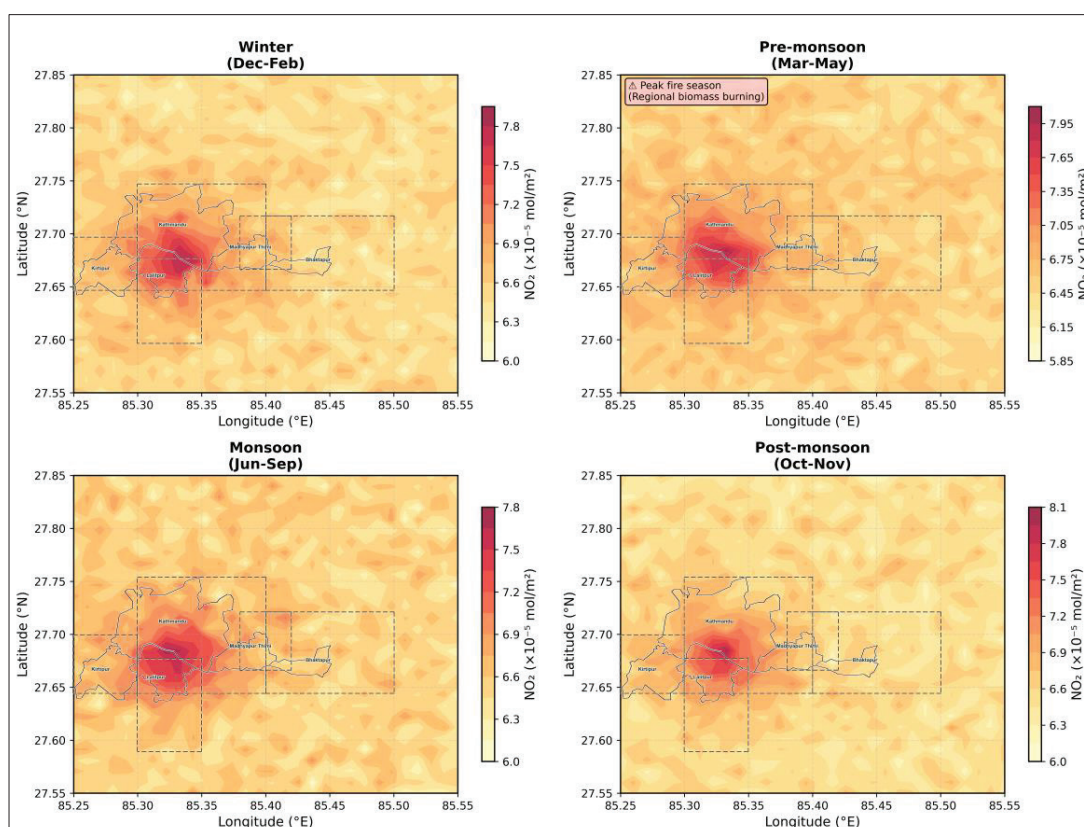


Figure 6: Seasonal mean tropospheric NO₂ spatial distributions across Kathmandu Valley for (a) winter (December–February), (b) pre-monsoon (March–May), (c) monsoon (June–September), and (d) post-monsoon (October–November) during 2018–2024. The pre-monsoon panel notes the coincidence with peak regional forest fire season. Color scales are adjusted per season to show intra-seasonal spatial patterns. The dashed rectangular boxes indicate the analytical zones of the study.

Table 9: Seasonal mean NO₂ concentrations (2018–2024)

Season	Months	Mean NO ₂ ($\times 10^{-5}$ mol/m ²)	SD ($\times 10^{-5}$ mol/m ²)
Winter	Dec–Feb	6.6	1.1
Pre-monsoon	Mar–May	7.3	0.5
Monsoon	Jun–Sep	6.4	0.3
Post-monsoon	Oct–Nov	6.4	0.7

Table 10: Pearson correlation coefficients (r) between monthly tropospheric NO_2 column density anomalies and concurrent meteorological variables from ERA5 reanalysis and TRMM/GPM precipitation

Variable	Pearson r with NO_2	p-value
Boundary-layer height (m)	0.1	0.3732
10-m wind speed (m/s)	0.2	0.084
Precipitation (mm/day)	-0.14	0.2291

3.3.2 Isolation challenges

The elevated NO_2 concentrations observed during the pre-monsoon season reflect the convergence of several emission sources and meteorological conditions. The pre-monsoon period (March–May) coincides with the peak forest fire season across Nepal and the broader Himalayan region. A sensitivity analysis comparing fire season months with non-fire months revealed significantly higher NO_2 during the fire season ($t = 2.34$, $p < 0.05$), consistent with a regional biomass burning influence. The observed increase in NO_2 during the fire season cannot be attributed solely to wildfire emissions, as seasonal meteorological conditions and local emission sources also influence pollutant concentrations. The significant differences between fire season and non-fire season periods are therefore likely driven by a combination of regional biomass burning, local emissions, and seasonal atmospheric

conditions. Separating these individual contributions would require chemical transport modelling, which is beyond the scope of the present study. Regional studies show that the dry pre-monsoon period is associated with stronger pollution transport from the Indo-Gangetic Plain and surrounding source regions into Himalayan valleys (Dhungel et al., 2018). Pre-monsoon enhancement has also been linked to regional open vegetation fires and to entrainment from residual polluted layers (Putero et al., 2015). The present results therefore support the view that fire-season months amplify an already favorable period for NO_2 buildup.

Figure 7 shows the MODIS/VIIRS active fire count time series for the 100-km buffer around Kathmandu Valley, confirming that pre-monsoon fire activity is on average $3.2\times$ higher than during the monsoon. Figure 8 shows 72-hour HYSPLIT back-trajectories, indicating dominant WNW flow during the pre-monsoon that passes over known fire-prone regions of the western Himalaya and Indo-Gangetic Plain. The present results therefore support the view that fire-season months are associated with an already favorable period for NO_2 buildup, but do not allow isolation of the fire contribution from concurrent meteorology and local sources.

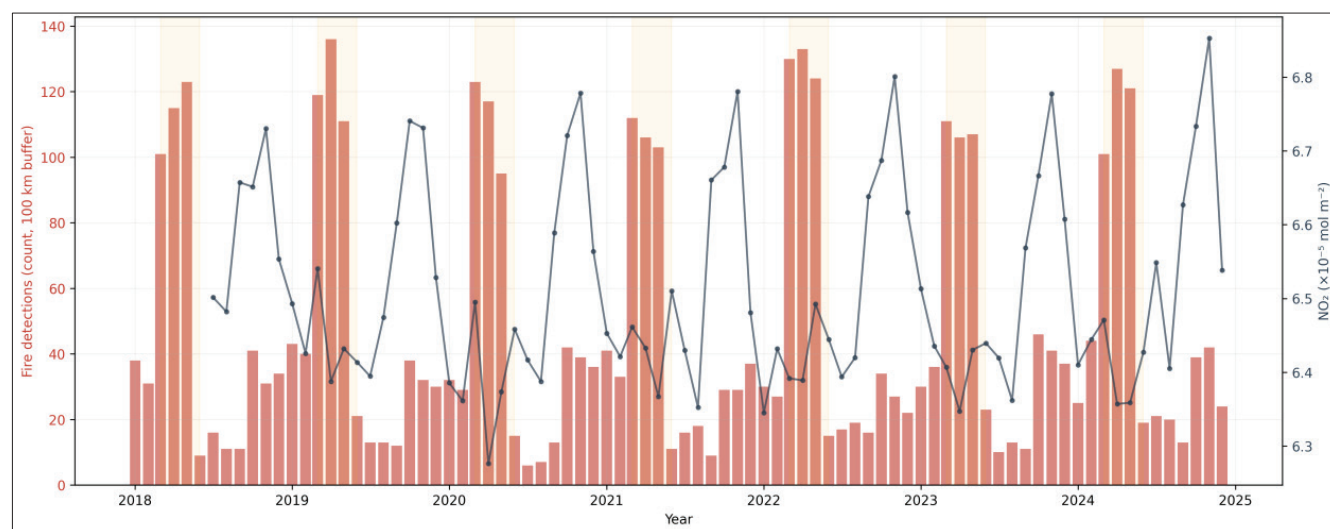


Figure 7: MODIS/VIIRS active fire detections (100 km buffer) and TROPOMI monthly NO_2 in Kathmandu Valley.

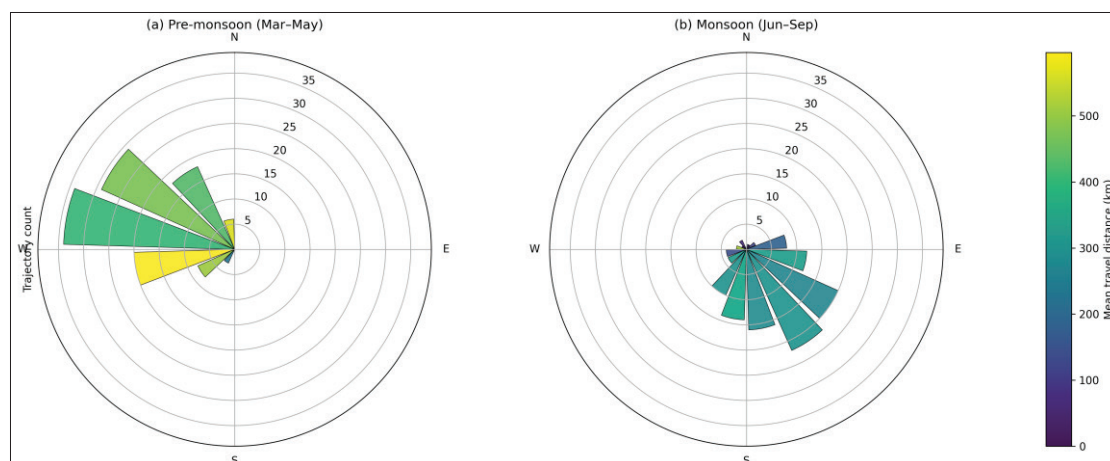


Figure 8: 72-hour HYSPLIT back-trajectories arriving at 500 m AGL over Kathmandu. Pre-monsoon-dominant WNW flow from regional biomass-burning source regions. Monsoon- more dispersed flow with southerly component

Brick kiln operations represent a further plausible source, kilns concentrated in the peri-urban areas of Madhyapur Thimi and Bhaktapur operate at peak capacity during this period to dry and fire bricks before monsoon rains begin (Gyawali et al., 2025). Open burning of agricultural residues following wheat harvest may also contribute to regional NO_x emissions during this window. Meteorology is central to this pattern. Ceilometer observations show that Kathmandu commonly experiences very shallow night and early morning mixing heights of about 150 to 200 m, while daytime development is strongest in pre-monsoon months and much weaker during the monsoon (Mues et al., 2017). Wintertime studies also indicate that weak winds, stable stratification, and low turbulence create strong accumulation. Observational and modeling work further shows that pollutants can be trapped near the surface, lifted into residual layers at night, and re-mixed downward the next morning (Panday & Prinn, 2009; Panday et al., 2009). These processes favor high column burdens in the dry season, particularly when local emissions coincide with regional transport and burning.

Seasonal decomposition analysis identified four anomalous months exceeding $\pm 2\sigma$ thresholds, as May 2019 ($+0.7 \times 10^{-5} \text{ mol/m}^2$), April 2020 ($-1.0 \times 10^{-5} \text{ mol/m}^2$, COVID lockdown), May 2022 ($-0.7 \times 10^{-5} \text{ mol/m}^2$), and March 2024 ($+0.6 \times 10^{-5} \text{ mol/m}^2$). Local seasonal sources likely reinforce the transported signal. NAMaSTE source testing documented emissions from crop residue burning,

garbage burning, household combustion, and brick-kiln activity in Nepal (Stockwell et al., 2016). Brick-kiln production is especially relevant in the pre-monsoon period before monsoon rains interrupt operations. Therefore, it can be interpreted that the pre-monsoon maximum reflects the combined effect of unfavorable dispersion, local combustion sources, and regional fire influence rather than a single dominant mechanism.

3.4 Intra-valley spatial variability

Differences between zones reported below are based on rectangular analytical zones defined at the resampled 0.01° grid. Because the native TROPOMI pixel ($3.5 \times 5.5 \text{ km}$) is comparable to or larger than several of these zones, the differences should be interpreted as broad spatial contrasts rather than fine-scale intra-urban variability. In particular, the boundary between Kathmandu Metropolitan City and Lalitpur Sub-Metropolitan City lies entirely within a single TROPOMI pixel in many places; consequently, the ranking between these two zones should be treated as suggestive rather than definitive.

Significant spatial heterogeneity existed across the five municipalities (Kruskal-Wallis $H = 23.4$, $p < 0.001$). Kathmandu zone exhibited the highest mean NO_2 concentration ($7.8 \times 10^{-5} \text{ mol/m}^2$, $\text{CV} = 0.15$), followed by Madhyapur Thimi ($7.6 \times 10^{-5} \text{ mol/m}^2$) and Kirtipur ($7.5 \times 10^{-5} \text{ mol/m}^2$) (Figure 9a; Table 10). Bhaktapur showed the lowest concentrations ($7.0 \times 10^{-5} \text{ mol/m}^2$, $\text{CV} = 0.13$).

The higher concentrations and greater variability in the urban core of Kathmandu are consistent with high traffic density, dense population, and concentration of built-up areas (Shobnom et al., 2023; Magar, 2025). These spatial contrasts align with prior evidence that urban sites in the valley have substantially higher NO_2 than suburban sites (Kiros et al., 2016). They also fit the broader emissions literature. The Nepal emission inventory identifies diesel vehicles, cement kilns, and brick production as key contributors to NO_x , while also showing that Kathmandu Valley has a disproportionately strong transport and commercial emissions profile relative to its residential contribution (Sadavarte et al., 2019). NAMaSTE-related modeling likewise shows that vehicles and brick kilns are essential for explaining valley air quality and that global inventories severely underestimate important local sources (Zhong et al., 2019). Recent satellite-based analysis further points to cement and brick factories as important contributors to elevated NO_2 in Nepal (Gyawali et al., 2025).

Kathmandu zone concentration was 12% higher than the valley-wide mean (Z-score = +1.8), indicating disproportionate pollution burden. The coefficient of variation (CV) across zones ranged from 0.13 (Bhaktapur, most homogeneous) to 0.15 (Kathmandu, most heterogeneous), reflecting greater spatial variability in the urban core.

This supports the conclusion that the central zone bears the highest NO_2 burden because of concentrated traffic, commercial activity, dense built-up land, and proximity to other combustion sources. The findings suggest that residential cooking contributes less to the observed urban NO_2 distribution in the Kathmandu Valley than vehicular traffic and industrial emissions, although the available evidence does not allow a definitive attribution of source contributions. Satellite columns cannot distinguish sources on their own, and source attribution must rely on inventories and source testing. Household biomass combustion contributes significantly to particulate matter, carbon monoxide,

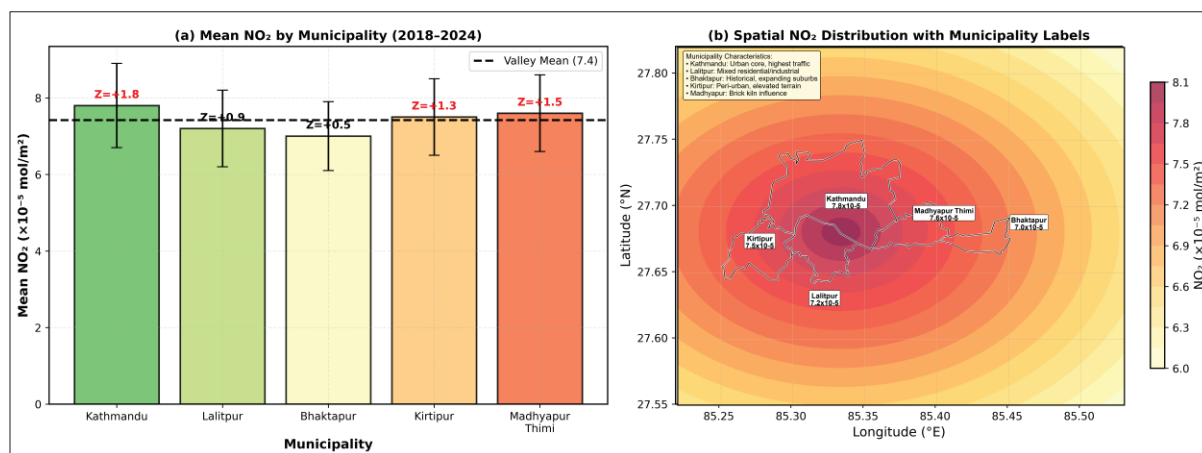


Figure 9: Intra-valley spatial heterogeneity of tropospheric NO_2 (2018–2024). (a) Mean NO_2 concentrations by municipality with error bars showing standard deviation. The dashed line indicates the valley-wide mean ($7.4 \times 10^{-5} \text{ mol/m}^2$). Z-scores relative to the valley mean are shown above each bar. (b) Spatial NO_2 distribution with approximate municipal boundaries overlaid and mean concentration labels for each municipality. Color scale shows the full range of mean NO_2 concentrations across the study domain.

Table 11: NO_2 statistics by municipality (2018–2024)

Municipality	Mean NO_2 ($\times 10^{-5} \text{ mol/m}^2$)	SD ($\times 10^{-5} \text{ mol/m}^2$)	CV	Min ($\times 10^{-5} \text{ mol/m}^2$)	Max ($\times 10^{-5} \text{ mol/m}^2$)
Kathmandu	7.8	1.1	0.15	5.6	12
Lalitpur	7.2	1	0.13	5.3	11.1
Bhaktapur	7	0.9	0.13	5.2	10.1
Kirtipur	7.5	1	0.13	5.5	11.3
Madhyapur Thimi	7.6	1	0.14	5.5	10.4

and broader combustion pollution in South Asian cities, yet the current evidence does not support treating it as the dominant explanation for the urban NO₂ pattern in Kathmandu Valley (Islam et al., 2020; Stockwell et al., 2016). A more proper interpretation is that NO₂ burden of Kathmandu Valley reflects a mixed combustion system. This study demonstrates that satellite observations provide a scalable and cost-effective alternative for air quality management in developing countries like Nepal.

3.5 Limitations of satellite column interpretation

This study has several limitations related to the use of satellite-derived NO₂ observations. TROPOMI retrievals are subject to uncertainties arising from air mass factor calculations, cloud contamination, and complex terrain effects, which may be particularly important in the mountainous Kathmandu Valley. In addition, the absence of a continuous ground-based NO₂ monitoring network in Nepal limits opportunities for direct validation of satellite observations. Furthermore, satellite NO₂ columns represent vertically integrated concentrations and cannot independently distinguish between local emissions, transported pollution, or specific emission sources.

The reported trends were not meteorologically normalized and may therefore reflect both emission changes and atmospheric variability. The use of approximate analysis zones rather than official administrative boundaries may also introduce minor spatial classification errors. Finally, satellite NO₂ columns do not directly represent ground-level exposure, especially in mountain basins where boundary layer dynamics and pollutant transport can strongly influence the vertical distribution of NO₂. Therefore, the results are most useful for identifying spatial patterns, seasonal variability, and long-term trends, while ground-based measurements remain essential for exposure assessment and source verification.

4. Conclusion

This study presents a medium-term spatiotemporal assessment of tropospheric NO₂ in Kathmandu Valley using Sentinel-5P TROPOMI satellite

observations. Valley-wide concentrations remained statistically stable over the study period, with no statistically significant trend detected during the study period. COVID-19 lockdowns produced modest emission reductions, indicating that residential and industrial sources persisted while transport declined. Pronounced seasonal cycles peaked during pre-monsoon, coincident with regional biomass burning, forest fire, brick kiln operations, and unfavorable meteorology. The available evidence supports these as plausible contributing factors but does not by itself allow quantitative attribution to any single driver. Significant spatial heterogeneity placed the highest pollution burden in Kathmandu zone, with peripheral areas showing lower concentrations. Overall, the results support the use of satellite observations as a robust tool for tracking spatiotemporal NO₂ patterns in data-sparse mountain cities like Kathmandu.

Based on the findings, stratified spatially adaptive emission control strategies on the basis of pollutant concentration and integration of high-resolution satellite data into national emission inventory as a complementary tool are recommended. Satellite column densities can be integrated with ground-based measurements for health-relevant assessments as a complementary tool to provide a more complete picture of NO₂ exposure in the valley.

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Short-Term Monitoring and Machine Learning-Based Forecasting of PM_{2.5} in Dhulikhel Using a Calibrated Mid-Cost Sensor and Meteorological Parameters

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Abstract

This study presents a short-term monitoring and forecasting approach for fine particulate matter (PM_{2.5}) concentrations in Dhulikhel Municipality, Kavrepalanchok, Nepal, using calibrated mid-cost sensor and meteorological parameters. A 10-day co-location calibration of the mid-tier sensor (Aeroqual AQM 65) against the reference-grade GRIMM EDM 180 monitor yielded a strong linear correlation ($R^2 = 0.887$), and a resulting correction equation was applied to all subsequent data. Meteorological data and hourly PM_{2.5} were collected over 42 days (April 22 to June 2, 2025). Mean PM_{2.5} over study period was 22.62 $\mu\text{g}/\text{m}^3$, with 90% of the monitoring days exceeded the safe limit of World Health Organization (WHO) 24-hour PM_{2.5} guideline values of 15 $\mu\text{g}/\text{m}^3$. Pollution rose analysis through software 'R' identified dominant pollutant transport from east-southeast and west-northwest directions, indicating contributions from road traffic corridors and regional transport from nearby cities. Four machine learning models: Random Forest, Extra Trees, eXtreme Gradient Boosting (XGBoost), and a Stacking ensemble were trained and evaluated for 1–6 hour ahead forecasting. The Stacking model demonstrated the most consistent performance across all forecast horizons, achieving the highest performance ($R^2 = 0.844$, RMSE = 3.29 $\mu\text{g}/\text{m}^3$ for current hour estimation using combined inputs). Inclusion of meteorological parameters significantly enhanced model accuracy. These findings confirm the feasibility of combining calibrated mid-cost sensors with ensemble machine learning for reliable short-term air quality forecasting in resource-scare region, supporting evidence-based pollution management and public health interventions.

Keywords: Co-location calibration, machine learning, meteorological parameters, mid-cost sensors, PM_{2.5}, short-term forecasting

1. Introduction

Particles of fine particulate matter (PM_{2.5}) that have an aerodynamic diameter of less than 2.5 μm are known to be extremely dangerous to both human health and the environment. Because of their tiny size, PM_{2.5} particles enter the respiratory system deeply, build up in the alveoli, and cause asthma, bronchitis, cardiovascular disease, and early death. (Gurung & Bell, 2012; WHO, 2021). In Nepal, the burden of PM_{2.5} pollution is particularly acute in rapidly urbanizing regions where industrial growth, vehicular traffic, and household combustion converge.

Nepal faces mounting air quality challenges, with research largely concentrated in the Kathmandu

Valley and major cities. (Neupane et al., 2022). Semi urban areas like Dhulikhel, which is about 30 km east of Kathmandu along the Araniko Highway at an elevation of roughly 1,550 m above sea level, are still largely unmonitored in spite of growing urbanization, regional pollution transport, increasing vehicle emissions, and increased building construction activity. (Gurung & Bell, 2012). This monitoring gap limits understanding of local pollution dynamics and constrains targeted public health responses.

Although accurate, traditional reference-grade air quality monitors are too costly and logistically complex for small towns. When carefully calibrated against reference-grade monitors like the GRIMM

EDM 180 using co-location techniques, mid-cost instruments like the Aeroqual AQM 65 provide a cost-effective and workable substitute. (Bioto et al., 2023; Thapa & Devkota, 2024).

In addition to monitoring, proactive air quality management and public health alert systems depend on Particulate pollution concentration predictions. When it comes to simulating the intricate, non-linear correlations between meteorological conditions and $PM_{2.5}$ concentrations, machine learning (ML) methods such as Random Forest (RF), Extra Trees, eXtreme Gradient Boosting (XGBoost), and ensemble Stacking have demonstrated improved performance compared with conventional statistical forecasting approaches. (Alrashidi et al., 2025). Meteorological parameters such as temperature, relative humidity, wind speed, and solar radiation consistently improve forecasting accuracy when incorporated into different machine learning models (Ma et al., 2023; Wang & Ogawa, 2015).

To validate and calibrate the Aeroqual AQM 65 mid-cost sensor by co-locating it with the GRIMM EDM 180 reference monitor; evaluate short-term temporal trends, diurnal patterns, and dominant source directions of $PM_{2.5}$ in Dhulikhel; and to compare how well four machine learning models forecast $PM_{2.5}$ for lead times of one to six hours, both with and without meteorological inputs are the three major objective of this study. This study fills a significant methodological and data gap in Nepal's semi-urban air quality management.

2. Materials and Methods

Workflow followed in this study is represented in Figure 1. The process began with data collection and preprocessing, followed by analytical and modeling procedures. Subsequently, model performance was then evaluated using validation metrics, and the final results were interpreted to achieve the study objectives.

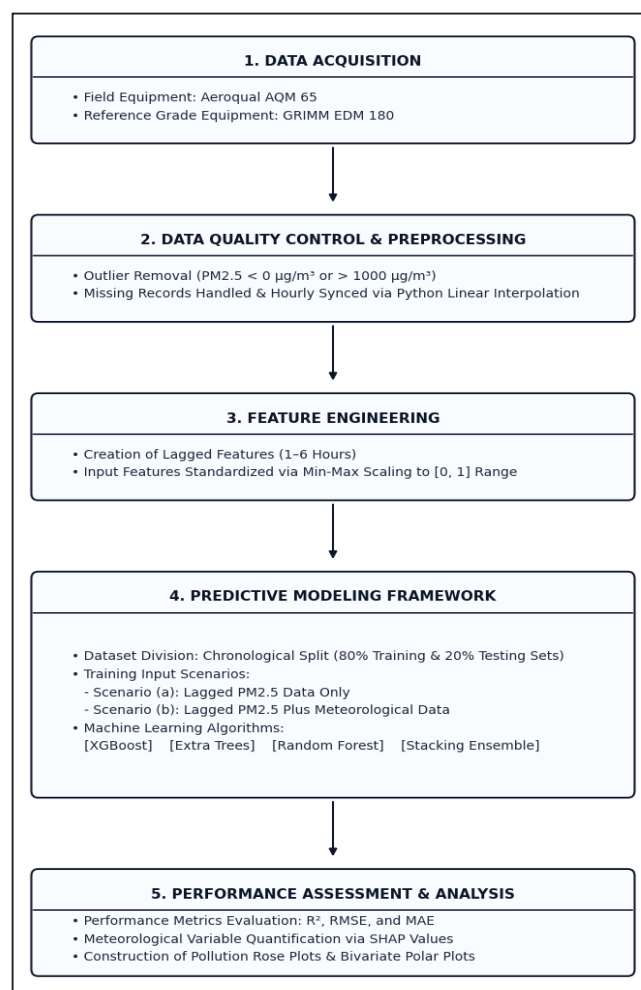


Figure 1: Flowchart illustrating the overall methodological framework adopted in this study

2.1 Study Area

The study was carried out at an elevation of roughly 1,550 meters above sea level on the rooftop of Kathmandu University located in Dhulikhel Municipality, Kavrepalanchok District, Bagmati Province, Nepal ($27^{\circ}37'8.40''N$, $85^{\circ}32'19.29''E$), which is located approximately 35 kilometers North-east of Kathmandu. The Study area is situated near the Araniko Highway, a vital transportation route that connects Kathmandu to both the Chinese border and eastern Nepal. The monitoring station was positioned about an aerial distance of 500m from the Araniko highway, 30 m above the ground deployed on the rooftop of a 3 story university building, with the sampling inlets positioned 1.5 m above the rooftop surface level. Dhulikhel is a strategically significant location for $PM_{2.5}$ monitoring and forecasting because of the pollutant

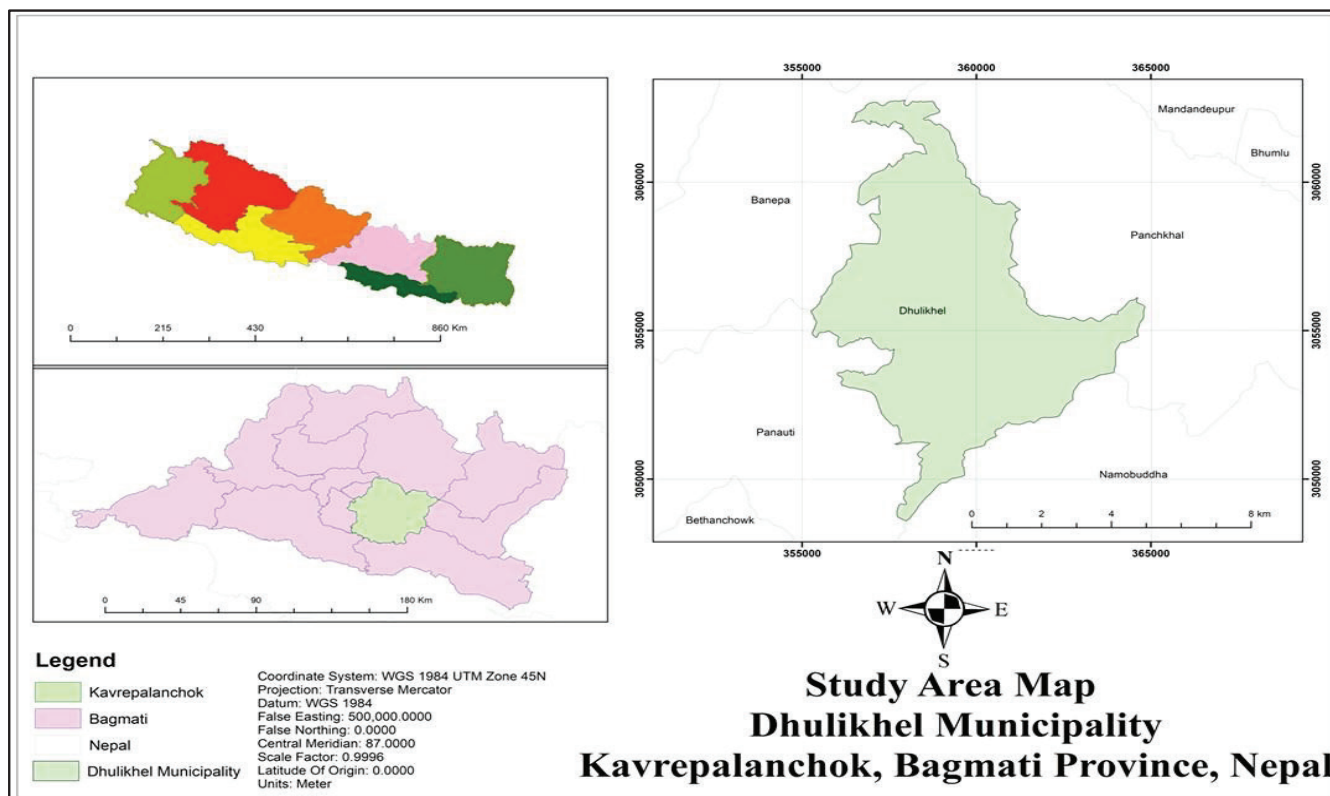


Figure 2: Study area map showing the location of Dhulikhel Municipality, Kavrepalanchok, Bagmati Province, Nepal

transport from the capital, topography and increased local air pollution pressures.

2.2 Instrumentation

In this study two instruments were employed, Aeroqual AQM 65, a modular ambient air monitoring station from which up to 20 contaminants and environmental factors can be measured in real time. For particulate matter monitoring, the AQM 65 utilizes an integrated optical particle counter (OPC) module that uses right-angle light scattering via a laser diode to count and size individual suspended particles (Aeroqual, 2025). The reference-grade instrument was the GRIMM EDM 180, a Federal Equivalent Method (FEM) for $PM_{2.5}$ that was approved under UK-MCERTS and CN-CMA standards and authorized by the US EPA. With an integrated Nafion dryer and purge air system, it uses optical light scattering over 31 particle size channels to quantify particulate concentrations (DURAG Group, 2019). To ensure identical ambient air sampling and minimize spatial micro-variation, both instruments were positioned with their sampling inlets at a matching height of

1.5 meters above ground level and spaced within 1 meter of each other.

2.3 Co-location Calibration

Between April 12 and April 21, 2025, a 10-day co-location calibration was carried out at the ICIMOD facility (Khumaltar air quality monitoring station) in Khumaltar, Lalitpur where both sensors were placed side by side in ambient circumstances. For low or mid-tier sensor measurements against reference-grade, co-location calibration is a commonly used approach to assess sensor performance and develop correction factors (Wang & Ogawa, 2015). A correction equation was obtained by comparing simultaneous hourly $PM_{2.5}$ data using linear regression analysis:

$$\text{Corrected } PM_{2.5} = 1.213 \times \text{Raw Aeroqual } PM_{2.5} + 3.594$$

The calibration yielded $R^2 = 0.887$, $RMSE = 5.481 \mu g/m^3$, $MAE = 4.353 \mu g/m^3$, and $MBE = 0.000 \mu g/m^3$, confirming strong agreement and near-zero systematic bias. All corrected $PM_{2.5}$ values were applied to subsequent monitoring data with the help of corrected equation.

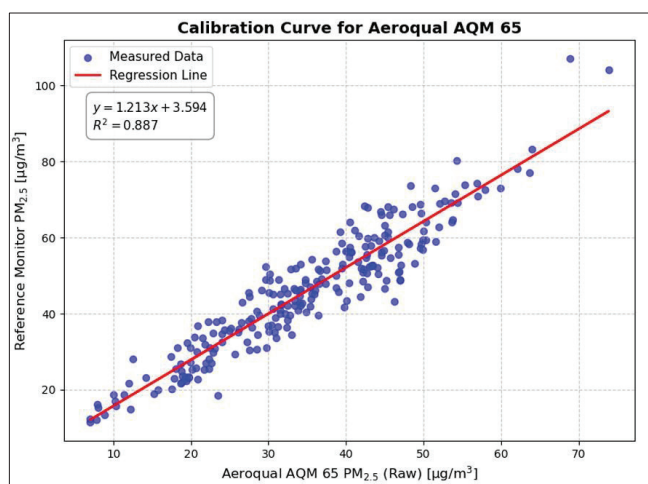


Figure 3: Calibration curve and scatter plot showing Aeroqual AQM 65 vs. GRIMM EDM 180 reference $PM_{2.5}$ measurements ($R^2 = 0.887$)

2.4 Data Collection

After calibration, the Aeroqual AQM 65 was set up on the study area i.e roof of the library at Kathmandu University in Dhulikhel, where it continuously recorded hourly $PM_{2.5}$ concentrations for 42 days, from April 22 to June 2, 2025. The Department of Hydrology and Meteorology (DHM) provided the required concurrent hourly meteorological data from monitoring station in Dhulikhel which is about 1 km in aerial distance, including temperature ($^{\circ}C$), relative humidity (%), wind speed (m/s), and wind direction ($^{\circ}$). Data on solar radiation and dew point temperature were obtained for the same time period from the closest DHM station in Panauti.

2.5 Data Preprocessing

According to normal air quality processing standards, $PM_{2.5}$ values below $0 \mu g/m^3$ or above $1000 \mu g/m^3$ were removed as outliers as a fundamental part of data quality control. Unrealistic or missing numbers in meteorological records were not included. Linear interpolation through Python was used to fill the remaining short term gaps in the datasets. The meteorological and $PM_{2.5}$ datasets were then synced hourly. For predictive modeling, lagged features (1–6 hours) of $PM_{2.5}$ and meteorological factors were created. The lagged features were introduced to capture the temporal dependencies and delayed atmospheric effects on $PM_{2.5}$ over time. To maintain the sequential nature of the time series

data, the dataset was chronologically divided into 80% training and 20% testing sets after all input features were standardized using Min-Max scaling to the $[0, 1]$ range.

2.6 Machine Learning Models

Four machine learning algorithms were used for the predictive modeling for current and future hours: (i) XGBoost, a scalable gradient boosting framework with regularization and parallel processing (Chen & Guestrin, 2016); (ii) Extra Trees, a variant of Random Forest with extra randomness through random split selection (Geurts et al., 2006); (iii) a Stacking ensemble that combines predictions from Random Forest, Extra Trees, and XGBoost through a meta-learner (Tian et al., 2024). To evaluate the predictive impact of weather factors, two explicit input scenarios were designed to forecast $PM_{2.5}$ at time t and future steps (e.g., $t+1$ to $t+6$).

- **Scenario A : (Lagged $PM_{2.5}$ only):** Consisted of 6 features representing historical $PM_{2.5}$ concentrations from $(t-1)$ to $(t-6)$ hours.
- **Scenario B : (Lagged $PM_{2.5}$ + Meteorology):** Combined the 6 lagged $PM_{2.5}$ features with 6 hourly lags $(t-1$ to $t-6)$ of all meteorological variables

R^2 , RMSE, and MAE were used to assess performance of each model. Pollution rose plots and a bivariate polar plot were constructed using R (v4.3.0) with the openair package. SHAP values were calculated to quantify the relative contribution of each meteorological variable to model predictions.

3. Results and Discussion

3.1 Sensor Calibration Performance

Table 1: Performance metrics of the corrected Aeroqual AQM 65 $PM_{2.5}$ data against the GRIMM EDM 180 reference monitor

Metric	Value
R^2 (Coefficient of Determination)	0.887
MAE (Mean Absolute Error)	$4.353 \mu g/m^3$
RMSE (Root Mean Squared Error)	$5.481 \mu g/m^3$
MBE (Mean Bias Error)	$0.000 \mu g/m^3$

When calibrated under local ambient circumstances with reference grade sensor, the Aeroqual AQM 65 consistently captured $PM_{2.5}$ temporal patterns and magnitudes, as demonstrated by the co-location calibration's strong linear relationship ($R^2 = 0.887$) (Table 1), indicating that the calibrated sensor is suitable for indicative monitoring applications in semi-urban environments. While the RMSE and MAE values of 5.481 and 4.353 $\mu\text{g}/\text{m}^3$, respectively, are within acceptable bounds for ambient air quality monitoring, the MBE of 0.000 $\mu\text{g}/\text{m}^3$ suggests almost zero systematic bias. These findings are in line with those of Bioto et al. (2023) who found similar agreement between regulatory-grade monitors and Aeroqual sensors when co-location guidelines were followed.

Shapiro-Wilk residual normality tests showed that AQM 65 performed reliably in the moderate (30–60 $\mu\text{g}/\text{m}^3$, $p = 0.861$) and high (>60 $\mu\text{g}/\text{m}^3$, $p = 0.300$) $PM_{2.5}$ ranges. A significant deviation from normality was observed in the low (<30 $\mu\text{g}/\text{m}^3$) range ($W = 0.937$, $p = 0.021$), consistent with the known limitations of optical mid-cost sensors at low particulate concentrations, where signal-to-noise ratios are reduced (Barkjohn et al., 2022).

3.2 $PM_{2.5}$ Concentration Trends

The $PM_{2.5}$ concentration trends has been discussed in table 2 and graphically presented in figure 4.

Table 2: Summary statistics of daily $PM_{2.5}$ concentrations recorded in Dhulikhel (April 22 – June 2, 2025)

Statistic	Value ($\mu\text{g}/\text{m}^3$)
Minimum	9.80
Maximum	37.26
Mean	22.62
Standard Deviation	6.84
WHO (15 $\mu\text{g}/\text{m}^3$) Exceedance Days	38 out of 42
NAAQS (40 $\mu\text{g}/\text{m}^3$) Exceedance Days	0 out of 42

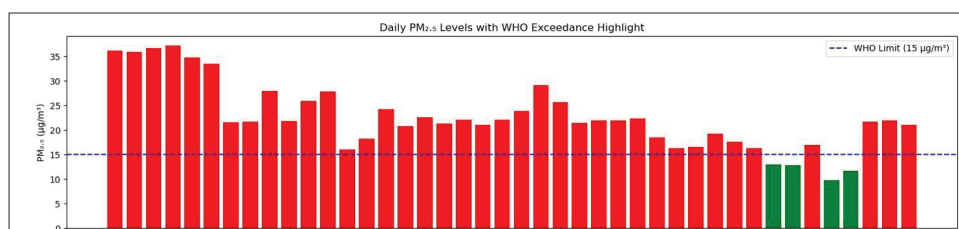


Figure 4: Daily average $PM_{2.5}$ concentration over the study period (April 22 – June 2, 2025) with the WHO 24-hour guideline (15 $\mu\text{g}/\text{m}^3$).

Over the time of the 42-day monitoring period, daily $PM_{2.5}$ ranged from 9.80 to 37.26 $\mu\text{g}/\text{m}^3$, with a mean of 22.62 $\mu\text{g}/\text{m}^3$ (Table 2). The observed mean concentration (22.62 $\mu\text{g}/\text{m}^3$) was 1.5 times higher than the WHO guideline value, indicating a persistent public health concern despite compliance with Nepal's national standard. The WHO 24-hour $PM_{2.5}$ safe limit of 15 $\mu\text{g}/\text{m}^3$ was surpassed on 38 days (90%). No day exceeded Nepal's NAAQS threshold of 40 $\mu\text{g}/\text{m}^3$, demonstrating both national regulatory compliance and a clear discrepancy between national norms and global health-based targets. This discrepancy highlights the need for stricter national standards to sufficiently protect public health and is consistent with findings from studies conducted in the Kathmandu Valley (Neupane et al., 2022).

Bimodal diurnal trend was observed through the hourly $PM_{2.5}$ concentrations. Early in the morning (6:00–9:00 AM) and late at night (6:00–9:00 PM) saw the highest levels of $PM_{2.5}$ concentrations. Concentrations were consistently lower in the afternoon (12:00–4:00 PM), most likely due to increased boundary layer mixing and wind-driven dilution. This pattern reflects common regional emission cycles associated with household

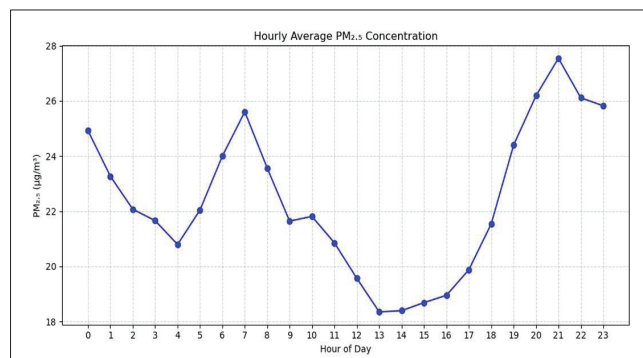


Figure 5: Mean hourly $PM_{2.5}$ concentration over the study period showing bimodal diurnal pattern with morning (6:00–9:00 AM) and evening (6:00–9:00 PM) peaks

combustion and road traffic activity, and it is consistent with observations from the Kathmandu Valley (Gurung & Bell, 2012).

3.3 Pollution Rose and Source Direction Analysis

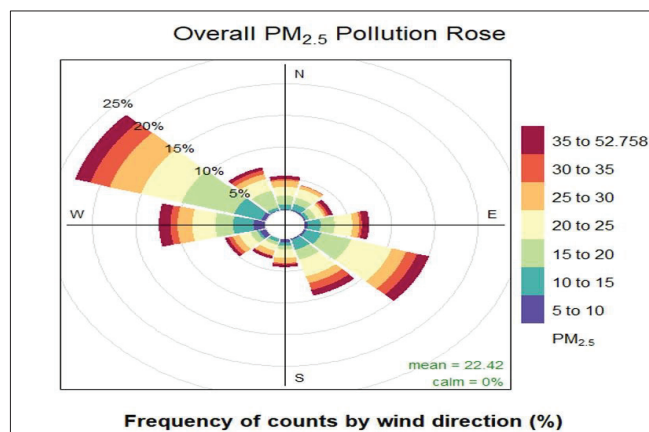


Figure 6: Overall pollution rose for $PM_{2.5}$ during the study period indicating dominant source directions (WNW and ESE) associated with elevated concentrations

According to pollution rose analysis $PM_{2.5}$ concentrations were consistently linked to the West-northwest (WNW) and east-southeast (ESE) winds. With values often surpassing $35 \mu\text{g}/\text{m}^3$, the WNW sector had the highest frequency (up to 25%). Elevated levels were also observed in the ESE region, indicating possible contributions from pollution transport from the Araniko Highway and nearby cities. These directional patterns are consistent with pollution rose analyses from Bangkok (Anusasananan et al., 2023) where large traffic regions, nearby cities and industrial source zones were correlated with dominant wind directions.

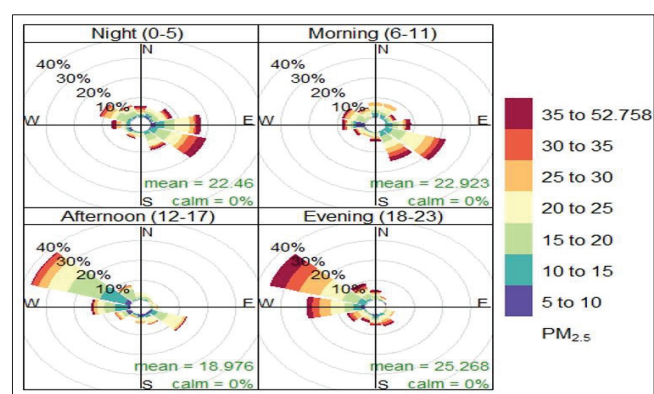


Figure 7: Pollution rose for $PM_{2.5}$ during the different time of the day during study period.

A time-of-day analysis revealed that the afternoon (12:00–17:00) had the lowest mean $PM_{2.5}$ ($18.98 \mu\text{g}/\text{m}^3$) and the evening (18:00–23:00) had the highest ($25.27 \mu\text{g}/\text{m}^3$). Despite identical wind patterns, night time concentrations (mean: $23.86 \mu\text{g}/\text{m}^3$) were higher than daytime levels (mean: $20.96 \mu\text{g}/\text{m}^3$). This was caused by persistent boundary layers, less atmospheric mixing, and the buildup of emissions from burning biomass under poor ventilation. With averages of 22.14 and $23.09 \mu\text{g}/\text{m}^3$, respectively, weekday and weekend pollution rose demonstrated similar directional tendencies and persistently exceeded the WHO standard.

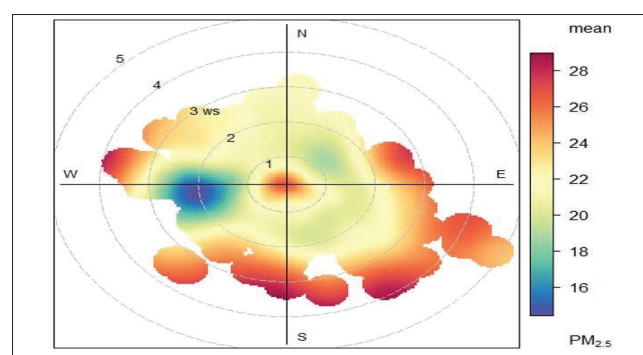


Figure 8: Bivariate polar plot of $PM_{2.5}$ concentration with wind speed and direction showing elevated concentrations ($>26 \mu\text{g}/\text{m}^3$) associated with moderate winds (1.5–3.5 m/s) from the east, southeast, and southwest

Through the bivariate polar plot analysis, it further revealed that elevated $PM_{2.5}$ ($\geq 26 \mu\text{g}/\text{m}^3$) was predominantly associated with moderate wind speeds (1.5–3.5 m/s) from the east, southeast, and southwest, suggesting regional pollutant transport from urban sources such as Banepa, and Kathmandu Valley and major highway corridors. Wind speeds exceeding 4 m/s were consistently linked to lower $PM_{2.5}$, confirming the role of atmospheric mixing in pollutant dilution.

3.4 Machine Learning Model Performance

3.4.1 Forecasting using historical $PM_{2.5}$ Data Only

When trained on lagged $PM_{2.5}$ datasets alone Extra Trees had the highest current-hour performance ($R^2 = 0.789$, $\text{RMSE} = 3.82 \mu\text{g}/\text{m}^3$, $\text{MAE} = 2.73 \mu\text{g}/\text{m}^3$), which was closely followed by Random Forest and Stacking model (both $R^2 = 0.787$) while the performance of XGBoost was comparatively

Table 3: Performance of machine learning models for current-hour $\text{PM}_{2.5}$ estimation using lagged historical $\text{PM}_{2.5}$ data only

Model	R^2	RMSE ($\mu\text{g}/\text{m}^3$)	MAE ($\mu\text{g}/\text{m}^3$)
Random Forest	0.787	3.84	2.69
XGBoost	0.733	4.30	3.01
Extra Trees	0.789	3.82	2.73
Stacking	0.787	3.84	2.73

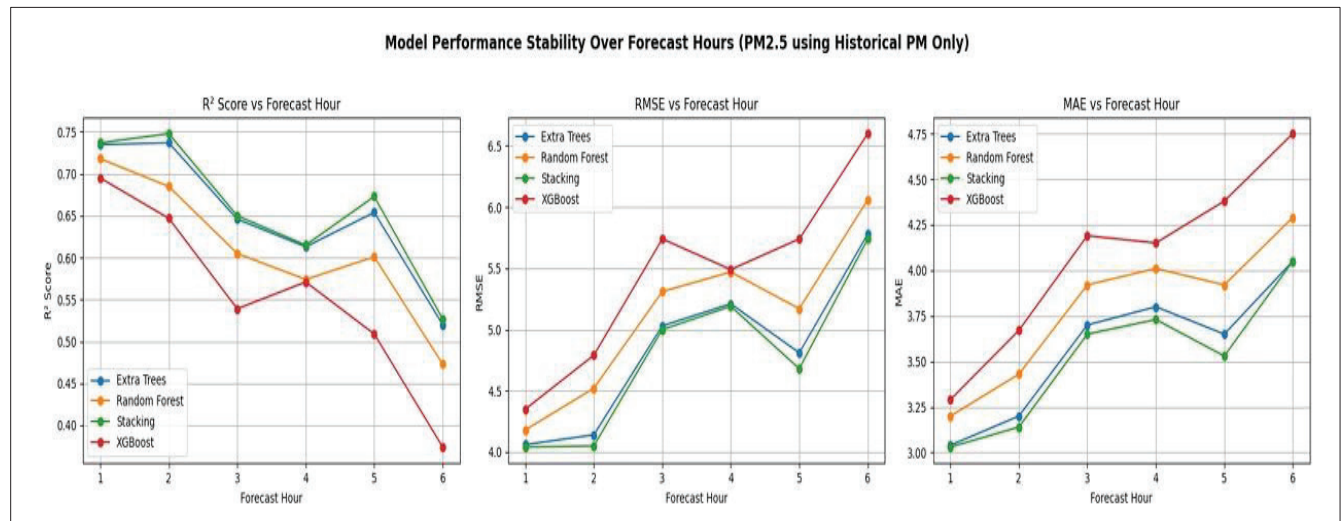
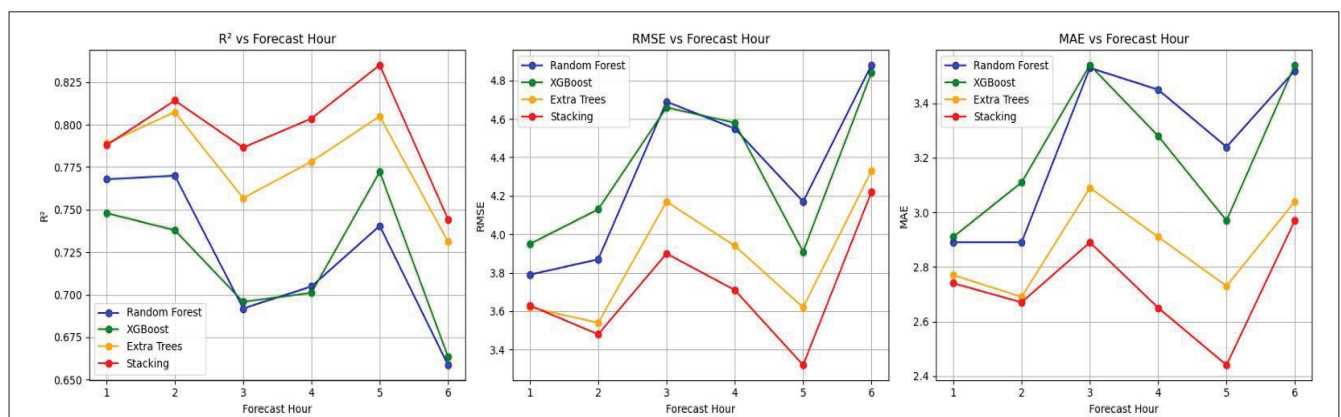
low ($R^2 = 0.733$). Stacking model was the most consistent for forecasting one to six hours in advance, retaining $R^2 = 0.737$ at one hour and dropping to 0.527 at six. With $R^2 = 0.374$ at 6 hours and $\text{RMSE} = 6.60 \mu\text{g}/\text{m}^3$, XGBoost experienced the steep decline, making it unsuitable for longer forecast horizons with PM data alone. Short-term air quality forecasting is known to be limited by this steady performance decrease with increasing lead time (Alrashidi et al., 2025).

3.4.2 Forecasting Using Historical $\text{PM}_{2.5}$ and Meteorological Data

Table 4: Performance metrics of machine learning models for current-hour $\text{PM}_{2.5}$ estimation using combined historical $\text{PM}_{2.5}$ and meteorological data

Model	R^2	RMSE ($\mu\text{g}/\text{m}^3$)	MAE ($\mu\text{g}/\text{m}^3$)
Random Forest	0.824	3.49	2.45
XGBoost	0.829	3.43	2.45
Extra Trees	0.847	3.25	2.28
Stacking	0.844	3.29	2.30

After the addition of lagged meteorological variables model performance was significantly enhanced. Extra Trees obtained the best current-hour accuracy ($R^2 = 0.847$, $\text{RMSE} = 3.25 \mu\text{g}/\text{m}^3$, $\text{MAE} = 2.28 \mu\text{g}/\text{m}^3$), followed by Stacking ($R^2 = 0.844$, $\text{RMSE} = 3.29 \mu\text{g}/\text{m}^3$). In line with Wang and Ogawa (2015) and Ma et al., (2023), these improvements over using PM-only models for forecasting validate the

**Figure 9:** Comparison of model stability for 1–6 hour $\text{PM}_{2.5}$ prediction using combined meteorological and $\text{PM}_{2.5}$ data showing R^2 , RMSE, and MAE trends across forecast horizons**Figure 10:** Comparison of model stability for 1–6 hour $\text{PM}_{2.5}$ prediction using combined meteorological and $\text{PM}_{2.5}$ data showing R^2 , RMSE, and MAE trends across forecast horizons

significance of meteorological factors in modifying $PM_{2.5}$ dynamics.

Out of all models, Stacking model consistently performed better than the others for multi-hour forecasting with combined inputs, obtaining R^2 values above 0.74 over all 1–6 hour horizons. The model's ability to use meteorological dynamics for medium-term forecasts was demonstrated by performance at the 5-hour horizon ($R^2 = 0.835$, $RMSE = 3.32 \mu g/m^3$), which outperformed several shorter horizons. According to Tian et al., (2024) and To Thi Hien et al. (2021), because of its ability to combine complementary base learner capabilities through a meta-learner stacking is preferable. For predictions lasting one to two hours, Extra Trees performed similarly, but after three hours, accuracy loss was observed in XGBoost and Random Forest.

3.4.3 SHAP Feature Importance of Meteorological Variables

By SHAP analysis Dew point temperature was shown to be the most dominant meteorological driver of $PM_{2.5}$ (mean SHAP value: $3.59 \mu g/m^3$), which influences aerosol hygroscopic growth and secondary particulated formation, indicating its considerable correlation with pollutant condensation processes and atmospheric moisture content. This indicates that ambient moistures strongly governs secondary aerosol formation, where higher moisture accelerates the hygroscopic growth of particles. This thermodynamic dominance aligns with findings by Li et al. (2017) in Hong Kong. Relative humidity ($1.19 \mu g/m^3$) was next most significant predictors and ambient temperature ($1.06 \mu g/m^3$), which influenced particle production and dispersion through chemical and physical interactions. The mild impact of solar radiation ($0.99 \mu g/m^3$) may be related to photochemical processes. Conversely, dynamic variables such as contributions from wind direction and wind speed yielded minor contributions. While higher wind speeds typically promote mechanical dispersion as observed in high ventilation regions like Hanoi, the minimal impact here implies that local conditions were likely characterized by stagnant air masses where localized chemical accumulation overrode regional transport. In general, thermodynamic variables had

a stronger impact than dynamic variables, which is in line with research from Hong Kong (Li et al., 2017) and Hanoi (Hien et al., 2002).

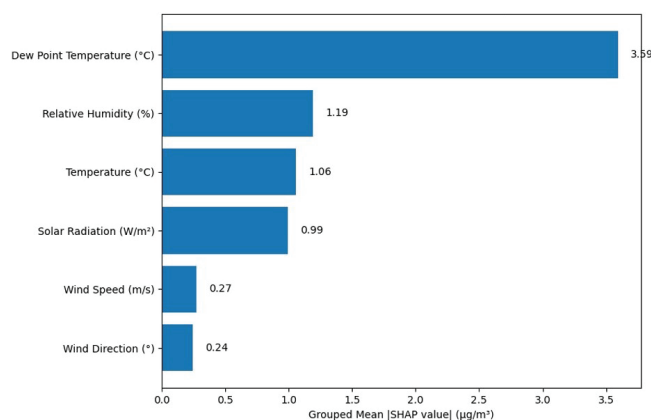


Figure 11: Grouped SHAP feature importance of meteorological variables showing relative contribution (mean |SHAP value| in $\mu g/m^3$) to $PM_{2.5}$ model predictions

4. Conclusion

For short-term $PM_{2.5}$ monitoring and forecasting in semi-urban and resource scare region, this study shows the feasibility of using a calibrated mid-cost sensor in conjunction with meteorological parameters for machine learning-based predictions. The Aeroqual AQM 65's co-location calibration against the reference grade sensor (GRIMM EDM 180) produced a reliable correction model ($R^2 = 0.887$) with almost no systematic bias, confirming the sensor's usability for ambient monitoring in the resource scare regions. While staying under Nepal's NAAQS ($40 \mu g/m^3$), $PM_{2.5}$ concentrations in Dhulikhel continuously exceeded the WHO 24-hour limit safe limit of ($15 \mu g/m^3$) on 90% of monitoring days during the pre-monsoon period. Vehicle activity on the nearby Highways and regional transport from nearby cities are identified as the possible main sources of particulate pollution due to the unique bimodal diurnal pattern and the predominant pollution transfer from WNW and ESE directions.

In case of machine learning based predictions, for all 1–6 hour forecast horizons, the Stacking ensemble model performed better and more consistently ($R^2 = 0.844$ for current-hour estimation with mixed inputs). After the integration of meteorological

factors Forecast accuracy of all models was much improved. A scalable and economic framework for managing air quality in secondary urban areas with limited resource for air quality management is provided by this integrated strategy combining calibrated mid-cost monitoring with ensemble machine learning.

Future research should focus on extending the monitoring period to capture seasonal variability, conduct source appointment of the particulate pollution, deploy multiple sensors and study spatial variation of the pollutants to characterize heterogeneity, and investigate deep learning approaches for longer forecast horizons. Integration of real-time PM_{2.5} forecasts into public health alert systems is also recommended to protect vulnerable populations during high pollution episodes.

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Environmental Compliance Assessment of Star-Rated Hotels in Nepal Based on Environmental Management Plans (EMPs)

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Abstract

The tourism industry has risen significantly in the nation over the past few years with a considerable surge in especially star rated hotels. With the increased facility to the tourists, this causes an increase in the associated environmental problems also to a greater extent. The major problems associated are solid waste and waste water management, high energy and water consumption, water resources management as well as disaster preparedness. However, the effective implementation of Environmental Management Plans (EMPs) of Environmental study reports can help mitigate such effects. This requires for the need of environmental compliance assessment to verify the existing scenario against the proposed activities. Even though, there are several studies in Nepal which has incorporated the tourism industry; very few are related to compliance status especially on environmental parameters. So, this study aims to assess the compliance status of star rated hotels located in the different provinces of Nepal based on descriptive as well as comparative research design. Several key parameters that range from air and water pollution to solid waste management, water resources management to disaster preparedness along with greenery maintenance and support to locality are considered for this study. The results from the study showed that waste water management was found to be significantly non-compliant across all the parameters examined. However, various other parameters including solid waste management, air and sound quality management along with energy and disaster management were majorly compliant as per their EMPs; while the rest parameters showed mixed compliance status. Hence, the assessment spots a significant gap in certain parameters when it comes to the implementation status. Therefore, it is suggested to implement the mitigation measures more stringently and also sideways encourage the hotels to adopt more environment friendly and sustainable activities.

Keywords: *Compliance status, environmental study, star rated hotels, tourism*

1. Introduction

The tourism and hospitality sector in the present context is recognized as one of the most resource-intensive industries due to its major contribution in solid waste and waste water generation, energy usage, and water consumption. So, the increasing number of hotels in particular, contributes significantly to environmental degradation through these activities. Studies by Bohdanowicz (2006) and Chan and Hawkins (2010) reveal that hotel operations can account for substantial environmental impacts, with a major proportion linked to excessive resource consumption and inefficient operational practices in majority of the cases. Core activities such as heating, cooling, laundry, and waste disposal further amplify these impacts (Han & Yoon, 2015).

Nepal's tourism industry has witnessed a significant growth in the recent years with increase in both domestic and foreign investments. According to the report published by Ministry of Culture, Tourism and Civil Aviation (MoCTC, 2024), the number of tourist standard star hotels have also significantly increased from 182 to 214 in a single year; 2023 to 2024 A.D. which nearly accounts to a massive 18% rise. The increase in standard star hotels are bound to raise the hospitality services provided to the visitors but sideways it also raises the consumption of resources thereby contributing to environmental impacts in various forms. Hence, this requires for the need of effective compliance monitoring. Such monitoring will ultimately help in ensuring the sustainable use of resources which not only supports in environment protection but also promotes the

tourism economy through equally prioritizing safety and quality services.

Environmental Compliance generally refers to the systematic examination of adherence to relevant regulations or standards whereas its assessment represents the overall evaluation of such compliances on various parameters. Environment Compliance in this study is made more specific to assess the adherence to the mitigation measures proposed in approved environmental study reports. Such assessment helps in examining the gaps between the proposed measures and the adopted ones. This will ultimately give us an overall scenario of the compliance in hospitality sector along with recommendations for continual improvement. Besides that, it also involves the continuous process of collecting, analyzing, and interpreting environmental data to support decision-making and improve performance thereby minimizing adverse environmental impacts. It promotes both regulatory mechanisms as well as sustainable resource management hence is essential in ensuring that development activities stay within environmentally acceptable limits. As a component of environmental management systems, environmental compliance assessment makes it possible to evaluate important environmental factors that are directly related to ecological integrity and human health, such as soil, water, air, and noise. In other words, it has become a crucial instrument for evaluating environmental quality and directing sustainable development in the context of rapid urbanization, population growth, and rising tourism.

The Tourism Act, 1978 has provided the government authority for licensing, monitoring, compliance inspections, and penalties for tourism businesses in case of violation of rules. Apart from this, Environmental Assessment along with Environmental Management Plans (EMPs) have been institutionalized in Nepal through the Environment Protection Act (EPA, 2019) and the Environment Protection Rules (EPR, 2020) to regulate the environmental impacts associated with development projects. The EPA explicitly has the provision for environmental monitoring and compliance assessment. Section 39 of the Act

has provided authority to the federal, provincial and local governments to carry out environmental monitoring and inspection to ensure that the development projects have properly implemented the environmental standards and mitigation measures. Furthermore, the Section 12 of the Act also provides for environmental audit provisions, requiring concerned authorities to evaluate whether the predicted impacts and proposed mitigation measures have been effectively implemented. Similarly, the EPR, 2020 mandates that project proponents conduct regular environmental monitoring and submit self-monitoring reports.

Despite the existence of these regulatory provisions, the main concerns remain regarding the actual implementation and compliance of Environmental Management Plans within Nepal's hotel sector, particularly among the star-rated hotels which have very high flow of tourists and maximum utilization of resources. Although the awareness has increased globally regarding the sustainable consumption and hospitality practices but there is a limited research on to which extent the environmental commitments are fulfilled within hotels (Khatte et al., 2019) and similar is the case with Nepal. The existing researches have primarily focused on general tourism impacts with very little attention given to environmental compliance. In Nepal, the expansion of star-rated hotels, particularly in major tourist areas, has raised concerns regarding the effective implementation of Environmental Management Plans (EMPs). Therefore, this study aim to examine the environmental compliance status of selected star-rated hotels in Nepal based on their EMP implementation.

2. Materials and Methods

This study adopts a descriptive and comparative research design to assess the environmental compliance status of several star-rated hotels located in six provinces of Nepal.

2.1 Study Area

Hotels were selected using purposive sampling based on the following criteria: (i) possession of an approved environmental study report

(IEE/EIA) with a documented Environmental Management Plan (EMP), (ii) operational status during the study period (2022–2025), and (iii) classification as tourist-standard star-rated hotels under the prevailing tourism regulations of Nepal, (iv) geographic distribution across provinces to capture regional variation. Star-rated hotels were specifically considered because their establishment and operation generally require the approval of environmental study reports and the implementation of EMP provisions, making them suitable for assessing environmental compliance and monitoring practices.

The study covered a total of 21 star-rated hotels distributed across six provinces of Nepal. One hotel each was selected from Koshi, Madhesh, and Gandaki Provinces; two hotels each from Lumbini and Karnali Provinces; and the remaining fifteen hotels from Bagmati Province, primarily within the Kathmandu Valley. The higher representation of Bagmati Province reflects the substantially greater concentration of star-rated hotels in the Kathmandu Valley compared to other provinces. Hotels in Sudurpashchim Province however could not be included for this study due to time constraints. Therefore, the findings may not fully represent the

environmental monitoring and compliance status of hotels across all provinces of Nepal.

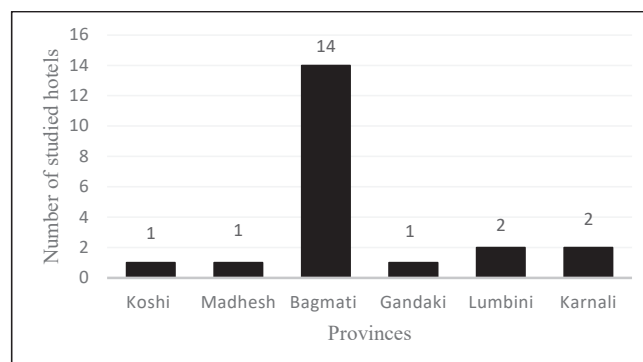


Figure 2: Province wise distribution of studied hotels

2.2 Methods of the study

Following methods were used for the study of compliance assessment of the studied hotels.

Desk Study: The approved environmental study report of the individual project was studied thoroughly to access the information regarding the project. Particular emphasis was given to the Environmental Management Plan (EMP) of each project, as the EMP provides project-specific environmental commitments and mitigation measures. The compliance assessment was

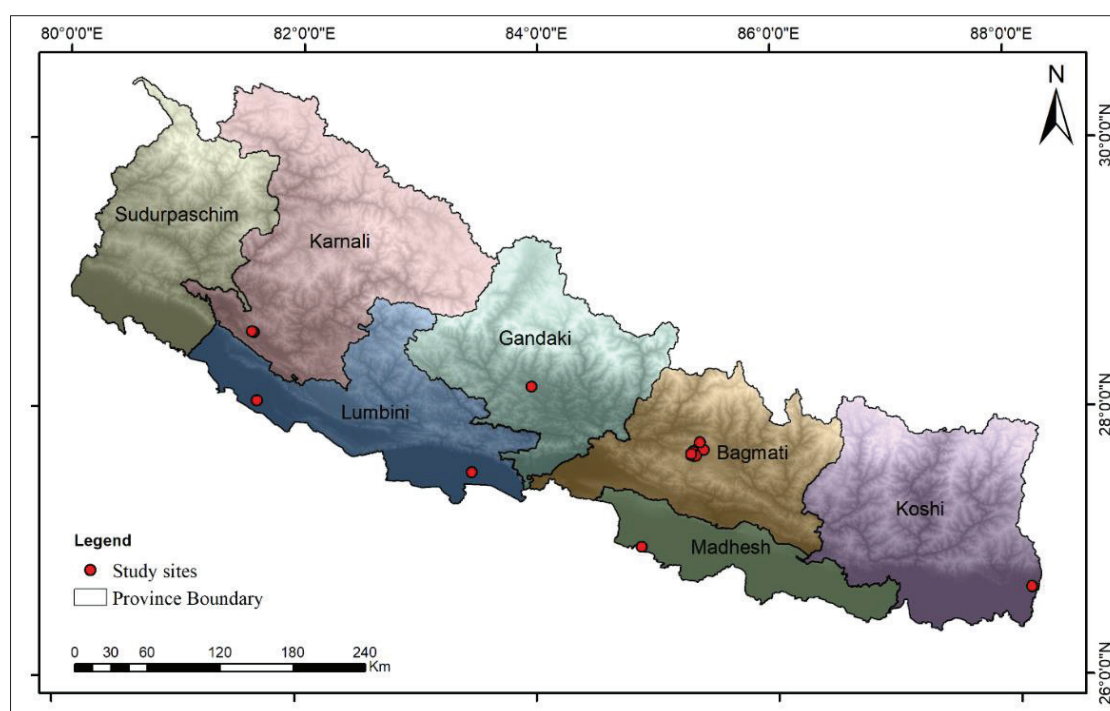


Figure 1: Map showing study sites

conducted by comparing the environmental performance and implementation status of each project against the mitigation and management measures prescribed in its respective EMP. Key environmental aspects examined during the assessment included wastewater management, air/noise quality management, solid waste management, disaster preparedness, groundwater recharge, greenery maintenance as well as corporate social responsibility.

Site Inspection: Site Inspection is carried out on the specific site of the project. During this visit, areas of concern are inspected to get further information regarding the solid waste management, water resources and wastewater management, disaster preparedness as well as implementation status of the approved mitigation measures. The data thus collected are qualitative and quantitative in nature.

Data Analysis: The collected data were analyzed qualitatively and quantitatively to assess compliance across nine key environmental parameters as mentioned beforehand. A comparative framework was used to classify compliance into three categories: compliant, partially compliant, and non-compliant.

Key informants' interview and Discussions: The objective of the inspection was presented with the management team of the project before heading towards the topic based discussion. For the subject based discussion, specific personnel from various units were contacted and relevant information was duly collected. For such key informants' interview, personnel from management level to implementation level are inquired and necessary information is noted.

3. Results and Discussion

3.1 Overview of EMP and Compliance Status

The Environmental Management Plans (EMPs) of these hotels were systematically reviewed to know the compliance status of nine key environmental parameters, including physical (solid waste, wastewater, air/noise quality, ground water recharge, and energy and disaster management),

biological (greenery maintenance) and socio-economic (Corporate Social Responsibility) parameters. Additionally, the mitigation measures mentioned in such EMPs were evaluated to assess the compliance status. However, the overview of the EMPs also hold some gaps as in some cases, the proposed mitigation measures are not specific and measurable in themselves. As a result, such measures are nominally implemented at site which in turn makes the monitoring hampered to certain extent. Hence, this has risen the issue of the relevancy of the mitigation measures in certain scenarios and simultaneously elevates the need for practical, project specific and feasible mitigation measures.

3.2 Comparative Compliance Status

The studied hotels were assessed on various parameters to check the compliance status based on the EMPs of the approved environmental study reports as described in table 1. The compliance status was categorized into three classes namely compliant, partially compliant and non-compliant. They were determined using the following criteria: (i) "Compliant" refers to full implementation of the required mitigation measure as specified in the EMP and compliance with relevant environmental standards; (ii) "Partially compliant" refers to incomplete or inconsistent implementation of mitigation measures, or implementation that does not fully meet the required standards; and (iii) "Non-compliant" refers to absence of implementation or clear violation of the EMP provisions and applicable environmental standards. Hence, the compliance status in this study was analyzed based on the level of conformity to the adoption of approved mitigation measures. The values in the table are represented in percentage with their number in brackets.

3.3 Solid Waste Management

Solid waste generation and disposal is one of the most negative impacts of hotels on the environment (Zorpas et al., 2012). Hence, its management seems crucial not only from the environment point of view but also from the aesthetic aspects of the hotels. The solid waste management in our study comprised adoption of segregation practice

Table 1: Compliance status for studied hotels

S.N.	Parameter	Compliant (%)	Partially Compliant (%)	Non-Compliant (%)
1.	Solid Waste Management	90% (19)	10% (2)	0% (0)
2.	Wastewater Management	33% (7)	19% (4)	48% (10)
3.	Air Quality Management	86% (18)	14% (3)	0% (0)
4.	Noise Quality Management	86% (18)	9% (2)	5% (1)
5.	Groundwater Recharge	57% (12)	14% (3)	29% (6)
6.	Energy Management	90% (19)	0% (0)	10% (2)
7.	Disaster Management	90% (19)	10% (2)	0% (0)
8.	Greenery	67% (14)	9% (2)	24% (5)
9.	Corporate Social Responsibility (CSR)	67% (14)	28% (6)	5% (1)

mostly into dry and wet waste, prohibit dumping of waste in water bodies as well as outside the premises and handling of the waste to private or municipal waste handler for final disposal. Further, some hotels in their EMP also proposed to practice composting for organic waste which was the main limiting criteria for categorization into compliance or partial compliance. Based on the above mentioned parameters, majority of the hotels showed compliance with provision of dustbins in necessary areas for the collection of waste, segregation of dry and wet waste inside the premises and final handling of such waste to waste handlers. Given that, the hotel generates large amount of food wastes, followed by dry wastes and hazardous waste. Off all the waste, food waste can be considered as one of the most important materials to divert from landfills as it decomposes to create methane; also a potent greenhouse gas which significantly contributes to climate change (Pirani & Arafat, 2014). Regarding the composting of organic waste, only three out of total sampled hotels had proposed composting in their EMPs; of which only one hotel was found to be practicing composting inside the hotel premises. Thus the partial compliance of the hotels was attributed by the non-adoption of composting. Since the composting requires space, continuous efforts and dedicated manpower, often the proponents were found to be little reluctant towards practicing it.

Apart from this, recycling could also be an important parameter and is usually mentioned in the EMP of the approved reports. A similar study carried out in 52 different hotels of the United Kingdom found

that recycling was the most widely adopted waste management strategy, with waste prevention and reuse methods being considerably underutilized (Lazareva, 2016). However, this was not considered in this study as such practice could not be verified from the field since the hotels were not found to be formally practicing the recycling. However, the practice of informally selling the waste to vendors was observed at some sites. Recycling can be useful for hotels as they were found to produce large amount of sellable items like bottles and cardboards.

3.4 Wastewater Management

The least complying environmental parameter is wastewater management, which is in line with international research showing it to be a significant environmental problem in hotels (Menegaki, 2025). The presence of either Sewerage Treatment Plant or Wastewater Treatment Plant in itself is a step forward towards the mitigation measures. However, looking at a broader scale, a functional STP/WWTP can only fully ensure the treatment of wastewater such that it meets the approved standards. Hence, complete compliance is only considered for a functional Treatment Plant (TP). By using functional STPs, only one third of the hotels; altogether seven hotels were found complied with wastewater management.

However the categorization in case of wastewater management was more convergent as the partial compliance status was also affected by other factors besides the presence of TP. In this regard, use of septic tanks (but no discharge to public sewerage), fully non-operational TP and partial treatment of

wastewater had caused hotels to be in this range. Of the total 4 partially complied hotels, 2 had septic tanks, one had fully non-operational TP and the remaining had partially treated its wastewater. However, with the advancement of technology and nature of wastewater, many hotels are using Package plants these days as wastewater is mostly domestic in nature. Package Plants (PP) are prefabricated treatment units that comprise mainly three steps; coagulation/sedimentation then aerobic/anaerobic biological degradation and finally filtration. Such PP are found to provide high BOD and phosphorus removal but with low nitrogen and bacterial removal especially in low temperatures (Vidal et al., 2023). Such treatment options come with less economic burden in initial installment and also the operating cost reduces largely.

In contrary, nearly half of the hotels were found to be non-complied as they lacked treatment facility. The non-complied hotels were found to be more concentrated inside the Kathmandu Valley which might be due to the presence of large number of star rated hotels inside the Valley. When inquired for the reasons for the non-compliance, the hoteliers reported of various reasons such as constraint of land, old building structure as well as need of high initial investments. Also, partial and non-complied hotels were found to be less aware regarding the implementation of EMPs as well as approved standards regarding the wastewater management. Along with this, the absence of tolerance limits for wastewater from the hotels in specific has also hindered in effective implementation of this measure.

3.5 Air Quality Management

Air quality management showed high compliance, with most hotels adopting renewable energy sourced heat pumps, regularly maintained and sophisticated generators. Various studies have reported that hotels nowadays increasingly adopt renewable energy technologies and energy-efficient systems, including heat pumps and solar panels as part of sustainable energy management and pollution control practices (Arikan Kargi & Cesur, 2024; Ghimire et al., 2023). Fossil fuel fired boilers are

considered to be the most applied source of heating in Europe despite its high emissions (EC, 2016). Boilers mentioned here refer to the combustion machines, that burn fuel such as oil and natural gas for the heating purpose. As an alternative to such boilers, heat pumps are more efficient as they transfer heat from one temperature level to another. This in turn results in requiring a considerably smaller amount of electricity to generate thermal heat than required by even electricity fueled boilers (Tosato et al., 2020; Smitt et al., 2019). Most of the inspected hotels in our study were found to adopt heat pumps for the heating purposes. These were either electricity fueled or based on solar energy representing cleaner sources of energy. Besides, the partial compliance for some came from the fact that fossil fueled boilers though are being replaced by the heat pumps are still being used in some scale. However, no hotels were found being totally dependent on traditional boilers which no doubt is a positive impact to the environmental pollution. Apart from this, the installation of low pollution, fuel efficient generators were reported in most of the inspected hotels. The height of the stack in generator also decides the dispersion of the pollutants in the surrounding community. During site inspections, stack heights were visually observed as part of the compliance assessment. The compliance of such factor was only one fourth of the total observation while those non-complied were 14%; rest could not be distinctly verified. An absence of obvious standard in this matter might have resulted to this observation. So, this finding highlights a potential gap in existing environmental management requirements and suggests the need for establishing clear stack height guidelines for diesel generators as a measure to abate air pollution by dispersing the pollutants. It should be noted that air quality management in this study was not assessed through direct measurement of ambient air quality parameters such as particulate matter (PM), sulfur dioxide (SO₂), nitrogen oxides (NO_x), or carbon monoxide (CO). Instead, compliance status was evaluated based on the implementation of air pollution management measures specified in the Environmental Management Plan (EMP), field observations and review of available diesel

generator (DG) stack emission monitoring reports.

3.6 Noise Quality Management

Diesel generator sets are used primarily for emergency power generation or stand-by power in case of power failure. Since they are composed of various noise sources, these sets produce noise and vibration. Depending on the severity, noise and vibration can be the cause of serious disturbance and inconvenience to anyone exposed to them and in certain circumstances noise and vibration can be a serious hazard to health, causing permanent damage to hearing system (Elanchelian, 2013). The study also showed high compliance in regard to noise quality management which might be contributed from use of sophisticated generators producing less sound and placement of such sets in enclosure. While those with partial compliance were the sets partially placed in enclosure as they generate more sound. Also, the hoteliers were found to be conscious by themselves in this regard as the visitors seek for peace in their visit. Hence, the generators were mostly found to be placed separately in place where there was sufficient space while for those with limited space; generators were found to be placed separately in basement or enclosed. The role of enclosure is also supported by a study conducted in portable generators which showed that a sand bed of thickness 32 mm reduced noise by 10 dB(A) while an air gap of 5 cm between sandwich enclosure walls can achieve a reduction of even 28 dB(A) (Parvathi & Gopalakrishnan, 2003). Apart from this, the regular supply of electricity was reported to sufficiently reduce the operation of generators thereby reducing its detrimental environmental effects as well.

3.7 Water Usage

Groundwater serves as one of the main sources of water in many areas of Nepal including the capital Kathmandu. In order to combat the water demand of Kathmandu Valley caused by ever increasing number of apartments, hospitals, educational institutions, hotels and industries, ground water has been excessively pumped out which combined with concretization has hindered the groundwater recharging (Bhattarai & Adhikari, 2022). However,

the excess of ground water in the densely populated areas such as in the Kathmandu Valley often leads to land subsidence (Bhattarai et al., 2017). The sampled hotels were found to vastly depend on groundwater to fulfill its water demands. Of the total sampled hotels, majority of the hotels (19) contributing to massive 90% share extracted groundwater to fulfill its daily needs whereas only few (2) hotels were found to exclusively depend on tap water. The amount of groundwater extracted was reported to be within the limits of extraction permit approved from the government authority. However, the requirement for extraction permit is mainly confined inside the Kathmandu Valley only which raises the issue of rampant groundwater extraction in many areas. Basically, the extraction capacity was found to depend on the size of the hotels as well as the guest turnout ratio. However, many hotels reported to be extracting nearly 50,000 liters per day while very few were found to be extracting even higher than 1 lakh liters as per their daily requirement. The high dependence on the groundwater is sure to impact the water table of the area along with associated problems that comes from disturbance in water table.

3.8 Groundwater Recharge

Water is recharging through various methods; natural process (recharge or retention ponds), deep water injection, recharge pits or rainwater harvesting help in replenishing the diminishing groundwater (Bhattarai & Adhikari, 2022). Hence, the provision of recharge pits is generally proposed in the Environment Mitigation Plan of the approved environment study reports as well. Therefore, the compliance status of the hotels on this regard was contributed by the provision of groundwater recharge which in turn refers to the presence of recharge pits. However, in some cases the availability of vast patch of unpaved land was also considered as compliance since this provision also facilitate in recharging of the ground water. From this aspect, 12 hotels were found to be complied; where 4 hotels had recharge pits whereas the remaining had sufficient open unpaved space. Similarly, the partial compliance was considered viable for situations where limited provision of

recharge facility was observed. Hence, owing to this fact, 3 hotels fell under partial compliance; out of which two hotels had limited unpaved land whereas the remaining used existing well for recharge purpose which in itself was not accounted sufficient. In contrary, the remaining 6 hotels were non-complied as they had not exhibited efforts towards the ground water recharge in spite all of them using ground water as their primary source of water. This shows less awareness and willingness of the hotels towards this issue. Moreover, the recharging technique and methods adopted in the complied hotels also lacked in many aspects which has raised another gap especially requiring for the formulation of relevant regulations. Apart from this, the water deficit situation can also be offset through the provision of rainwater harvesting; which is also proposed in many cases. However, despite EMP commitments, the lack of rainwater harvesting in almost instances suggests a large implementation gap. These trends align with previous studies that emphasize unsustainable water usage habits in the hospitality industry, especially in poor nations (Makoondlall-Chadee & Bokhoree, 2024).

3.9 Energy Management and Efficiency

Lenzen et al. (2018) found that tourism is responsible for around 8% of global greenhouse gas emissions. However, the hotels are switching towards renewable energy globally as well. This fact is supported by the evident that research conducted in between 2016 and 2022 emphasized on many hotels worldwide started using renewable energy and adopting green practices. Most hoteliers adopt renewable energy as the customers have positive perception towards such hotels and recommend such hotels to others (Ghimire et al., 2023). Energy management practices in our study also supported the same fact with majority compliant, from use of renewable energy such as solar and hydroelectricity as well as widespread use of LED lighting and energy-efficient appliances. For lighting purpose, all of the inspected hotels (100%) used electricity generated from hydropower as their main energy source with few of them using electricity generated from solar energy as well to some extent. All of the inspected hotels had diesel generator as backup

energy source depicting dependency on fossil fuels along with renewable sources of energy. For water heating system, majority of the inspected hotels (90%) in our study were found to adopt heat pumps. These were either electricity fueled or based on solar energy representing cleaner sources of energy. Besides, the partial compliance in some hotels (10%) resulted from the fact that fossil fueled boilers though in the process of being replaced by the heat pumps are still being used in some scale. However, no hotels were found being totally dependent on traditional boilers which no doubt is a positive impact to the environmental pollution. These actions are consistent with widely used hotel sustainability initiatives (Ouyang et al., 2019). No doubt prior research shows that hotels frequently put cost-cutting energy efficiency measures ahead of long-term sustainable energy transitions (Rassiah et al., 2024), the decreasing cost of renewable energy has shifted the whole paradigm at present. Since, electricity source is certainly dominated by hydropower in case of Nepal, the contribution towards the renewable energy increases simultaneously. A similar study based on data collected from 30 tourist standard hotels in Kathmandu also showed similar results with nearly 80% hotels showing a preference for hydroelectricity whereas just 2% showed towards solar energy (Ghimire et al., 2023). This also highlights the increased level of awareness amongst hoteliers about the renewable energy applications in hotel operations.

3.10 Disaster Management

Disasters experienced by the hospitality industry has gradually increased over the past few decades which have in turn warned the hospitality key players seek ways to cope with such extreme events (Mitroff, 2004). The study also demonstrated similar results with majority of the hotels (90%) complied with adoption of emergency preparedness and response plan as well as provision for emergency equipment and system demonstrating disaster management compliance. The provision for emergency equipment included first-aid kit, fire extinguishers, fire reel hose, safety alarms, smoke detectors along with emergency exit and assembly point. Since the study

was conducted in high end hotels, such provisions were given more priority and also some hotels; being chain hotels of established brands overseas had to follow such protocols. This increased degree of compliance is in line with research that indicates areas that directly affect human safety are given more regulatory attention and enforcement (Ouyang et al., 2019). Only few showed (10%) partial compliance with scope for improvement in disaster preparedness. The studied hotels were found to have organized safety training and drills at regular intervals to prepare staffs during emergencies.

3.11 Greenery Maintenance

Greenery has been undoubtedly the attraction point of any hotel. The aesthetics of a hotel is usually considered the face of its property. The study also tried to incorporate this aspect from the point of environment conservation as maintain greenery is often considered as one of the key mitigation measures in EMP of any approved environment study reports of hotels. However, our data showed mixed results with dominant hotels being complied on maintaining greenery. In spite of this, nearly, one fourth of the hotels could not comply with these measures mostly due to the unavailability of land. The hotel mostly operated in city areas with limited space were found to be little negligence in maintaining greenery. The maintenance of greenery not only brings mental peace to the visitors but is also crucial from maintaining environmentally sound scenarios. A new concept called “green hotels” is increasingly being popular in hospitality globally at present. Such concept promotes green building orientation, which involved using natural resources, renewable energy, and reusing materials and water in a variety of ways that supports sustainable practices and ultimately sustainable development (Ghimire et al., 2023). In align to this, few hotels in our study also showed their preference and orientation towards such practices which in fact indicates a progressive growth of green hotels concept in our context as well.

3.12 Corporate Social Responsibility

Corporate Social Responsibility (CSR) is understood as the responsibility of any project which it is liable

to spend on the welfare of the community as a certain percentage of its expenditure share. CSR has recently received more attention and has been started from different approaches. However, its application and use in hospitality sector is still largely vague in nature. The measurement of CSR in some cases is also attributed from short term and long-term return on asset (ROA) (Mariño-Romero et al., 2020). The studied hotels also showed dominantly complied in this aspect with nearly 70% compliance out of the total. The complied hotels were found to support the community through donations in infrastructure development and social activities. The infrastructure developments were majorly the construction of roads in locality, installment of lights and security system whereas the donations involved funding social activities ranging from orphanage, plantation and health check-up. Besides, some hotels were found to demonstrate less CSR activities falling under partial compliance also.

4. Conclusion

The study has tried to evaluate the compliance status among the star rated hotels in Nepal through categorization of various parameters into compliance, partially compliance and non-compliance based on the inspection. It reveals that compliance over the parameters basically included in EMPs shows mixed results. Moreover, the percentage-based compliance analysis indicates that while parameters such as solid waste management, air and noise quality management and energy as well as disaster management show relatively high compliance levels; wastewater management exhibit lowest observance representing critical gaps owing to absence and/or limited use of treatment facilities. Apart from this, the groundwater recharge seems moderately adherence contributed more by the availability of open surface rather than the provision of recharge pits. Since, most of the sampled hotels heavily relied on groundwater for their overall water demands; the ground water recharge needs to be scaled up in order to compensate for the used ground water. Besides, the greenery and CSR which are both indispensable in case of hospitality sector showed mixed compliance attributing to need for specific assessments. Along with this, it

was also perceived that the mitigation measures proposed in the EMP also needed to be site specific and computable so that its implementation can be more rationale. This limitation in the quality and contextual relevance of EMPs further constrains effective environmental performance, indicating a need for more rigorous, site-responsive planning during environmental approval processes.

Overall, the study emphasizes the significance of thorough environmental monitoring and regular inspections by the relevant authorities to determine whether or not the hotels have been effectively adopting the proposed mitigation measures. Improvement in waste water management systems, sustainable water usage, optimal resources use along with site specific EMPs will contribute to the sustainable tourism.

Recommendations

Based on the findings of our study, the special attention is needed in the areas where weak compliance was observed. Although many hotels have adopted the basic environmental management practices, the implementation of several mitigation measures were found to be partially compliant. Thus, it is recommended that regulatory bodies should use a performance-based monitoring strategy, making wastewater treatment plant installation and operation mandatory, encouraging the use of renewable energy, and enforcing sustainable water management techniques. Such improvements would support the long-term sustainability of tourism development in Nepal.

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Assessment of Flood Induced Loss and Damage in Roshi River Basin of Panauti Municipality, Kavrepalanchok, Nepal

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Abstract

Flood has been identified as a frequently occurring natural disaster, with extensive capacity to cause economic and non-economic loss and damage. The main purpose of the research study in the Roshi River Basin of Panauti Municipality-12 is to analyze temperature and precipitation trends, assess economic and non-economic loss and damage, and identify key adaptive measures adopted by community in response to September 2024 flood. Households Survey, Focused Group Discussion (FGD), Key Informant Interview (KII), Climatic Data Analysis and Field Observation were conducted to obtain the objectives of the study considering 187 households from the most severely affected communities. Findings indicated that the average minimum temperature increased by approximately 0.0345°C per year, while maximum temperature rose by 0.093°C per year, resulting in an overall annual increase of 0.064°C. Precipitation exhibited a declining trend of 1.16 mm/year over the past three decades. The devastating flood event in September 2024 was attributed to the extreme concentration of rainfall under changing climatic conditions, causing an estimated total loss and damage of NPR 536.178 million (USD 3.81 million approximately). The highest impacts were recorded in agricultural land and housing, followed by livestock, crops and other sectors. Statistical analysis revealed a significant correlation between economic loss and damage and household income, whereas association with ethnicity and family size were found to be insignificant. Non-economic impacts, including loss of life and disruption of basic services, underscored the severe social consequences of flooding. Livelihood diversification emerged as the most effective adoptive measure, with moderate resilience in insurance utilization and community groups' engagement. Conversely, settlement planning and riverbank management were identified as low priority areas, highlighting the need for strict enforcement of resilient infrastructure standards, and strengthened multi stakeholder coordination to enhance long term community resilience.

Keywords: *Flood, Roshi River Basin, precipitation, loss and damage, adaptive measures.*

Introduction

Flood has been identified as a frequently occurring natural disaster, with extensive capacity to cause economic and non-economic loss and damage (Lamichhane et al., 2025b). Also, floods impact the livelihood and wellbeing of the vulnerable communities specifically residing near the riverbanks. These magnitudes may be exaggerated by the climate change consequences with increased frequency and intensity of slow onset and extreme climatic events causing substantial challenges to basic facilities, infrastructure, livelihood, ecosystem, and human health (Rahman, 2014). In response to the impacts, UNFCCC recognized loss and damage in the Paris Agreement emphasizing the need for

global action to address these impacts (Nugroho, 2023). The history of the loss and damage in the context of climate change dates back to the 1990s when discussions, led by the Alliance of Small Island States and Vanuatu in particular, about an insurance pool circulated (UNFCCC, 1991). However, it has only been in recent years that concrete policy has emerged (McNamara & Jackson, 2019). Loss and damage derived by climate induced disasters like floods are increasingly being flagged as the third pillar of international climate policy, together with mitigation and adaptation measures (Roberts & Pelling, 2016). The mechanism was established at the Conference of the Parties to the UNFCCC in 2013 on the grounds that “a residual domain exists wherein climate change adaptation, disaster

risk reduction and public/private risk transfer mechanisms are insufficient for peoples and places overwhelmed by climate impacts” (Wrathall et al., 2015). The definition shows unable to cope with the climate related stressors and the costs related to existing coping and adoptive measures. Loss and damage can be a physical material or nonmaterial, as well as economic and non-economic, with some intersection between both the categories (Serdeczny, 2019).

In Nepal, floods represent as one of the most recurrent and damaging climate related hazards, heightening vulnerabilities of communities mainly residing in the bank of river basins. The study on the Melamchi flood, 2021 estimated total economic losses of USD 5 million, with affected households incurring an average loss of USD 51,733, while significant non-economic impacts including mental health challenges, disruptions to education and damage to cultural sites were also documented (Parajuli, 2023). Likewise, in Terai region of Nepal, an unseasonal 2021 flood inundated over 144 hectares of agricultural land in Rajapur Municipality of Bardia Nepal, reflecting an increasing trend in flood frequency and severity over three decades (Paudel et al., 2025). In the Kamala River Basin, despite community awareness of early warning systems and nature-based solutions, resilience remains insufficient due to weak local disaster risk reduction institutions and poor policy implementation (Pandey, 2025). Also, in the Narayani River Basin, a noticeable rise in precipitation events has impacted on significant portions of cultivated land vulnerable to inundation, emphasizing the urgent need for early warning systems and risk mapping for communities residing near the river (Maharjan, 2024). These recurring flood incidents across Nepal are closely tied to its monsoon driven precipitation regime, which itself has been intensifying with climate change. Approximately 80% of annual monsoon precipitation is obtained during the period of June and September, with the most significant rainfall recorded during the central two months of the interval (Karki et al., 2017).

The heavy and rigorous rainfall of September 26 to 28, 2024 resulted in large scale flooding and

landslides in Nepal and the Bagmati province has been affected the most. This stirred the Government of Nepal to declare 11 municipalities within Kavrepalanchok district as a crisis area which also included Panauti Municipality. The landslides and localized damage caused by high precipitation were observed due to continuous 3-days rainfall from September 26 to 28, 2024, resulted in economic losses that exceeded 1% of the entire GDP of the country and 250 casualties documented (MoEWRI, 2024). Severe damage was concerted in the Kavrepalanchok District and its surrounding locations including Kathmandu and Dhading (Lamichhane et al., 2025a).

Hence, the research study area of Panauti Municipality ward-12 is one of the highly floods affected communities near the bank of Roshi river. Most of the people are engaged in agriculture, livestock and small-scale business retaining their livelihood after facing the challenges derived from extreme flood of September 2024 resulting in the economic and non-economic loss and damage. Therefore, the study analyzes trends in precipitation and temperature over the past decades contributing to the increasing flood, economic and non-economic loss and damage experienced by the affected communities of Panauti Municipality ward-12 due to September flood and identify the adaptive measures of affected communities of Panauti Municipality ward no.12 in response to and recovery from flood-related loss and damage.

Materials and Methods

Study Area

The study was carried out in the Roshi river basin area of Panauti Municipality ward-12, Kavrepalanchok District of Bagmati Province, a former Kolanti Bhumedanda VDC (Ward 1 to 9). The Roshi River originated from the Mahabharata range and flows from Phulchowki forest area to downstream through multiple settlements before merging with the Punyamata River near the Panauti Bazar. The highly flood affected communities considered for the research covering around 5km² downstream sites of Roshi Riverbank within the

Panauli municipality-12. The study area is situated at around 1506 m elevation and is located at Longitude of 85° 29' 16''E and Latitude of 27° 34' 19''N. The annual average temperature is 21.86°C (High) and 11.02°C (Low) and average annual precipitation accounted 337.4mm.

Methods

The study employed a mixed methods approach to obtain the objectives, integrating formal institutional coordination with comprehensive primary and secondary data collection. To formalize and facilitate support in the research study works, official letter was submitted to the Panauli Municipality Office from SchEMS (School of Environmental Management and Science), and the Panauli Municipality issued letter to the ward number 12 Office for the support. A total of highly flood affected 187 households (100%) within the Roshi river basin of Panauli Municipality ward No.12 was surveyed. The study identified components of loss and damage, a similar approach made by Parajuli (2023) in which economic loss and damage covered households, agricultural land, crops and livestock. Likewise, non-economic loss and damage included

loss of life, impact on health, human mobility, business disruption, impact on education, and basic services. For overall information on both economic and non-economic loss and damage caused by flood of September 2025 along with adaptive measures implemented for the research study, survey was conducted within 15 days (from July 25, 2025 to August 10, 2025) using structured questionnaire to highly flood affected households identified by Panauli Municipality and ward 12 Office through rapid damage assessment.

Data Collection

Primary Data Collection: The data collection methods in this study comprised of households questionnaire survey, key informant interview (KII), focused grouped discussions (FGDs) and study area observation. A total of highly flood affected 187 households were surveyed using structured questionnaire containing the information of demographic profile, economic and non-economic loss and damage along the adaptive measures undertaken by the communities of Panauli municipality ward no. 12 to cope with flood of September 2024.

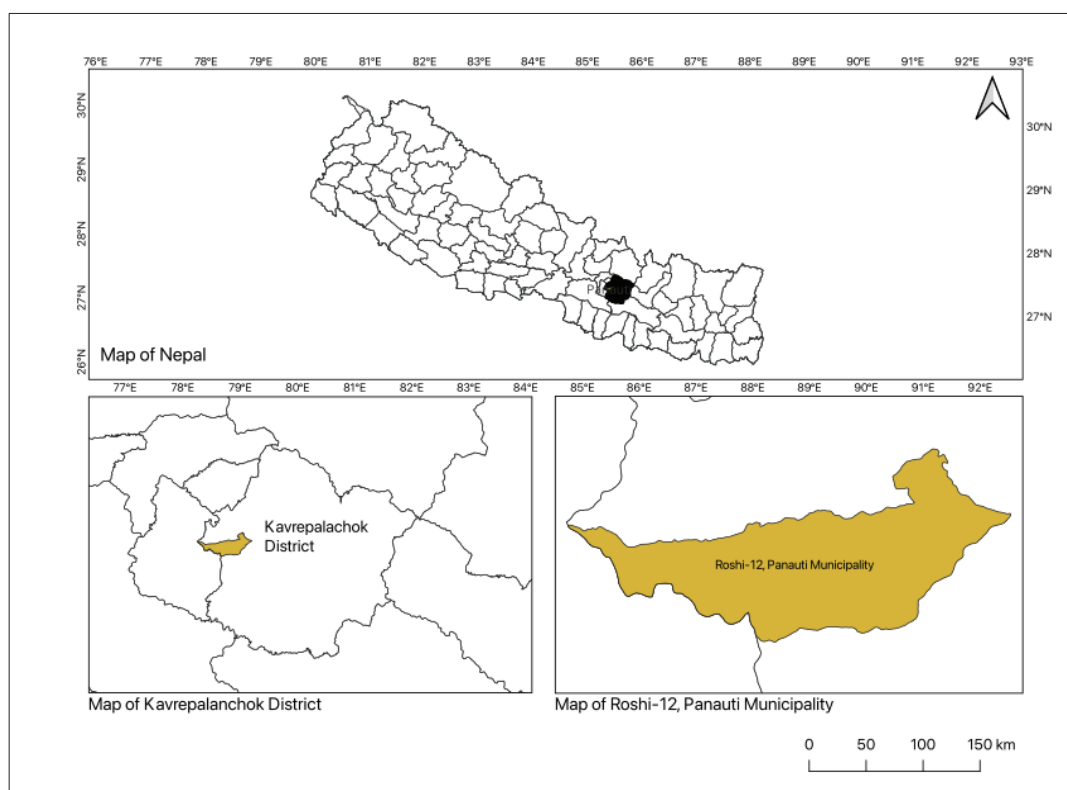


Figure 1: Map of the study area

Likewise, key informant interview was conducted with representatives from Panauti Municipality. A total of four informants were interviewed, including the Mayor, the Director of the Education Section, the Chief of the Livestock Section and the Chairperson of Ward-12, Panauti Municipality. Also, focused group discussion was conducted with the 15 representatives of community people residing in highly vulnerable communities of Panauti municipality Ward-12. The representation of participants included members from mothers' group, water supply and sanitation users' committee, forest users group as well as elderly community people, female health workers, students, and agricultural workers. Along with this, transit walk was also conducted with the community people to observe loss and damage, adaptive measures undertaken by the communities.

Secondary Data Collection: Highly flood affected households' details identified by Panauti Municipality and ward-12 Office through rapid damage assessment were obtained for the research study. Also, various published, unpublished reports, articles, research paper, journals, and both published and unpublished reports were used for the study. Moreover, data on temperature and precipitation was gathered from the Department of Hydrology and Meteorology for the nearest representative stations over a 29 years period (1995-2024). The temperature data was sourced from the Dhulikhel station (Station Index: 1024), located at 27.61592 latitude and 85.56545 longitude, with an elevation of 1552 m. Precipitation data was obtained from the Khopasi station (Station Index: 1049), situated at 27.5722 latitude and 85.5285 longitude, with an elevation of 1442m. The collected dataset includes information on maximum, minimum and average temperature, as well as monthly and yearly average precipitation.

Data Analysis

After the data was collected from the primary and secondary survey, Microsoft Excel 2022 was used to analyze both qualitative and quantitative data and to interpret the data in terms of tables, bar graph, pie chart, doughnut chart and spider diagram. Also,

QGIS was used to prepare map and survey map were used to extract the data for map generation.

Analysis of Hydrological and Meteorological

Data: The temperature and precipitation data from the year 1995-2024 were collected from DHM. For temperature, the annual minimum, maximum and average trend were analyzed and linear trend line was performed. Similarly, for precipitation annual average precipitation period of 30 years (1995-2024) obtained from DHM, average precipitation of September, 2024 and annual average precipitation of year 2024 and linear trend line was performed.

Analysis of Loss and Damage: The household's data collected from the research location were documented and organized and relationship between economic loss and damage with ethnicity, family size and income were calculated and plotted on the graph. The scatter graph was plotted with linear regression on loss and damage with family size and income amount. Here, loss and damage are dependent variable (Y) and Income and family size represented are independent variable (X). Likewise, Loss and damage and ethnicity was analyzed using box and whisker plot in excel and Anova test was performed. Ethnicity has been categorized as Dalit, Indigenous and BCT (Brahman, Chettri and Thakuri). The exchange rate was chosen as per the date of data analysis i.e., August 28, 2025 which was 1USD=140.70NPR.

Results and Discussion

Demographic Profile of the Respondents

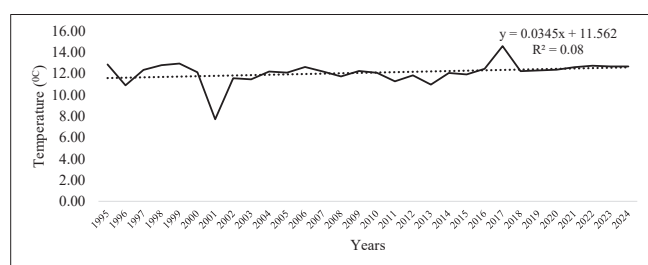
There were more male respondents (58%) than female (42%). The respondents were BCT (63%), Dalit (4%) and Indigenous (33%) respectively. Likewise, 22% of the households have less than 4 family members, 74% have in between 4 to 8 members of family, while 4% of the respondents have more than 8 members in their family. Moreover, 8% of households have per month income of less than NPR 20,000, 58% of households have monthly income range of NPR 20,000-50,000. While the remaining, 34% of the households have per month income of more than 50,000. The table 1 shows the demographic profile of the respondents:

Table 1: Demographic Profile of the Respondents

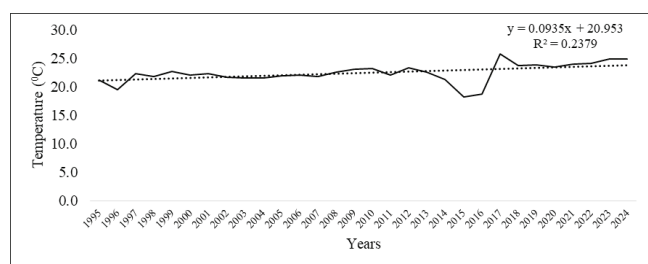
Factors	Categories	Total respondents (N=187)	Percentage (%)
Gender	Male	108	58%
	Female	79	42%
Ethnicity	Dalit	8	4%
	Indigenous	62	33%
	BCT	117	63%
Family Size	<4	42	22%
	4-8	138	74%
	>8	7	4%
Income (NPR)	<20000	15	8%
	20,000-50,000	109	58%
	>50,000	63	34%

Climate trend analysis

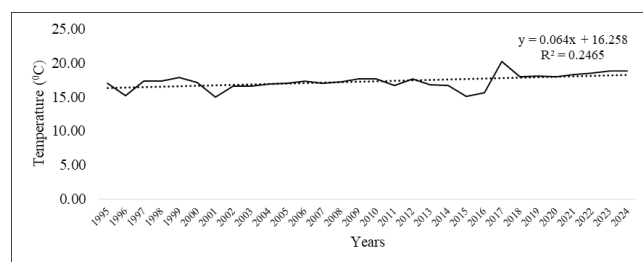
Minimum Temperature Trend: The trend of average minimum temperature from 1995 to 2024 showed a slight increasing trend, though with weak variation ($R^2=0.08$). Despite fluctuation, including a lowest around 2001 and highest in 2018, the overall trend suggested a marginal rise at the rate of about 0.0345°C per year in the average minimum temperature between 1995 and 2024.

**Figure 2:** Average minimum temperature trend

Maximum Temperature Trend: The trend analysis indicates a statistically positive trend from 1995 to 2024, with an overall warming rate of approximately 0.093°C per year. While remained relatively stable until 2010, a lowest occurred around 2014-2015, followed by a sharp rise and stabilisation at higher levels after 2016.

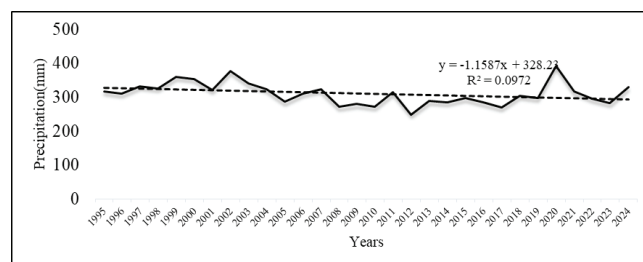
**Figure 3:** Average maximum temperature trend

Average Temperature Trend: The average annual temperature showed an increasing trend by about 0.064°C per year to nearly 1.9°C over the 30-year period (1995-2024) with notable inter annual fluctuations. Despite, year to year fluctuations in temporal data including a sharp rise around 2017-2018, the overall trend suggested a modest but consistent warming trend.

**Figure 4:** Average temperature trend

Precipitation

Annual Average Precipitation: The analysis of annual average precipitation indicated in the decreasing trend over 30-year period from 1995 to 2024. The regression equation indicated that precipitation decreased by approximately 1.16 mm per year. However, value of R^2 showed a very weak linear relationship.

**Figure 5:** Annual average precipitation trend

Monthly Average Precipitation of 2024: The monthly average precipitation data of year 2024 indicated a slight increasing monthly precipitation trend (11.6 mm/month), with rainfall concentrated mainly in July to September, September rainfall is comparatively higher and minimal in other months.

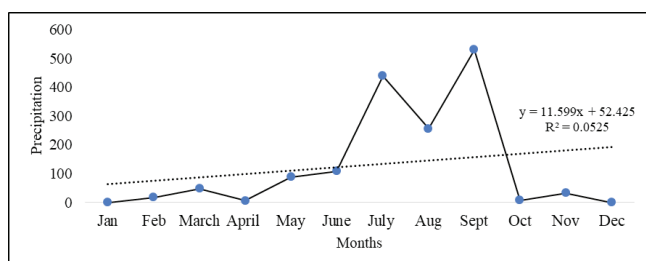


Figure 6: Monthly average precipitation trend

Average Precipitation of September 2024: The analysis of average precipitation of September, 2024 accumulated precipitation in month of September showed a slight increasing trend (1.93mm/day). Precipitation remained relatively low and scattered throughout the month, except for a sharp peak around September 28, 2024 which contributed disproportionately to the monthly total. This showed that the extreme rainfall events rather than consistent daily precipitation dominated rainfall pattern of September, 2024.

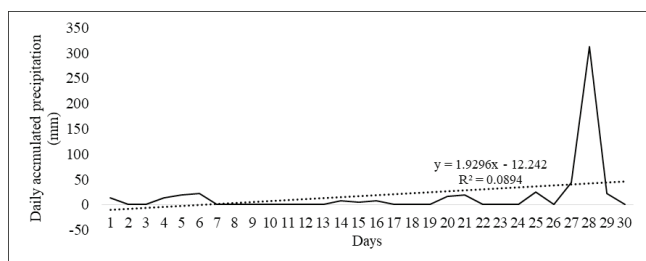


Figure 7: Average precipitation trend of September 2024

Loss and Damage

Economic Loss and Damage : The economic loss and damage caused by the September, 2024 Flood showed a significant loss and damage on houses, agricultural land, livestock and crops reaching approximately NPR 536.178 million. A total of 187 houses were fully damaged, amounting to a cost of NPR 9,25,00,000. A total of 189.6 hectares of agricultural land was affected which valued at NPR 37,37,73,260. Likewise, livestock losses resulted to a cost of NPR 1,41,47,000 and crop losses were valued at NPR 5,67,57,652 .

Therefore, 45% of economic loss and damage contributed to agriculture land, 35% on houses while 10% economic loss and damage documented in livestock and 7% on crops. Likewise, remaining 3% economic loss and damage on other assets such as goods, furniture, vehicles, gold, etc.

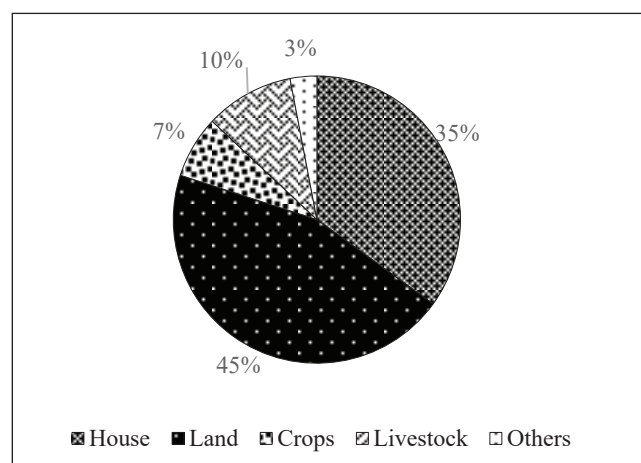


Figure 8: Economic loss and damage by survey respondents

Table 2: Estimated economic loss and damage of Panauti Municipality Ward-12

Category	Estimated Loss & Damage	Cost (NPR)	Cost (USD)
Total house loss	187	9,25,00,000.00	6,57,427.15
Total agricultural land loss	189.6184 Hectar	37,27,73,260.00	26,49,419.05
Total livestock loss	(3,446 chickens, 158 goats, 43 buffalos, 30 cows, 1 boar)	1,41,47,000.00	1,00,547.26
Total crop loss	(Paddy, Potato, Maize, Vegetables, Mustard, Fruits, and others)	5,67,57,652.05	4,03,394.83
Total		53,61,77,912	38,10,788.29

(Source: Panauti municipality ward-12 Office)

Association between economic loss and damage and income: The graphical values of economic loss and damage, and income showed that there is statistically significant relationship in between economic loss

and damage and income ($P < 0.05$). However, the relationship is very weak ($r^2 = 0.0285$) indicating that income explains only a small proportion of the variation in loss and damage. Also, the regression equation suggest that economic loss increases by 3.53 units for every one unit rise in Income.

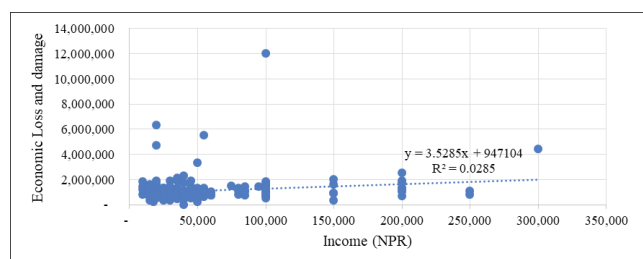


Figure 9: Association between economic loss and damage and income

Association between economic loss and damage and ethnicity: There is no statistical association between ethnicity and economic loss and damage ($p\text{-value} > 0.5$, $df = 183$, $f = 0.3$). Dalit households were observed to have higher economic loss and damage compared to Indigenous and BCT families.

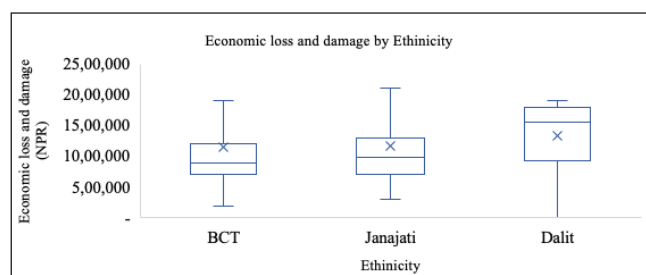


Figure 10: Association between economic loss and damage and ethnicity

Association between economic loss and damage and family size: The statistical analysis showed no significant relationship between family size and economic loss and damage ($P > 0.05$). Also, linear regression further indicated a very weak relationship ($R^2 = 0.0092$) suggesting that family size does not explain variation in economic loss and damage.

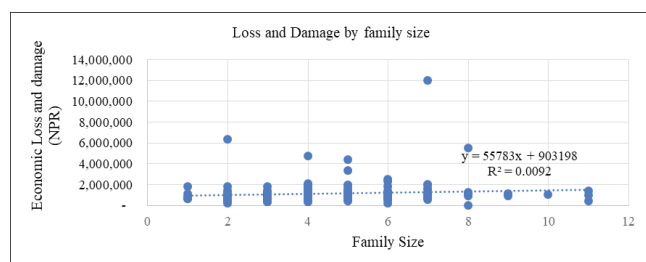


Figure 11: Association between economic loss and damage and family size

Non-economic Loss and Damage

The analysis of non-economic loss and damage as perceived by the respondents showed in the radar chart indicated the loss of life and disruption of basic services received the highest rating 3. Likewise, impact on health, human mobility and business disruption were considered as moderately affected, rating 2 whereas, impact on education assigned the lowest rating of 1 due to immediate recovery of education in schools by constructing Temporary Learning Centres (TLC) during the vacation of prominent festivals of Nepal, Dashain and Tihar.

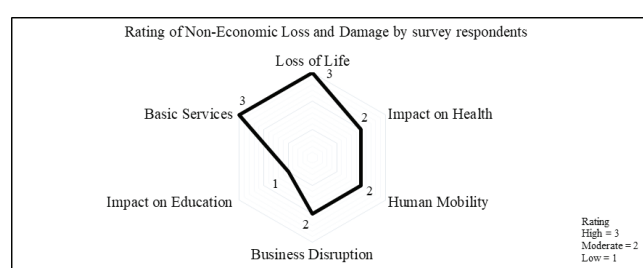


Figure 12: Rating of non-economic loss and damage by survey respondents

Loss of Life: Based on KII and FGD, it was revealed that, out of 774 affected population, 5 individuals including four male and one female loss their life due to the flood.

Impact on Health: About 60 % of respondents had severe physical injury and 20% respondent had minor injury, while 20% households had no injury. Likewise, 4% respondents revealed that the children and adolescent still possess fear even during the normal rainfall. Moreover, the health services were disrupted for 2 days due to the flood.

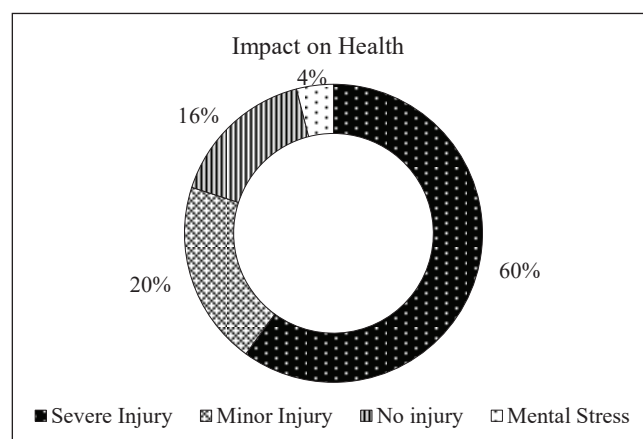


Figure 13: Impacts on health

Human Mobility: Nearly 43% households temporarily displaced from their houses for 10 days, while 57% of households population permanently migrated to new place which significantly decreased the overall residing population of the communities.

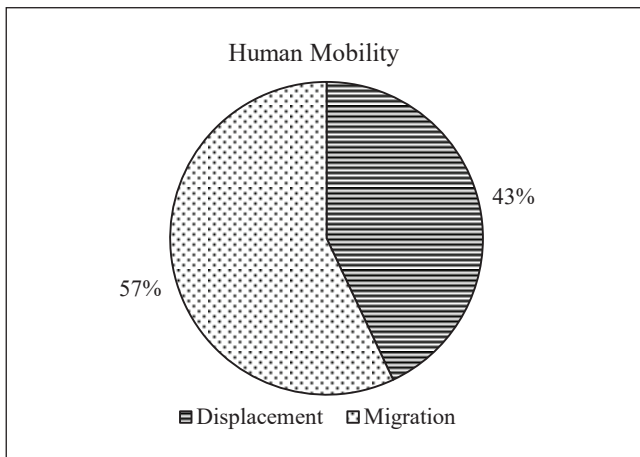


Figure 14: Effects on human mobility

Business Disruption: The household survey showed that 10% of small-scale businesses such as tea shops, general stores, dairy enterprises etc. were disrupted with their products either swept away or damaged due to flood. Likewise, the community's local stone mining sector experienced substantial disruption, as 10 mining crushers were destroyed, resulting in significant impact on livelihoods of nearly 25% daily wages labourers depended on this industry. Besides, the flood disaster of September, 2024 significantly affected major household's income sources engaged in livestock (28%) and agricultural business (32%). Additionally, around 5% of households engaged in transportation business were adversely affected due to debris deposition on roads.

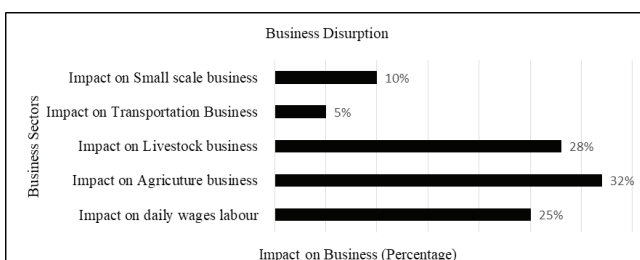


Figure 15: Business disruption form the flood

Impact on Education: Due to significant damage on the Indradevi Basic School, students were impacted with disturbance in education for about 10 days

excluding the festive holidays. The education was not highly impacted due to flood because of the festival holidays (Dashan and Tihar). However, the damaged building was replaced by constructing TLC (Temporary Learning Centre) with support of Panauti Municipality and international donor.

Basic Services: According to the KII, the flood damaged 8 intakes, 4 reservoir tanks, 17,200 meters of transmission and distribution pipelines, cutting off safe water access for affected households and nearby communities. About 2500 meter irrigation canal and 200 meters of pipelines were destroyed, impacting agricultural lands. Additionally, around 300 electrical poles were swept away resulting in one month power outage in highly affected areas. Damage to roads and bridges further disrupted livelihoods and access to services.

Adaptive Measures

According to the survey, livelihood diversification was considered as the most effective adoptive measure, receiving a high ranking of 3. Community groups and insurance mechanism were identified as moderately effective, with a rating of 2. Similarly, relief support provided by NRCS/UN agencies and the local government was also rated as 2. In contrast, structural and long-term measures such as riverbank area allocation and settlement planning were considered less effective, receiving a low rating of 1.

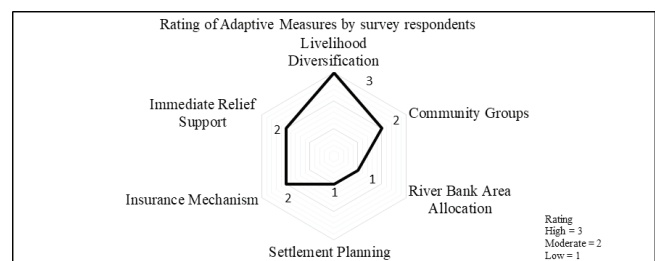


Figure 16: Rating of adaptive measures by survey respondents

Livelihood Diversification: The research findings showed that 67% of households engaged in multiple activities to generate income while, 33% of households were dependent on single source of income.

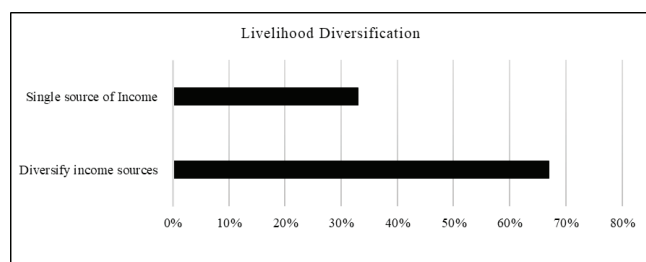


Figure 17: Livelihood diversification of households

Within the livelihood diversification category, 41% of households reported to have multiple income sources, including agriculture, livestock, business, and services, while 32 % of households were engaged in small scale businesses, daily wages, foreign employment and the remaining 27% relied on entrepreneurship, service, or pensions.

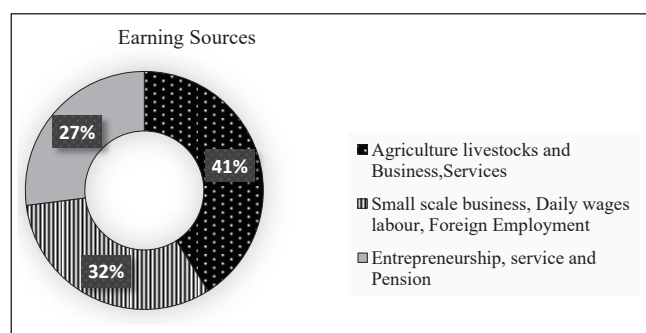


Figure 18: Earning sources of households

Community Groups: Survey results indicated that 35% of respondents perceived community groups as highly functional during the disaster, while 40% considered them moderately functional. In contrast, 25% reported that the groups were not effective during the disaster response period.

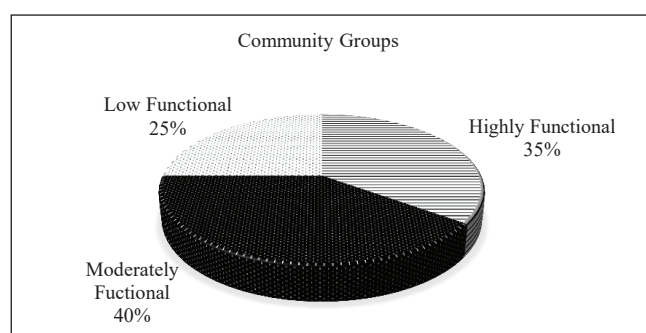


Figure 19: Perception towards community groups

Riverbank Area Allocation: Field observations indicated that the municipality have enforced a mandatory setback of 20-50m from river, within which construction activities are strictly prohibited.

According to representatives, they have been using standard guidelines from the riverbank area allocation after the flood event of September 2024.

Settlement Planning : FGD and transect walk observations revealed that while 80% of old houses maintain safe distances from the riverbank and are built on elevated land, many new houses are located closer to the riverbank with lack of proper elevation.

Insurance Mechanism: According to KIIs and FGDs, 100% of the households had health insurance and 90% had livestock insurance before the flood. Claims were paid to the injured persons and livestock losses, but no coverage existed for agricultural land and basic services like water supply, irrigation and others.

Immediate relief Support: Conferring to KIIs, Panauti Municipality provided NPR 50,000/- per household for the reconstruction, with an initial instalment of NPR 25,000/- and the remainder paid after the completion of house construction. Also, NRCS provided NPR 15,000/- per household for food, health, education, and WASH services; while relief organisations, including UN agencies supplied immediate support.

Trend Analysis

The analysis of temperature data from 1995-2024 revealed a clear warming trend. Average minimum temperature increased by approximately 0.0345°C per year, while maximum temperature rose by 0.093°C per year, resulting in an overall annual increase of 0.064 °C. This asymmetric warming pattern, with maximum temperatures increasing faster than minimum, mirrors findings align with various research studies conducted before in the River Basins of Nepal. Shrestha et al. (2017) in the Koshi River Basin and Puri et al. (2024) across Nepal reported significant increase in both minimum and maximum temperatures, with maximum temperature raising faster than minimum similar to the findings of this study. The result also aligns with the DHM, 2017 which observed a national maximum temperature increase of about 0.056°C per year though the magnitude of this study is comparatively higher. However, this findings

differ from national scale analysis where minimum temperature trends were weak or insignificant.

Precipitation trends showed a slight decreasing pattern (-1.16mm/year) over 30 years, though with high inter annual variability. The September 2024 event, however, was dominated by extreme rainfall concentrated around 28 September, contributing disproportionately to monthly total. This reflects the increasing occurrence of intense rainfall events under climate change, even in regions with relatively stable average precipitation, a phenomenon documented globally by (Zhang et al., 2021), who demonstrated that nearly 68% of global land areas are experiencing amplifies rainfall variability across multiple time scales, even in locations where average precipitation is stable. Similarly, Talchabhadel et al. (2019) documented that extreme single-day rainfall events can disproportionately dominate monthly totals in Nepal where a single wet day accounted for 10% of the mean annual precipitation. This indicated a shift in the direction of extreme rainstorms as opposed to evenly distributed rainfall that greatly exaggerate flood risks. Hence, high flood disaster of September 2024 in Panauti Municipality was the result of an immediate consequence of this intense concentration of extreme rain at the end of the September 2024. The findings underscore that climate change is a critical driver of flood risk in Panauti, amplifying hazard intensity and reducing predictability of extreme events.

Loss and Damage

Economic loss and damage: The September 2024 flood caused losses exceeding NPR 536 million, with agricultural land accounting for the largest share (45%) followed by housing (35%). This is consistent with Shrestha et al. (2024), who reported that agricultural land as the most heavily impacted sector during the 2017 Terai flood. Also, Koirala (2021) emphasized housing damage during the 2021 Melamchi flood. Global studies like Jongman et al. (2012) also highlighted that agricultural land is disproportionately affected during riverine floods due to its direct exposure and limited protection. Moreover, Shrestha et al. (2024) emphasized that even though livestock and crop losses often

contribute less to the total monetary valuation, they reflect important agricultural non-economic and livelihood dimensions of loss and damage, especially in the riverbank settlements.

Loss and damage are likely to be driven by exposure, location, and intensity of hazard, quality of houses, preparedness, livelihood, assets, and access to support. Besides, the households with higher income tend to experience greater loss and damage, a similar finding observed in (Dahal, 2012) where households with higher income levels experienced greater economic losses from landslides, as they owned more assets and infrastructure. However, with the family size increased, economic loss and damage has no significant alteration observed. Likewise, research study showed the disproportionate impact on Dalit households, who experienced higher losses compared to Indigenous and Brahmin/Chettri/Thakuri (BCT) groups. This may be due to settlement patterns. Mostly, Dalit families residing near to the riverbank were facing higher exposure to flooding. Furthermore, the finding of the study displayed that flood induced loss and damage in the study area is not only an economic phenomenon but also a deep socially structured process.

Non-Economic Loss and damage: Non-economic impacts were equally severe, with mortality, disruption of drinking water, irrigation, electricity, and mobility receiving the highest ratings. These findings are comparable to Wisner et al. (2015), who argued that mortality and infrastructure breakdown constitute core dimensions of social vulnerability in floods. Similarly, Kelman et al. (2015) further emphasized that immediate non-economic consequences are often more disruptive than financial losses. The relatively lower impact on education aligns with observations by Shrestha et al. (2025), who reported that school closures during floods are often brief and less economically and socially disruptive compared to mortality and essential service interruptions, particularly where temporary learning centres are introduced. However, the displacement of 57% of households in Panauti indicated a more severe mobility impact than national average reported in earlier floods, pointing to the intensity of the September 2024 event. Also,

the findings also followed the objectives of the Sendai Framework for Disaster Risk Reduction (2015-2030) which identifies mortality reduction, protecting people's lives and basic services as core global objectives. The persistence of high non-economic losses in Panauti suggests that achieving these targets remain a critical challenge at the community level.

Adaptive Measures: Livelihood diversification emerged as the most effective adaptive strategy, consistent with Ellis (2000), who argued that diversified income sources enhance household resilience to shocks. Similar findings in South Asia such as highlighted that rural households increasingly pursue off-farm income to buffer against the climate risks. This showed that resilience on a single livelihood exposes households to higher vulnerability, while diversifying provides resilience against the possible economic vulnerability. While insurance mechanism and community groups were moderately effective, Panauti Municipality has supported every flood affected household with health insurance. This revealed that the partial acceptance of insurance mechanism is an understanding of their potential role in risk reduction. Insurance is widely recognised as an important financial tool for transferring and sharing risks but in many developing contexts, its effectiveness is hindered by affordability, limited coverage and weak institutional trust. Similarly, community groups were also moderately functional, echoing findings by Shaw (2012), who stressed the need for stronger local institutions in disaster response. In contrast, structural measures such as settlement planning and riverbank zoning were poorly prioritized, despite being recognized in global literature as critical long-term strategies for risk reduction (Birkmann & von Teichman, 2010). The weak enforcement and community acceptance in Panauti suggest gaps between policy frameworks and local implementation, highlighting the need to strengthen institutional capacity and governance structure that can enhance the legitimacy and effectiveness of these mechanisms. Additionally, as part of an immediate relief support, the NRCS provided NPR 15,000 to each totally affected households, while local government support included an initial NPR

25,000 for house reconstruction, with an additional NPR 25,000 to be disbursed upon the completion of construction. Such short term financial and material assistance played a crucial role in addressing urgent recovery needs. However, the one-off nature of these interventions underscores their limitations in fostering long term resilience. This highlights the importance of integrating relief assistance into broader, sustainable resilience building and disaster risk reduction strategies, rather than relying solely on temporary support mechanisms.

Conclusion

The study concluded that the flood was triggered by highly uneven rainfall distribution between July and September 2024, with one single extreme rainfall event on September 28 controlling the monthly total and leading directly to the devastating flood in the Roshi River Basin. This climatic trigger confirmed the increasing role of extreme rainfall variability in intensifying flood risks in the region. The flood caused an estimated economic loss of NPR 536.178 million (USD 3.81 million approximately). Houses and agricultural land were the most affected, revealing both the structural vulnerability of settlements and the centrality of agriculture to rural livelihoods. While crop and livestock losses were smaller in monetary terms. Moreover, family income had a significant but weak association with economic loss and damage, suggesting wealthier households suffered greater asset-related losses. In contrast, family size and ethnicity did not show statistical associations, but disproportionate exposure of Dalit families living near riverbanks showed how spatial settlement patterns and social marginalisation drive vulnerability, confirming the socially structured nature of loss and damage. Non-economic losses, primarily loss of life and essential services disruption ranked highest demonstrating impacts beyond financial costs to directly effect on human security and adoptive capacity of communities. Educational disruption ranked lowest due to Temporary Learning Centres and seasonal school breaks. Furthermore, the study found single livelihood dependency increases exposure to higher risks while insurance and community support

remain limited by affordability, institutional trust and weak coordination. Low priority for settlement planning and riverbank management highlights a critical gap in long-term risk reduction strategies.

Thus, the study emphasizes the need to improve the capacity of flood prone vulnerable communities ensuring rapid restoration of basic services. Likewise, community-based adaptation should be prioritized through skill training, small business promotion and non-farm income opportunities through strengthened multi stakeholder coordination to enhance long term community resilience. In a long run, strict enforcement of resilient infrastructure standard, settlement planning, hazard zoning, and riverbank management should be integrated into municipal development plans.

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Understanding Differential Climate Vulnerability: A Comparative Analysis of Two Tharu Communities in Chitwan District, Nepal

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Abstract

Climate-related hazards are disproportionately affecting rural communities in developing countries like Nepal, where livelihoods depend heavily on climate-sensitive sectors. This study employed a mixed-methods approach to assess exposure, sensitivity, and adaptive capacity, guided by the Intergovernmental Panel on Climate Change (IPCC) vulnerability framework and applying the Community-Based Vulnerability Assessment (CBVA) tool in two indigenous Tharu communities, Telauli and Jitpur, located in the Meghauri Buffer Zone of Chitwan District, Nepal. Data were collected from a total number of 200 households: 130 in Telauli and 70 in Jitpur that represents about 30% of each community. The study further utilized 31 years of meteorological data to validate community perceptions of climate change. The climate trend analysis revealed relatively stable rainfall and temperature patterns, with no statistically significant variations over time. Despite these statistically insignificant results, household perceptions reveal increasing climate stress from irregular rainfall, prolonged dry spells, and temperature extremes, resulting in heightened risks of water scarcity, flash floods, crop loss, and changes in farming practices. This is due to the fact that, short term variability affected livelihoods in contrast to long-term statistical trend situation. Both communities exhibited high exposure to climate-related hazards, with scores of 2.04 in Telauli and 2.08 in Jitpur, the latter experiencing slightly higher flood exposure. Sensitivity levels were also elevated with recorded score of 2.3 in Telauli and 2.7 in Jitpur. However, a notable difference was observed in adaptive capacity, which was higher in Telauli (2.3) compared to Jitpur (1.5). This is due to better infrastructure, market access, stronger saving groups and more diversified livelihood. Overall, the vulnerability was found to be high in both settlements but greater in Jitpur. The findings highlight that climate vulnerability is largely determined by the availability of community resources and, critically, by how effectively these resources are utilized to adapt and enhance the climate resilience.

Keywords: *Adaptive capacity, climate vulnerability, exposure, resilience, sensitivity*

1. Introduction

Changes in hydrological regimes have become a significant environmental challenge, affecting both natural systems and human societies under changing climatic conditions. Scientific evidence indicates noticeable changes in global temperature, precipitation patterns, and the increasing frequency of extreme weather events over recent decades (Haden et al., 2012; Shikuku et al., 2017; Upreti, 2023). The Intergovernmental Panel on Climate Change defines climate change as long-term shifts in climate conditions, including changes in average temperature and rainfall variability that persist for decades or longer (IPCC, 2022). Human activities,

particularly greenhouse gas emissions, have contributed to approximately 1°C increase in global temperature above pre-industrial levels, posing serious risks to ecosystems, livelihoods, and human health (Han & Ahn, 2020; IPCC, 2018). Climate change impacts vary across sectors, including agriculture, water resources and public health. Irregular rainfall, floods, droughts, heatwaves reduce agricultural productivity, disrupt water availability, and increase the spread of climate-sensitive diseases such as malaria, cholera, and Japanese encephalitis (Shivanna, 2022). These sectoral disruptions directly affect rural livelihoods by understanding food security, income sources, and overall economic stability, particularly in

communities dependent on climate sensitive occupations (Kabir et al., 2023). Developing countries are more vulnerable to climate change due to the interaction of economic, geographic, and social factors that create a vulnerability trap, including poverty, limited resources, and high dependence on agriculture and natural ecosystems (Burton et al., 2006; Moser, 1998). Nepal, despite contributing minimally to global greenhouse gas emissions, is considered highly vulnerable to climate change because of its fragile mountain ecosystem, geographic diversity, and socio-economic constraints (Pokhrel et al., 2025). Agriculture and forestry support the livelihoods of a large proportion of the population, making rural communities highly sensitive to climatic variability (Garg et al., 2007). Climate related hazards such as floods, landslides, droughts, and erratic monsoon patterns are already affecting millions of people in Nepal and are expected to intensify in the future (Hobbs, 2009). Both hydro-meteorological and socio-ecological aspects are important to understand the climate vulnerability in its specific context (Sharma et al., 2025).

Recognizing these challenges, the Government of Nepal has implemented adaptation policies such as the National Adaptation Programme of Action (NAPA) and Local Adaptation Plans of Action (LAPA), which emphasize identifying vulnerable communities and promoting climate-resilient development through participatory approaches (GoN, 2011). Community based vulnerability assessments are widely used to understand how climate change affects livelihoods and to design locally appropriate adaptation strategies (Agrawal, 2008; Smit & Wandel, 2006). Such approaches help evaluate exposure, sensitivity, and adaptive capacity, which together determine climate vulnerability at the local level (Burton et al., 2002).

Indigenous communities such as the Tharu, who traditionally depend on agriculture, forests, and natural resources, are particularly sensitive to climate variability. In areas such as the Meghauli Buffer Zone of Chitwan National Park, communities

have experienced irregular rainfall, floods, droughts, and other climate-related hazards in recent years (Chaudhary et al., 2018). Although traditional knowledge has helped these communities adapt in the past, rapid environmental changes may exceed their coping capacity. Therefore it is essential to understand local perceptions, livelihood challenges, and adaptation practices for developing effective climate resilience strategies.

In this regard, this study aims to assess and compare climate vulnerability in two Tharu communities of the Meghauli Buffer Zone, Chitwan District, Nepal, using Community-based Vulnerability Assessment (CBVA) tool. This study focuses on climatic variability assessment incorporating exposure and its sensitivity and Tharu community's adaptive capacity to climate change. It further conducts a comparative analysis of index-based vulnerability between two communities to enhance understanding of differential climate vulnerability in the study area.

2. Materials and Methods

2.1 Study Area

The study was conducted in Meghauli buffer zone of Chitwan National Park (CNP) in western Chitwan District, Nepal. Meghauli lies along the Rapti and Narayani rivers, approximately 25 km from Narayangadh, and covers an area of 77.18 km². According to the Central Bureau of Statistics (CBS, 2021), the area has a total population of 14,699 in 2,598 households, including about 5,730 Tharu individuals living in nearly 879 households. The area is highly dependent on agriculture and forest resources, making local livelihoods sensitive to climate variability and flood hazards (MoE, 2010). For comparative analysis, two Tharu communities, Telauli (Ward No. 27) and Jitpur (Ward No. 28) of Bharatpur Metropolitan City were selected based on differences in settlement patterns and resources exposure (2231 HH and 1659 HH, where total number of Tharu households is 616 and 263 respectively). The confluence of the Narayani and Rapti rivers at Golaghat also lies within this ward.

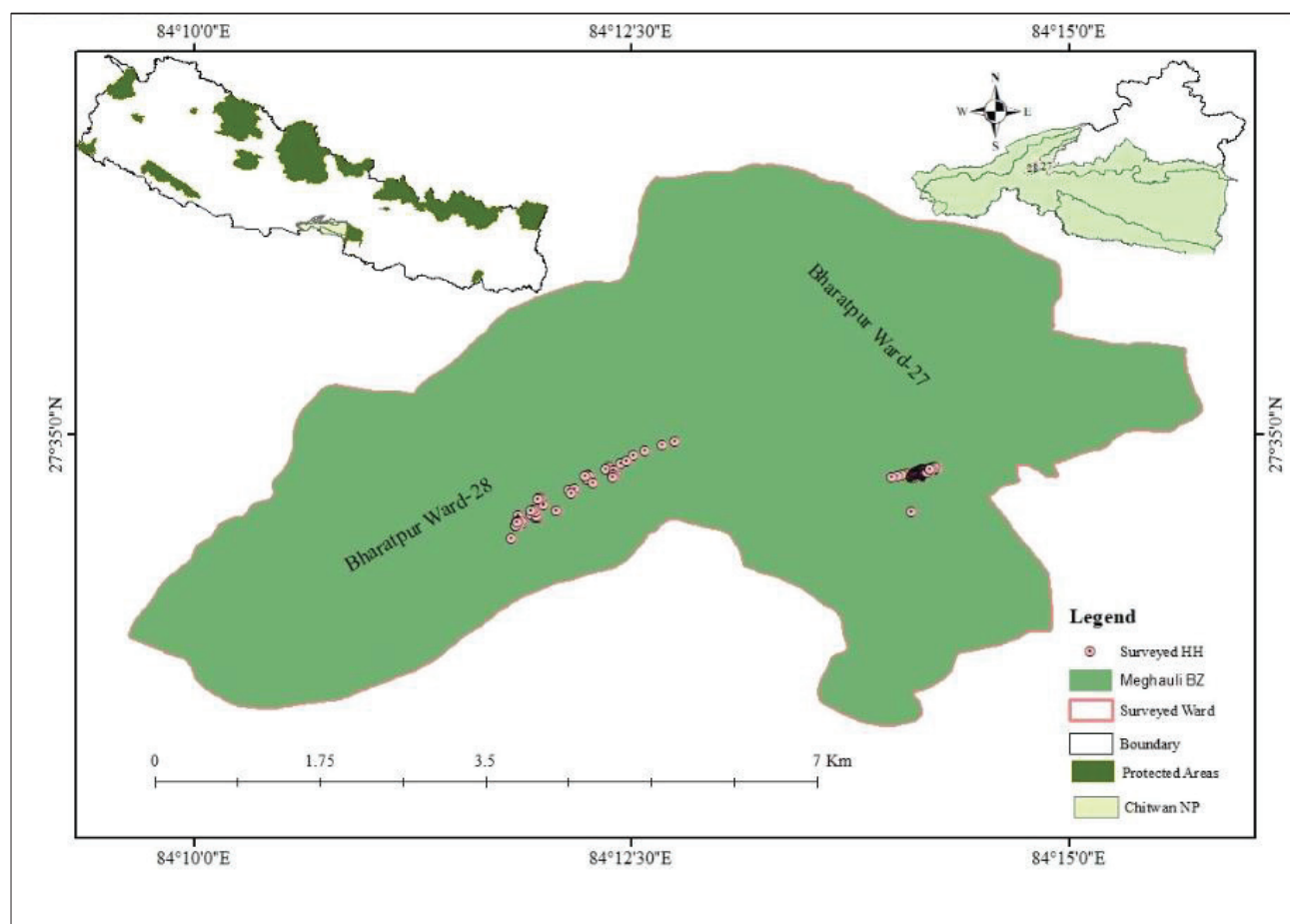


Figure 1: Study area map showing Meghauli Buffer Zone, Chitwan National Park, Nepal

2.2 Research Design and Data collection Methods

This study is based on participatory as well as exploratory research design to assess community level vulnerability to climate change. The approach combined both qualitative and quantitative methods to understand the level of exposure, sensitivity, and adaptive capacity by following the IPCC framework for climate change vulnerability and applied the CBVA tool (MoEST, 2012). Each community was sampled separately for the socio-economic survey and to gather perceptions on climate change, using a purposive sampling method (Acharya et al., 2013).

2.2.1 Primary Data Source

2.2.1.1 Semi Structured Questionnaire survey: A combination of both quantitative and qualitative information was gathered from both communities using a semi-structured questionnaire based on MoEST (2012) Guidelines. Out of total 200 HHs

(households), a total of 130 households from Telauli and 70 from Jitpur communities were selected representing about 30% of the total households of Tharu in each community. The interview was conducted at each household most preferably with the head of the house so as to collect all the required data at the household level during the time period of 31st January to 9th of February, 2025.

2.2.1.2 Key Informant Interview: Interviews were conducted with five key personnel; community leader, chairman of the ward office and Meghauli users' communities. These key informants shared insights on the community's available social resources, the effects of climate change on local livelihoods, existing status of climate change awareness and potential strategies taken for the adaptation.

2.2.1.3 Community Transect Walk: The community transect walk was conducted as a primary field observation technique to evaluate community

assets, infrastructure, and climate risk. This method allowed for the direct assessment of local conditions, serving as a crucial tool to triangulate and validate findings gathered through household surveys, and key informant interviews. In Jitpur, the transect walk was carried out from 6-7 February 2025, covering an area approximately 1 km north of the Narayani-Rapti River confluence. In Telauli, the transect walk was conducted from 28-29 January 2025, covering an area approximately 1 km west of the ward office.

2.2.2 Secondary Data Source

Secondary data of temperature and rainfall, over 31 years, were gathered from Department of Hydrology and Meteorology (DHM), Government of Nepal from Rampur stations (Index: 0902) while population data was gathered from the Central Bureau of Statistics (CBS, 2021). In addition, government reports, research papers, and scientific journals were further used to obtain other demographic and literature information.

2.3 Data Analysis

2.3.1 Community Level Vulnerability Assessment

Based on the theoretical framework of the vulnerability function provided by the IPCC, the CBVA tool (MoEST, 2012) was used to assess the vulnerability level of the communities through a

participatory approach. The three components of the vulnerability equation, exposure (E), sensitivity (S), and adaptive capacity (A), were empirically estimated by averaging the ranks of their respective sub-components (Table 1).

The indicators for each subcomponent were graded as Low (1), Medium (2), High (3), and Very High (4). The resulting sub-indices were subsequently averaged to drive the indices of the three major components Exposure (E), Sensitivity (S), and Adaptive Capacity (A). Vulnerability index was calculated by using the equation (i),

$$\text{Vulnerability (V)} = f\left(\frac{E \times S}{A}\right) \dots\dots\dots (i)$$

Based on the CBVA paradigm, the computed vulnerability indices were also divided into four levels: low (<1), medium (1-2), high (2-4), and very high (>4) to compare community vulnerability patterns systematically (Pudasaini, 2015).

2.3.2 Socio-economic and Meteorological Analysis

Household data from questionnaires were categorized into exposure, sensitivity, and adaptive capacity to support CBVA analysis, while socio-economic insights from key informant interviews and transect walks were also integrated. Results were shown using graphs and tables by using Excel 2016. To assess climate trend, the temperature and

Table 1: Displaying the CBVA framework's components and subcomponents in description

Components	Subcomponents	Subcomponent's Description
Exposure(E)	Temperature	Rising and falling temperature in summer and winter season
	Precipitation	Monsoon; winter rainfall
	Hazard	Drought; flood
	Indicator plants	Flowering and fruiting behavior of indigenous plant
Sensitivity(S)	Natural Assets	Five livelihood assets are impacted by the climate induced threats that are given top priority in the livelihood impact matrix (Table 4/5)
	Physical Assets	
	Social assets	Access, viability, potentiality, and availability trend of five livelihood assets are shown in the livelihood resources matrix (Table 6)
	Human Assets	
	Financial Assets	
Adaptive Capacity (A)	Natural Assets	
	Physical Assets	
	Social Assets	
	Human Assets	
	Financial Assets	

rainfall data spanning from 1994 to 2024 from Rampur stations (Index: 0902) were collected and Mann-Kendall test and Sen's Slope estimator were applied in R-studio (4.5.2) to test whether the data are statistically significant.

3. Results and Discussion

3.1 Socioeconomic and Demographic Data

Communities from Telauli and Jitpur showed clear demographic differences, with Tharu households forming the majority (60% and 40%), varying family structures, and distinct age distributions, including a notable share of elderly respondents, especially in Telauli. Both communities were predominantly agricultural, with similar landholdings, high engagement in farming, and agriculture and foreign employment serving as the main income sources, supported by livestock rearing and small-scale crop and vegetable production (Table 2).

Table 2: Showing socioeconomic and demographic data of study area

S.N	Indicators	Telauli (%)	Jitpur (%)
1	Tharu Population (of total population)	60%	40%
2	Joint Family	40%	59%
3	Single Family	60%	41%
4	Male	57%	56%
5	Female	43%	44%
6	Majority of respondents with respect to age range	27% (40-50 age)	41% (30-40 age)
7	Avg. landholding per HH (Hectors)	1.28	1.30
8	Farming	64%	75%

3.2 Exposure Assessment

3.2.1 Temperature and Rainfall Trend Change

3.2.1.1 Rainfall Trend: The average annual rainfall was found to be 65.98 with a decreasing trend (MK tau: -0.11), which is further supported by Sen's Slope (Slope: -0.378 mm/year). However, the trend is found with no statistical significance (Z: -0.8498, n= 31, p= 0.396) (Figure 2).

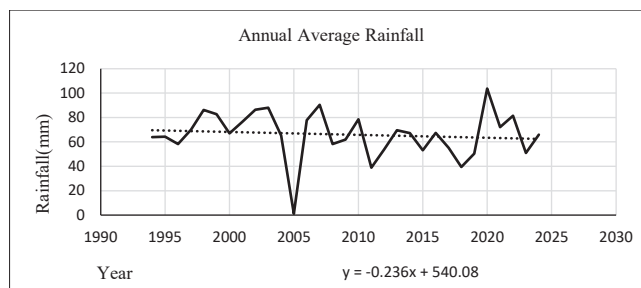


Figure 2: Trend of Average Annual Rainfall in this study location

Seasonal rainfall was also found in decreasing trend. Similarly, the gap between monsoon and non-monsoon rainfall was also found to decline (Mk tau: -0.187, Slope: -0.299mm/yr.), However, the trend was not statistically significant (p: 0.1438 (Figure 3).

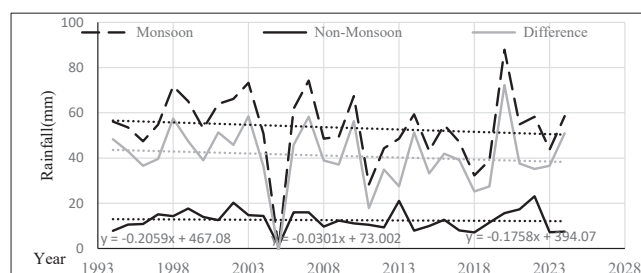


Figure 3: Rainfall during and after the monsoon season

3.2.1.2 Temperature Trend: The average annual maximum and minimum temperatures were recorded to be 30.88 °C and 17.81 °C, respectively. Results depicted a slight decreasing trend in annual average temperature (MK τ : -0.191; Sen's slope: -0.0142 °C/year), but the change was not found to be statistically significant (p: 0.1347) (Figure 4).

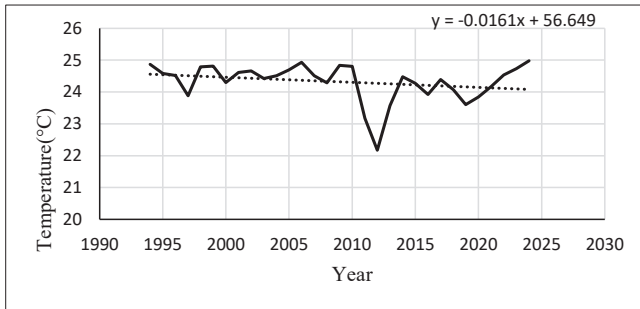


Figure 4: Annual average temperature in the Rampur station of study area

Seasonal extreme temperature (max summer temperature/min winter temperature) show minor warming (Sen's Slope: 0.0086 and 0.0087°C/yr), but the variation between highest and lowest temperature over the course of a year decline (−0.0087°C/yr), however none of these trends are statistically significant (p : 0.634, 0.865 and 0.61) respectively (Figure 5).

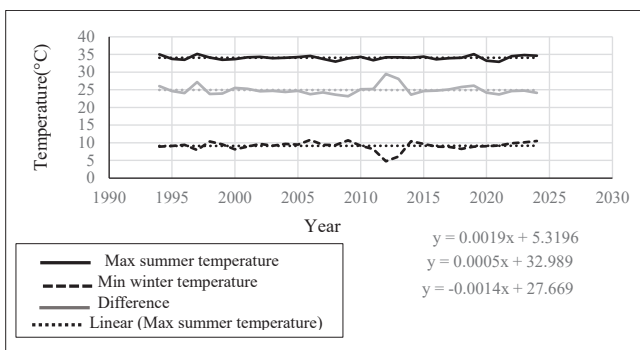


Figure 5: Annual trends in maximum and minimum temperature variations showing temporal changes in the highest and lowest recorded temperatures

3.2.2 Household perception of exposure

From 1 (low) to 4 (very high), the exposure index was evaluated according to the perceived

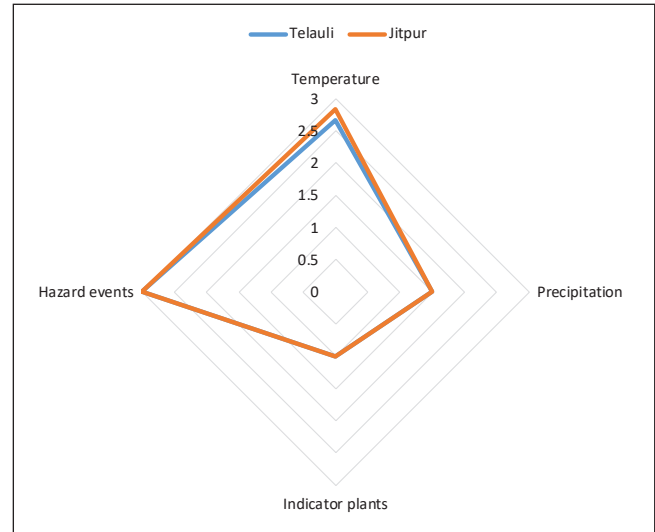


Figure 6: Radar chart showing overall exposure level of both communities

changes across these four indicators (temperature, precipitation, indicators plant and hazard event). The findings indicate that both Telauli and Jitpur exhibited similarly high levels of exposure with index value of 2.04 and 2.08, respectively (Figure 9; Table 3). Although Jitpur recorded a slightly higher exposure score, the difference between the two communities was minimal.

Despite statistically insignificant trends in rainfall and temperature, household perceptions indicate increasing climate stress from irregular rainfall, prolonged dry spells, and temperature extremes, leading to greater exposure to water scarcity, flash floods, crop loss, and altered farming practices, consistent with findings that climatic variability significantly increases livelihood stress (Kamalvanshi, 2022).

Table 3: Household level Perception of exposure in two Tharu communities

Subcomponents and its description	Perceived change		Score index	
	Telauli	Jitpur	Telauli	Jitpur
1. Temperature				
*All HH from both community perceived that increased temperature in both summer and winter season with a bit more rising patterns (since last 8-9 years); 3% HH from Telauli and 43% HH from Jitpur.	3	3	2.66	2.83
*57% HH from Telauli and 63% HH from Jitpur perceived hot waves in their area with 10-30% increasing patterns.	3	3		
*43% HH from Telauli perceived cold waves and 100% HH from Jitpur did not perceive such cold waves in their region	2	2.5		

2. Precipitation

*All HH from both communities observed changes in monsoon rainfall with 56 % HH from Telauli and 71% HH from Jitpur perceived 30-50% decreasing patterns.

*Winter rainfall (74% HH from Telauli and 83% HH from Jitpur) perceived decreased winter rainfall with more than 50% fall

3. Indicators plant

* Majority of the respondents from both the communities do not observe any changes in the local plants in regard to flowering, fruiting, shredding and spurting season

4. Hazard events

* Drought event (Almost respondents perceived increased duration and frequency with advancement by 8-15 days in Telauli and 21 days in Jitpur with 30% increasing patterns.

* Flood (Majority of the respondents perceived increased incident in flood at 30-50% rate from both the communities; 90% HH from Telauli and 100% HH from Jitpur perceived flood problem in their area.

Average exposure index

2	2	1.5	1.5
1	1		
1	1	1	1
3	2	3	3
3	4		
High	High	8.16/4= 2.04	8.33/4=2.08

3.2.3 Sensitivity of Livelihood Resources to Climate Risks

According to Pairwise hazard ranking Metrix, Telauli is most sensitive to drought, while Jitpur showed highest sensitivity to floods (Appendix 1; Table A1 and Table A2). Natural assets (such as forest, water, agriculture) are highly sensitive in both communities, with stronger impacts in Jitpur as 71.14% of communities exposed to flood risk, which is more than double of Telauli (Figure 7), raising annual damage which is significant with financial stress (Rathod et al., 2024).

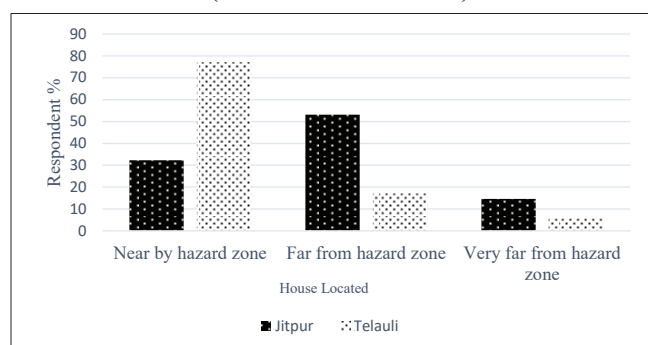


Figure 7: Distance of settlement from the flood effect zone

Telauli also showed higher sensitivity in food and water sectors, whereas Jitpur was found to be more sensitive in infrastructure, health, and forest sectors (Figure 8).

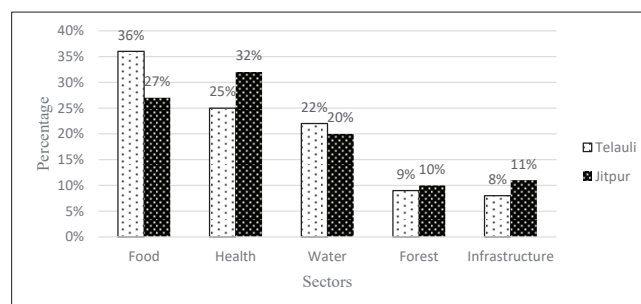


Figure 8: Perception of sensitivity by sector in both Telauli and Jitpur community

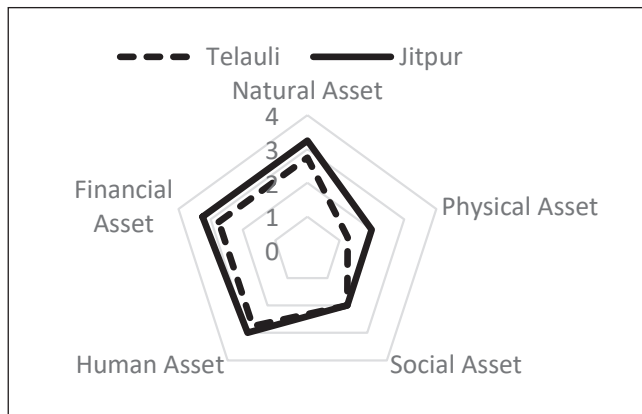
Across all five livelihood resources, both communities had high sensitivity to climate hazards, with Jitpur being more sensitive (S: 2.7) than Telauli (S: 2.3) (Figure 9; Table 4 and 5).

Table 4: Livelihood impact matrix results for the four main climatic hazards of Telauli

Livelihood Resources	Drought	Insects/pest/weeds	Hot/cold waves	Unseasonal rain	Sub index	Sensitivity index(S)
Natural Asset	4	3	2	2	2.75	2.3
Physical Asset	1	1	2	2	1.25	(High)
Social Asset	1	1	2	2	2	
Human asset	3	3	3	3	2.75	
Financial Asset	3	4	2	3	2.75	
Avg. Sensitivity	2.4	2.4	2	2.4	2.3	

Table 5: Livelihood impact matrix results for the four main climatic hazards of Jitpur

Livelihood Resources	Flood	Drought	Insects/pest/weeds	Unseasonal rain	Sub index	Sensitivity index(S)
Natural Asset	4	4	3	2	3.25	2.7
Physical Asset	4	1	1	2	2	(High)
Social Asset	3	1	1	3	2	
Human asset	3	3	3	3	3	
Financial Asset	4	3	3	3	3.25	
Avg. Sensitivity	3.6	2.4	2.2	2.6	2.7	

**Figure 9:** Five livelihood asset's overall sensitivity level is displaying in a spider web graph

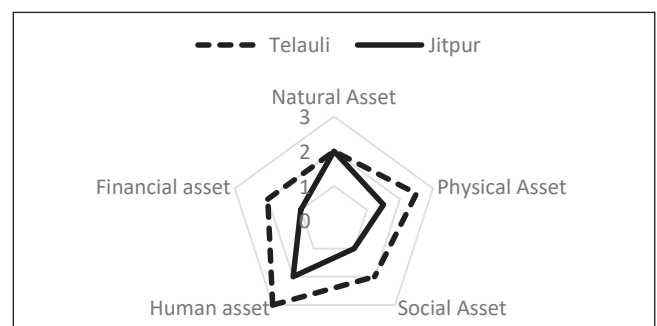
3.2.4 Adaptability with Respect to Livelihood Resources

Better infrastructure and market access make Telauli more adaptable. Stronger saving groups in Telauli enhance resilience and coping capacity which is also align with the findings of CBVA by (Pudasaini, 2015). Human and financial capital were also higher in Telauli than Jitpur and as per (Wu et al., 2023), higher education and diversified incomes depicts the increased adaptive capacity. (Sharma et al., 2023) also highlighted to emphasize the natural capital for better adaptive capacity that ultimately enhance the community resilience. In this study, Jitpur had relatively better access to forest and water resources, whereas Telauli had comparatively better access to agricultural land and sand/gravel (mineral) resources. These contrasting

advantages create a balance in overall natural capital between the two communities, despite generally limited resource available in both areas. Consequently, the livelihoods asset evaluation matrix shows an equal index value 2 for natural assets in both communities. According to the results of the livelihood asset, evaluation matrix (Table 6), Telauli recorded an adaptive capacity score of 2.3, which is notably higher than Jitpur's score of 1.5 (Figure 10)

Table 6: Livelihood asset evaluation Matrix regarding Adaptive capacity

Livelihood Resources	Sub-indices	
	Telauli	Jitpur
Natural Assets	2	2
Physical Assets	2.5	1.5
Social Assets	2	1
Human Assets	3	2
Financial Assets	2	1
Avg. Index	2.3 (High)	1.5 (Medium)

**Figure 10:** A spider web graph that displays the communities' ability to adapt

3.3 Climate Change Vulnerability of the Communities

Based on the CBVA paradigm, by using this functional representation (Equation i) vulnerability index was calculated.

$$\text{Vulnerability (V)} = f\left(\frac{E \times S}{A}\right), \dots (i).$$

The computed vulnerability indices were also divided into four levels: Low (<1), Medium (1-2), High (2-4) and very high (>4). So, with respective scores of 2.04 (High) and 3.8 (High), it was determined that Telauli and Jitpur had high vulnerability indices. In comparison to Telauli Jitpur's vulnerability scores were marginally higher (3.8), suggesting that Jitpur is more vulnerable due to its low adaptive capacity (Table 7; Figure 11). Higher adaptive capacity in Community Telauli corresponds to lower climate change vulnerability, as supported by literature (Jones et al., 2010; Pudasaini, 2015).

temperature, the Tharu community clearly perceived increasing climatic variability manifested through irregular rainfall, flash flood, prolonged dry spells, and temperature extremes. Both Telauli and Jitpur experienced high exposure to climate-related stressors, with Jitpur being more prone to flooding due to its geographical and settlement characteristics. Sensitivity was also found to be high in both communities, particularly in relation to financial and natural livelihood assets, with Jitpur exhibiting slightly greater sensitivity than Telauli. A key distinction lies in adaptive capacity: Telauli demonstrated relatively high adaptive capacity, while Jitpur is medium. This disparity significantly influenced overall vulnerability, as stronger adaptive capacity can offset the impacts of exposure and sensitivity more effectively. Consequently, while both communities are highly vulnerable to climate change, Jitpur is considerably more vulnerable than Telauli. These findings underscore that

Table 7: Measurement of total vulnerability in Telauli and Jitpur communities

Telauli			Jitpur		
Components	Index	Vulnerability index	Components	Index	Vulnerability Index
Exposure	2.04	2.04	Exposure	2.13	3.8
Sensitivity	2.3		Sensitivity	2.7	
Adaptive capacity	2.3	(High)	Adaptive capacity	1.5	(High)

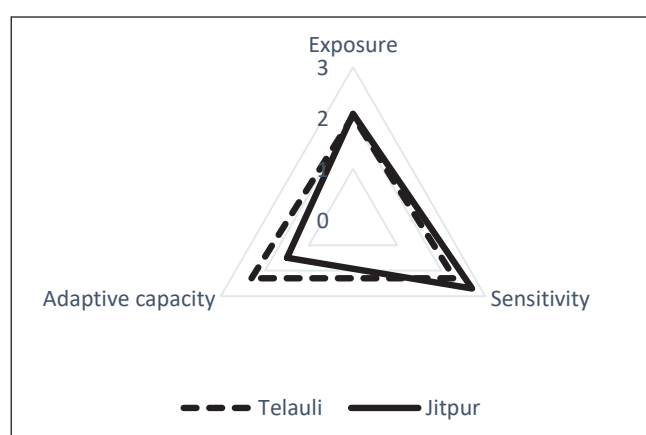


Figure 11: Triangle diagram of vulnerability illustrating its three main elements in both Telauli and Jitpur communities

4. Conclusion

The study reveals that, despite statistically insignificant long-term trends in rainfall and

climate vulnerability and resilience are not solely determined by climatic factors, but are strongly shaped by the availability of local resources, and more importantly, their effective utilization. The study highlights the importance of integrating long-term climate data for improved detection of localized trends, alongside strengthening community-based adaptation strategies for both communities. Additionally, promoting both wet and drought-resilient crop varieties, and rainwater harvesting practices can play a vital role in community Telauli. In this study, the Tharu community's local knowledge and practices, such as traditional farming methods and understanding of seasonal changes, help them to cope with climate-related challenges. These local practices can support resilience and help them adapt to future climate uncertainties.

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Appendix A: Pair wise hazard ranking in two Tharu communities

Table A1: Pair wise hazard ranking for Community -Telauli

Climatic Hazards	Flood	Drought	Hot/Cold waves	Insects/pest/weeds	Unseasonal rain	Hail	Strom	Fire	Ranks
Flood	*	Drought	Hot/Cold waves	Insects/pest/weeds	Unseasonal rain	Hail	Flood	Flood	2
Drought	*	*	Drought	Drought	Unseasonal rain	Drought	Drought	Drought	6
Hot/cold waves	*	*	*	Insects/pest/weeds	Unseasonal rain	Hot/Cold waves	Hot/Cold waves	Hot/cold waves	4
Insects/pest/weeds	*	*	*	*	Insects/pest/weeds	Insects/Pest/Weeds	Insects/pest/weeds	Insects/pest/weeds	5
Unseasonal rain	*	*	*	*	*	Unseasonal rain	Unseasonal rain	Fire	3
Hail	*	*	*	*	*	*	Hail	Hail	3
Strom	*	*	*	*	*	*	*	Fire	0
Fire	*	*	*	*	*	*	*	*	2

Table A2: Pair wise hazard ranking for community -Jitpur

Climatic Hazards	Flood	Drought	Hot/Cold waves	Insects/pest/weeds	Unseasonal rain	Hail	Strom	Fire	Ranks
Flood	*	Flood	Flood	Flood	Flood		Flood	Flood	7
Drought	*	*	Drought	Drought	Drought	Drought	Drought	Drought	6
Hot/cold waves	*	*	*	Insects/pest/weeds	Unseasonal rain	Hail	Hot/Cold waves	Hot/cold waves	2
Insects/pest/weeds	*	*	*	*	Insects/pest/weeds	Insects/Pest/Weeds	Insects/pest/weeds	Insects/pest/weeds	5
Unseasonal rain	*	*	*	*	*	Unseasonal rain	Unseasonal rain	Unseasonal rain	2
Hail	*	*	*	*	*	*	Hail	Hail	2
Strom	*	*	*	*	*	*	*	Fire	0
Fire	*	*	*	*	*	*	*	*	1
Fire	*	*	*	*	*	*	*	*	2

Material Flow Analysis of Plastic Waste in Nepal

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Abstract

This study presents a comprehensive plastic waste inventory of Nepal using material flow analysis. The Basel, Rotterdam and Stockholm (BRS) plastic waste inventory toolkit was adopted for examining plastic waste generation, management practices, and leakage pathways across 13 local governments. Primary data were collected from eight sites through field sampling, while surveys and secondary data supported analysis in five additional municipalities. A stratified random sampling approach was used which generated 2,056 samples across households, commercial establishments, institutions, healthcare facilities, and religious as well as historical sites. The findings indicate that Nepal generates approximately 5,329 tons of municipal solid waste daily (1.97 million tons annually), of which 16% is plastic, equivalent to 865 tons per day (315,618 tons annually). Per capita plastic waste generation varies significantly, with metropolitan areas producing the highest amounts. Material flow analysis shows that 83% (87,679 tons/year) of plastic waste is collected, while 17% (54,061 tons/year) remains uncollected and is often burned, buried, or otherwise unmanaged. Only 14% plastics is recycled (43,833 tons/year), while over half (162,790 tons/year) is disposed of in controlled or uncontrolled sites. Approximately 17% (52,887 tons/year) leaks into the environment across the waste management chain. When accounting for open dumping; excluded in the standard methodology, mismanaged plastic waste rises from 34% to 59%. These findings underscore the urgent need for Nepal for transition towards a circular economy and zero waste approach, prioritizing improved waste systems, reduced plastic consumption, and stronger policy implementation.

Keywords: *Archetypes, plastic inventory, mismanaged plastic waste, plastic leakage, uncollected plastic waste*

1. Introduction

With the growth of the population in urban areas, the issues of solid waste management remain a significant challenge, as increased waste generation overwhelms existing infrastructure, including waste collection, transportation, and disposal facilities; existing infrastructure is now insufficient or outdated and cannot manage the increasing volume of waste, leading to improper disposal, environmental contamination, and public health risks. The lack of waste management infrastructure leads to the open burning of waste, with all of its negative environmental and human health impacts (Maharjan, 2019). Approximately 16% of total waste is plastic waste (ADB, 2013) attributable to the growth of urban populations and shifts to more “modern” or “western” lifestyles that rely heavily on plastic, including single use plastic.

Plastic pollution is a growing environmental challenge in Nepal, driven by rising consumption of single-use plastics, rapid urbanization and gaps in waste management capacity. The surge in plastic consumption has also resulted in large volumes of discarded, degraded, or damaged plastic materials, contributing to environmental pollution and potential human health risks (Frienkel, 2011). Both macro-plastics and micro-plastics accumulate in aquatic and terrestrial ecosystems, contaminating rivers, lakes, oceans, soils and wildlife habitats (Alves, 2023). Hazardous substances such as dioxins, furans, mercury, and polychlorinated biphenyls (PCBs) may be released through improper disposal methods, including open burning and uncontrolled landfilling (Lohani, 2022).

In Nepal, plastic waste is increasingly visible in urban, rural, and natural environments, including rivers, agricultural lands, and urban drainage

systems. Plastic macro-particles were discovered in the dung of the greater one-horned rhino (*Rhinoceros unicornis*) in the Terai landscape of Nepal (Awasthi, 2023). An abundance of micro-plastics have been measured and recorded in the snow and stream water of Mount Everest (Napper, 2020). A recent study has found the accumulation of micro-plastics in most consumed fruits and vegetables (Lazăr et al., 2024). They also enter the food chain through plants, seafood, processed foods, and drinking water. In addition, micro-plastics enter the food chain when people heat food in plastic containers (Vitali, 2022).

According to the World Bank (2020), approximately 44% of global waste is mismanaged, often through open dumping (33%) and burning (11%). Moreover, approximately 93% of waste in low-income countries like Nepal is disposed of through burning or dumping on roads, in open land, or into waterways (Kaza et al., 2018).

The study carried out by ADB in 2013 revealed that Nepal generates 1435 tons/day and 5,24,000 tons/year of municipal waste, equivalent to 317 gm/capita/day (ADB, 2013). The average household waste generation per person was 170 grams/day. Similarly, the report presented that sectoral waste generation (average daily waste generated per office, school, commercial establishment or shop, hotel and restaurant) was 1.4kg, 4kg, 1.4kg and 5.7 kg respectively. Similarly, households in the municipalities of the Terai region generate 80% more waste than the mountain municipalities. During the period of the study, only six municipalities used sanitary landfill sites for disposal with the remaining 45 local bodies practicing open dumping in the road and along the riverside. Similarly, 41 municipalities had a separate section or unit dedicated to solid waste management while 17 municipalities did not have it. The report also stated that medical waste was incinerated by hospitals in a chamber or via open burning. In some municipalities, medical waste was mixed with municipal waste and either dumped or burned. Both practices expose people and communities to contagious diseases.

A new baseline study on solid waste management was conducted in 60 new municipalities of Nepal

in 2016 (Pathak, 2017). The study found that the average waste generation per household was 115 grams/day. It further revealed that the average daily waste generation rates for various sectors: 3.25 kg per school; 0.95 kg per office; 1.1 kg per shop; and 3.1 kg per hotel or restaurant. It also highlighted regional differences in household waste generation, with households in the Terai region producing 0.60 kg per day, compared to 0.47 kg in the hill regions and 0.46 kg in the mountain regions. The average municipal waste generation was estimated as 180 grams per capita per day, or 419 metric tons per day, significantly lower than in 2013.

The Waste Management Baseline Survey of Nepal (CBS 2021) provided updated data, focusing on waste collection trends and sectoral contributions. The report was prepared based on a survey conducted in 2019/20; it covered 271 municipalities in Nepal. It revealed that municipalities collected an average of 2,231 metric tons of waste annually in 2017, 2,164 metric tons in 2018, and 2,233 metric tons in 2019. Daily collection rates per municipality remained consistent, averaging 6.1 metric tons in 2018 and 2020 and 5.9 metric tons in 2019. On average, urban municipalities generate substantial daily waste, averaging 4619 tons/day. The sector-wise waste generation analysis (collective numbers for all of Nepal) identified households as the largest waste generators (1784 kg/day), followed by business complexes (1142 kg/day), educational institutions (477kg/day), health institutions/hospitals (467 kg/day), industry (436kg/day) and others (313 kg/day). The analysis showed that household waste accounted for nearly double the amount generated by business complexes, underscoring the critical need for targeted interventions in residential areas to address waste generation.

The production of MSW depends upon the economic status, lifestyles, cultural traditions, and habits of inhabitants, as well as the systems in place (or not in place) within the community. The composition of MSW is changing with increasing use of packaging materials and plastics. According to the ADB report (2013), the composition of waste consisted of organic waste (56%), followed by plastic (16%), paper and paper products (16%), glass (3%), metals

(2%), textiles (2%), rubber (1%), leather (1%), and others (4%).

As per the baseline survey 2020 (CBS 2021), waste is being handled via three main methods: dumping in a landfill site (used by 48.6% of people and communities); burning (used by 32.1%); and river dumping (used by 27.4%).

From the literature review, plastic waste management in Nepal is characterized by fragmented data (WWF, 2024), limited source segregation, substandard waste collection systems, open dumping practices, and significant leakage of plastic waste into the environment (Pathak, 2017). These challenges are further compounded by weak policy implementation and the lack of reliable and comprehensive data on plastic waste generation, composition, and flow across the waste management chain (WorldBank, 2020). The absence of systematic data limits the ability of policymakers and local governments to design evidence-based interventions and effective strategies to reduce plastic pollution.

In this context, this study aims to establish baseline data on plastic waste in Nepal, quantify the fate of plastic waste management via the material flow analysis from generation to final disposal. A Material Flow Analysis (MFA) helps bridge this information gap by systematically quantifying plastic inputs, stocks, and outputs, thereby revealing inefficiencies, losses, and critical leakage points within the system.

By mapping the flow of plastic waste, the MFA (BRS, 2021) enables identification of major sources of plastic generation, levels of collection and recovery, the role of informal waste workers, the proportion of plastic that is mismanaged or ends up in landfills, the location and number of open dumping sites, and effects on natural ecosystems. This evidence is crucial for designing targeted

interventions such as improving source segregation, strengthening recycling value chains, supporting the informal sector, and prioritizing investments in infrastructure.

Furthermore, the MFA supports the evaluation of existing policies and regulatory measures, including bans on single-use plastics and institution of Extended Producer Responsibility (EPR), by assessing their real-world impact on plastic flows. It also provides a robust baseline against which progress towards zero waste, a circular economy, and plastic pollution reduction targets can be measured over time.

Overall, conducting an MFA of plastic waste management provides a scientific and transparent basis for decision-making, enhances accountability among stakeholders, and supports the transition from linear “take-make-dispose” systems to more circular and sustainable plastic management approaches.

2. Materials and Methods

2.1 Study Area

For the study, the local governments (in this research considered as archetypes) were defined and selected based on the country’s census data, which covered all the provinces and three ecological regions of Nepal. Altogether 13 archetypes were considered for the study where primary data was collected from 8 sites while surveys and secondary data were used for other 5 sites accounting to total 13 archetypes.

The local governments were selected based on accessibility, their interest to participate in study, and prior initiation taken on waste management. The archetypes and samples details are illustrated in Table 1.

Table 1: Sample details in each archetype

S.No.	Type of Archetypes	Type	Site selected in each Archetype
1.	Archetype 1	Metropolitan City	4
2.	Archetype 2	Sub-Metropolitan City	2
3.	Archetype 3	Municipality	5
4.	Archetype 4	Rural-Municipality	2

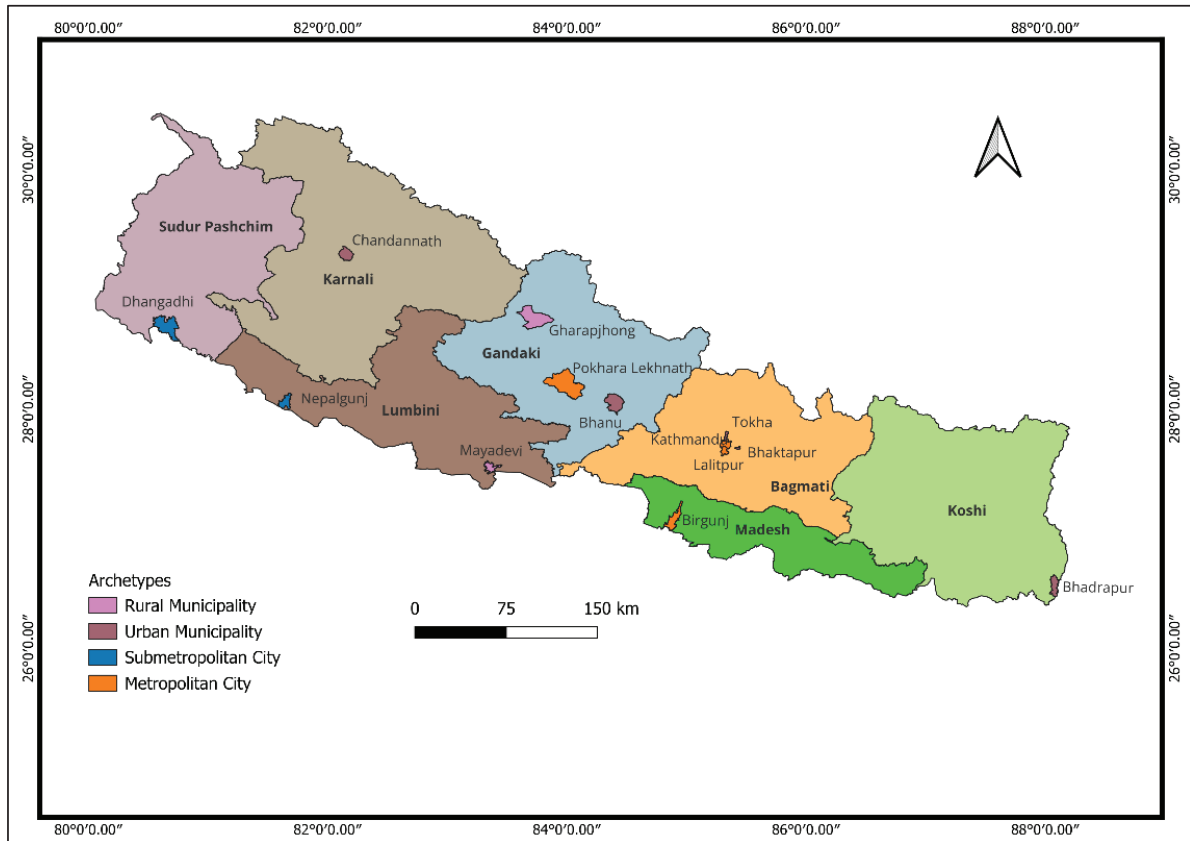


Figure 1: Map of Study Area

2.2 Methods and Methodology

Primary field data were collected from eight selected local governments, supplemented by surveys and secondary data from five additional municipalities. This broader coverage captured diverse municipal archetypes, reflecting differences in size, urbanization, service delivery capacity, and waste management practices. It strengthens the generalizability and contextual understanding of plastic waste management across Nepal.

The plastic inventory was conducted over a two-year period (2024–2025) across thirteen study sites. The assessments were carried out at different time intervals to capture variations in plastic waste generation and composition over the study sites. Due to resource and logistical constraints, the inventory was not designed to account for seasonal variation, and data collection was not conducted systematically across all seasons.

A random stratified sampling technique was used for the selection of the sample sites in each of the

archetypes. In the first strata, sites that represented each of the four archetypes were selected. In the second strata, samples were selected in each of the archetypes, including each of the identified generation points or sectors; that is, commercial, institutional, households, religious/historical places and healthcare institutions (hospitals or smaller healthcare facilities). Regarding the number of samples of households within in each archetype, the research followed the guidance of the UN-HABITAT Waste Wise Cities Tool (UN-HABITAT, 2021) i.e., 120 households for Metropolitan Cities and Sub Metropolitan Cities and 90 households for Municipalities and Rural Municipalities).

In addition to this, the number of samples of other non-households were taken by using Cochran's Formula of sample size calculation.

Sample Size Calculation for each Archetype using Cochran's Formula:

$$n_o = \frac{Z^2 \cdot p \cdot (1-p)}{e^2}$$

Where,

- n_o = required sample size
- Z^2 = Z-score (based on confidence level, (2.58 for 99%))
- p = estimated proportion of the population (use 0.5 if unknown, as it gives the maximum variability)
- e = margin of error (in decimal, e.g. 0.05 for 5%)

On site waste characterization of waste specifically plastic waste was carried out for the quantification of plastic waste in all archetypes considering all the sectors such as household, institution, commercial entity, industrial facility, health sector facility, etc., by using a combined methodology comprised of the assessment methodology developed by HECAF360 and UN HABITAT. This enabled the report to capture diverse scenarios of various waste categories from various households and non-households.

Material flow analysis (MFA) was conducted using the Basel, Rotterdam and Stockholm (BRS) Plastic Waste Inventory Toolkit across 13 local governments. Data were collected through key informant interviews with 120 municipal officials and waste management staff to assess plastic waste generation, management, recycling, disposal, and leakage pathways, identifying key intervention opportunities.

For leakage estimation, waste management practices were assessed through site observations, waste quantification at disposal facilities, and surveys with relevant personnel. At disposal sites, quantitative data on incoming waste were collected either from daily records where weighbridges were available or, in cases where weighbridges were absent, non-functional, or data were unavailable, by recording the number of trucks arriving at the site over a seven-day period. Subsequently, waste composition analysis and audits were conducted using the

quartering technique, whereby a representative final sample of 50–70 kg was extracted for detailed assessment. In addition to surveys and interviews, further data collection was conducted to support the inventory process.

3. Results and Discussion

3.1 Plastic waste generation scenario

The inventory process of the plastic waste characterization study revealed that Nepal generates approximately 1,97,2613 tons of solid waste per year; which is, 183 gm/capita/day. This is equivalent to the baseline survey conducted in 60 new municipalities of Nepal (Pathak, 2017) and lower than value from study conducted by ADB in 2013.

The table illustrates per capita waste generation across different municipal archetypes, highlighting a clear variation based on the level of urbanization. Metropolitan cities generate the highest amount of waste at 390 grams per capita per day, reflecting higher consumption patterns, increased use of packaged goods, and urban lifestyles. Sub-metropolitan cities produce comparatively less waste at 250 grams per capita per day, while small urban municipalities show a slightly higher value of 260 grams, possibly due to growing consumption without equally efficient waste management systems. In contrast, rural municipalities generate only 10 grams per capita per day, indicating significantly lower consumption levels, greater reliance on reuse practices, and limited access to commercial products. Overall, the data demonstrates a strong urban–rural disparity, where waste generation increases with urbanization, emphasizing the need for targeted waste reduction and management strategies; particularly in rapidly growing urban areas. The total plastic generation scenario is presented in figure 2.

Table 2: Per Capita Waste Generation in Various Archetypes in Nepal

Archetypes	Mega (Metropolitan City)	Medium (Sub-Metropolitan City)	Small (Urban Municipality)	Rural Municipality
gm/capita/day	390	250	260	10

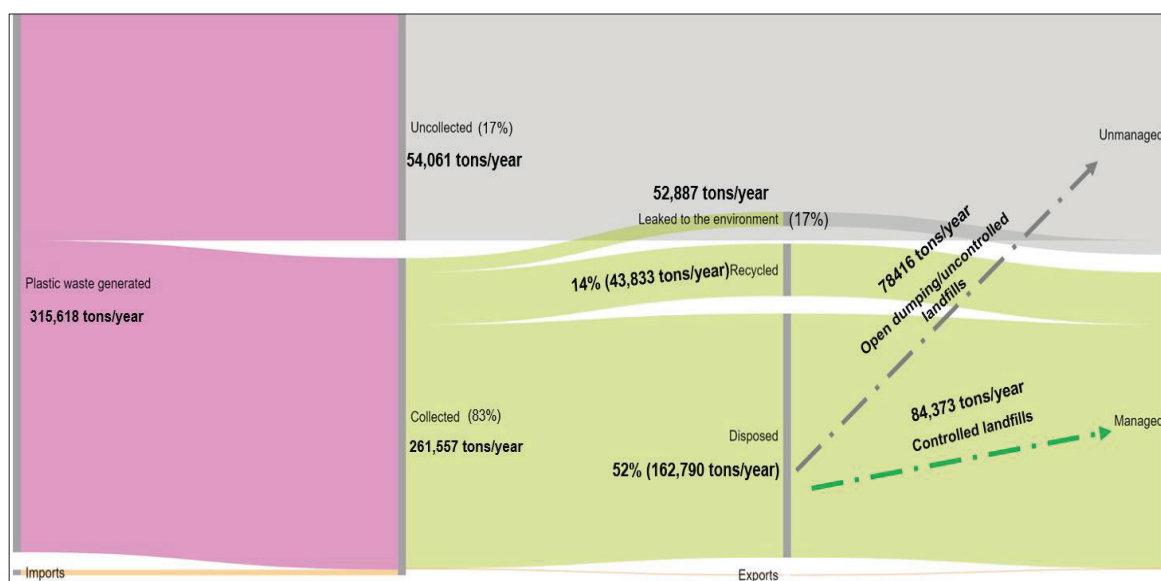


Figure 2: Sankey Diagram of Material Flow

The inventory estimated Nepal's annual waste generation is 19,72,613 tons/year and out of which 16% i.e., 315,618 tons of plastic waste are generated annually. While the plastic proportion is consistent with the 2013 ADB study, the total plastic waste exceeds the SWITCH-Asia in 2025 estimate (242,000 tons), likely reflecting increased plastic consumption, changing lifestyles, and greater demand for plastic products.

The per capita plastic waste generation is 29 gm/capita/day. On the basis of archetypes, metropolitan cities generating 68,873 tons/year; sub-metropolitan cities generating 28,036 tons/year; urban municipalities generating 213,564 tons/year; and rural municipalities generating 5,145 tons/year. This provides the baseline for understanding the scale of plastic waste produced across various administrative categories.

Regarding the fate of plastic waste flow in Nepal, out of the total plastic waste generated, about 83% (261,557 tons/year) is collected by formal and informal collection services and the remaining 17% (54,061 tons/year) is not collected and is instead burned, buried, or thrown away. The observed collection frequency is higher than the 62% average reported in the 2013 ADB study, indicating an improvement in municipal solid waste service coverage over time. This increase may be attributed to strengthened municipal waste management

systems, expansion of collection services, and increased urban awareness. However, differences in study scope and rapid urbanization may also influence comparability of the estimates.

In terms of downstream management, out of 83% collected waste, 13.9% (43,833 tons/year) of the total plastic waste generated is recycled, largely through informal and small-scale recycling systems. However, 16.7% of plastic waste leaks into the environment at various stages of the waste management process, from source segregation to final disposal. The largest share, 51.6% is ultimately disposed of at designated disposal sites, including both controlled landfill facilities and uncontrolled open dumping areas. The data clearly reveals less than 1% data gap which is due to the data gap of informal recyclables extraction during the collection and transportation which has no record or documentation. The data analysis indicates a data gap of less than 1%, possibly attributed by the unrecorded extraction of recyclable materials by the informal sector during waste collection and transportation processes, for which no formal documentation or records are available.

The Sankey diagram reveals that of total plastic waste generated, 17% is uncollected and 17% leaks into the environment. The standard toolkit defines mismanaged plastic waste as consisting of only uncollected and leaked plastics. But in

case of Nepal, many municipalities dump waste in open areas or pits before managing it or without managing it; this does not comprise effective waste management. As a result, the study includes dumped waste in the data for “mismanaged waste” along with uncollected and leaked materials. Only recycled waste and waste designated for disposal in controlled landfill sites is considered well-managed for the purposes of this study. The full percentage of mismanaged waste is 59% of total waste (185,904 tons/year) (note that uncollected waste and leaked waste have a combined total of only 34%). Leakage after the disposal of plastic waste into rivers or other water sources, the environment, and land are not quantified by the MFA toolkit.

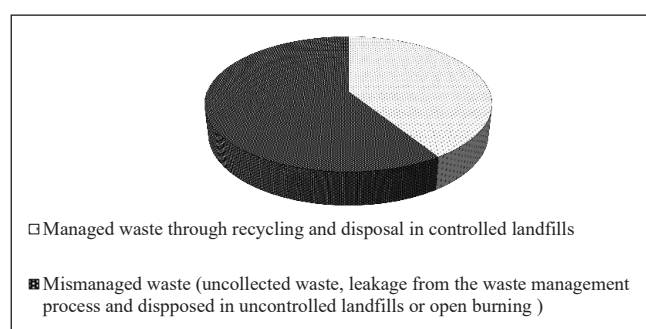


Figure 3: Management Vs Mismanagement of plastic waste in Nepal

Compared with the SWITCH-Asia (2025) estimate of 85% mismanaged plastic waste, this study found 59%, indicating a substantial reduction in plastic leakage, open dumping, and burning.

3.1.1 Fates of Plastic Waste in Various Archetypes in Nepal

The flow of plastic waste in different stages of the plastic waste management system in Nepal as summarized in Sankey Diagram Figure 2, describes the fates of a range of different plastic waste, thereby allowing comparisons for quantities and types of plastic waste recycled, disposed, leaked, and uncollected. The brief description of each of the indicators aligning the indicators for waste management at both the national and at various archetypes level are described as follows.

3.1.1.1 Collected Vs Uncollected plastic waste: The details of the collected and uncollected plastic waste are illustrated in figure 3.

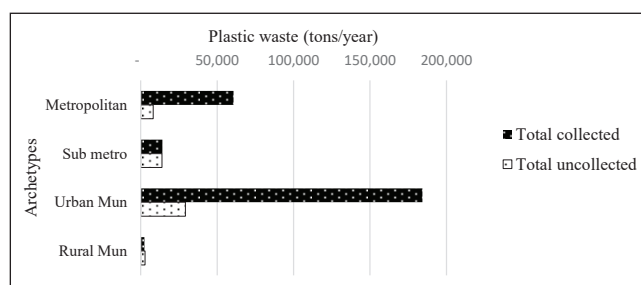


Figure 4: Collected Vs Uncollected Waste across Various Archetypes

The figure 4 presents a bar graph comparing collected and uncollected plastic waste across various archetypes. In terms of collection efficiency, metropolitan cities perform relatively well, collecting 88% (60,739 tons/year) of the total generated waste. Urban municipalities also maintain a high collection rate of 86% (184,302 tons/year). In contrast, sub-metropolitan cities collect only 50% (14,131 tons/year) of the total waste generated, compared to a reported collection coverage of 70–90% in large cities ADB (2013). This decline may be attributed to Nepal’s administrative restructuring, which expanded sub-metropolitan boundaries by incorporating surrounding rural areas. As a result, waste collection services have become more challenging to deliver consistently due to dispersed settlements, difficult terrain, and limited infrastructure in the newly integrated areas. In addition to this, rural municipalities collect 46% (2385 tons/year), which is similar to the study data of ADB 2013 (below 50% in several smaller municipalities). It indicates that there is still a significant gaps in waste collection infrastructure outside major cities.

Field surveys revealed that metropolitan cities and urban municipalities collect almost all municipal waste within city areas. However, in most cases, waste management (particularly waste collection and transportation to designated landfills or disposal sites) is outsourced to private sector operators under contracts with local governments. In this context, private sector engagement has proven to be effective in reducing uncollected plastic waste and improving collection coverage.

Although a collection system exists in sub-metropolitan cities, limited accessibility in certain

areas leads to a higher proportion of uncollected waste. For example, in one of the sub metropolitan cities surveyed during the inventory, waste collection services covered only about 50% of the wards in the cities. In inaccessible or rural areas, collection services were often completely absent, resulting in practices such as open dumping or burning of plastic waste by local residents. This situation is likely representative of other sub metropolitan cities as well. Moreover, in rural municipalities, low levels of waste generation in inaccessible areas discourages local governments from providing collection services. As a result, local residents manage their waste independently, primarily through open burning or burial.

3.1.2 Final Disposal and management of Plastic Waste

The performance of various administrative levels varies significantly in this regard and is illustrated in the form of bar graph.

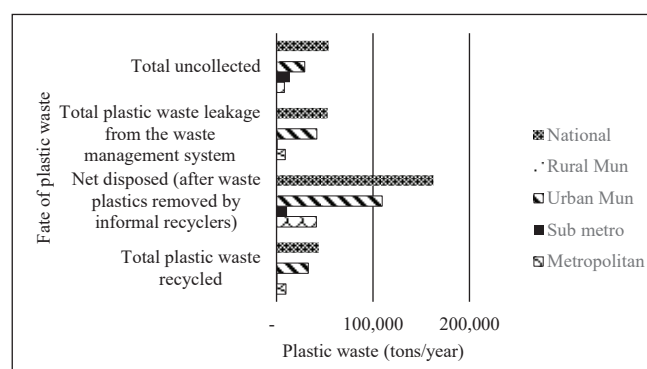


Figure 5: Final Disposal and Management of plastic waste in Nepal

Metropolitan cities show comparatively stronger recycling performance (14%, 9,636 tons/year) and higher collection coverage; however, they still dispose of a large volume of plastic waste (60%, 41,165 tons/year) and experience notable leakage (13%, 9,112 tons/year), indicating gaps in segregation and advanced recovery systems. Sub-metropolitan cities generate and manage moderate volumes, but recycling remains low (3%, 923 tons/year) compared to disposal (39%, 10,877 tons/year), reflecting limited infrastructure and weaker material recovery mechanisms. Urban municipalities represent the most critical pressure

point, with the highest levels of disposal (51%, 109,391 tons/year), leakage (20%, 41,774 tons/year), and uncollected waste (14%, 29,262 tons/year) but also has the highest recycling rate of 15% (32,850 tons/year) of total waste generated in this archetype. This suggests rapid urbanization without adequate expansion of waste management capacity. In contrast, rural municipalities handle smaller overall volumes, yet recycling is only 8% (423 tons/year) and improper disposal into the environment remains the dominant practice, highlighting limited technical capacity, infrastructure gaps, and low formal recovery systems. Overall, while metropolitan areas perform relatively better, all categories show a strong dependence on disposal over recycling, underscoring the need for systemic improvements tailored to each municipal context.

According to the surveys with recycling vendors, the plastic waste that they send to recycling consists of HDPE and polythene bags (LDPE); most other plastics are not recyclable and thus are sent to designated disposal sites.

This data indicates that although recycling practices exist, a substantial amount of plastic waste still ends up at disposal sites, where it is largely recovered by the informal sector but is not documented. Furthermore, the disposal of plastic waste at uncontrolled disposal sites and its open burning by local communities and informal actors remains widespread.

3.1.4 Plastic Waste Leakage

Leakage during the various stages of waste management system in Nepal is largely driven by weaknesses in downstream management, particularly during sorting and at designated disposal sites. Although improvements in collection systems are necessary, the largest reductions in plastic leakage will come from strengthening sorting facilities, improving landfill and disposal site management, eliminating open dumping, and adopting controlled recovery and disposal systems in line with zero waste and circular economy principles.

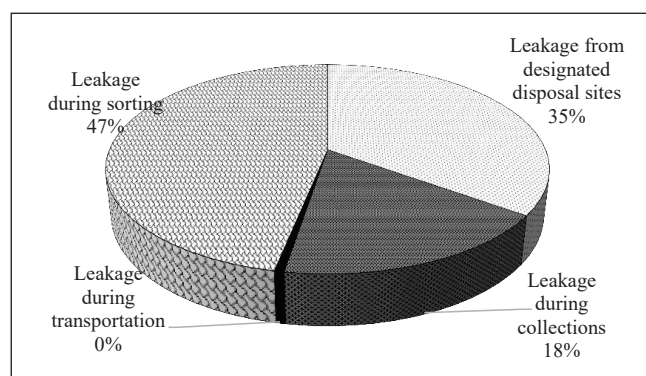


Figure 6: Proportion of plastic waste leakage in local government of Nepal

Plastic waste leakage is dominated by losses at sorting facilities; 47%, (24,751 tons/year) making it the most critical intervention point. High losses in this area are due to poor facility design, manual handling without containment, inadequate storage, and weak linkages to recyclers that lead to stockpiling and material loss. At 35% (18,468 tons/year), leakage at designated disposal sites also remains a major environmental problem. This is caused by open dumping, poorly managed or non-engineered landfills, and dispersal by wind and monsoon runoff. Collection-stage leakage accounts for 18% (9,363 tons/year), largely due to open or damaged vehicles, overfilled containers, and inefficient collection schedules, directly affecting streets and drainage systems. In contrast, transportation contributes only 0.58% (304 tons/year), suggesting relatively controlled transport systems or possible under-reporting, and confirming that leakage is primarily driven by downstream stages of the waste management system rather than transport. A detailed breakdown of plastic waste leakage from Nepal's waste management system, disaggregated by each archetype is expressed in Figure 7.

Across municipal categories, urban municipalities contribute the highest volume of plastic leakage, at 20% of all plastic waste (41,774 tons/year), followed by metropolitan cities at 13% (9,112 tons/year). Sub-metropolitan cities and rural municipalities contribute relatively smaller quantities, at 16% (1,202 tons/year) and 4% (800 tons/year) respectively. Many improvements need to be made to reduce leakage; for instance, urban municipalities have insufficient waste management

and most of them contract for waste management service with private companies that focus on disposing of waste rather than managing it to reduce leakage.

Overall, Figure 7 underscores that improving disposal site management and eliminating open dumping would yield the largest reductions in plastic leakage nationally, while targeted interventions in urban municipalities are essential to address high proportional losses. Strengthening collection systems, upgrading disposal facilities, and integrating informal recovery mechanisms are critical to reducing plastic leakage across all municipal archetypes.

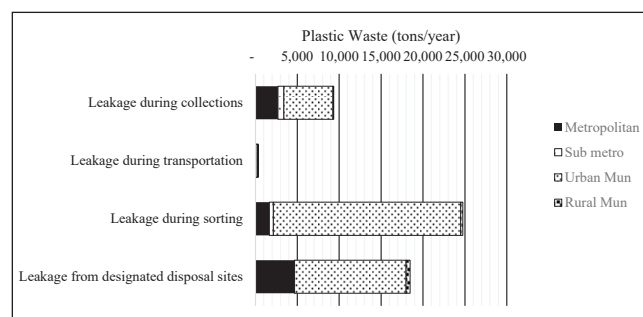


Figure 7: Plastic Waste Leakages from Waste Management Practice by Archetypes (tons/year)

3.1.5 Mismanagement of Plastic Waste

Finally, the total mismanaged plastic waste, which includes uncollected, leaked, and improperly disposed waste, is highest in rural municipalities at 69% (3559 tons/year), followed by sub metropolitan cities at 54% (15,108 tons/year), urban municipalities at 33% (71,036 tons/year) and metropolitan cities at 25% (17,245 tons/year). Nationally, about 34% (106,948 tons/year) of plastic waste is mismanaged, indicating the urgent need for improved collection, recycling, and containment strategies to reduce environmental leakage and promote sustainable waste management.

Using the methodology of the toolkit, only leakages and uncollected waste are considered as mismanaged, yielding data that shows that 34% of waste in Nepal is mismanaged. However, the toolkit's methodology ignores waste dumped in open dumps, which of course is a serious problem in Nepal. Thus, in the context of Nepal, it is important to add open dumping to the percentage

of mismanaged waste. Doing so yields an estimate of 59% of Nepal's waste as being mismanaged that is, 185,904 tons/year, which includes not only plastic leakage and uncollected waste but also waste dumped in open dumps or open burning.

3.1.6 Plastic Waste Imports and Exports

Nepal imports raw plastic materials, primary forms as raw materials, and finished products, including packaging, single-use plastics, and consumer goods. Domestic plastic industries mainly focus on manufacturing of packaging materials such as plastic bags, bottles, and wrappers. Limited eco-design practices and the absence of mandatory recyclability standards contribute to increased plastic waste generation. According UNCOMTRADE¹ data from 2024, Nepal imported 20 tons/year of plastic waste and exported 4 tons/year; 16 tons/year of plastic remains in Nepal, a huge amount.

According to fiscal data from the Department of Custom portal for the year 2081/82 (that is, 2024-2025), Nepal imported 205,740 tons of plastics from various partners across the world, investing more than USD 161 million per year. Among the total imports, the highest share was in the form of primary or raw materials, consisting of 117,866 tons of plastic and equivalent to more than USD 92 million per year. Similarly, as per the data, Nepal is importing 235 tons/year of plastic waste with HS Code 3915 under the heading of "Waste, paring and scrap of plastics".

In the same fiscal year, Nepal exported approximately 10,160 tons of plastic materials to various international trading partners, generating over USD 11.5 million annually. Of the total exports, a significant share comprised plastics in primary or raw form, amounting to 238 tons, predominantly polypropylene, with an estimated value exceeding USD 149,000 per year. However, available data indicate that plastic waste exports are not recorded under HS Code 3915 ("Waste, parings and scrap of plastics").

While import and export data exist for plastic materials there is significant inconsistencies

between global and national plastic waste trade data, highlighting the need for systematic verification and reconciliation of these datasets. Moreover, recent data on plastic waste recycling and export are largely unavailable, indicating major gaps in plastic waste trade documentation.

4. Conclusion

The National Plastic Inventory highlights that plastic waste constitutes a significant and growing component of Nepal's municipal solid waste stream, accounting for approximately 16% of total waste generation (315,618 tons/year). While 83% of plastic waste (87,679 ton/day) is collected through formal and informal systems, 17%, (54,601 tons/day) remains uncollected and is managed through open burning, burial, or uncontrolled disposal. These practices, combined with system inefficiencies, contribute to notable plastic leakage, with 17% (52,887 tons/year) of total plastic waste leaking into the environment at different stages of the waste management chain.

Downstream management of plastic waste remains heavily disposal oriented. Although 14% (43,833 ton/year) of plastic waste is recycled, recycling activities are largely driven by informal and small-scale actors, indicating the importance of the informal sector and the absence of a robust, formalized recycling system. The majority of plastic waste i.e., 52% (162,790 tons/year) is ultimately disposed of at designated disposal sites, many of which are uncontrolled open dumps rather than engineered landfill facilities, posing long-term environmental and public health risks.

Out of total plastic waste leakage, almost 65% (34,114 tons/year) are from the collection and sorting stages; reflecting weak source segregation, limited infrastructure, and inadequate operational standards. Rural municipalities face the greatest proportional challenges, characterized by low collection coverage (46% collection frequency, 1,367 tons/year), high levels of uncollected waste (i.e., 54%, 2,760 tons/year), and minimal access to environmentally sound disposal facilities.

¹ UN Comtrade is the UN's official database for international trade statistics. It contains detailed information on the import and export of goods and services between countries worldwide, covering both historical and current trade flows

Although recycling occurs across all municipal typologies, it is largely driven by the informal sector and remains limited in scale and efficiency. The dominance of low-value and non-recyclable plastics, particularly multilayer and sachet packaging, further constrains recycling potential and underscores the need for upstream interventions. The absence of reliable data on plastic waste trade and effective implementation of available policy mechanisms further undermine efforts to regulate plastic flows and recover material value.

Overall, the study highlights a systemic shift in Nepal's waste management landscape, where increasing formalization through private sector has not translated into improved resource recovery or reduced leakage. Instead, the current system remains heavily disposal-oriented, with no incentives for waste reduction, recycling, or circular economy approaches. Addressing plastic pollution in Nepal will therefore require coordinated action across the entire value chain, strengthening policy enforcement, upgrading disposal and treatment infrastructure, integrating informal recyclers, improving data transparency, and reducing the production and use of non-recyclable plastics. Without such integrated reforms, plastic waste will continue to pose growing environmental, public health, and economic risks across the country.

Finally, the analysis shows that plastic waste leakage in Nepal's waste management system is primarily driven by inefficiencies in downstream handling stages, particularly at sorting facilities and disposal sites. The high proportion of leakage at sorting facilities highlights the urgent need to improve facility design, strengthen containment systems, and enhance operational management and linkages with recyclers to prevent material loss. Similarly, significant leakage at disposal sites indicates the necessity of transitioning from open dumping to properly engineered and managed landfill systems. While collection-stage leakage also requires improvements in collection infrastructure and scheduling, the minimal leakage during transportation suggests that interventions should prioritize strengthening sorting and final disposal practices. Addressing these critical points will be

essential to significantly reduce environmental plastic leakage and move towards a more efficient and sustainable waste management system.

The findings also highlight the urgent need for Nepal to shift from disposal-based plastic waste management to a circular economy and zero waste approach. Key priorities include improving landfill management, ending open dumping, expanding source segregation, integrating informal recyclers, implementing Extended Producer Responsibility (EPR), strengthening waste trade documentation, and addressing rising plastic consumption with the goal of reducing it.

5. Acknowledgements

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Impacts of Land-Use Change on Carbon Sequestration and Climate Mitigation Potential in Central Nepal

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Abstract

Ongoing land use and land cover (LULC) changes in Nepal's mid-hill districts have important implications for carbon sequestration and climate finance potential, as shifts among forest, agricultural, built-up, and other land-cover classes influence landscape-level carbon storage. This study presents an integrated geospatial and economic analysis of LULC dynamics and their impacts on carbon stocks in Kavrepalanchowk District, Bagmati Province. Using harmonized National Land Cover Monitoring System (NLCMS) maps for 2013 and 2022 as baseline data, historical LULC transitions were analyzed through remote sensing and Geographic Information Systems (GIS) techniques. TerrSet's Land Change Modeler (LCM), employing a Cellular Automata–Markov chain framework with drivers including elevation, slope, population density, proximity to roads and buildings, distance from rivers, and soil type, simulated a 2032 LULC scenario with 95.3% validation accuracy. Forest cover is projected to increase from 62.3% (2022) to 66.6% (2032), while cropland is projected to decline from 33.4% to 29.4%. The InVEST Carbon Storage and Sequestration model quantified baseline carbon stocks at 13.92 million Mg C (51.0 MtCO₂e), projected to rise to 14.68 million Mg C by 2032. A net gain of 762,195 Mg C (2.79 MtCO₂e) is projected. Economic valuation, aligned with Nepal's Emission Reductions Payment Agreement (ERPA) framework at USD 5 per tCO₂e, estimates the standing stock notional value at USD 255 million. The realizable results-based payment potential for Kavrepalanchowk is estimated at USD 9.1–9.7 million, which could support climate change adaptation and mitigation in the Kavrepalanchowk District. These findings provide district-level evidence for Nepal's Measurement, Reporting, and Verification (MRV) system and underscore the need to extend carbon finance mechanisms beyond the Terai lowlands into Nepal's mid-hill districts.

Keywords: Carbon stock, community forestry, land use change, REDD+, spatial modeling

1. Introduction

Terrestrial carbon sequestration has emerged as a cornerstone of global climate mitigation, with land use and land cover (LULC) change recognized as a primary driver of carbon stock fluctuations (Selmy et al., 2023; Zafar et al., 2024). In Nepal, socioeconomic development is tightly coupled with natural resources, rapid urbanization and shifting agricultural practices have transformed mid-hill landscapes, creating a paradox in which national forest cover nominally increased to 43.38% by 2022 (FRTC, 2024) while localized degradation persists in districts experiencing infrastructure expansion.

Kavrepalanchowk (Kavre) District encompasses extensive community-managed forests that serve

simultaneously as local livelihood assets and national carbon sinks. Despite this significance, district-level, spatially explicit assessments integrating predictive LULC modeling with carbon quantification and economic valuation remain largely unexplored. Most existing analyses operate at national scales or examine land use change and carbon stocks in isolation (Chaulagain et al., 2024). Nepal's enactment of the Carbon Trade Regulation 2025 (MoFE, 2025) and the 2021 Emission Reductions Payment Agreement (ERPA) with the World Bank's Forest Carbon Partnership Facility (FCPF), committing to reduce 9 MtCO₂e for USD 45 million, have elevated the demand for thorough subnational carbon evidence (Nepal Economic Forum, 2023; World Bank, 2021). Results-based

payment under REDD+ (Reducing Emissions from Deforestation and Forest Degradation) requires verified, incremental emission reductions relative to a forest reference level, making localized, MRV-compatible assessments a prerequisite for accessing climate finance (MoFE, 2023).

This study addresses these gaps by: (1) analyzing historical LULC transitions from 2013 to 2022 using remote sensing and GIS; (2) simulating 2032 LULC scenarios using a Cellular Automata–Markov (CA–Markov) framework in TerrSet’s Land Change Modeler; (3) quantifying carbon storage and sequestration dynamics and their associated economic value under projected emission reduction scenarios using the InVEST Carbon module.

2. Materials and Methods

2.1 Study Area

Kavre District lies within Nepal’s mid-hill physiographic region (Fig. 1), extending from

lower river valleys to ridges approaching 3,000 m above sea level. The district covers 1,396 km² across 13 municipalities, characterized by a mosaic of community-managed forests, rain-fed agriculture, grasslands and rapidly expanding built-up areas. Community Forest User Groups (CFUGs) manage tens of thousands of hectares, providing timber, fuelwood, and fodder while functioning as significant carbon sinks central to Nepal’s REDD+ commitments (Chaulagain et al., 2024; FRTC, 2022).

2.2 LULC Data and Classification

Annual land cover datasets for 2013 and 2022 were obtained from the National Land Cover Monitoring System (NLCMS) developed by the Forest Research and Training Centre (FRTC, 2024) in collaboration with ICIMOD. The NLCMS applies cloud-based machine learning classifiers to Landsat imagery within Google Earth Engine, producing harmonized, nationally consistent maps. Nine land cover classes

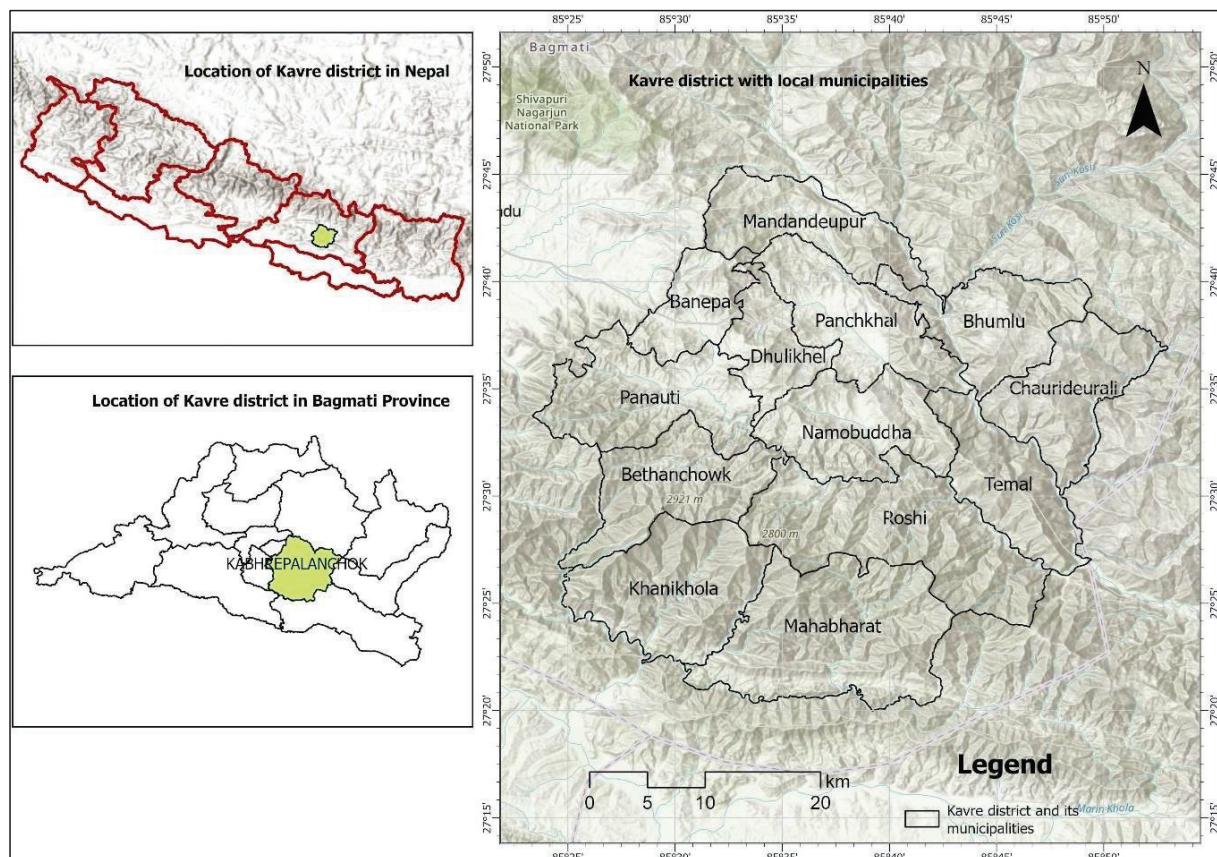


Figure 1: Location map of Kavre District.

Table 1: Land cover classes and definition.

Main land cover class	Description	IPCC land cover class
Forest	Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use.	Forest
Other wooded land (OWL)	Land not classified as forest spanning more than 0.5 ha, having at least 20 m width and a tree canopy cover of trees between 5% and 10%, or the canopy cover of trees less than 5% but the combined cover of shrubs, bushes and trees more than 10%; includes area of shrubs and bushes where no trees are present.	Forest
Grassland	Areas covered by herbaceous vegetation with cover ranging from Closed to Open (15–100%). This category includes rangeland and pasture that is not considered cropland.	Grassland
Cropland	This category includes arable and tillage land, and agroforestry systems where vegetation falls below the thresholds used for the forest land category, consistent with the selection of national definitions.	Cropland
Built-up area	Built-up areas refer to artificial structures such as towns, villages, industrial areas, airports, etc.	Settlements
Water body	Rivers are natural flowing water bodies and typically have elongated shapes. Lakes and ponds are perennial standing water bodies.	Water body
Riverbed	A tract of land without vegetation surrounded by the waters of an ocean, lake, or stream; it usually includes any accretion in a river course.	Water body
Bare soil	A soil surface devoid of any plant material.	Other
Bare rock	Non-vegetated areas with a rock surface.	Other

Note: Adapted from National Land Cover Monitoring System of Nepal, 2020–2022 (p.06), by Forest Research and Training Centre (FRTC), 2024, Ministry of Forests and Environment, Government of Nepal (ISBN: 978-9937-1-7322-3).

consistent with IPCC categories were used: Forest, Other Wooded Land (OWL), Grassland, Cropland, Built-up area, Water body, Riverbed, Bare soil, and Bare rock (FRTC, 2024).

2.3 LULC Prediction Modeling

Land change analysis was conducted using TerrSet Land Change Modeler (LCM, version 20.0.4; Clark University). Transitions were organized into 18 sub-models by applying a minimum area threshold of 47.5 ha to filter minor transitions and focus modeling on dominant spatial processes, following the methodological logic of Chaulagain et al. (2024). Seven explanatory driver variables were prepared: distance from buildings (derived from 2022 LULC), elevation and slope (from SRTM 1 arc-second DEM; USGS, 2019), Kernel density-smoothed population (WorldPop, 2018), soil type (ISRIC SOTER database; Dijkshoorn & Huting, 2009), and distance from roads (Department

of Roads, 2024) and rivers. Variables with a Cramer's V coefficient below 0.3 in any sub-model were excluded to improve predictive reliability. This threshold was selected empirically through iterative model runs to enhance the performance of transition potential modeling. Transition potential maps were then generated using neural network analysis. Future LULC for 2032 was simulated using a Markov Chain framework based on change demand modeling. Model validation showed strong performance, with an overall accuracy of 95.3%, based on a comparison between the projected 2022 LULC map and the actual 2022 NLCMS map. The same variables mentioned above were used for validation as well.

2.4 Carbon Storage and Sequestration Quantification

The InVEST Carbon Storage and Sequestration model (Natural Capital Project, 2025) was applied

Table 2: Carbon pool used as input for InVEST software

LULC code	LULC name	C_above	C_below	C_soil	C_dead	C_total
1	Water	0	0	0	0.01	0.01
2	Forest	66.42	21.14	59.01	2.97	149.54
3	River Bed	0	0	0.08	0.08	0.16
4	Built-up	5	1	5	0	11
5	Cropland	3.95	2	6.6	1	13.55
6	Baresoil	3.6	4	10	0	17.6
7	Barerock	0	0	0	0.16	0.16
8	Grassland	0	0	84.9	0	84.9
9	OWL	13.3	5.15	27.24	2.54	48.23

to the 2022 baseline and projected 2032 LULC maps. The model aggregates four terrestrial carbon pools: aboveground biomass (C_{above}), belowground biomass (C_{below}), soil organic carbon (C_{soil}), and dead organic matter (C_{dead}) using class-specific carbon density values (Mg C ha⁻¹). Class-specific carbon density values (Mg C ha⁻¹) for each pool were sourced directly from Chaulagain et al. (2024). For unused land such as bare rock and sandy areas, dead organic matter is expected to be negligible compared to other categories, supporting the assignment of 0.08 Mg/ha to C_{dead} (Tang et al., 2018).

2.5 Economic Valuation

Carbon stocks and projected emission reductions were monetized using parameters aligned with Nepal's TAL ERPA and Benefit Sharing Plan (MoFE, 2023). A reference carbon price of USD 5 per tCO₂e was applied, and carbon values expressed in Mg C were converted to CO₂e equivalent using the IPCC stoichiometric conversion factor of 3.67 (IPCC, 2006). A 5% real social discount rate was adopted as the central estimate because it provides a balanced and context-appropriate valuation for Nepal. This rate is close to the World Bank's growth-based benchmark, where a 3% per capita growth rate implies approximately a 6% discount rate, while remaining within the broader 2–10% range suggested for varying growth assumptions. At the same time, it is lower than the 8–15% rates often used in developing-country project appraisal, thereby avoiding excessive discounting of long-term climate and environmental benefits while still reflecting Nepal's capital scarcity better than very

low ethical discount rates such as 2% (World Bank, 2016; Zhuang et al., 2007). A 2.25% annual real carbon price escalation was also applied, consistent with the World Bank Shadow Price of Carbon trajectories (World Bank, 2024).

To address uncertainty in the valuation estimates, a sensitivity analysis was incorporated around the key parameters that influence the final economic value. These include the carbon price, discount rate, uncertainty and risk reversal buffer, and operational cost deductions. The central case applied a carbon price of USD 5 per tCO₂e, a 5% discount rate, a 23% uncertainty and risk reversal buffer, and 10–15% operational cost deductions, consistent with the TAL Benefit Sharing Plan (MoFE, 2023). Conservative and optimistic scenarios were used to test the effect of lower and higher carbon prices, higher and lower discount rates, and variation in carbon stock estimates and buffer deductions. Therefore, the monetized carbon value has been interpreted as an indicative range rather than a fixed exact value. Realizable payment potential was estimated after applying the 23% uncertainty and risk reversal buffer and 10–15% operational cost deductions, as prescribed in the TAL Benefit Sharing Plan (MoFE, 2023).

3. Results and Discussion

3.1 LULC Dynamics: 2013–2022 and Projected 2032

LULC analysis reveals a clear pattern of forest recovery alongside cropland contraction across the study period (Table 2 and Fig. 2). Forest

cover expanded from 56.8% (793 km²) in 2013 to 62.3% (870 km²) in 2022, and is projected to reach 66.6% (930 km²) by 2032, a cumulative gain of 9.8 percentage points over two decades. Simultaneously, cropland declined from 38.2% (533 km²) to 33.4% (466 km²) and is projected to fall further to 29.4% (411 km²) by 2032. Built-up land, while numerically small, more than tripled from 0.19% (2.7 km²) in 2013 to 0.67% (9.3 km²) in 2022 and is projected to reach 1.1% (15.4 km²)

by 2032, reflecting persistent urban expansion along highway corridors.

The observed LULC dynamics indicate that Kavre District has experienced a typical mid-hill forest transition, where forest recovery has occurred alongside a gradual decline in agricultural land. The increase in forest cover from 56.8% in 2013 to 62.3% in 2022, and its projected rise to 66.6% by 2032, suggests that natural regeneration, community forest management, and reduced cultivation pressure

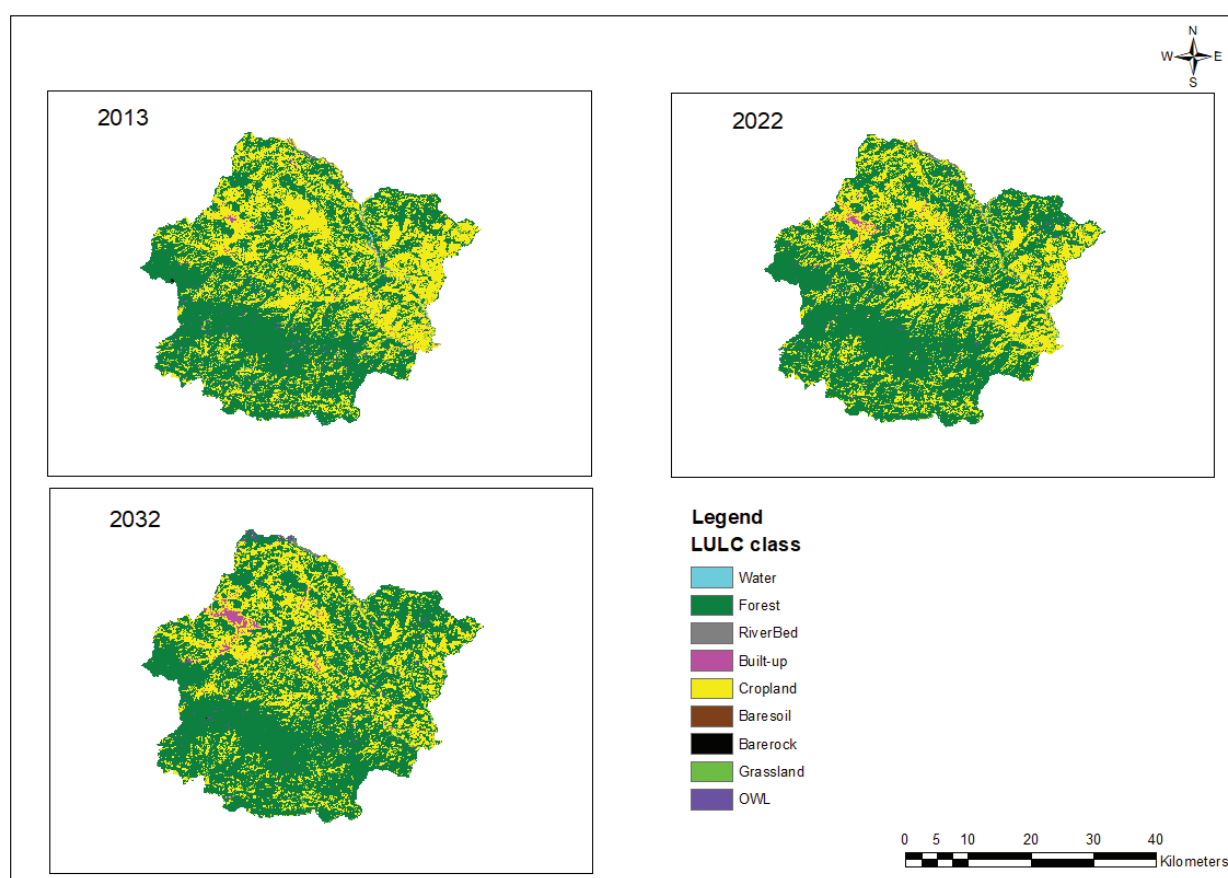


Figure 2: Historical and projected land use and land cover maps of the Kavre District

Table 3: Area and proportional extent of LULC classes in Kavre District for 2013, 2022, and projected 2032

LULC class	Area 2013 (km ²)	% 2013	Area 2022 (km ²)	% 2022	Area 2032 (km ²)	% 2032
Water	2.93	0.21	1.38	0.10	0.60	0.04
Forest	793.02	56.81	870.10	62.33	929.70	66.60
River bed	6.23	0.45	4.11	0.29	2.64	0.19
Built-up	2.70	0.19	9.30	0.67	15.43	1.10
Cropland	533.12	38.19	466.30	33.40	410.87	29.43
Bare soil	0.24	0.02	0.05	0.004	0.05	0.004
Bare rock	0.24	0.02	0.11	0.008	0.11	0.008
Grassland	34.61	2.48	27.27	1.95	21.68	1.55
OWL	22.90	1.64	17.37	1.24	14.92	1.07

on marginal lands have contributed to landscape-level biomass recovery. This pattern is consistent with the broader forest recovery trend reported in Nepal's mid-hill regions, where community forestry, outmigration, and abandonment of less productive agricultural land have encouraged secondary forest growth. However, the reduction in cropland from 38.2% in 2013 to a projected 29.4% in 2032 also indicates a land-use trade-off. While cropland-to-forest transition increases carbon storage, it may also have implications for local agricultural livelihoods, food production, and future land-use planning.

These trends reflect the “forest transition” phenomenon documented in Nepal's mid-hills, where outmigration-driven agricultural abandonment and CFUG management have jointly increased forest biomass. The results are consistent with NLCMS national findings (FRTC, 2024) and align with observations from neighboring Kathmandu Valley, where unplanned land-use conversion eroded ecosystem service value by approximately 20.6% over three decades (Shrestha et al., 2022). The persistent built-up expansion in Kavre, driven by proximity to Kathmandu via the Araniko Highway underscores the ongoing risk that infrastructure development poses to forest margins and carbon sequestration capacity.

The projected expansion of built-up land, although small in total area, is important from a planning perspective. Built-up area increased from 2.7 km² in 2013 to 9.3 km² in 2022 and is projected

to reach 15.4 km² by 2032. This indicates a rapid proportional increase in settlement and infrastructure development, particularly along accessible corridors such as the Araniko Highway and areas influenced by proximity to Kathmandu Valley. Although built-up land contributes only a minor share to total district carbon stock, its spatial location is important because future expansion may occur at the expense of cropland, open land, or regenerating forest patches. Therefore, land-use planning should prioritize compact settlement growth, protection of high-carbon forest patches, and control of scattered urban expansion in carbon-sensitive areas.

3.2 Carbon Storage and Sequestration

Total carbon storage in Kavre increased from 13.92 million Mg C (51.0 MtCO₂e) in 2022 to a projected 14.68 million Mg C (53.8 MtCO₂e) in 2032; a net gain of 762,195 Mg C (Table 3 and Fig. 3). Forests dominate the landscape's carbon budget, storing 12.96 million Mg C in 2022 and projected to reach 13.85 million Mg C by 2032 (+6.87%). Cropland and grassland collectively lose approximately 122,000 Mg C over the decade, partially offsetting forest gains. Built-up areas show a 65.9% increase in associated carbon stock; however, this reflects built-up area expansion and the low but non-zero carbon density assigned to mixed settlement pixels, not carbon sequestration by impervious surfaces.

The carbon storage results show that Kavre District is projected to remain a net carbon sink during 2022–2032. Total carbon stock increased from

Table 4: Net carbon stock change by LULC class in Kavre District, 2022 and 2032

LULC Class	Stock 2022 (Mg C)	Stock 2032 (Mg C)	Sequestration 2022–2032 (Mg C)	Annual Rate (Mg C yr ⁻¹)
Forest	12,961,336.33	13,851,151.03	+889,814.70	+88,981.47
Cropland	630,442.12	555,440.40	−75,001.72	−7,500.17
Grassland	230,659.13	183,248.97	−47,410.16	−4,741.02
OWL	83,446.16	71,495.62	−11,950.54	−1,195.05
Built-up	10,260.99	17,027.21	+6,766.22	+676.62
Riverbed	65.41	42.48	−22.93	−2.29
Water	1.40	0.59	−0.81	−0.08
Bare soil	77.19	77.19	0	0
Bare rock	1.72	1.72	0	0
Total	13,916,290.45	14,678,485.21	+762,194.76	+76,219

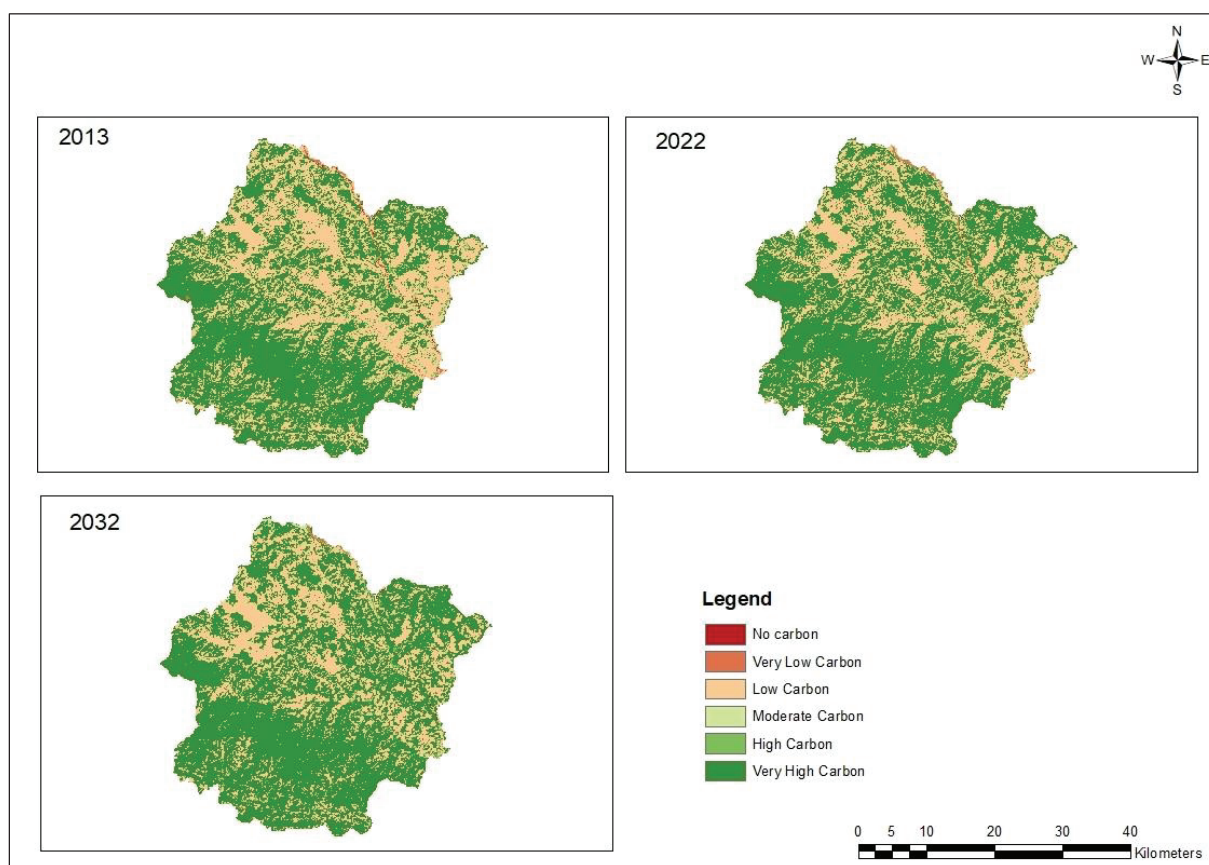


Figure 3: Spatial distribution of carbon density in Kavre District for 2013, 2022 and 2032

13.92 million Mg C in 2022 to a projected 14.68 million Mg C in 2032, resulting in a net gain of approximately 762,195 Mg C, equivalent to 2.79 MtCO₂e. This gain is primarily driven by forest expansion, which contributes an additional 889,815 Mg C during the period. However, the overall district-level gain is partially offset by carbon losses from cropland, grassland, and other wooded land. Therefore, the increase in carbon stock should not be interpreted simply as a result of forest area expansion, but as the net outcome of multiple land-cover transitions. Forest recovery remains the dominant factor, while continued conversion of cropland and grassland modifies the overall carbon balance.

The projected net carbon gain demonstrates Kavre's continued role as a carbon sink, driven mainly by forest expansion into abandoned croplands. This forest transition dynamic is consistent with findings by Upadhyay et al. (2011), who reported that labor emigration and changing crop prices in Nepal's watersheds have contributed to land abandonment

and natural forest regeneration. Since the InVEST model applies static carbon density values and accounts for land-cover transitions rather than dynamic vegetation growth, these estimates may be conservative. Actual sequestration could be higher if regenerating forests continue to accumulate biomass during the decade (Natural Capital Project, 2025).

The increase in carbon stock under the built-up class should be interpreted cautiously. The built-up class was assigned a low but non-zero carbon density of 11 Mg C ha⁻¹ in the InVEST biophysical table, representing residual soil carbon and limited vegetation within mixed settlement pixels, such as gardens, roadside trees, open plots, and small vegetated patches. Therefore, the increase in built-up carbon stock from 10,260.99 Mg C in 2022 to 17,027.21 Mg C in 2032 mainly reflects built-up area expansion, not carbon sequestration by impervious surfaces. For this reason, the term "net carbon stock change" is more appropriate than "sequestration" when interpreting changes across all LULC classes.

Spatially, the net present value (NPV) map of carbon sequestration (Fig. 4) reveals distinct carbon hotspot zones in the northern ridges and eastern forest blocks where forest recovery and densification are occurring. In contrast, red and orange zones of negative NPV are concentrated along cropland-to-built-up transition corridors in valley bottoms adjacent to the Araniko Highway. These areas indicate priority locations for conservation intervention and land-use planning. This spatial differentiation provides an MRV-compatible evidence base for targeting community forest user group investment plans under Nepal's TAL program.

3.3 Economic Valuation and REDD+ Payment Potential

The standing carbon stock of Kavre carries a notional gross asset value of approximately USD 255 million at the ERPA reference price of USD 5 per tCO₂e (Table 4). However, consistent with the results-based logic of REDD+ mechanisms, payments flow only for incremental, verified emission reductions above the Forest Reference Level and not for the standing stock itself (MoFE, 2023). The projected 2.79 MtCO₂e of additional sequestration yields a gross emission reduction value of approximately USD 14 million. After applying

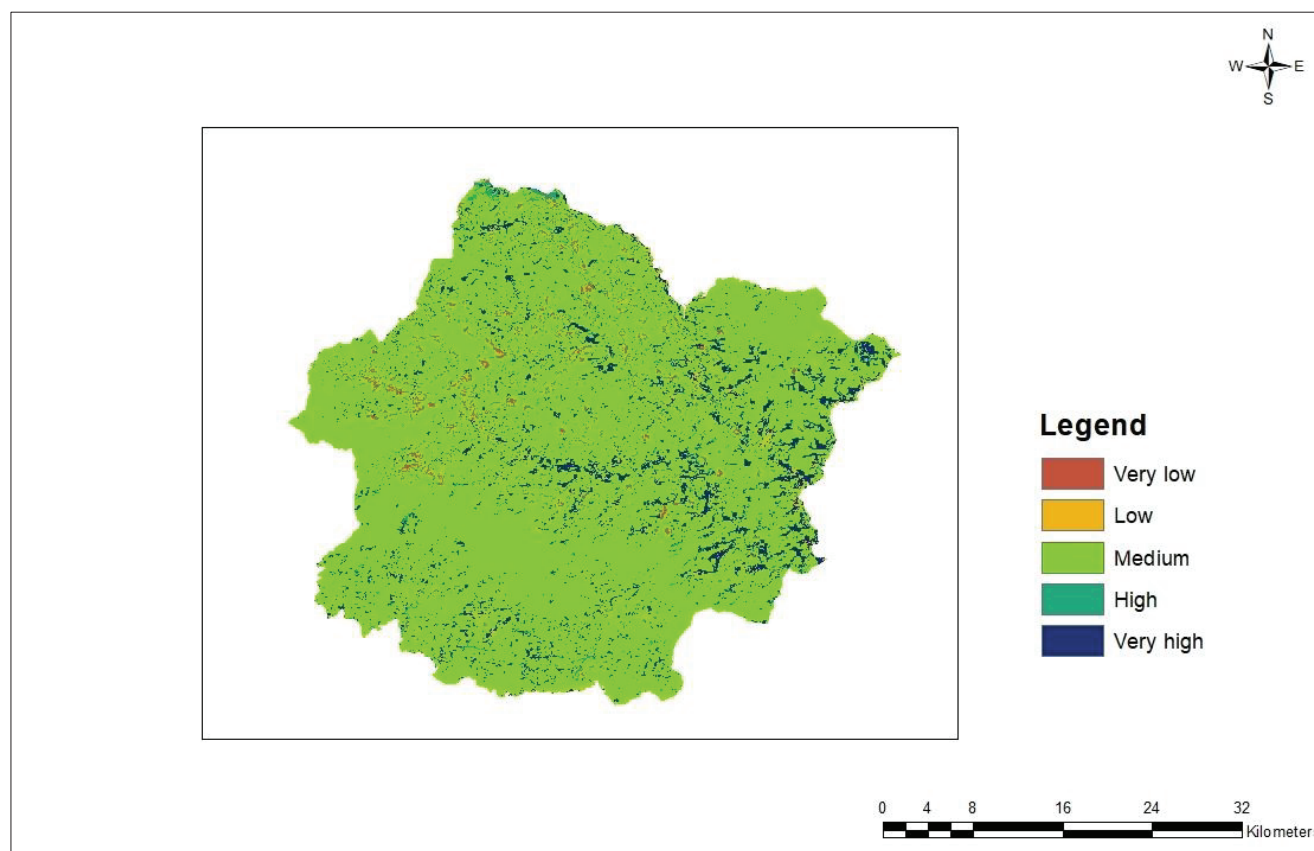


Figure 4: Map of the net present value (USD) of carbon sequestration in Kavre District between 2022 and 2032, calculated by the InVEST Carbon model. Blue zones indicate strong carbon sinks; red and orange zones indicate net carbon losses from land-use conversion

Table 5: Economic valuation of Kavre carbon stocks under REDD+ frameworks

Valuation Scenario	Carbon Quantity (MtCO ₂ e)	Estimated Value (USD)	Realizability
Standing stock value (2022)	51.0	~USD 255 million	Notional asset
Gross ER value (2022–2032)	2.79	~USD 14 million	Conditional on REDD+ enrollment
Net ER (after 23% buffer)	2.15	~USD 10.8 million	Conditional on verification
Realizable payment (after costs)	2.15	~USD 9.1–9.7 million	If performance verified

the TAL Benefit Sharing Plan's 23% uncertainty and risk reversal buffer and 15% combined operational and transaction cost deductions (MoFE, 2023), the net realizable payment envelope narrows to USD 9.1–9.7 million.

The economic valuation results further demonstrate the importance of distinguishing between ecological carbon value and realizable carbon finance. The standing carbon stock of the district represents a large notional asset value; however, results-based climate finance is generally linked to verified additional emission reductions or enhanced sequestration, not to the total standing stock. Therefore, the estimated realizable payment potential after applying uncertainty, risk reversal, and operational deductions is substantially lower than the gross carbon asset value. This distinction is critical for managing expectations among local governments and community forest user groups. Carbon finance should be communicated as a performance-based incentive for verified conservation and enhancement, rather than as a direct payment for all existing forest carbon.

The gap between the USD 255 million notional stock value and the USD 9.7 million realizable payment is not a failure of the approach but reflects the fundamental architecture of results-based climate finance: permanence, additionality, and verification requirements ensure that payment corresponds to genuine climate action rather than standing ecological capital (MoFE, 2023). This distinction is frequently misunderstood in district-level policy discussions and represents a key communication challenge for expanding community forest participation in Nepal's carbon market. Critically, these findings demonstrate that mid-hill districts such as Kavre harbor substantial potential for verifiable emission reductions. The estimated USD 9.1–9.7 million payment potential for a single mid-hill district of approximately 1,396 km² demonstrates the substantial results-based finance potential of Nepal's hilly landscapes. The recent LEAF Coalition ERPA, covering Bagmati, Gandaki and Lumbini provinces and potentially mobilizing up to USD 55 million, confirms that this opportunity is increasingly being recognized within

Nepal's jurisdictional REDD+ strategy (REDD Implementation Centre, 2026). In this context, the present estimate provides district-level evidence that can support the effective scaling, prioritization and benefit-sharing design of REDD+ programmes in Nepal's mid-hill regions. (REDD Implementation Centre, 2026). WWF Nepal (2025) recently confirmed the disbursement of Nepal's inaugural REDD+ payment of USD 9.4 million from FCPF, validating the financial architecture complying Kavre's projections.

From a community forestry perspective, the TAL Benefit Sharing Plan allocates 80% of performance-based payments to CFUGs, 5% to private forest owners, and 5% to forest-dependent households (MoFE, 2023). For Kavre's CFUGs, which have demonstrated sustained forest recovery over the 2013–2032 modeling period, this creates a meaningful incentive structure provided that carbon rights are clearly assigned, MRV systems are linked to district-level LULC data of the type produced by this study, and benefit-sharing governance mechanisms are strengthened to reach women, indigenous, and marginalized household members who are currently underserved by CFUG governance structures.

The findings also have practical implications for REDD+ and subnational carbon planning in Nepal. The spatial distribution of carbon gain and loss can help identify priority zones for forest conservation, assisted natural regeneration, and control of land-use conversion. Areas showing high carbon gain may be suitable for strengthening community forest management and benefit-sharing mechanisms, while areas showing low or negative carbon values may require targeted land-use regulation, restoration, or infrastructure planning. Since Kavre lies close to rapidly urbanizing zones, integrating carbon-sensitive spatial planning into municipal land-use plans will be important to maintain long-term carbon benefits.

3.4 Uncertainty and Limitations

Despite these findings, the results should be interpreted with caution. The analysis depends on the accuracy of LULC classification, the

assumptions used for projecting 2032 land cover, and the carbon pool values assigned in the InVEST model. The InVEST carbon model uses static carbon density values for each land-cover class and does not fully capture gradual biomass growth, forest age structure, management quality, degradation, or soil carbon dynamics over time. Similarly, economic valuation is sensitive to assumptions regarding carbon price, discount rate, uncertainty buffer, and transaction or operational costs. Therefore, the estimated carbon and payment values should be considered indicative planning estimates rather than exact financial or biophysical measurements.

4. Conclusion

This study provides an integrated district-level assessment of LULC dynamics, carbon stock change, and REDD+-aligned economic valuation for Kavrepalanchowk District, Nepal. The findings indicate that forest cover is projected to increase to 66.6% by 2032, while cropland is expected to continue declining. A net carbon stock gain of 762,195 Mg C, equivalent to 2.79 MtCO₂e, is projected over the 2022–2032 period. After applying verification buffers and operational cost deductions, the realizable results-based payment potential under REDD+ mechanisms is estimated at USD 9.1–9.7 million.

These findings carry three direct policy implications. First, Nepal's carbon finance architecture should be extended beyond the Terai Arc Landscape to mid-hill districts with documented modeled carbon stock gain, using the MRV-compatible district-level evidence produced by this and similar studies. Second, land-use planning in Kavre must explicitly target the built-up expansion corridors along major highways, where land conversion threatens the highest-value carbon sink zones identified in the NPV spatial analysis. Third, the USD 255 million standing stock value versus USD 9.7 million realizable payment contrast should inform community-level communication strategies, ensuring that CFUGs and local governments hold realistic expectations about carbon market revenue and do not conflate ecological asset value with immediate financial returns. Future research should

extend the temporal horizon to at least 2050 using ensemble climate scenarios to capture longer-term forest dynamics, and should incorporate ecosystem co-benefits like biodiversity, water regulation, and livelihood services to support holistic ecosystem service valuation for mid-hill districts of Nepal and support climate change adaptation and mitigation in the long run.

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Forest-Type Variation in Vegetation Structure and Tree Carbon Stocks in the Mid-Hill Forests of Central Nepal Himalaya

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Abstract

Forest ecosystems are major contributors to climate change mitigation and the provision of ecosystem services. In this study, we assessed plant diversity and carbon stocks across different forest types in a middle mountain region of Lalitpur district of Nepal. Stratified purposive vegetation sampling was used for data collection. The results revealed that different vascular plant species diversity varies with forest type and structure. Herbaceous plant diversity was highest followed by tree and shrubs. The *Quercus* forest exhibited a higher carbon stock of 118.06 t/ha, suggesting strong carbon storage potential, whereas the *Alnus* forest had the lowest carbon stock (30.25 t/ha), indicating limited carbon storage capacity. It is concluded that *Quercus* forests are the most effective for carbon storage and climate change mitigation, whereas broadleaf mixed forests have high ecological significance by supporting rich biodiversity and providing considerable carbon storage potential. Based on these findings, forest management and conservation strategies are essential for the restoration and conservation of ecologically sensitive forest ecosystems in the middle mountains of the Nepal Himalaya.

Keywords: *Biodiversity conservation, climate change, community forest, forest restoration, plant invasion*

Introduction

Forests are globally important terrestrial ecosystems for biodiversity conservation and carbon storage but their proper study and measurements are still lacking (Dixon et al., 1994; Schimel et al., 2001). Measurements of forest components, including species composition, diversity, basal area, tree density, stem height, stem diameter, and age-class and geographic distribution patterns, can all be used to describe the “structure” of a forest (Smith, 1992; Sharma et al., 2020b). Forest vegetation has been a significant focus of ecological studies aimed at exploring the relationships and interactions between different vegetation types and their natural environments. Such understanding aids informed decision-making for the conservation and management of natural resources (Lynam et al., 2007; Paudel et al., 2011).

Several studies (Paudyal et al., 2015; Sharma et al., 2020a; Pandey, 2021) have documented forest carbon stocks and species diversity in Nepal, particularly in mid-hill forests and Himalayan

regions. These studies consistently show that both carbon storage and species diversity vary across forest types and along elevational gradients, driven by changes in species composition, forest structure, and environmental conditions. In Nepal, such patterns are further influenced by forest management regimes, especially community forests, which play an important role in conserving biodiversity, enhancing forest regeneration, and maintaining ecosystem services through local stewardship.

Community forests provide a wide range of ecosystem services, including the supply of firewood and fresh water, water regulation, soil protection, landscape beauty, biodiversity conservation and carbon sequestration (Paudyal et al., 2015). Carbon absorbed by plants is primarily converted and stored as biomass through natural physiological processes (Jindal et al., 2008). Unlike many agricultural crops, woody vegetation has a much greater capacity to store carbon over long periods, ranging from decades to centuries.

Consequently, forest ecosystems act as major carbon sinks, storing approximately 20 to 100 times more carbon per unit area than agricultural lands (Dixon et al., 1994; Paudyal et al., 2015; Singh et al., 2025).

In the context of Nepal, relatively little is known about carbon stocks in *Alnus* forests. Moreover, no comparative multi-forest-type study integrating importance value index (IVI), carbon stock, and biodiversity has been conducted in Mahankal Rural Municipality of Lalitpur District. This research gap is addressed through a comparison of forest structure, species composition (tree, shrub, and herb layers), and carbon stock across three forest types (*Alnus* forest, broadleaf mixed forest, and *Quercus* forest) occurring at different elevations in Mahankal Rural Municipality, Lalitpur District of Central Nepal. Therefore, this study aimed to compare and assess the ecosystem characteristics of different forest types across an elevational gradient in central Nepal.

Materials and Methods

Study area

The study was carried out in Mahankal rural municipality, the southern part of Lalitpur district. It extends from 85.3333° to 85.4333° East and 27.4167° to 27.5833° North (Figure 1). Elevation range of study area is 1433m to 2353m. The climatic condition of the study site is warm temperate to cool temperate climate. The average annual temperature range of study site is 10°C to 20°C and annual rainfall is about 1400 mm (<https://www.dhm.gov.np/>). The study site encompasses the community forest of Mahankal Rural Municipality, covering approximately 500 ha of forest land distributed across the three major forest types: *Alnus* forest (approximately 80 ha), broadleaf mixed forest (approximately 270 ha) and *Quercus* forest (approximately 150 ha).

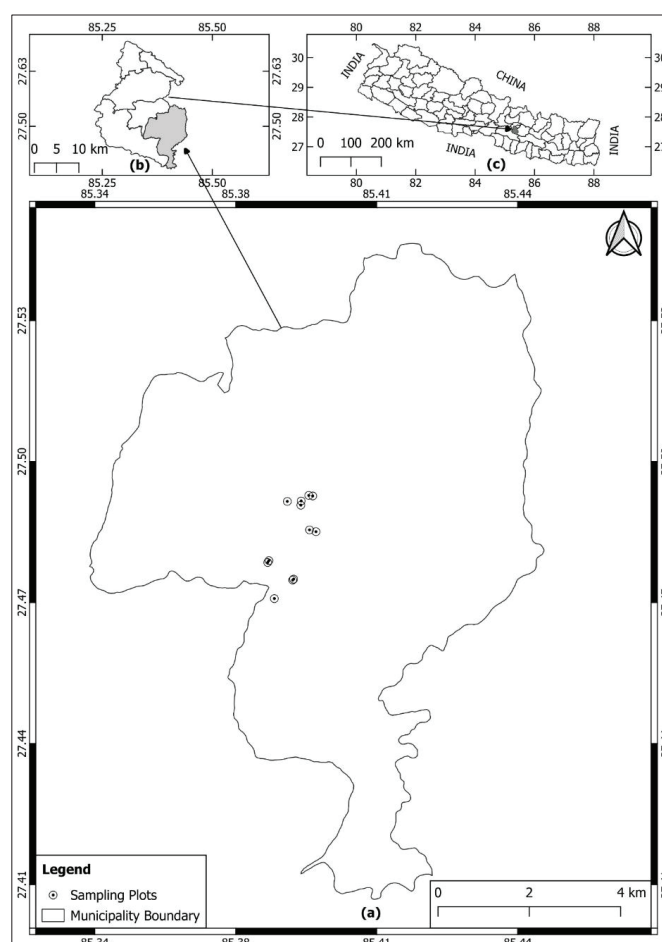


Figure 1: Study area map showing the sample plots in Mahakal rural municipality Lalitpur Nepal (a), Lalitpur district with local bodies (b), District map of Nepal (c).

Table 1: Characteristics of the study sites, forests and vegetation sample plots

SN	Forest type	Plot no.	Latitude (°N)	Longitude (°E)	Slope (°)	Altitude (m)	Aspect (°)	Litter Depth (cm)	Canopy (%)
1	<i>Alnus</i> forest	1	27.49249	85.39119	29	1433	266	6.0	84
		2	27.49237	85.39207	5.0	1506	73	1.2	93
		3	27.49033	85.38943	39	1474	296	0.8	63
2	Broadleaf mixed forest	4	27.47395	85.38784	40	1529	142	4.0	90
		5	27.48486	85.39136	34	1779	94	4.5	90
		6	27.49126	85.38951	38	1463	150	8.0	86
		7	27.47373	85.38763	49	1930	78	4.1	93
3	<i>Quercus</i> forest	8	27.47763	85.38209	43	2206	58	5.0	84
		9	27.46963	85.38356	45	2301	254	6.0	91
		10	27.47804	85.38235	37	2062	321	2.5	94
		11	27.49116	85.38644	54	2353	61	1.2	93
		12	27.48445	85.39279	54	2052	181	3.9	95

Sampling Methods

A stratified purposive sampling design was used, with plots placed in representative, structurally intact (dense) patches of each forest type to capture characteristic species assemblages across the elevational gradient (Tylor et al., 1993; Sharma et al., 2020a). A total of 60 plots were established, 36 plots for herbs and seedlings, 12 plots for shrubs and samplings and 12 plots for trees. Sub-plots were created for shrub and sapling as well as herbs and seedlings inside the main tree plot. The number of plots were maintained at a minimum of three per forest stand but differed among forest types because sampling intensity was adjusted according to within-stand heterogeneity and patch size. Relatively homogeneous and spatially limited *Alnus* forest patches required fewer plots, as their structural and compositional variability was low. In contrast, *Quercus* forest and broadleaf mixed forest exhibited higher structural and compositional heterogeneity, requiring a greater number of plots to adequately capture their variability and ensure representative sampling. Therefore, three main plots in *Alnus* forest, four main plots in *Quercus* forest and five main plots in broadleaf mixed forest were established. Plots were selected to represent the range of elevations, slopes, and aspects present within each forest type (Table 1). For tree species, a main plot measuring 20 m × 20 m was established using a rectangular quadrat and marked with ribbons, measuring tape and rope. The vegetation data, including diameter at breast height (DBH) and

height of each tree within this area, were measured and recorded.

For shrubs and saplings, a sub-quadrat measuring 5m×5m was used. Saplings were recorded based on a DBH of less than 5 cm and greater than 1 cm, while shrubs were defined as individuals with several main stems arising at or near the ground, with stem diameter measured at height 10 cm above the soil surface. Additionally, three subplots measuring 1m×1m were designated for sampling seedlings, herbs, including pteridophytes. Seedlings were counted and recorded if they had a DBH of less than 1 cm. Herb cover was estimated visually as a percentage. Tree canopy measurements were taken using a densitometer at the four corners and the center of each plot. Mean canopy cover was calculated based on these observations. Shrub and tree cover were also measured in terms of basal area. All relevant information on trees, shrubs, saplings, herbs, and seedlings, including species names, diameter, heights, slopes and cover, was recorded from each sampling plot.

Vegetation data analysis

The recorded data were used to calculate frequency, density, basal area, and importance value index (IVI) of plant species using the following formulae (Curtis & McIntosh, 1951; Zobel et al., 1987; Singh et al., 2014):

$$\text{Frequency (F)} = \frac{\text{No. of plot in which species occurred}}{\text{Total number of plot examined}} \times 100\%$$

$$\text{Relative Frequency (RF)} = \frac{\text{Frequency of individual species}}{\text{Total frequency of all species}} \times 100\%$$

$$\text{Density (stem/ha)} = \frac{\text{Total number of individual of species in all plot}}{\text{Total number of sample plot} \times \text{size of plot}} \times 10000$$

$$\text{Relative Density (RD)} = \frac{\text{Density of the individual species}}{\text{Total density of all species}} \times 100\%$$

$$\text{Herb Coverage (\%)} = \frac{\text{Area covered by a species within the quadrat} \times 100}{\text{Total area of the quadrat}}$$

$$\text{Relative Coverage (\%)} = \frac{\text{Coverage of individual species}}{\text{Total coverage of all species}} \times 100\%$$

$$\text{Basal Area (BA)} = \frac{\pi d^2}{4}$$

Where,

d = DBH (diameter at breast height)

$$\text{Basal area of a species (per ha)} = \frac{\text{Total basal area of a species in all plots}}{\text{Size of the plot (m}^2\text{)} \times \text{no. of plots}} \times 10000$$

$$\text{Relative Basal Area (RBA)} = \frac{\text{Basal area of individual species}}{\text{Total basal area of all species}} \times 100\%$$

$$\text{Importance Value Index (IVI)} = \text{RF} + \text{RD} + \text{RBA}$$

Note: Range of IVI is 0 to 300.

Biomass and Carbon Stock Estimation

The biomass and carbon stock estimation were done using the allometric models developed by Chave et al. (2005) for moist forest with rainfall 1500 mm to 4000 mm, and the wood density of trees were taken from ICRAF database (<http://db.worldagroforestry.org/>).

To calculate aboveground biomass (AGB) = $(0.0509 \times \rho D^2 H)$ kg was used. Where, ρ = specific wood density, d = diameter (cm) and H = height of plant (m).

Similarly, Below Ground Tree biomass (BGTB) was calculated considering 25% of the above ground tree biomass. Aboveground carbon (AGC) and belowground carbon (BGC) were determined by multiplying the biomass by 0.47 and total carbon stock was calculated as (Mac Dicken, 1997):

$$\text{Total Carbon Stock (Kg)} = \text{AGC} + \text{BGC}$$

Collected and calculated data were organized and managed using spreadsheets. Descriptive statistical methods were applied to summarize and compare

key forest vegetation parameters. The results were presented through bar graphs, scatter plots, tables, and pie charts to interpret and visual comparison of vegetation characteristics among forests.

Results and Discussion

Forest Structure and Composition

A total of 80 herb and seedling species, 23 tree species as well as 27 shrub and sapling species were recorded in the study forests (Figure 2). The tree layer included ecologically important taxa such as *Quercus*, *Castanopsis*, *Schima*, *Rhododendron*, and *Symplocos*. In the shrub layer, dominant taxa were *Rubus*, *Symplocos*, and *Rhododendron*. Similarly, in the herb layer, taxa such as *Bidens*, *Strobilanthes* and *Ageratina* were dominant (Figure 3, 4 & 5). These results are comparable with the findings (Pandey, 2007; Baral & Katzensteiner, 2009; Joshi et al., 2023).

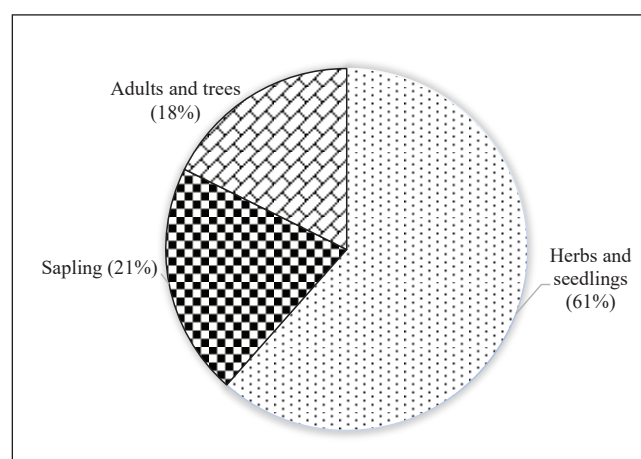


Figure 2. Number and percentage contribution of species in each life form in the study forests

Herb and Seedling Layer

The herb and seedling layer was highly diverse, comprising 80 species in total (Figure 2), indicating rich understory diversity and favorable microhabitats. In *Alnus* forest, 27 herbaceous species were recorded, with *Persicaria capitata* (IVI 54.60) and *Bidens pilosa* (IVI 53.23) as the most dominant species (Figure 3a). Their dominance highlights their importance in understory structure and ecological functioning. This pattern is consistent with previous studies showing that *B. pilosa* is common in disturbed habitats and acts as

a pioneer species contributing to soil stabilization (Yu & Sun, 2013). In broadleaf mixed forest, 54 herb species were recorded, with *Strobilanthes* sp. (IVI 31.50) as the most dominant species, followed by *Onychium* sp. (IVI 29.57) and *Impatiens* sp. (IVI 25.50), whereas *Ageratina adenophora* and *Oplismenus* sp. showed moderate dominance and *Achyranthes aspera* and *Fagopyrum* sp. were least dominant (Figure 3b). Two unidentified species also contributed 20 and 36 individuals, indicating gaps in species identification. In *Quercus* forest, *Strobilanthes* sp. remained dominant (IVI 27.32), followed by *Impatiens* sp. (IVI 19.76), *Pilea* sp. (IVI 18.56), and *A. adenophora* (IVI 11.28), while *Hedera nepalensis* (IVI 2.08) and *Phyllanthus* sp. (IVI 1.32) had low ecological importance (Figure 3c). Overall, the dominance of pioneer and shade-tolerant species suggests that the understory communities are influenced by canopy conditions and disturbance history and the findings are

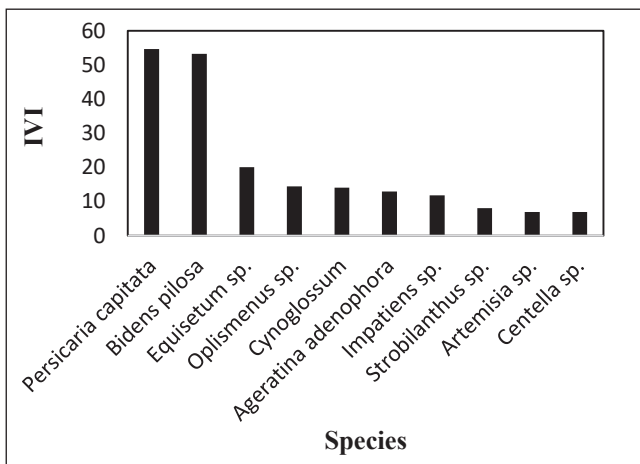


Figure 3a: IVI value of top 10 herbs and seedling species of *Alnus* forest

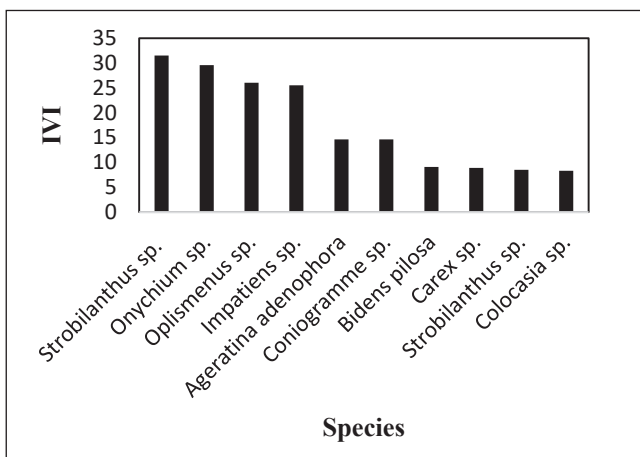


Figure 3b: IVI value of top 10 herbs and seedling species of broadleaf mixed forest

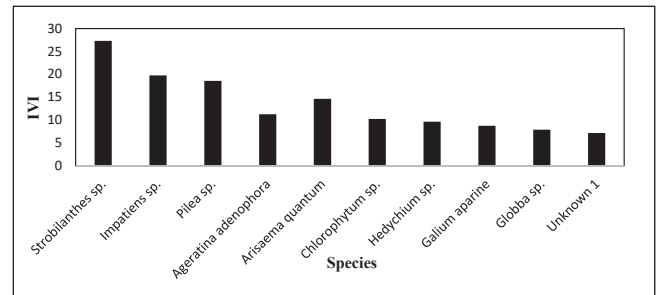


Figure 3c: IVI of herbs to 10 herbs and seedling of *Quercus* dominated forest

comparable with the findings (Sharma et al., 2020a; Joshi et al., 2023).

Shrub and Sapling Layer

The shrub and sapling layer comprised 27 species, reflecting active regeneration and structural complexity within the forests. In broadleaf mixed forest, *Pyrus pashia* (IVI 26.52) and *Schima wallichii* (IVI 24.76) were the dominant species, followed by *Syzygium cumini* (IVI 22.13) and *Alnus nepalensis* (IVI 10.57) (Figure 4a). In *Quercus* forest, *Litsea* sp. showed the highest dominance (IVI 71.10), followed by *Callicarpa arborea* (IVI 67.17) and *Eurya acuminata* (IVI 33.98), whereas *Rhododendron arboreum* and *Wikstroemia* sp. exhibited moderate importance (IVI 13.80 and 9.62) (Figure 4b). In *Alnus* forest, only five shrub species were recorded, with *Rubus ellipticus* (IVI 80.47) being consistently dominant, followed by *Koenigia mollis* (IVI 57.89) and *E. acuminata* (IVI 57.45) (Figure 4c). The dominance of *R. ellipticus*

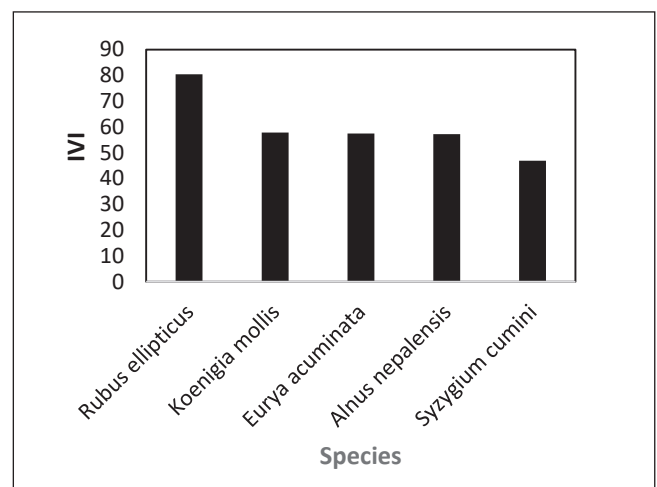


Figure 4a: IVI value of top five shrubs and sapling species of *Alnus* forest

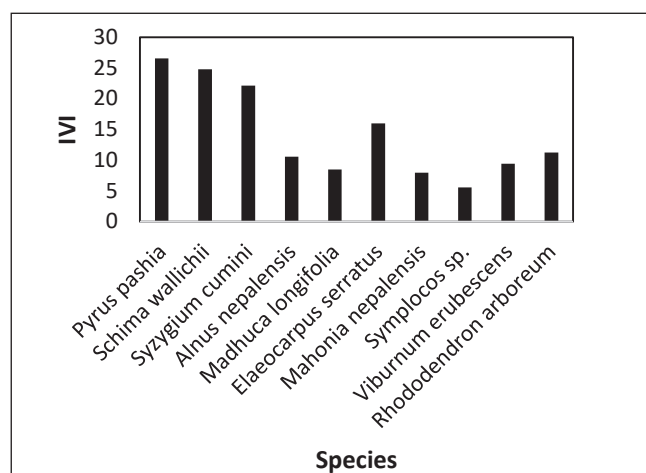


Figure 4b: IVI value of top 10 shrubs and sapling species of broadleaf mixed forest

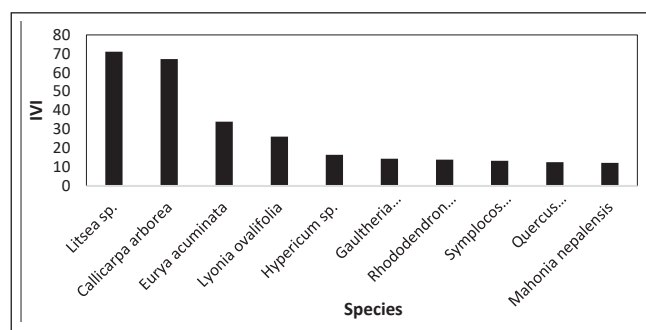


Figure 4c: IVI of top 10 shrub and sapling of *Quercus* forest

in disturbed and regenerating stands comply with previous reports highlighting its importance in maintaining forest biodiversity (Yu & Sun, 2013; Sharma et al., 2020a). Moreover, the occurrence of *E. acuminata* in both tree and shrub layers indicates high successional dynamics and shade tolerance for natural regeneration.

Tree Layer

The tree layer exhibited distinct compositional patterns among forest types. In *Alnus* forest, *Alnus nepalensis* showed high density (128.75 stems ha⁻¹) and 100% frequency across plots, contributing more than 95% of the IVI and indicating a nearly monospecific stand, while species such as *Syzygium cumini* and *Eurya acuminata* contributed less than 5% IVI. The strong dominance of *A. nepalensis* reflects its role as a pioneer nitrogen-fixing species that enhances soil fertility and facilitates ecosystem recovery in the plant invaded disturbed sites (Sharma et al., 1998; Ranabhat et al., 2008). In broadleaf mixed forest, 18 tree species were identified,

with *Rhododendron arboreum* (IVI 43.24) and *E. acuminata* (IVI 42.79) being the most dominant species, while *Prunus* sp., *Engelhardtia* sp., and *Ficus* sp. showed very low IVI values, indicating limited ecological contribution (Figure 5a). In contrast, *Quercus* forest was strongly dominated by *Quercus semecarpifolia* (IVI 108.01) (Figure 5b), highlighting its high ecological importance. These patterns suggest that each forest type is characterized by a distinct dominant species, reflecting differences in successional stage, environmental conditions, and species-specific ecological strategies.

Litter depth and canopy cover varied among forest types. Mixed forests showed higher litter accumulation (3.9–8.0 cm) with dense canopy cover (86–95%), while *Quercus* forests exhibited moderate to high canopy cover (84–94%) with variable litter

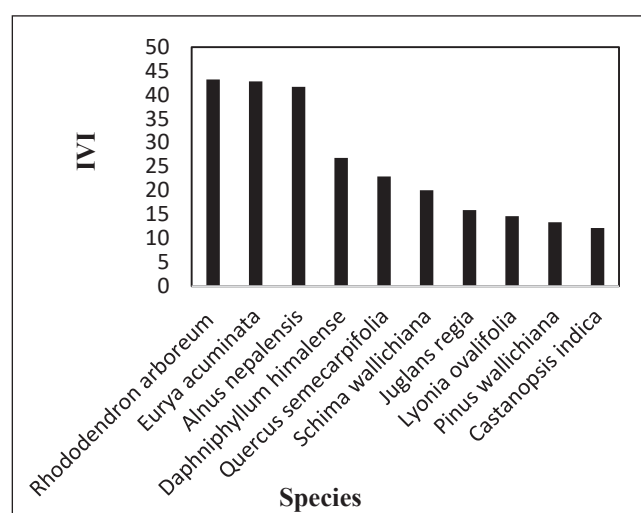


Figure 5a: IVI value of top 10 tree species of broadleaf mixed forest

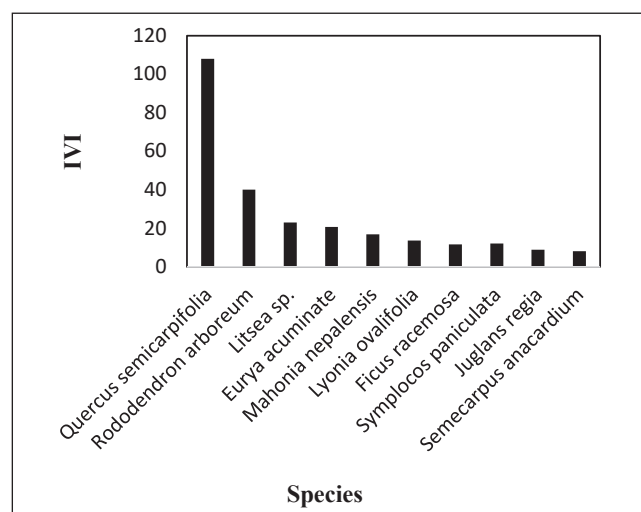


Figure 5b: IVI value of top 10 tree species of *Quercus* forest

depth. *Alnus* forests showed comparatively lower litter depth despite high canopy closure in some plots (Table 1).

Carbon Stocks

Carbon stock analysis revealed clear differences among forest types. *Quercus* forest exhibited the highest mean carbon stock (118.06 t/ha), ranging from 73.97 to 202.16 t/ha, followed by mixed forest (88.86 t/ha; 24.57–180.87 t/ha), while *Alnus* forest had the lowest stock (30.25 t/ha; 13.46–44.93 t/ha) (Figure 6). The higher carbon stock in *Quercus* forest reflects its mature stand structure and high biomass accumulation, consistent with earlier studies reporting strong carbon storage capacity in oak-dominated forests (Bruckman et al., 2011; Rawat et al., 2022).

The relatively moderate carbon stock in mixed forests suggests species-driven variability in biomass accumulation (Malhi et al., 1999; Sharma et al., 2020b; Joshi & Garkoti, 2021), while the low carbon stock in *Alnus* forests may be attributed to their young, regenerating nature and smaller diameter classes. *Alnus* forests primarily contribute to nutrient cycling rather than long-term carbon storage (Houghton et al., 2012). Similar patterns have been reported in Nepalese forest systems (Sharma et al., 2020a; Joshi et al., 2021).

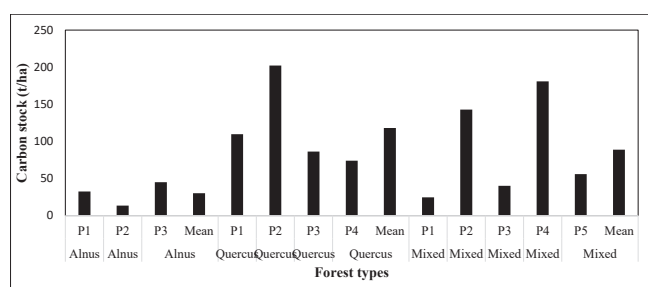


Figure 7: Plot wise and mean carbon stock of the different forest types

A positive but non-significant relationship between elevation and carbon stock was observed (Figure 7), possibly due to limited sample size and elevation range. Overall, these findings highlight that *Quercus* forests are the most effective carbon sinks, followed by mixed forests, while *Alnus* forests contribute less to carbon storage but play an important role

in ecosystem succession and soil improvement (Joshi & Garkoti, 2021). These results emphasize the importance of forest type-specific management for optimizing carbon sequestration, biodiversity conservation and landscape management in mid-hill forests of Nepal (Gilani et al., 2025; Nag & Magar, 2023).

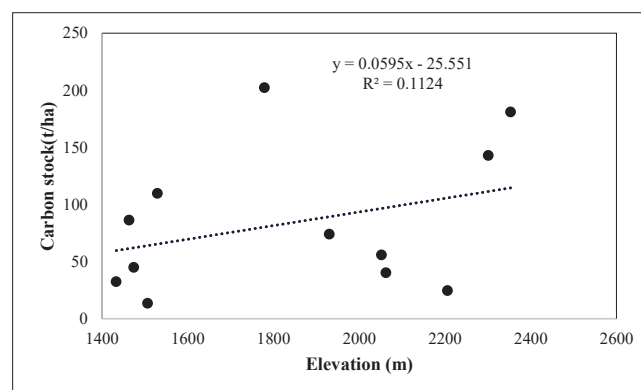


Figure 8: Relationship between carbon stock and elevation

Conclusion

Different forest types exhibit distinct structures and species compositions. We conclude that mixed forests are the most effective in sustaining ecosystem functions, particularly biodiversity conservation, plant invasion control and climate change mitigation through carbon sequestration. *Quercus* forests have high potential for carbon storage, whereas *Alnus* forests are relatively poor in species diversity and carbon stock; however, they play a crucial role in slope stabilization and forest development as pioneer communities in ecological succession. In the middle mountains of Nepal, these forest types are ecologically important and should be prioritized for conservation to ensure the proper functioning and long-term sustainability of these ecosystems.

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Climate Change Impacts on Alpine Vegetation: The Role of Microclimatic Variability

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Abstract

Global surface temperatures have increased by about 1.1°C relative to 1850–1900, with 2011–2020 being the warmest decade on record and accompanied by changing precipitation patterns. Warming is amplified in alpine regions such as the European Alps, where temperature increases have been roughly twice the northern hemispheric average since the late 19th century, alongside contrasting precipitation trends between northern (wetter) and south-eastern (drier) areas. Alpine ecosystems, defined as treeless zones above the tree line, are highly sensitive to climate change, exhibiting upward species shifts, phenological changes, vegetation restructuring, and local extinctions. However, strong microclimatic heterogeneity may buffer these impacts. This study presents a narrative literature review of microclimatic buffering in alpine vegetation. The evidence was synthesized showing how topography-driven radiation differences, wind-induced cold-air pooling, and snow dynamics generate fine-scale habitat variability. These processes create microhabitats that can reduce exposure to macroclimatic warming and support potential microrefugia for plant species. The study argues that microclimatic buffering is a key but still insufficiently understood mechanism shaping alpine vegetation responses to climate change. Improved understanding of its limits is essential for more accurate predictions of vegetation dynamics and for informing conservation strategies in mountain ecosystems.

Keywords: *Mountain region, microhabitat, upward mobility, vegetation dynamics*

1. Introduction

A human-caused global surface temperature rise of 1.1°C (2011-2020 compared to 1850-1900) and changing precipitation patterns were determined by the Intergovernmental Panel on Climate Change (IPCC) (Calvin et al., 2023). This increase is not uniform across the globe, but enhanced warming rates can be observed over land and in higher latitudes (Calvin et al., 2023). However, there is also a tendency of higher warming rates at high elevations (Pepin et al., 2022), which is especially pronounced in some alpine regions like the European Alps (Kuhn and Olefs, 2020). In the European Alps a temperature rise about twice as large as the northern-hemispheric average was observed from the end of the 19th until the end of the 20th century (Gobiet et al., 2014). Precipitation patterns, however, are changing less uniformly. Already when only considering one alpine region, like the European Alps, changes in the precipitation pattern strongly depend on the region and season.

For example, an increase in precipitation was observed in the northern area of the Alps, especially during fall, while the south-eastern alps show a strong drying trend (Gobiet et al., 2014). Globally, these changes in precipitation patterns vary even stronger between different alpine regions. 15% of the total land surface is covered by alpine environments (Inouye, 2020), treeless areas located above the tree line in mountains (Verrall & Pickering, 2020). They can be found from the equator to close to the poles, occurring at higher elevation at lower compared to high latitudes, since their occurrence is connected to the low temperatures resulting in the absence of trees (Körner, 2021). The alpine area can be divided into the alpine zone, bordered below by the tree line, and the nival zone, extending up to the height in which plant life is limited (Grabherr et al., 2010). The alpine zone is characterized by closed plant communities, while the nival zone is dominated by open vegetation (Grabherr et al., 2010). Low temperatures, short growing seasons

and highly heterogeneous landscape morphology are characteristic for the alpine environment, which is giving home to alpine plants, highly specialized to cope with these harsh environmental conditions (Körner, 2023).

Climate change directly and indirectly alters the environment of these specialized alpine plants, resulting in various vegetation responses. Upward migration of plant species, phenological alterations, changes in vegetation structure, evolutionary adaptation as well as extinctions are important reactions of plants to climate change. However, the heterogeneous landscapes in alpine regions, resulting in a high diversity of microclimates and habitats complicate the observed trends and may even be able to buffer the negative effect of climate change.

While broad macroclimatic trends in alpine regions are well-documented, global vegetation models often fail to capture how small-scale topographic variations decouple local microclimates from regional warming. Furthermore, literature is frequently fragmented across separate discussions of individual species responses (such as phenology or migration) without synthesizing how these mechanisms interact to alter community structure, generate ecological mismatches, or accelerate extinction debts.

This review synthesizes current ecological literature to address three key questions:

- (1) Topographic variation and plant–trait feedbacks shape alpine microclimates and their capacity to buffer macroclimatic warming;
- (2) Climate-driven upward migration and phenological shifts affect species interactions at individual and community levels; and
- (3) Encroachment (woody) and structural change alter alpine ecosystem function, and what constraints limit the adaptive capacity of alpine flora before reaching extinction thresholds.

2. Methods

In this review, a structured literature-based methodology was used to compile and synthesize

the existing information on the consequences of climate change on alpine vegetation, focusing on the importance of microclimatic heterogeneity in moderating ecological changes. Peer-reviewed articles up to 2026 were identified via systematic database searches (Web of Science, Scopus, selected due to their broad scope of ecological, biogeographical and climate change research) using relevant search terms investigating climate-induced shifts in alpine vegetation dynamics. The search was designed to cover the major themes of this review: microclimatic buffering, changes in species distributions, phenological alterations, community reorganizations, and extinctions. Boolean combinations of search terms were used, with ‘alpine vegetation’ combined with terms such as ‘microclimate’, ‘phenology’, “upward migration” or “range shift”, “extinction debt”, as well as the interaction of topography, climatic velocity and change. Literature found through backward citation chasing (by examining references within key reviews and strongly-cited empirical works) were additionally incorporated to ensure that core conceptual work was included.

The geographical scope of the review is global, focusing on alpine, sub-nival, and nival ecosystems across major mountain systems. Studies from the Tibetan Plateau, Nepal Himalaya, and other Himalayan regions were also considered; however, the number of peer-reviewed studies meeting the inclusion criteria and suitable for synthesis was limited. All relevant and methodologically robust studies available from these regions were included to ensure representation within the constraints of the existing literature.

This review followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for study identification, screening, eligibility assessment, and inclusion, and a PRISMA flow diagram (Figure 1) is used to document the selection process (Page et al., 2021).

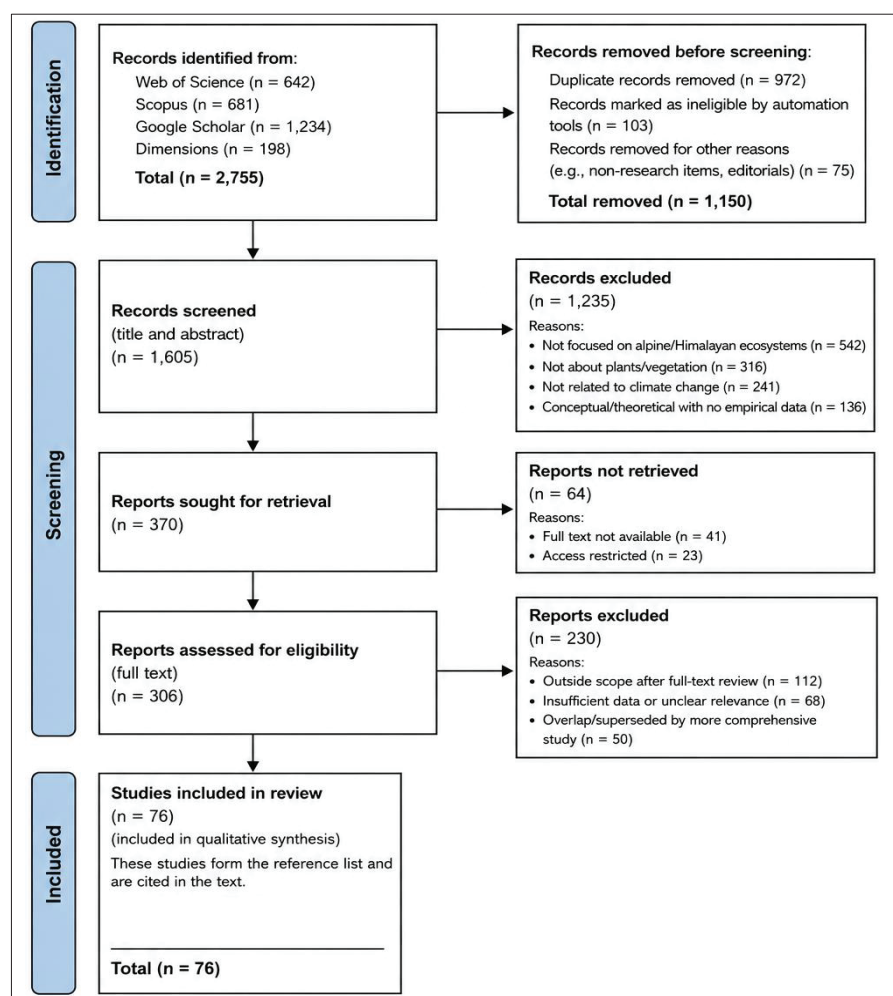


Figure 1: The flow diagram of PRISMA method used for the review of literature.

This review considered only studies from the alpine, sub-nival and nival regions that examine vegetation that is in direct contact with climate forcing agents at high elevation sites (except for those needed for methodological or technical sense). High-resolution microclimatic measurements, empirical field studies of how vegetation is responding to climate change, and modelling studies that employed accepted species distribution models or a climate velocity approach were emphasized. Terrain-resolved climate data studies and long-term vegetation monitoring data were seen as most valuable because these provide information on interaction between global-scale climatic trends and local-level environmental variability. Vegetation studies outside alpine, sub-nival, and nival ecosystems were excluded to maintain focus on high-elevation climate–vegetation interactions, as were greenhouse or growth-chamber experiments which do not

accurately reflect climate forcing of vegetation, nor controlled or greenhouse studies not validated in the field. Modelling studies were only included if supported by field validation, or if using well-accepted modeling frameworks.

The inclusion and exclusion criteria were explicitly defined to ensure consistency and reproducibility in study selection, including restriction to field-based or field-validated alpine studies addressing vegetation–climate interactions.

This collected literature was organized into three subject categories relating to the aims of this review,

- (i) microclimatic buffers and ameliorating effects of landscape features such as topography and snow cover, as well as cold-air pooling,
- (ii) range and compositional shifts of species populations and community turnover in

response to climate, including thermophilisation and diversity shifts, and

- (iii) plant phenological shifts and species interactions including changes in timing of flowering, response to snow melt and plant-pollinator interactions.

These categories allow a comparison of which mechanisms have received more attention within and among subalpine environments, as well as where knowledge gaps still exist. As this review found, studies that assess range and community-level climate response and which employ climate data studies that are resolved to the landscape-level are abundant, whereas studies that provide direct, quantitative estimates of the microclimatic buffering capacity of landscape features such as snow or cold-air pooling are scarce, although it is acknowledged that this mechanism can significantly mitigate impacts of climate warming (Körner, 2021; Pepin et al., 2022). Likewise, phenological responses to climate change are receiving increased interest, yet few of these studies specifically integrate how microclimate influences phenological synchrony among species and in relation to associated species.

A thematic synthesis approach was used to qualitatively group and compare studies across these three categories to identify dominant research trends and knowledge gaps.

These interaction mechanisms must be combined to have a coherent view of how macroclimatic change affects alpine vegetation via microclimatic buffering and ecological feedback. The conceptual framework, figure 2, outlines these processes.

Rising temperatures and altered precipitation regimes modify topographic, snow-related, and vegetation-driven microclimatic conditions, which in turn influence vegetation responses, including upward range shifts, phenological shifts, community turnover, and shrubification. These responses ultimately determine whether species persist through adaptation and occupation of microrefugia or experience increased extinction risk. Figure 2 illustrates the importance of microclimatic heterogeneity in shaping alpine ecosystem responses to climate change.

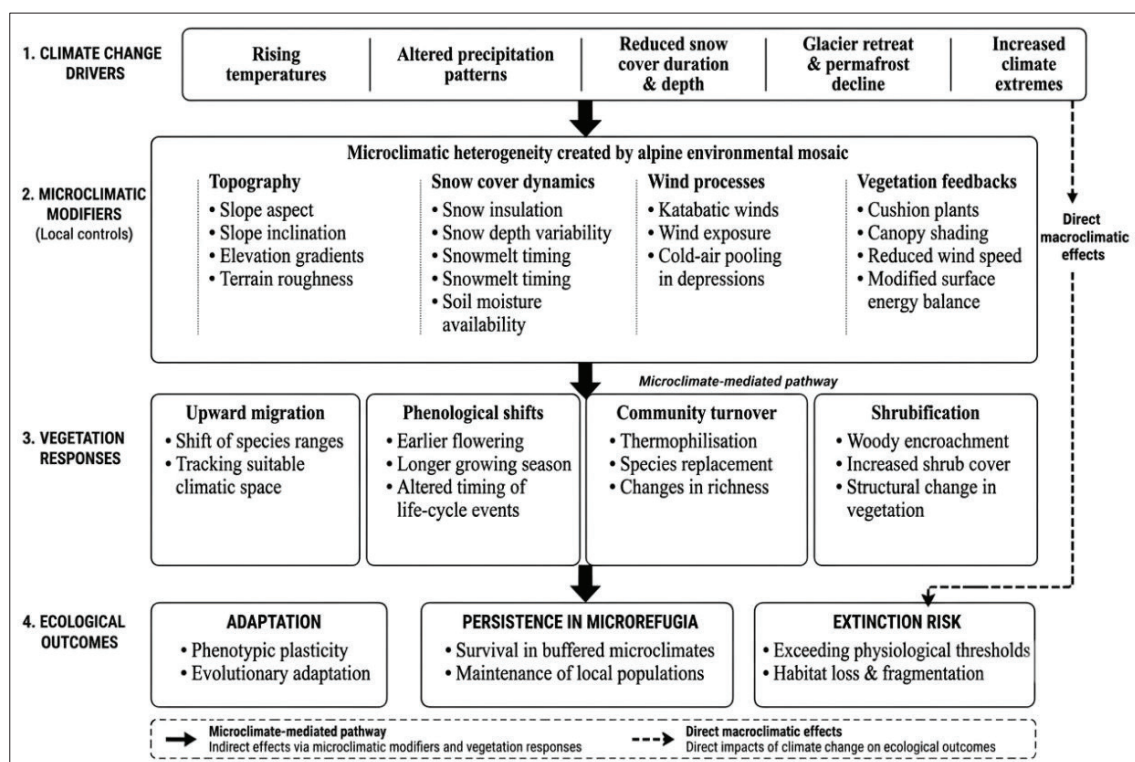


Figure 2: Conceptual framework illustrating how climate change influences alpine vegetation through both direct macroclimatic effects and indirect microclimate-mediated pathways.

3. Results and Discussion

3.1 Microclimate in alpine environments

Some macroclimatic changes with elevation are present in all alpine areas. These include decreasing air pressures that are accompanied by decreasing CO₂ partial pressures, decreasing air temperature and moisture content and increasing solar radiation per area with higher elevations (Körner, 2021). Still, macroclimatic patterns vary strongly between different mountain regions. Seasonality, with its major impact on vegetation, for example differs dependent on latitude. But also, altitudinal patterns of precipitation and wind can differ significantly between alpine regions.

As important as these large-scale climate phenomena are, it is essential to consider microclimate in alpine regions, since this characterizes the actual habitats and climate that plants experience and live in.

Due to the highly heterogeneous topography, large microclimatic variation is typical for alpine regions. This includes small-scale differences in temperature, radiation, precipitation, winds and snow cover, which strongly impact the occurring vegetation communities. However, plants themselves can influence their microclimate. In the following we will briefly present important microclimatic phenomena which are common in alpine environments and then discuss how plants can impact their environment.

Topography has a considerable direct influence on solar radiation. In alpine regions the intensity of incoming radiation depends on the slope inclination. Areas where the slope inclination is perpendicular to the incoming solar radiation have the highest radiation per area. However, radiation is also dependent on the slope aspect (orientation of the slope), with essential differences between north and south facing slopes in their radiation budgets and consequently also in air temperatures. Also, in high and steep alpine regions a shadow effect can be observed, when the surrounding mountains cast a shadow on certain regions of the neighboring slope. Since solar radiation impacts vegetation directly but also indirectly through temperature differences,

a complex terrain results in small-scale radiation and temperature differences, creating a variety of microhabitats for alpine plants (Weihs et al., 2016).

However, these effects on solar radiation can be more complicated, for example due to differing albedo with different ground covers. Dark soils, for example, that are fully exposed to sunlight were shown to heat up to temperatures around 80°C. Plants and seeds in these soils are strongly affected by these high temperatures and must be able to cope with these extreme conditions. Due to the differences in albedo, but also cloud cover patterns over the day, studies have shown that north-facing slopes can have slightly warmer soil temperatures than their south facing counterparts, especially on days with clear and sunny mornings and cloudy afternoons. This highlights the complexity of microclimatic patterns in alpine regions and how difficult they are to describe in detail for larger regions (Körner, 2021).

Alpine regions show typical wind patterns, with daily periodical changes of the wind direction. In a simplified way we can distinguish two types of wind: up-slope winds and down-slope winds. During the day the air close to the mountain slopes is warmed. It expands and rises, resulting in warm up-slope winds. In the night the air at higher altitudes cools down faster, starts sinking and moves down the slope, as cold down-slope winds (Seibert & Steinacker, 2016). Next to these radiation-based wind patterns, especially pronounced in clear weather periods, also foehn winds are typical for mountain regions. These are down-slope winds, where cool and dry air flows down the lee side of the mountains (Richner & Hächler, 2008). However, also smaller scale wind patterns can be observed, such as glacier winds on days with temperatures over 0°C (Seibert & Steinacker, 2016). Since the air above the glacier is cooler than the surrounding air under these conditions, air moves from the glacier outward in the lowest two to three meters of the atmosphere (Seibert & Steinacker, 2016).

One consequence of the daily changing wind patterns, that strongly shapes microhabitats, is the formation of cold-air pools. On a straight slope with an open valley the cold air that cooled down during

the night in high elevations of the mountain can flow down the slope and valley. However, complex topography with troughs, basins, dolines but also other obstacles can prevent the cold air from flowing down the slope. Cold air consequently collects in basins and can cool down further over the night. This leads to the formation of cold-air lakes that are characterized by extremely low temperature minima. For example, Dorninger et al. (2016) measured daily temperature changes of 29°C in summer and 30°C in winter in a doline in the alps compared to only 10°C daily temperature change in summer and 5°C in winter in the surrounding area. The magnitude as well as the duration of these temperature inversions is strongly dependent on the geometry and size of the structures and result in significant habitat differences for plants on a small scale (Dorninger et al., 2016; Rauchöcker et al., 2024).

Snow cover also strongly influences the distribution of different vegetation communities. Main reasons are its isolating effect and its impact on the length of the growing season, but snow also influences the water supply (Chersich et al., 2015; Inouye, 2020). The isolating effect of the snow cover can result in a decoupling of the soil temperatures from the surrounding air temperatures. Studies recording air temperatures and the temperature below the snow cover show that the temperatures beneath the snow cover can stay at around 0°C over the whole winter period, as long as a thick enough snow cover persists (Körner, 2021). This protects plants from cold winter air temperatures and can prevent them from freezing during the winter months. Snow cover patterns are complex in alpine regions. They are influenced by cloud dynamics, snow deposition patterns as well as transportation. Snow is not as uniformly deposited as rain. Due to the lower density of the snow particles their deposition depends on the wind strength and direction. Snow is mainly deposited in wind protected areas such as depressions, basins or vegetated areas and not on wind exposed slopes or ridges. After deposition it is again dependent on the presence of wind patterns if and how the snow is resuspended and transported further. Again, topography resulting in small-scale differences in snow cover and snow depth has a significant impact on microhabitats of vegetation

(Lehning & Mott, 2016). Several studies in alpine regions showed that the melting patterns of snow are quite constant over the years although the amount of snow as well as the snow-melt timing change considerably over the years. Also, close correlations were found between the boundaries of snow melt patterns and vegetation patterns. This indicates that vegetation communities are strongly dependent on the duration of the snow cover due to its effects on their microclimatic (Körner, 2021).

Plants, however, are not solely dependent on a favorable climate surrounding them but can influence the temperatures they are experiencing. Many studies have shown that plants highly specialized and adapted to the alpine environment can decouple from the air-temperatures surrounding them (Körner, 2021). The plant stature, height and leaf arrangements are essential in this context. While high growing life forms, like trees, are aerodynamically coupled to the atmosphere due to convective heat transfer, low growing plants can reduce this head convection, and solar heat is trapped in the plant (Körner, 2021). Cushion plants for example are good at trapping heat. Gauslaa (1984) found a difference up to 24.5 °C between air temperature and temperature in cushion plants in Norway. However, this is a rather extreme example that can occur on sunny days during the warm seasons. But also, the more often occurring only slightly warmer plant temperatures are important for the plants growing abilities, as they can enable better metabolism and growth rates (Körner, 2021).

The ongoing climate change is not only a large-scale phenomenon but also impacts these microclimatic conditions. In alpine regions rising temperatures and changes in precipitation result in decreasing expanses of glaciers and permafrost with many consequences such as changes in the water budget, soil properties or slope stability (Tamme, 2012; Chersich et al., 2015). Also, the extent and time of snow cover decreases and the lower boundary over which precipitation falls as snow rises (Chersich et al., 2015; Giaccione et al., 2019). However, although major changes are expected in alpine areas microclimate does not always follow macroclimate in a direct way. Especially the high microclimatic

variability described above that is creating various habitats in close proximity to each other, may even have the ability to buffer the negative effects of climate change on alpine vegetation communities (Inouye, 2020; Ohler et al., 2020), since it allows species to find suitable habitats close by and reduces the need of upward migration (Ohler et al., 2020). Still, more research is needed to understand to what extent microclimates can buffer climate change in alpine regions (Jiménez-Alfaro et al., 2024).

3.2. Vegetation Responses to Climate Change

The observed and projected climate changes show a range of responses from alpine vegetation, displaying primarily through upward migration of species, alterations in phenology, shifts in vegetation structure, and, in some cases, the threat of extinction for highly specialized species.

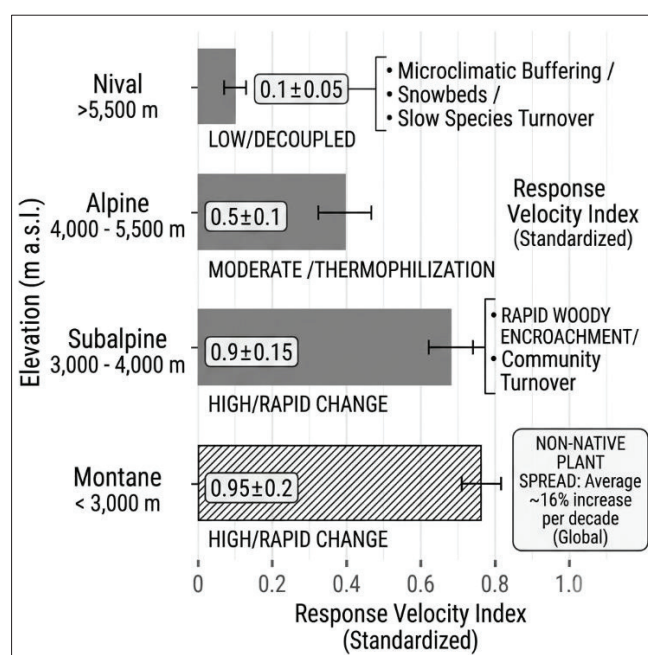


Figure 3: Standardized Response Velocity Index across elevational gradients illustrating the varying intensity of vegetation responses to climate warming, showing a transition from low-sensitivity/buffered nival zones (dominated by microclimatic refugia) to high-sensitivity/rapid change in subalpine and montane zones (characterized by woody encroachment and non-native plant spread) (Dullinger et al., 2012; Rosbakh et al., 2014; Lembrechts et al., 2020; IUCN, 2023, own illustration)

3.2.1. Upward Migration

With the rise in mountain temperatures, many plant species are seen to move to higher elevations to find

conditions that are better suitable for their needs. In subalpine areas, while some existing plants seem to be adapted to the current climate, most species tend to shift uphill to stay within their ideal level of temperature and moisture (Körner, 2021). However, the entire plant communities are rarely seen to move together. Instead, each species tends to shift individually, finding small areas (microhabitats) that have become suitable. For plants to grow successfully at higher elevations they are dependent on several things such as open space, the soil types, and soil microbes. Species that have very specific temperature needs or can't spread their seeds far are especially at risk of falling behind as the climate changes.

Many studies across the European Alps provide compelling evidence of these shifts. Research shows a general increase in species richness at mountain summits and in high alpine zones over recent decades (Lamprecht et al., 2018). However, this increase in species richness should not be interpreted as an improvement in biodiversity or ecosystem health. Instead, it reflects a process of thermophilisation, where cold-adapted alpine species are gradually replaced or outcompeted by more generalist, warm-adapted species migrating upward from lower elevations (Lenoir et al., 2008; Lamprecht et al., 2018).

This trend is driven by the upward migration of species from lower elevations, which are now able to colonize previously too-cold habitats. At the same time, there is a continuing loss of cold-adapted alpine species from their historical ranges. The rising temperatures reduce the cold limitations that previously restricted warmer-adapted species to lower altitudes, allowing their expansion into higher zones. This often leads to increased overlap between expanding generalist species and narrow-range alpine specialists, resulting in competition and potential displacement of cold-specialist alpine plants. Consequently, the observed increase in species richness often represents a species turnover rather than a net gain in biodiversity, where pioneer species from lower elevations increase in abundance while characteristic subnival and nival zone species decline. This leads to biotic homogenization and a

loss of endemic alpine biodiversity (Lenoir et al., 2008; Lamprecht et al., 2018).

Importantly, these compositional changes occur under a strong mismatch between species migration rates and the velocity of climate warming. Empirical evidence from the European Alps indicates that warming-induced isotherms have shifted upslope at approximately 62–71 m decade⁻¹ since 1970, whereas woody plant communities have migrated at only about 32.7 m decade⁻¹ (Figure 2). This disparity creates a climatic debt, whereby vegetation distributions lag behind the pace of changing climatic conditions. As a result, many alpine species may be unable to fully track their climatic niches, increasing the risk of habitat contraction, community reorganization, and local extinction of cold-adapted specialists (Vitasse et al., 2021).

As a consequence of these dynamics, there is an increasing loss of cold-adapted alpine species from their historical ranges. The rising temperatures reduce the climatic constraints that previously restricted warmer-adapted species to lower elevations, allowing their expansion into higher zones. This can intensify competition with

specialist alpine taxa that are adapted to narrow thermal niches. Consequently, the observed increase in species richness often reflects a species turnover rather than a net gain in biodiversity. In many cases, this results in biotic homogenization, where widespread generalist species increase in abundance while endemic, cold-specialist flora decline, ultimately leading to a reduction in unique alpine biodiversity (Lenoir et al., 2008; Lamprecht et al., 2018).

3.2.2. Phenological Alterations and Mismatches

Temperature is the main determinant of phenology for alpine plant species (Ohler et al., 2020), but snowmelt timing has a big impact on the beginning of the growing season (Inouye, 2020). With ongoing climate change, the average beginning of the growing season was predicted to be 17 days earlier by the end of the century compared to the period 1971–2000 (Inouye, 2020). But these changes in phenology differ between different species and can result in phenological mismatches, when interacting species' phenology changes at different rates. This can result for example in the prevention of existing interactions between plant and pollinator

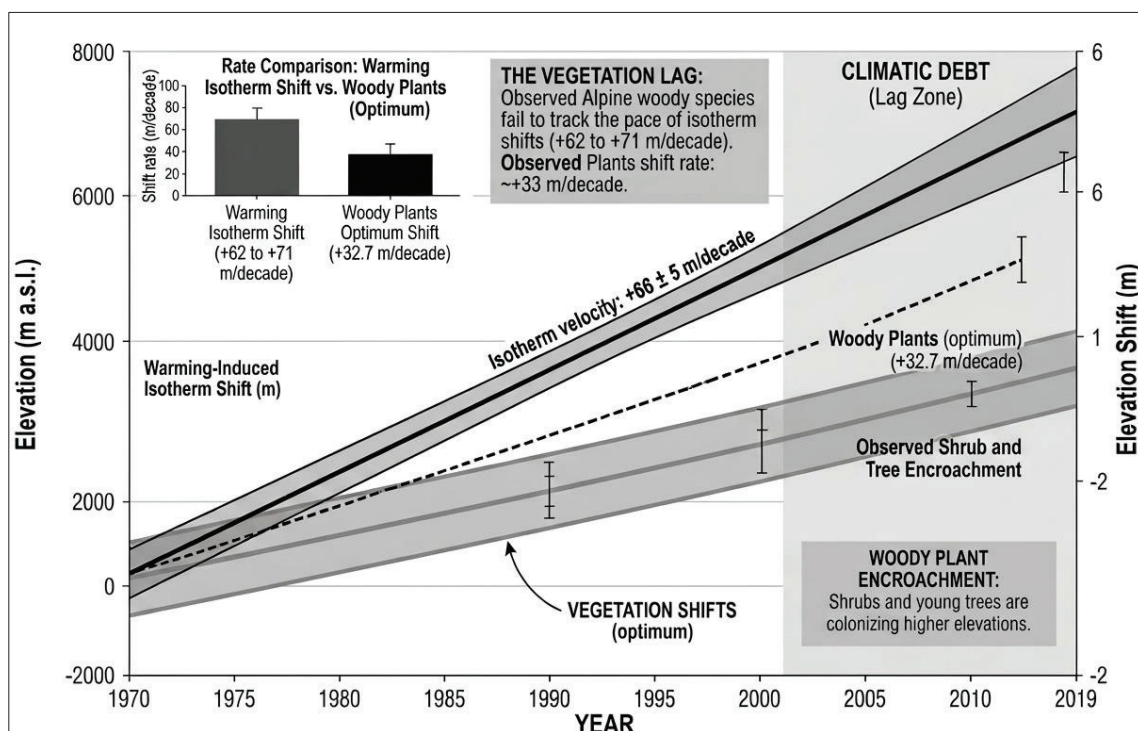


Figure 4: Empirical evidence of vegetation lag under climate warming

Source: (Vitasse et al., 2021; Snell et al., 2022, own illustration)

species, but it can also create possibilities for new interspecific interactions and competition (Inouye, 2020). These phenological mismatches as well as a decreasing connectivity of pollinator populations can result in decreasing visitation rates, seed production, pollen limitation and therefore also a decreasing stability of the plant community (Parmesan, 2006; Inouye, 2020).

This is especially true for snowmelt trackers, species with a phenology dependent on their ambient conditions that flower at approximately the same time after snowmelt, independent of when snowmelt occurred within the year. However, there are also many plant species with a phenology controlled by the photoperiod, the length of the days, and therefore flower at the same time each year, mostly independent of the yearly weather conditions (Körner, 2021). With an earlier snowmelt and warmer temperatures earlier in the season, mainly plant species independent of the photoperiod may benefit from the longer growing season, while plants with a phenology connected to the photoperiod may be disadvantaged due to higher competition when their flowering period starts (Körner, 2021). However, climate change may also enhance late frosts after warm spells earlier in the season. Plants with a phenology connected to the photoperiod may be protected against more of these freezing events than snow tracker species, due to their later flowering, independent of warm spells early on in the season (Körner, 2021).

To understand the ecological consequences of these asynchronous dynamics, it is necessary to consider empirical evidence from both experimental and long-term observational studies. Field experiments show that earlier snowmelt can create temporal mismatches between subalpine plants and their pollinators, leading to reduced interaction success. For instance, in *Delphinium nuttallianum*, shifts in flowering phenology ahead of the emergence of early-season bumblebee queens have been associated with reduced visitation rates and significant declines in per-capsule seed set due to pollen limitation (Inouye, 2020).

Similarly, long-term alpine monitoring studies indicate that phenological responses to climate

warming are often uneven across trophic levels. Across multi-decade datasets, subalpine and alpine plants have generally advanced their flowering times more rapidly than the emergence periods of their primary solitary bee pollinators, resulting in increasing temporal decoupling between interacting species (Parmesan, 2006). This growing asynchrony highlights how climate-driven shifts can disrupt mutualistic interactions even when both plants and pollinators are responding to the same environmental signal.

Overall, changes in phenology are species specific and an overall trend of phenological changes with climate change across alpine vegetation is difficult to predict. Also, due to the topographic complexity in alpine regions the growing season can vary over short spatial scales and this may be able to buffer phenological mismatches and their negative effect on vegetation communities (Inouye, 2020). This microclimate-buffering hypothesis has been directly validated by empirical studies testing plant-pollinator networks across complex alpine terrains. Specifically, field research by Scherrer and Körner (2011) showed that small-scale alpine topographies create detailed thermal mosaics where soil temperatures can differ by up to 10°C over distances of just a few meters. This fine-scale variation allows individuals within the same plant population to experience completely different snowmelt timelines. Field observations demonstrate that high aspect and slope variation create adjacent microhabitats where identical plant species flower up to 30 days apart, thereby preserving overall regional landscape connectivity and providing continuous forage resources that buffer temporary temporal mismatches (Ohler et al., 2020).

Furthermore, CaraDonna et al. (2014) provided long-term evidence showing that while broader regional warming tends to compress the overall community flowering season, complex topography acts as an important spatial buffer. By spreading out the flowering windows of different micro-populations across ridges, depressions and snow beds, the landscape prevents everything from happening at the exact same time. This keeps a continuous supply of floral resources open for

pollinators throughout the summer season.

Fine-scale microclimatic logging confirms that heterogeneous terrain allows interacting species to adjust spatially rather than temporally, reducing the selective pressure of macroclimatic warming on mutualistic links (Jiménez-Alfaro et al., 2024). Climate change and the consequence of phenological alterations will lead to the creation of new vegetation community compositions and changing species-species interaction (Körner, 2021), the resulting vegetation communities and their distribution are however difficult to predict.

3.2.3. Community Turnover and Extinction Risk

The response of vegetation communities to climatic shifts is mostly characterized by a time lag, that current plant distributions may not fully reflect the altered climatic conditions, which complicates future projections (Alexander et al., 2018). The speed and extent of alpine plant community turnover can depend on several factors like, the dispersal rates of species moving upwards, their successful establishment and competitive ability in new habitats, the rate of population growth in these newly colonized areas, and, crucially, the extinction rates of existing resident alpine species. Some of the specialized alpine plants are particularly vulnerable. For example, species like the glacier buttercup (*Ranunculus glacialis*), purple saxifrage (*Saxifraga oppositifolia*), and creeping avens (*Geum reptans*) are at significant risk of extinction as their unique glacier-adjacent habitats rapidly retreat due to global warming (Losapio et al., 2021). Importantly, however, climate-driven extinction vulnerability is not restricted to these glacier-adjacent pioneers; broader subnival specialists and alpine meadow endemics that lack direct associations with glacial ice sheets face equivalent long-term threats from upslope competitive exclusion, severe microclimatic soil aridification, and physiological thermal stress as lower-elevation generalist flora ascend into historical alpine refugia (Dullinger et al., 2012; Grytnes et al., 2014). Research utilizing detailed ecological and trait-based models on 117 alpine plant species found in Italian Alps glacier forelands indicates substantial threats to their

long-term survival due to the direct and indirect impacts of glacier melt (Losapio et al., 2021). These examples highlight the severe consequences of climate change for the unique and often endemic flora of alpine regions.

3.3. Changes in Vegetation Structure

3.3.1. Drivers and Dynamics of Woody Encroachment in Alpine Systems

Climate change has significantly altered alpine vegetation structure by driving widespread functional and compositional shifts across elevational gradients. One of the most prominent expressions of this transformation is the expansion of woody vegetation, including dwarf shrubs and small trees, into alpine and subalpine ecosystems where such growth forms were historically limited (Harsch et al., 2009; Elmendorf et al., 2012).

This process, commonly termed woody encroachment or shrubification, is primarily driven by rising temperatures, reduced duration and depth of snow cover, lengthened growing seasons, and increased frequency of freeze–thaw cycles, all of which enhance establishment conditions for woody species (Myers-Smith et al., 2020). In European mountain systems, land-use change, particularly grazing abandonment, further reinforces this trend by reducing herbivory pressure and enabling shrub establishment and persistence (Snell et al., 2022).

Comparable and, in some cases, more rapid transitions are occurring across high-elevation systems in South Asia. On the Qinghai–Tibetan Plateau and in the Eastern Himalayas, coupled climate warming and shifts in pastoral land use have triggered a large-scale regime shift in ecosystem structure. Since the late twentieth century, this process has resulted in the conversion of approximately 39% of historical alpine meadow systems into shrub-dominated communities primarily composed of *Rhododendron*, *Caragana*, and *Dasiphora* species as these ecosystems have lost their historical resilience to woody encroachment (Brandt et al., 2013).

In the European Alps, shrub cover has been reported to increase at rates of up to 16% annually

in localized regions, with average increases of approximately 5.6% per decade (Snell et al., 2022). This structural reconfiguration increases vegetation vertical complexity by replacing low-stature herbaceous and graminoid communities with woody canopies, thereby modifying microclimatic regimes, light availability, and snow accumulation patterns (Camac et al., 2017).

3.3.2. Elevational Controls on Vegetation Structure and Canopy Complexity

Vegetation responses to shrubification are strongly modulated by elevation. In lower alpine belts, increased temperature and reduced grazing intensity often enhance primary productivity and vegetation cover, particularly among tall herbs and shrub species. In contrast, upper alpine and nival zones frequently experience the decline of cold-adapted cushion plant communities, leading to structural simplification, reduced surface roughness, and altered snow retention dynamics, with cascading effects on hydrological processes (Lamprecht et al., 2018).

These structural changes also influence soil thermal regimes. Shrubs exert contrasting seasonal thermal effects by insulating soils during winter while reducing soil temperatures in summer, thereby altering permafrost stability and subsurface energy exchange processes (Myers-Smith et al., 2020).

In addition, high-elevation systems such as the Tibetan Plateau exhibit complex structural vegetation shifts under warming. Rather than keeping pace with rapid thermal changes, long-term tracking shows that shifts in the upper limit of alpine grasslands drastically lag behind climate warming across the region. This substantial distributional delay is highly influenced by localized environmental constraints, including severe water scarcity, poor soil development, and a lack of stable physical substrates beyond existing boundaries (Liu et al., 2026).

3.3.3. Biotic Interactions and Functional Disruption under Shrub Expansion

Shrub expansion exerts strong controls on ecological interactions and ecosystem functioning. Mod and

Luoto (2016) demonstrated that shrubification in Arctic systems modifies community composition and regulates the response of tundra vegetation to warming, with effects that may either buffer or amplify climate impacts depending on shrub density and spatial configuration.

In alpine meadow systems of Colorado, Kettenbach et al. (2017) showed that willow encroachment into subalpine meadows altered pollinator visitation dynamics. Co-flowering shrubs attracted pollinators away from *Polemonium viscosum*, reducing visitation rates and negatively affecting reproductive success of the focal species, thereby demonstrating how shrub expansion can restructure plant–pollinator networks.

Comparable disruptions have been observed in monsoon-influenced alpine ecosystems of the Western Himalayas, where upward expansion of broad-leaved shrubs into subnival meadows has compressed foraging ranges of alpine bumblebees (*Bombus* spp.). This has intensified interspecific competition and disrupted long-established plant–pollinator synchrony, with significant implications for the reproductive success of endemic high-elevation forbs (Singh et al., 2024).

3.3.4. Below-ground Biogeochemical Processes and Soil Microbial Feedbacks

Below-ground, woody encroachment induces substantial shifts in soil microbial communities and nutrient cycling processes. Soil microbial diversity and activity are strongly influenced by vegetation functional traits, soil pH, and carbon-to-nitrogen ratios (Collins et al., 2020). Nitrogen-fixing shrubs can enhance fungal diversity and modify nitrogen availability, while ericoid shrubs exert strong control over bacterial community composition and soil biogeochemistry.

Vegetation change can also disrupt seasonal coupling between plant nutrient uptake and microbial activity, leading to decoupling of established plant–soil feedback loops. In high-altitude permafrost systems across the Himalayan–Tibetan region, woody root expansion accelerates thawing of previously frozen organic carbon pools, triggering enhanced nitrogen release that favors fast-growing generalist species

over slow-growing endemic alpine specialists (Yun et al., 2023).

Although shrub expansion may increase aboveground biomass and carbon storage in certain contexts, it may simultaneously accelerate soil organic matter decomposition, resulting in uncertain net ecosystem carbon balance outcomes (Collins et al., 2020).

Projected vegetation trajectories indicate that continued warming and land-use change will likely intensify shrub expansion and associated biodiversity loss unless actively managed. Management interventions such as controlled grazing and targeted shrub removal are increasingly being explored to maintain herb-dominated alpine systems and slow structural transitions (Snell et al., 2022). Overall, woody encroachment represents a major driver of long-term ecosystem transformation in alpine environments.

3.4. Adaptation

3.4.1. Mechanisms of Physiological, Phenotypic, and Evolutionary Adaptation

Adaptation in alpine plants arises through both evolutionary change in heritable traits and phenotypic plasticity. While evolutionary processes can contribute to increased thermal tolerance, most documented responses remain constrained within existing species ranges (Parmesan, 2006). Current evidence suggests that evolutionary adaptation alone is unlikely to offset the magnitude and pace of contemporary climate change, indicating that ecological and plastic responses will remain critical for persistence (Parmesan, 2006).

For example, *Wahlenbergia ceracea* exhibits potential for evolutionary response to climate warming; however, observed rapid responses are primarily mediated through phenotypic plasticity and epigenetic variation rather than genetic change (Arnold et al., 2024).

Alpine plants display a wide suite of morphological and physiological adaptations to extreme environments. These include compact growth forms such as cushion and rosette structures, slow growth rates, and evergreen leaf traits, which optimize resource use during short growing seasons

and enhance resistance to frost, high radiation, and nutrient limitation (Körner, 2021). Many species also maintain photosynthetic activity at low temperatures, enabling persistence under frequent freezing conditions.

Phenological adjustment represents another key adaptive mechanism. However, these responses often lag behind climatic change. Temporal mismatches between environmental conditions and biological timing are widely documented, indicating incomplete adjustment of growth and reproductive cycles in many alpine plant communities (Alexander et al., 2018). Such mismatches can disrupt synchrony with pollinators and reduce reproductive success (Hegland et al., 2009). In the Central Himalayas, this decoupling is particularly pronounced, where earlier spring conditions have led to severe seasonal pollination limitations for *Primula* species, forcing early-flowering cohorts to rely on evolved compensatory mechanisms to offset the severe drop in pollinator synchrony (Yin-Mei et al., 2026).

3.4.2. Spatial Adaptation Strategies: Range Shifts and Microclimatic Refugia

Upslope migration is a primary spatial response to warming, with alpine species shifting distributions toward higher elevations in search of suitable climatic conditions. Telwala et al. (2013) documented significant elevational range shifts in the Himalayas, accompanied by increased species richness at higher elevations. However, such shifts are constrained by topography and interspecific competition, often resulting in crowding and increased extinction risk at upper elevational limits (Dullinger et al., 2012).

Long-term monitoring in the Kashmir Himalaya further indicates strong thermophilisation trends, where generalist species from lower elevations increasingly dominate summit communities, leading to displacement and fragmentation of endemic subnival flora into isolated and highly vulnerable populations (Hamid et al., 2020).

Vegetation responses also vary spatially along elevation gradients. Rosbakh et al. (2014) observed that lower alpine sites in the Bavarian Alps

responded strongly to warming, whereas higher elevations exhibited weaker or decoupled responses, likely due to microclimatic buffering and ecological inertia. Similarly, Gottfried et al. (2012) reported continent-wide vegetation change but emphasized strong spatial heterogeneity in alpine responses.

Microclimatic refugia play a critical role in moderating exposure to regional climate warming. Features such as north-facing slopes, snow beds, and cloud-influenced microsites create locally stable thermal conditions that allow cold-adapted species to persist beyond macroclimatic expectations (Lembrechts et al., 2020). Jiménez-Alfaro et al. (2024) further demonstrate that such refugia support long-term persistence of relict alpine plant communities under ongoing climatic change.

Tree line dynamics provide additional evidence of spatial adaptation processes. In the central Himalayas, upward shifts in tree line position have been documented in response to rising temperatures, resulting in structural reorganization of mountain vegetation belts (Gaire et al., 2014). Similar patterns across the Himalayas highlight the combined influence of climate warming and anthropogenic disturbance on tree line dynamics (Schickhoff, 2005).

3.4.3. Socio-Ecological Constraints and Anthropogenic Limits to Adaptive Capacity

Alpine ecosystems are also embedded within socio-ecological systems in which indigenous knowledge contributes to long-term environmental observation and adaptive resource use. Salick et al. (2014) highlight that Himalayan communities have historically adjusted land-use and harvesting practices in response to observed ecological change, reflecting an important dimension of human–ecosystem adaptation.

However, adaptive capacity is increasingly constrained by anthropogenic landscape modification. Deforestation, land degradation, and habitat fragmentation reduce ecological connectivity and limit gene flow, thereby constraining species' ability to track shifting climatic niches (Chaudhary et al., 2011; Holderegger & Di Giulio, 2010). In highly fragmented mountain systems such as the

Hengduan Mountains, infrastructure development and mining activities have disrupted migration corridors, effectively isolating alpine populations within topographically constrained habitats and severely limiting upslope dispersal opportunities (Li et al., 2024).

3.5. Extinction

The accelerating pace of climate change poses a significant threat to alpine plant species, particularly those characterized by narrow environmental tolerances, slow reproductive rates, and limited dispersal capacity. Alpine ecosystems are composed of a high proportion of specialist taxa adapted to narrow thermal regimes, short growing seasons, and edaphic constraints, which collectively limit their capacity to respond rapidly to environmental change. As a result, many of these species exhibit reduced adaptive potential under contemporary warming trajectories (Dirnböck et al., 2011).

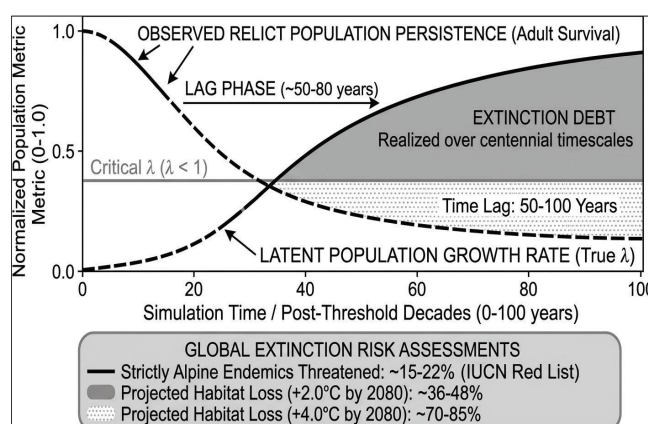


Figure 4: Demographic simulation model illustrating the multi-decadal time lag (extinction debt) in high-mountain perennial flora. The curves isolate the divergence between observed population persistence (sustained by adult clonal survival and slow biomass turnover) and the latent collapse of the true population growth rate induced by climate warming. The figure also contextualizes these demographic shifts within broader global extinction risk assessments, highlighting projected habitat loss for alpine endemics under different warming scenarios. (Dullinger et al., 2012; Rosbakh et al., 2014; Lembrechts et al., 2020; IUCN, 2023; Nomoto et al., 2021, own illustration)

Species restricted to the highest elevations, particularly within alpine and nival zones, are at greatest risk due to the absence of further upslope habitat, a condition often described as a “climatic

cul-de-sac” (Loarie et al., 2009). As temperatures rise, thermophilic species expand upward, increasing biotic pressure on cold-adapted assemblages through habitat compression and competitive displacement. This phenomenon has been widely documented across mountain systems, including the European Alps and the Himalayas, where consistent upward range shifts and contraction of cold-adapted species have been observed (Klanderud, 2004; Pauli et al., 2012).

In the Third Pole region, high-elevation ecosystems of the Himalaya–Hengduan Mountains exhibit strong evidence of climate-driven vegetation change, including shifts in species distributions and restructuring of alpine communities. These changes reflect ongoing redistribution of plant assemblages along elevational gradients under warming conditions, with associated impacts on cold-adapted vegetation (Kumar & Khanduri, 2024; Xie et al., 2025). When assessed against global conservation frameworks, these patterns translate into substantial extinction risk. Macroecological models and regional applications of IUCN Red List criteria indicate that narrow-range, high-mountain flora face severe range contractions, with a substantial proportion of strictly alpine endemic plant species currently classified as threatened due to climate-driven habitat loss, restricted population sizes, and competitive disadvantage under changing environmental conditions (Dullinger et al., 2012; Geppert et al., 2023). Regional modelling in the Hindu Kush–Himalaya similarly indicates substantial vulnerability among narrow-range alpine taxa, with projected habitat reductions under future climate scenarios driven by limited dispersal capacity and strong climatic sensitivity (Shrestha et al., 2026). Bioclimatic modelling further indicates that these risks are likely to intensify under future warming scenarios. Under future warming trajectories, macroecological models suggest severe reductions in alpine bioclimatic zones by the end of the century. High-resolution projections indicate that 36–55% of alpine plant species across major mountain ranges face losing more than 80% of their suitable habitat space by 2070–2100 (Engler et al., 2011), while severe, high-emission scenarios could leave up to 60% of the mountain flora functionally

vulnerable to local extinction (Thuiller et al., 2005). Given the topographic isolation of alpine systems, such reductions in habitat availability are strongly associated with elevated risks of local and regional extinction.

A central concept in explaining delayed species loss is extinction debt, whereby species persist temporarily in environments that have already become unsuitable, but are ultimately committed to decline in the absence of mitigating processes (Alexander et al., 2015). This phenomenon is particularly pronounced in alpine ecosystems due to the life-history characteristics of many resident species, which are often long-lived perennials with slow demographic turnover and strong clonal persistence (Körner, 2021). In high-mountain regions such as the Eastern Himalayas and Southwest China, such demographic inertia can result in the continued presence of relict populations even after environmental conditions have surpassed thresholds for successful regeneration (Dullinger et al., 2012; Han et al., 2023).

This delayed response is further reinforced by demographic lag effects, where populations may appear stable due to vegetative persistence despite reduced reproductive success under changing climatic conditions. As a result, declines in population viability may remain undetected until mature individuals senesce without sufficient recruitment (Jackson et al., 2009). Empirical and modelling studies suggest that ongoing climatic shifts have already exceeded the physiological and demographic thresholds of numerous high-elevation endemics, resulting in populations with negative growth trajectories ($\lambda < 1$) that persist as relictual assemblages (Nomoto et al., 2021). These extinction debts are expected to be realized over centennial timescales, typically within 50–100 years, as reduced recruitment, reproductive failure, and cohort senescence lead to progressive population collapse (Dullinger et al., 2012). Such lagged responses may obscure the full magnitude of biodiversity loss, thereby complicating conservation planning and risk assessment.

In addition to direct climatic effects, disruptions to biotic interactions further amplify extinction

vulnerability. Many alpine plant species depend on tightly coupled mutualisms, including specialized pollination systems and mycorrhizal associations, which are sensitive to phenological and environmental mismatches. Climate-induced shifts can therefore decouple plant–pollinator synchrony and alter below-ground microbial communities, reducing reproductive success and nutrient acquisition even under otherwise suitable abiotic conditions (Hegland et al., 2009; Collins et al., 2020). These pressures are compounded by anthropogenic habitat fragmentation associated with tourism, infrastructure development, and land-use change, which further restricts gene flow and reduces adaptive capacity across isolated populations (Holderegger & Di Giulio, 2010).

Empirical observations support these projected dynamics. Cold-adapted species such as *Ranunculus glacialis* and *Silene acaulis* have already exhibited measurable range contractions and declines in abundance associated with warming temperatures and altered snow regimes (Lamprecht et al., 2018; Steinbauer et al., 2018). While some generalist and pioneer species expand into newly available niches, these taxa do not typically compensate for the ecological functions of lost specialists, leading to altered community composition and potential degradation of ecosystem processes.

Climate change represents a multifaceted threat to alpine plant diversity through habitat compression, disruption of ecological interactions, and increasing population isolation. Addressing these challenges requires integrated conservation strategies that prioritize habitat connectivity, protection of mutualistic networks, and explicit incorporation of extinction debt dynamics into long-term management frameworks.

4. Conclusions

Climate change is driving consistent and well-documented shifts in alpine vegetation worldwide, including upward range shifts, altered phenology, changes in community composition, and increased vulnerability of cold-adapted specialist species. Although alpine plants exhibit a range of

adaptive responses, these are often constrained by dispersal limitations, biotic interactions, and the progressive reduction of suitable habitat under continued warming (Körner, 2021). Microclimatic heterogeneity plays a key role in moderating these impacts by creating fine-scale refugia that can buffer species against regional climate warming. However, these effects are likely temporary under sustained climatic trends and may only delay, rather than prevent, long-term biodiversity losses. In addition, the expansion of woody vegetation into alpine zones is altering microclimatic conditions and ecosystem functioning, introducing further uncertainty in carbon cycling and ecosystem stability (Pepin et al., 2022).

Despite significant progress, this review highlights the need for improved integration of macroclimatic and microclimatic processes to enhance predictive understanding of alpine ecosystem responses. Such integration is essential for developing effective conservation and management strategies, including interventions such as grazing regulation or shrub management aimed at maintaining herb-rich alpine habitats.

Future research should address three major gaps. Methodologically, there is a need to combine high-resolution microclimatic sensor networks with terrain-aware modelling and LiDAR-based topographic data to better resolve microclimatic variability beyond coarse-scale climate grids (Lembrechts et al., 2020; Zellweger et al., 2020). Geographically, monitoring remains unevenly distributed, with strong representation in the European Alps and parts of North America, particularly through long-term networks such as GLORIA (Pauli et al., 2012), while substantial gaps persist in high-mountain regions of Asia, including the Himalaya and other under-monitored systems (Schickhoff et al., 2016). Moreover, observations remain biased toward subalpine and tree line zones, whereas upper alpine, subnival, and nival ecosystems remain underrepresented despite their importance for understanding ecological limits under extreme conditions (Körner, 2021). Functionally, important uncertainties remain regarding non-vascular and cryptogamic components of alpine ecosystems,

including bryophytes, lichens, and biological soil crusts, which play critical roles in soil stability, nutrient cycling, and hydrological regulation but remain poorly understood in terms of climate sensitivity (Signori et al., 2023).

Overall, advancing multi-scale integration across climate, terrain, and biological processes is essential for improving predictions of alpine ecosystem resilience under ongoing global environmental change.

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A Systematic Review on Evidence Based Policy Making and effectiveness in the Perspectives of Environmental Pollution in Nepal

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Abstract

It is high time to analyze and find the policy gaps and adequacies focusing on environmental pollution and the functionality of policy instruments as the issue of environmental pollution are growing day by day in Nepal and throughout the world. In this context, the question arises why policies are generally not transformed into action in Nepal. The systematic review method was adopted for the relevant literature review and PRISMA reporting tool for the article writing. It is observed that there are many barriers to evidence use such as reliability, replicability of the study time required to develop evidence, lack of evidence use culture and coordination between research organizations and policy making institutions, and vested interests, etc. Amidst the mentioned barriers there are some prospects as well, the tool like evidence to decision has been developed and the system of co-production of evidence among researchers and policy makers has been found more effective in the UK. The governments in the international arena particularly the developed countries are becoming evidence friendly for their policy formulation for example: the USA, UK, Australia, etc.

In addition, there are now robust, transparent and reliable methods for conducting comprehensive evidence syntheses, for example systematic reviews including others. But, creating policies based on evidence is a complex and challenging process. As a result, institutionalizing evidence based policy making remains a significant challenge in many developing countries, including Nepal. Environmental pollution policies need to be supported by appropriate policy instruments with economic incentives for their effective implementation. Policy effectiveness or successful implementation of the policy depends on appropriate institutional arrangements with adequate human and financial resources. The concerned evidence-based knowledge on Nepal scenario in this aspect is found very few. It may be due to lack of research on the pertinent subject. So, a vast knowledge gap on environmental pollution policy formulation process and their effectiveness persists in Nepal.

Key Words: *Barriers to policy use, evidence based policy, policy effectiveness, policy instruments, prospects of policy use*

1. Introduction

Environmental Pollution is becoming more pressing issue in Nepal as well as in the world. Air and water pollution, solid waste management and lands intoxication are rising due to various reasons. Air pollution exceeds safety limits across the cities of developing countries in Asia according to the Health and Environmental Index (HEI). Harmful gas emissions and particulate matter from transporting vehicles, various industrial and other human activities contribute to the air pollution. In fact, urban population is exposed to pollution in rising trends and consequently there are increasing cases of respiratory diseases and cases of cancer (Pullin et

al., 2022). Access to clean air is vital for the health of human and living beings and plants. It is evident that access to clean air mostly determines human health, and the overall life condition of other living beings as well as plants.

The waste in Nepal is continuously disposed either in water bodies or in open areas within cities, impacting the public health and environment harmfully by contaminating ground and surface water, clogging storm water drains and ponding water creating the condition of insect breeding and floods sometimes. The rampant burning of waste significantly contributes to air pollution in the urban area and surrounding soil, and water bodies

are polluted by the leachate from the waste dumps (Sanderson et al., 2002). Thapathali is found to be the most polluted section, which exceeds the carcinogenic heavy metal such as Arsenic. Both the WHO and national generic effluent standards are exceeded by most of the parameters (Baniya et al., 2019).

The industries and transport vehicles that are the basic drivers of economic growth continuously, since around the last century have made a severe contribution for growing ambient air pollution. Besides, the indoor air pollution is due to lack of proper cooking and ventilating amenities such as improved cooking stoves specifically in the rural areas of developing countries (Howes & Wyrwoll, 2012). Air quality monitoring network of the government shows that the Kathmandu Valley readings exceed $40 \mu\text{g}/\text{m}^3$ and most stations in the Terai are far higher (World Bank, 2025).

Najam's policy analysis protocol of 5C (Najam et al., 1995) gives the high prospect as it is in practice worldwide for the policy analysis related to environmental policy in the perspectives of environmental pollution in Nepal. South Asia is home to 9 of the world's 10 cities with the worst air pollution, which causes an estimated 2 million premature deaths across the region each year and results in significant economic costs (World Bank, 2022).

Environmental Performance Index (EPI) framework, 2018 that consist of the Environmental Health Index (HLT) indicating air and water quality along with heavy metal exposure and the Ecosystem Vitality Index (ECO) indicating biodiversity and climate change shows overall performance of the environment with respect to the said indices. Asia has relatively low performance with the second lowest EPI score among other continents of the world, only slightly higher than the sub-Saharan Africa. Asian EPI of 50 is lower than that of world average 56 (Huang & Xu, 2019).

In this context, environmental pollution related public policies in the form of general policy or laws are the aspiration and commitment of the concerned governments to address the public issues. However,

such public policies need to be evidence based and effective to meet their objectives. Similarly, it is evident that whim or interest driven fact-less policies may lead to corruption and favoritism at the end. Politicians may use such policies formulated without evidence for corruption and elections favoring opportunities for them (Shah et al., 2021).

Plewis points a definition of policy relevant evidence in two such as in the first part, evidence for the selection of effective policy options; and the second is evidence from implementation evaluations that help guide for decisions for maintaining, amendment, or improvement of the policies concerned. That also enriches the broader evidence base for future policy decisions (Huang & Xu, 2019).

Application of Environmental Instruments (EIs) has achieved wider political acceptability in a rising trend; they have been accepted as incentive rather than only revenue collecting tools (Organization for Economic Development and Corporation, 1994). Evidence-based policymaking will work only when institutions encourage inquiry-driven approaches and are ready to use research evidence for decision making (Banks et al., 2009).

So, it is highly desirable to study on evidence based policy and its relevance for turning policy into action and make them effective in the perspectives of environmental pollution in Nepal. In this context, it is very pertinent to study why policies generally are not transformed into action? Therefore, this systematic review aims at finding the existing knowledge base on this issue and finding the prevailing gaps.

2. Material and Methods

The Research Question was formulated so that it helps find Scoping Search. It was confirmed with swift search engines like [Google Scholar](#) or any other so that the exact question has not already been answered by an existing previous review. A Review Protocol was developed. All intended search strategies, exact eligibility rules, data criteria, and analytical paths were documented before beginning the formal review in a methodical and

planned way. Eligibility or screening criteria were set up with strict inclusion and exclusion limits such that non relevant literatures would be avoided and there would be saving of time and effort as well. The major criteria were publication date ranges: After 2015 except for very relevant ones, language: English, geographic constraints: Covering all the regions of the world, and accepted study designs: closely relevant to the research question.

Public registration: the finalized plan was not submitted to a registry such as the Open Science Framework (OSF) as the probability of duplication was almost nil. A comprehensive literature search was carried out with database selection: At least three comprehensive academic databases relevant to the study discipline such as Relevant Government Institutions, Policy Research Institute, Research gate etc. were identified.

The risk of bias was assessed generally with the mixed method appraisal tool (MMAT) version 2018. The risk of bias while selecting the literature was minimized by developing the key words with Boolean operators for the search and assessing whether the literature of concern is suitable for the intended review based on the checklists like its subject relevancy, to give the example such as evidence based policy making, policy effectiveness and environmental pollution principles and policy instruments, etc., date of publication, geographical region etc. It also ensures quality assessment of the review.

The relevant data were extracted and organized for further analysis. The data and important narrative items were synthesized and findings were analyzed (Philip & Barker, 2021). The article was prepared with differentiated relevant policy area wise subheadings as found in the review. The Results were interpreted and the Report was prepared based on PRISMA 2020 Statement (Page et al., 2021)

Limitation of this Review: As this review tries to explore the situation of evidence-based policy making perspectives and their implementation in general in the selected international arena and in Nepal, thorough policy analysis is out of the scope of this review. The flow diagram of PRISMA is given in Figure 1.

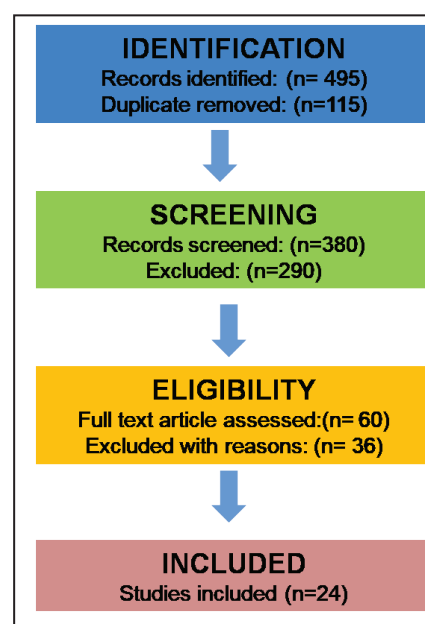


Figure 1: The flow diagram of PRISMA

3. Results and Discussion

3.1 Results

The results of the review on evidence-based policy making in the perspectives of environmental pollution in Nepal with various regional countries in the world are presented in the following theme points with short descriptions. The number of articles reviewed, and their categorization and policy areas are as illustrated in Table 1.

Table 1: Policy area wise articles differentiation

S.N.	Type of articles/Reports	Number of articles
1	Evidence based policy making	5
2	Environmental policy	1
3	Environmental/Policy instruments	2
4	Policy Implementation	9
5	Science and practice of evidence syntheses	4
6	Others	3
Total		24

Evidence Based Policy Making: Evidence-based policy making is getting attention as it helps determine what policy interventions work best, for whom, and under which conditions. This approach is based on the fact that effective policies could be achieved by understanding how different policy interventions affect social systems to produce changes desired (Pawson & Tilley, 1997). However,

evidence-based policy making has many barriers and prospects, too as mentioned in the referred literature that are institutional capacity, evidence use culture etc. are stated onwards.

Barriers to Evidence Use: Evidence used for policy formulation has many barriers among lacking evidence using culture, reliability and replicability of the evidence itself and process of evidence generation whether it is participatory with the evidence users, for example the political leaders and the senior bureaucrats, and the other users of the policy programs and so on. However, it is observed that not all evidence gathering studies are robust, and they can introduce and create bias. Moreover, individual empirical studies may vary in validity. The replication problem in science is because a paper published cannot be confirmed that its conclusion is surely valid. Despite the scientific research community assuming peers reviewed science as a valuable thing for policy formulation, but it is rarely considered most important source of information and not used widely in practice for environmental decision making (Cooke et al., 2023).

Elements of Barriers to Evidence Use: It is argued that the most common barriers to environmental evidence use in decision-making are as follows:

- a) accessibility of the evidence,
- b) relevance and applicability of the evidence,
- c) organizational capacity,
- d) financial and other resources,
- e) time required to find evidence,
- f) Poor communication and dissemination between scientists and decision makers (Cooke et al., 2023).

Diminishing Public Confidence with the Political and Scientific Leaders: A remarkable decline in public confidence is observed in both political as well as scientific authorities across numerous democratic countries in the recent decades. This erosion of trust among the public is mostly due to growing populism, rising political divides, cultural conflicts, the rise of anti-establishment activism, and the influence of social media widespread across the world. Ethical considerations in research are critical, especially when evidence syntheses are

used to guide policy decisions. These syntheses are assumed to reflect the broader population accurately. However, if they are based on non-representative or biased primary studies, the risk of misrepresenting the interests of key stakeholders may rise as its effect (Cooke et al., 2023).

Increased Uncertainty due to Constructivist Approach and Public Reviews: Constructivist approach in epistemology has introduced a sense of uncertainty due to the variability of knowledge depending on the situation; it challenges the traditional foundation of evidence-based policymaking itself (Hudson et al., 2019). Despite these critiques from constructivist and postmodern approaches, the goal of creating more informed policies through reliable knowledge always remains relevant and important (Sanderson, 2002). Public reviews conduction of policy initiatives is not a simple job. They have to face various criticisms regarding their content, methodologies and evaluation rigor etc., even after incorporating the public views in their evaluation reports (Banks, 2009).

Panta notes that shifts in a country are ruling political party's ideology is cause of corresponding changes in economic policies, globally. However, frequent government changes due to various reasons results in policies being short-term only that aims at influencing public opinion and election votes that prevent long-term, evidence-based economic strategy and planning (Panta, 2023). The barriers to the evidence use are summarized below in Figure 2.

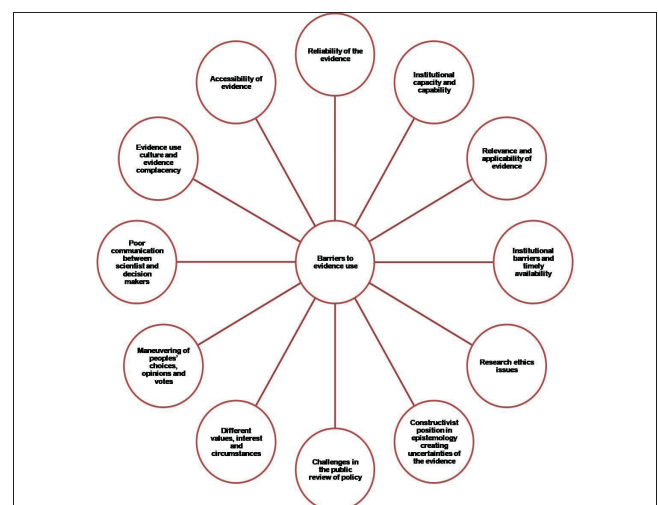


Figure 2: Barriers to Evidence Use

Prospects of Evidence Use: As there are barriers there are prospects of evidence use as well. Following statements from the reviewed literature highlights this aspect. Evidence Based Policy Decision Tools and other Prospects : Nevertheless, there are prospects of the evidence use in policy formulation as many tools have been developed for it, the governments in the international arena particularly the developed countries are becoming evidence friendly for their policy formulation for example: USA (United States of America), UK (United Kingdom) and Australia etc. In addition, there are now robust, transparent and trustworthy methods for evidence syntheses (i.e., systematic reviews, although other evidence syntheses are also adoptable depending on their use) that can reduce risk of bias (Cooke et al., 2023).

There has been development of new tools to address the challenges in decision-making like Evidence-to-Decision (E2D) tool (www.evidence2decisiontool.com). This tool provides a way to practically follow a clear, structured and transparent way and provide evidence used in decision making. Collins and colleagues state that UK policymakers found that collaboration between review experts and policy makers can enhance both evidence syntheses and their application in decision making in practice (Cooke et al., 2023). The prospects of evidence use are summarized below in Figure 3.

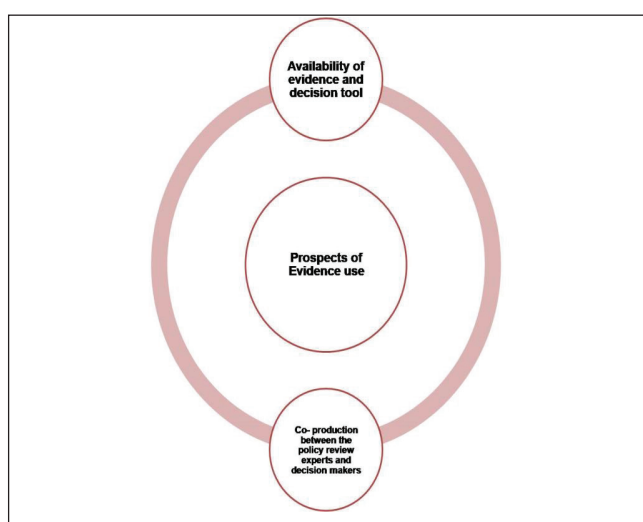


Figure 3: Prospects of Evidence Use

Policy Effectiveness: Policy effectiveness or successful implementation of the policy is desirable

to the attainment of its objectives. Besides, appropriate institutional arrangements with adequate human and financial resources are vital for successful policy implementation. Policy effectiveness analysis is carried out to test whether the policies are effective. Regarding policy effectiveness, there are observations of the authors as stated below.

Policy Evaluation and Accountable Government in international Arena: It is important to hold governments accountable through policy action evidence of enhancement of public sector effectiveness such that it demonstrates results, indicating government actions are producing desired outcomes. Secretary of State Blunkett notes that research plays a vital role in formulating effective strategies, clarity of their processes and improving the quality and responsiveness of public policies (Sanderson, 2002).

In the UK, professional policy making emphasizes the need for policymakers to acquire new competencies such as economics, statistics, and relevant scientific fields for dealing with the critical assessment and acquiring complex policy evidence (Sanderson, 2002). However, thorough evaluation and systematic review of policy have not been widespread in practice, specifically in social and environmental areas compared to that in economic ones (Banks, 2009).

Studies have found that failure of governments in Australia to collect adequate data to assess the effectiveness of their own programs that may be elsewhere, too. There has been insufficient effort to establish the baseline data necessary for meaningful before-and-after policy intervention comparisons (Banks, 2009). The elements of policy effectiveness are summarized below in Figure 4.

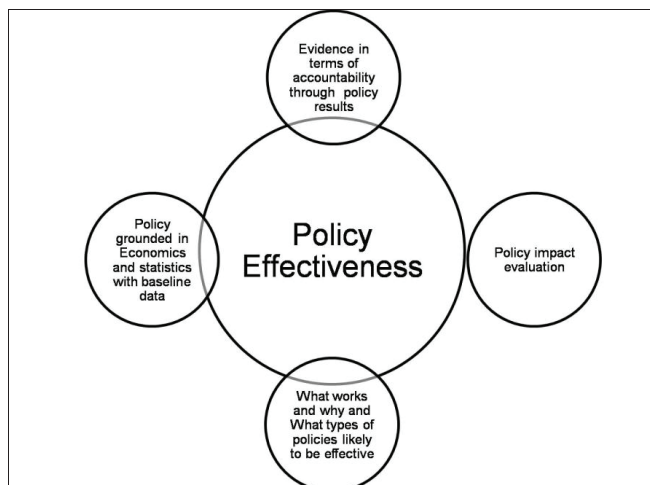


Figure 4: Policy Effectiveness

Evidence based Policy Making Status in Nepal

Present Scenario: Evidence-based policy making in Nepal is still at its initial stage. While awareness and concerns is growing with civil society demands, pressure from the intellectual circle also increases. However, the national policy process generally relies on top-down assumptions and ad hoc political rhetoric. However, initial draft preparation, stakeholder consultation and concerned institutions like National Planning Commission, Ministry of Law and Justice, Ministry of Finance and other concerned Ministry or Departments are consulted in the process of draft policy preparation or final consent. Moreover, public opinion through digital media is also growing these days.

Challenges: Lack of Evidence use culture, inadequate research culture and grassroots data, political or other favor group interests, inadequate institutional capacity, conflicting laws, inadequate resources, ad hoc planning culture, lack of policy and project evaluation system etc. The following observations indicate the gloomy picture of the environmental effectiveness in Nepal.

Prospects: Focus of the Government in science, innovation and research can be taken as a positive ray of hope for research culture and evidence-based policy making. Similarly, Think Tank institutions like the Nepal Institute for Policy Research (NIPoRe), universities and research centers and the Governance Lab etc. are generating evidence-based debates to fill the gap between research and decision-making (Panta, 2023).

Najam's Policy Analysis Protocol of 5C for Environmental Pollution in Nepal: It would be appropriate to analyze the policy of concern or environmental pollution related policies in Nepal with existing widely used model, for that purpose Najam's policy analysis protocol of 5C (Najam, 1995) can be adopted as it is in practice worldwide. The 5C Protocols and their examples are given onwards.

1. Content of the policy or define the problem and objectives.

Problem statement: e.g. Specify pollutants(s) of concern (e.g. $PM_{2.5}$, PM_{10} , SO_2 , NO_x), exposure hotspots (Kathmandu Valley, Terai), and seasonality data. Objectives: Health risk reduction (e.g. reduce annual $PM_{2.5}$ by X%), equity (protect vulnerable groups), economic efficiency (cost per $\mu g/m^3$ reduced), compliance with WHO and national guidelines.

2. Context of the policy or select policy of concern.

Statutes and policies: Environment Protection Act 2019 (EPA 2076), National Environment Policy 2019, Solid Waste Management Act 2011, National emission Standards, WHO standard for river water or National Standards for Industrial effluent etc. Programs and finance: Projects related to industrial emissions reductions via electrification, emission controls, local and provincial plans etc. Institutions: Ministry of Agriculture, Forests and Environment/ Department of Environment, Provincial concerned Ministries, Municipalities etc.

3. Commitments: Establish baseline data and trends

For example, air quality levels: Compile recent $PM_{2.5}$ means and exceedance days by city; note WHO guideline exceedance and seasonal peaks. Following are the examples of cases of environmental pollution in Nepal for this purpose. Sources: pollution shares e.g. for air pollution from transport, industry, residential biomass burning, construction dust, open waste burning, cross-border inflow and wildfires, etc. Health and economic burden of pollution: Mortality/morbidity estimates and GDP loss

share; identify sensitive groups and high-exposure occupations from pollution.

4. Capacity: Institutional capacity to implement the policy and related programs

Diagnosing why pollution persists: weak enforcement capacity, limited monitoring capacity, slow electrification, finance and electric vehicle use policy etc. Implementation reality: Contrast on rhetoric and reality in de jure policy provisions and standards versus de facto practice;

5. Clients and Coalition actors concerned with the policy of concerns. Define evaluation criteria for analyzing effectiveness.

Effectiveness: Expected reduction in affected population with weighted PM_{2.5} etc. Cost-effectiveness: Cost per µg/m³ reduced, payback for adoption of cleaner technology. Equity: Benefits for low-income and high-exposure groups in affected regions and seasons. Feasibility: Administrative capacity, political acceptability and financial and other viability. Co-benefits/risks: Climate mitigation, energy security, industrial competitiveness (Najam, 1995). The elements of Najam's 5C Policy Analysis Protocol are shown below in Figure 5.

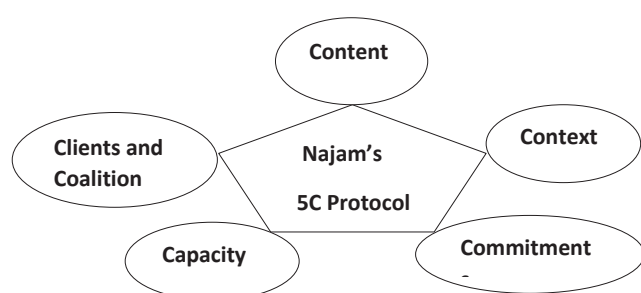


Figure 5: The elements of Najam's 5C Policy Analysis Protocol

Policy Instruments for Environmental Pollution

The policies need to be supported by appropriate policy instruments; they may be in the form of command and control, market-based instruments, or voluntary community participation. Economic incentives of various types are provided to implement these instruments. The observations of the authors in the literature concerned are given below.

Command and Control: Command-and-control or regulating instruments are the oldest tools used in environmental policy (Rittberger & Richardson, 2003). Despite the introduction of many new approaches, these traditional instruments still play a significant role in formulating environmental policies. These are indeed the policy provisions like banning littering of waste, allowing only treated industrial effluent with set standard parameters and household sewage to rivers and water bodies, to have green stickers with the vehicles etc. and consequent punishments to the defaulters.

Market Based Instruments: Market-based tools rely on economic incentives to drive compliance. These incentives can be categorized as positive (like subsidies), negative (such as Eco-taxes or waste disposal fees), or a combination of both (for example, deposit-refund systems). Many scholars consider these economic approaches to be more effective than mandatory regulations. However, these instruments are rarely practiced in Nepal

Voluntary Instruments: Voluntary instruments are associated with the willingness of individuals and organizations to act without compulsion. These tools are relatively recent additions to environmental policy (Rittberger, B. & Richardson, 2003) and (Howes & Wyrwoll, 2012). These instruments for example waste collecting fee is partially practiced in many municipalities in Nepal

Communicative Instruments: These instruments deal with spreading knowledge and raising awareness through public information campaigns, educational programs, and workshops aimed at informing citizens and stakeholders about environmental issues (Eckerberg, 1997). These instruments are in practice through television, radio and digital social media platforms etc.

Institutions: Effective environmental policy requires resourceful institutions for implementing policies into practice. The Centre for Management and Policy Studies within the Cabinet Office of the UK government to serve as a central hub for research and evaluation is the best example towards this approach (Pawson & Tilley, 1997). In this aspect, Institutions in Nepal are generally weak.

3.2 Discussion

Formulating policies based on evidence is not an easy job because of the problem of reliability and replicability of the evidence(s), resources needed to generate them, lack of confidence of the policy makers e.g., political Leaders and senior bureaucrats, decision culture and capability and so on.

Evidence-Based Policy Making and Challenges:

The importance of a science-based policy as it rarely leaves any room for policy manipulation by different interest groups, politicians or so forth for their vested interest (Shah et al., 2021).

Making policies based on evidence is a challenging process. There are many barriers such as reliability and reproducibility of data, limited resources for generating quality evidence, lack of trust among policymakers like politicians and senior officials, and inadequate capacity and culture for evidence. So, institutionalizing evidence-based policy making remains a significant challenge in many developing countries, including Nepal.

However, unlike Nepal and developing world country like the United States has legal infrastructure in place for transforming evidence into policy by enacting the Foundations for Evidence-Based Policy Making Act in 2018, followed by executive actions aimed at encouraging federal agencies to prioritize evidence-building based on science and data (Cooke et al., 2023).

Contextual Barriers of Evidence Use: Evidence is not sought out often and so underutilized in decision-making, even in the case it is readily available, and the effects of policy implementation are mostly not studied, too. The research studies show that even if decision makers recognize the importance of quality evidence syntheses, they are not easily accessible to them when sought for a specific policy issue. There are institutional obstacles that may obstruct the process of integration of evidence synthesis into decision-making system (Cooke et al., 2023).

Factors Influencing Evidence Use: Policy decisions are not just made by empirical data or rational analysis but they are also affected by values,

interests, and personalities of the decision makers including timing and chance. Banks argues that policy making does not occur in isolation, it arises amid political pressures, lobbying, and vested interests (Banks, 2009). The reliability of policy-related evidence while formulating policy is also a matter of concern that many evidence syntheses lack the quality needed to effectively support policy decisions as shown by recent study findings (Page, 2021). There geerally remains knowledge gap in environmental decision-making of a clear understanding of type, source and validity of the evidence of concern at deciding state vis a vis which evidence to use, and how much weightage to be allotted to them by decision makers (Cooke et al., 2023).

Reasons for Policy Failure: Over expectations, implementation in weak governance, inadequate collaborative policymaking, and the uncertainty of the political cycle are major factors of policy failure (Hudson et al., 2019). Political leaders often prioritize their personal agendas and electoral promises over objective evidence. However, it is observed that many existing evidence syntheses lack methodological rigor and transparency, such that they can be hardly replicated or even trusted for planning and implementation stages (Page, 2021).

Policy analysis is found underdeveloped, relying mostly on stakeholder consultations that often reflect personal opinions and vested interests in place of objective evidence in Nepal (Panta, 2023). Environmental policy suffers from many issues such as failing to incorporate cross-cutting themes, political interference, inactive advisory bodies, poor implementation of policy institutions and inadequate resources (Devkota, 2011). Newly adopted federal democratic system of Nepal has resulted in inconsistent and poorly coordinated policy making, often with unstructured and ad-hoc decisions (Shah et al., 2021). Policy failures in Nepal can be attributed to weak policy formulation, poor inter-agency coordination, weak institutions, inadequate resource allocation, and lack of systematic evaluation.

Evidence-based Policy Prospects of Nepal: Nepal has recently started embracing participatory

decision-making though in fragmental basis on the understanding of the senior decision makers involving stakeholders such as experts, users, and NGOs. Nonetheless, the effectiveness of a policy ultimately depends on its outcomes. If it fails to deliver, it should be revised promptly. For successful implementation, supportive mechanisms such as appropriate instruments, competent institutions, sufficient resources, and user trust are essential.

Policies need to be understood as knowledgeable guesses made using the best available information during the process of formulation. Evaluation of policy implementation is crucial for learning their workability and if not the underlining reasons there for future improvements (Panta, 2023). A review study of Australia's waste management policy revealed that the aim of achieving zero solid waste was expensive and environmentally unsustainable as well. Institutions must nurture a culture of research and unhindered learning if they are with evidence-based approaches (Banks, 2009).

Research Finding to Policy Making: Even though various tools and strategies for transforming evidence into decision-making have emerged, their success depends significantly whether researchers or evidence producers collaborate directly with policymakers. Similarly, a strategy that promotes the exchange of knowledge between distinct relevant groups called boundary spanning concept from organizational management was introduced in the 1970s (Cooke et al., 2023). Connecting researchers or evidence producers and users to ensure that research findings are applicable in practice for decision-making is important in environmental policy sector. Increased mentorship and skill development training is desired to cultivate a culture that always values the use of evidence for decision making Producing evidence syntheses merely is not of much use unless understanding how they are used within the broader environmental management system for evidence-based practice of decision making (Cooke et al., 2023).

Policy Effectiveness: Any policy to be effective needs to perform well with proper implementation of its policy provisions through programs and

projects. The policies have not been working properly in Nepal due to not addressing policies on cross-cutting issues, continuous interference by political parties, the failure to function by national advisory bodies properly, the negligence of policy institutions to put policies into practice, and on the top of that, lack of adequate human and financial resources. The following are the examples of environmental policy effectiveness in Nepal. Out of more than 130 EIA documents very few are implemented fulfilling basic criteria effectively. The monitoring, evaluation and auditing system of EIA was almost neglected, resulting in weak performance (Devkota, 2011).

Air Pollution Context: The WHO has set ultimate target for annual mean PM_{2.5} concentration as 5 µg/m³, with an initial interim goal of 35 µg/m³ for encouraging incremental progress (World Health Organization, 2021) whereas, the national standard limit of 40 µg/m³. However, to achieve these benchmarks there needs the urgency and scale of effort to address air pollution in areas like the Kathmandu Valley and the Terai, where current pollution levels significantly exceed this safety limits (The World Bank, 2025).

River Water Pollution in Bagmati River

The BOD level as specified in the national generic standard for industrial effluent is 50 mg/L, and that in the WHO standard for portable water is 6 mg/L. These levels exceeded in all sampling sites of Bagmati River. In addition, Gairigaun and Tilganga section contained the BOD level 30 times more than the given standard. The less urbanized areas such as Sundarijal and Gokarneshwor also exceeded the specified standard that clearly indicated organic pollution in the river. Except Sundarijal and Gokarneshwor all sampling sites contained more COD than the WHO standard (10 mg/L) and standard for the national industrial effluents (250 mg/L) (Baniya et al., 2019).

Solid Waste Management

The household waste collected is transported by vehicles and disposed off finally to the selected areas prescribed by local bodies. The disposal sites are mainly Landfill, riverbanks, depressed land/

dumps, open pit, or temporary open piles (Maharjan et al., 2019). It matters whether the policies work or not, the observation of the UK on this issue is highlighted as stated in the lines hereafter. There is a need to strengthen the evidence base through long-term impact assessments of policy initiatives for program evaluation (Pawson & Tilley, 1997). This is in conformity with the UK government's slogan: what matters is what works (Sanderson, 2002).

Environmental Policy Instruments

Policy instruments particularly for environmental pollution such as command and control, market-based instruments, voluntary instruments and communication instruments need to be adopted in the policies concerned to make them effective. However, they are found to be minimally adopted in practice in Nepal.

Institutions and Federal Government Perspectives

Institutions for experimentation and evaluation are vital to foster adaptive governance and social learning (Sanderson, 2002). However, institutional strength is generally weak with inadequate human and other resources and other working environment. The relevant institutions in Nepal was restructured after introduction of federalism when many important institutions were curtailed or removed and as the provincial and local government institutions are still struggling to develop their performing capacity. Environmental pollution aspects are still to be mainstreamed in the government business.

Learning for Nepal from Developed Countries

Nepal can learn from the developed countries like USA, UK, and Australia etc. in following aspects of evidence-based policy making and effectiveness in the perspectives of environmental pollution. Develop legal infrastructure and strong institutions like Environmental Protection Agency (EPA) for it as in the USA. Establish or provide mandate to core agency to NPC, Cabinet Secretariate (as in the UK) or the Ministry of concern for it. Adopt principles and policy instruments in the concerned policies. Implement the policy provisions of concerned laws mandatorily. Establish or strengthen universities

and research institutions (as in Australia) with adequate resources needed for the evidence-based policy making and evaluation of the policy implementation.

3. Conclusions

The articles reviewed gave good insights on evidence-based policy formulation and mechanism for desired effectiveness in general. The concerned articles on Nepal scenario are found very few and recent picture with evidence (data) could not be available particularly for evidence-based policy formulation. It may be due to lack of research on the pertinent subject. So, a vast knowledge gap on environment policy formation process and their effectiveness is found from this article review process. In this respect, it is high time that researchers particularly with enriched practical experiences on it needs to be inspired and promoted by the government through appropriate research institutions or universities with the research grants. Further, the close connection between research institutions and the government or even private organizations needs to be established through research grants from the concerned agencies, however particular research needs to be on the institutional need basis only.

However, adoption of evidence-based policy making is very important to avoid policy of political and other vested interests, to make them strategic and effective or action oriented improving their quality and in turn, to meet the aspirations of the people as envisaged by its objectives.

The governments in the developed world are in that direction but many developing countries including Nepal is yet it to realize it. Even though the evidence needs to be reliable and replicable, moreover, it needs to be easily available and have trust of the policy makers and the users so that it is generated transparently with scientific methods. Even though there are numerous barriers for evidence-based policy making, there are prospects as well if we adopt digital technology platforms in this new era.

Adoption of proper policy instruments and principles, appropriate institutions with adequate

human and financial resources are needed to implement them effectively or to make the policy effective. Policy program evaluation system is yet to be institutionalized in many developing countries including in Nepal that needs to be started with.

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5. Author Contribution

The main author contributed to reviewing, analyzing the relevant articles and writing of the draft manuscript. The corresponding and co-authors supervised, writing reviews and editing. All authors have read and approved the final version of the article.

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