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Temporal Analysis of Climate Variability and PM2.5 Concentration Trends in Gaya city, Bihar: A 30-year Assessment (1990 – 2023)

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ABSTRACT
Climate change has a significant implication in urban environment especially on public health, water resources, agriculture and ecosystems. The predominantly affected areas are climate-sensitive regions like eastern India. The study examines changes in temperature, rainfall, PM2.5 (pollution pressure) and land use/land cover (LULC) over Gaya City, Bihar, during the period of 1990 - 2023. The result shows a constant increase in minimum, average and maximum temperature, leading to a narrowing of diurnal temperature.. Rainfall indicates high interannual variability with no clear long-term trend, indicating increased uncertainty in climate. PM2.5 exhibits an upward trend with short-term variation and recent partial falls. Regardless of intermittent improvement, annual mean concentrations remain constantly high from the standard values suggested by the national and WHO guidelines.. The LULC study reveals an extension of built-up areas, increases in forest cover, and a decline in grassland and cropland, indicating the combined effect of afforestation and urbanisation. These interacting climate and anthropogenic changes are likely to intensify environmental stress, with implications for rainfed agriculture, urban heat island effects, and pollution levels. The study emphasizes the need for an integratedclimate adaptation, land management, and pollution control strategies at the district levels.
KEYWORDS: *Land use land cover, PM2.5, Rainfall variability, Temperature trends, Urbanization*

1. INTRODUCTION

Climate change is identified as one of the most crucial environmental challenges of the 21st century (Kabir et al. 2023), affecting the temperature, precipitation patterns, pollution dynamics, and land use systems (Kabir et al. 2023). Anthropogenic activities such as urbanization, industrialization and transportation are the key drivers of changing climate as they increase emission of greenhouse gases in the atmosphere (Kabir et al. 2023). IPCC's Sixth Assessment report (IPCC 2023), has again emphasized that mean annual temperature is rising and trend related to the rainfall is uncertain. The report further states that human – induced global warming has reached 1.1°C above 1850 - 1900 levels, with more than 50% chance of surpassing 1.5°C by 2040. Global temperature continues to rise, with the decade of 2011 - 2020 being the warmest on record. It is expected that a consistent rise in temperature would increase the risk of extreme environmental conditions such as heat waves, intense precipitation and drought, sea level rise and henceforth collapsing of whole ecosystem. However, the regional impact may be an existential crisis to vulnerable communities.

Pollution is another critical, intertwined environmental crisis after climate change (World Bank, 2023). Pollution directly causes over 6.5 million deaths annually and is also a cause of ecosystem degradation (World Bank, 2023, National Institute of Environmental Health Sciences, NIEHS, 2023). Moreover, increasing temperature amplifies pollution toxicity indicating an interplay with changing climate. Further, air pollution is a driver of global warming and exacerbates extreme weather conditions. It is also an important environmental issue of the Indo-Gangetic plains, where increase In vehicular emission, rapid urbanization, industrial activities and biomass burning contribute significantly in air quality degradation

(Singh et al. 2023). The percentage of PM 2.5 (fine particulate matter) in total air pollution is crucial and is highly variable spatio-temporally depending upon the local pollution sources (NIEHS 2023). PM 2.5 is highly important because it has the ability to cross respiratory system, causing serious cardiovascular and respiratory illness (NIEHS, 2023). .

While global and national-scale assessments are abundant, district-level analyses are warranted for understanding localized impacts and for designing context-specific adaptation strategies. The Gaya city in Bihar is predominantly agrarian (Krishi Vigyan Kendra, Gaya, 2023) and largely dependent on monsoonal rainfall, making it highly vulnerable to climatic variability and extremes. Approximately 55% of agriculture in India is rainfed, and Gaya follows a similar pattern. Any alteration in temperature and rainfall therefore directly affects crop productivity, water availability, and rural livelihoods. At the same time, rapid urbanization, land use change, and increasing pollution (increase traffic density and anthropogenic activities expansion) loads are modifying the local climate through mechanisms such as the urban heat island effect and land–atmosphere interactions (Kabir et al. 2023, Singh et al. 2023). However, long-term city-level trend analysis are limited. This study aims to assess long-term changes in climate variables, land use and land cover (LULC) and associated environmental transformations over the Gaya city from 1990 to 2023. The study further intends to assess temporal variations in PM2.5 concentrations in Gaya city from 2001 to 2022, to interpret the trends in the context of policy and environmental degradation.

2. MATERIAL AND METHODS

2.1 Study Area

The city of Gaya is located in southern Bihar and covers a total geographical area of approximately 493,774 ha. Land use is dominated by agriculture (about 228,648 ha), followed by infertile land (27,836 ha). Forest cover is relatively low (about 77,836 ha), though recent decades have seen modest gains due to afforestation initiatives (Krishi Vigyan Kendra, Gaya, 2023). The city experiences a tropical monsoon climate, characterized by hot summer, a humid monsoon season, and mild winters.

2.2 Data collection

2.2.1 Climate Data

Temperature data comprising minimum, maximum and average values for a period of 33 years (1990 – 2023) were analysed to identify long-term trends and rates of change. Rainfall data were examined to assess annual totals, variability, and extreme years.

2.2.2 IMD Gridded Daily Temperature Data

Daily gridded maximum (T_{max}) and minimum (T_{min}) temperature data were obtained from IMD, Pune in NetCDF (.nc) format at a spatial resolution of 1° × 1°, arranged over a 31 × 31 grid spanning 7.5°N–37.5°N latitude and 67.5°E–97.5°E longitude, with data available from 1951 onwards (Srivastava et al., 2009). Temperature values are expressed in degrees Celsius (°C). This gridded product was prepared by spatially interpolating daily maximum and minimum temperature records from the IMD surface meteorological observational network across India, following quality-controlled procedures consistent with those adopted for the gridded rainfall dataset.

2.2.3 IMD Gridded Daily Rainfall Data

Daily gridded rainfall data were sourced from the India Meteorological Department (IMD), Pune in NetCDF (.nc) format. The dataset provides daily precipitation estimates at a spatial resolution of 0.25° × 0.25° (latitude × longitude), covering 135 × 129 grid points across India, with the domain starting at 6.5°N and 66.5°E (Pai et al., 2014). Rainfall values are expressed in millimetres (mm) and the dataset spans from 1901 to the present. This gridded product was developed by spatially interpolating observed daily rainfall records from 6,995 quality-controlled rain gauge stations across India using the Shepard (1968) distance-weighted interpolation technique (Pai et al., 2014). The dataset has been extensively validated against global gridded precipitation products and is widely accepted as a benchmark for climatological and hydrological studies over the Indian subcontinent.

2.3. Pollution and Anthropogenic Pressure Assessment

Concentration of PM 2.5 was analysed for a period of 22 years (2001 - 2022). A time series approach was used to examined inter-annual variability.

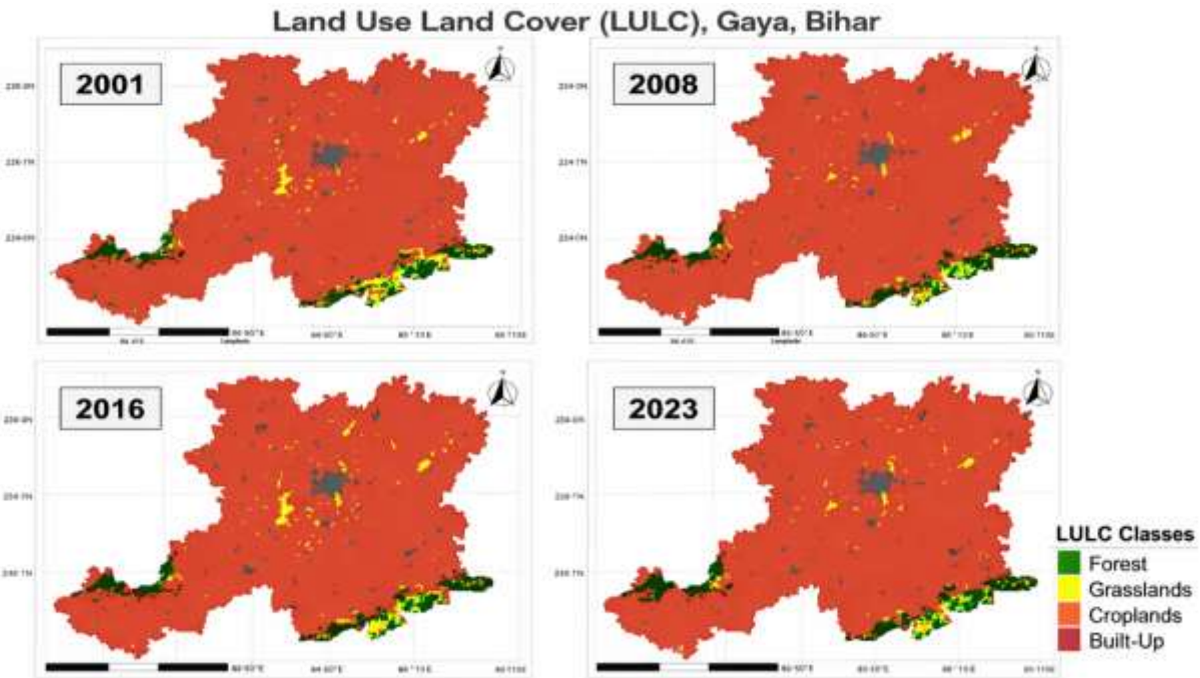
2.3.1. Satellite-Derived Surface $PM_{2.5}$ (ACAG, V6.GL.02.04)

Annual and monthly ground-level fine particulate matter ($PM_{2.5}$, μg/m^3) concentration data were obtained from the Atmospheric Composition Analysis Group (ACAG) at Washington University in St. Louis through their publicly accessible Sat$PM_{2.5}$ data repository (https://sites.wustl.edu/acag/surface-pm2-5/). The Version 6 Global dataset (V6.GL.02.04) was used in the present study, which provides gridded $PM_{2.5}$ estimates at a high spatial resolution of 0.01° × 0.01° (~1 km) in NetCDF (.nc) format, covering the period 1998–2023.

2.4 Land Use/ Land Cover Analysis

The land use land cover (LULC) study was conducted to analyse the change occurred in the city of Gaya over the 22 years. This study analyses LULC changes from 2001 to 2023, focusing on four primary classes: Built-up, Cropland, Forest, and Grassland. The LULC study was perform for whole above-mentioned years, however, in the present study we are focusing on the year 2001, 2008, 2016 and 2023 at eight year interval and the result are shown in figure 1.

Figure 1: Land use land cover change (with land cover classes) for the year 2001, 2008, 2016 and 2023.



Land Use Land Cover (LULC) mapping for the years 2001, 2008, 2016, and 2023 in Gaya district, Bihar, was carried out using the MODIS Land Cover Type product (MCD12Q1, Version 6.1), accessed through Google Earth Engine (GEE). GEE is a cloud-based geospatial processing platform that enables access to multi-petabyte satellite archives and allows for large-scale analysis without the need for local storage or heavy computation. The MODIS dataset provides annual global land cover at 500-meter spatial resolution, classified using supervised algorithms based on MODIS Terra and Aqua reflectance data. The study utilized the International Geosphere-Biosphere Programme (IGBP) classification scheme, and four dominant land cover categories: forest, grassland, cropland, and built-up were extracted. The data was clipped to the district boundary, reclassified to ensure consistency across years, and analyzed for spatiotemporal changes through pixel-based area estimations. Final mapping and visualization were performed using QGIS for enhanced cartographic representation and interpretation. The selected MODIS product is widely validated and suitable for assessing long-term LULC dynamics at the district level.

2.3 Data Processing and Extraction in R

All time-series extraction and spatial data processing were performed in the R programming environment (R Core Team, 2022; version ≥ 4.x) using the packages: ncdf4, terra, raster, dplyr, lubridate, and CLimd.

2.3.4 Data Integration

The three individually extracted time-series datasets, viz., temperature, rainfall and PM2.5, were merged into a unified data frame, aligned by year and months, spanning the complete study period. Data completeness was assessed for each variable, and any identified missing values were handled through linear interpolation or flagged and excluded from trend and correlation analyses, as appropriate.

2.4 Statistical Analysis

2.4.1 Descriptive Statistics

Descriptive statistics including mean, standard deviation (SD), minimum, maximum, and coefficient of variation (CV) were computed for all three variables - annual/seasonal $PM_{2.5}$, rainfall, and temperature - across the study period to characterize their distributional properties and inter-annual variability.

2.4.2 Trend Analysis

Long-term temporal trends in $PM_{2.5}$ concentrations and meteorological variables were evaluated using the non-parametric Mann–Kendall (MK) trend test (Mann, 1945; Kendall, 1975), which is robust to non-normality and the presence of outliers in environmental time-series data. The Sen's Slope estimator (Sen, 1968) was applied to quantify the magnitude of change (per year or per decade) for statistically significant trends. These analyses were conducted using the Kendall and/or trend packages in R. The seasonal Kendall test was additionally employed where seasonal decomposition of the signal was warranted to account for intra-annual periodicity.

3. RESULTS AND DISCUSSION

3.1 Temperature Trends (1990 – 2023)

Analysis reveals a clear increasing trend in minimum, maximum and average temperatures in the Gaya city (Fig. 2, 3, and 4; Table 1). The rate of increase is highest for minimum temperature (~ 0.03 °C per year), followed by average temperature (~ 0.02 °C per year), while maximum temperature showed a relatively slow increase (~ 0.014 °C per year).

Figure 2: Interannual variation in mean minimum temperature over Gaya city from 1990 to 2023.

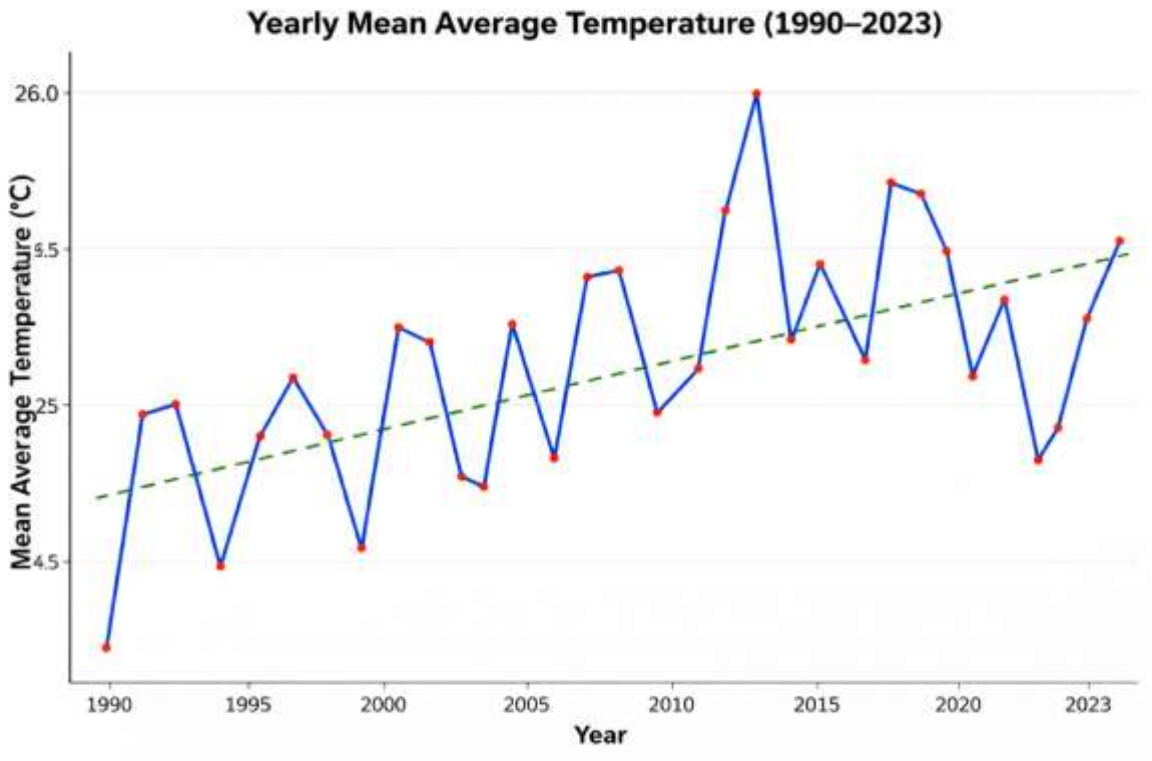


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Figure 3: Interannual variation in mean average temperature in Gaya city from 1990 to 2023.

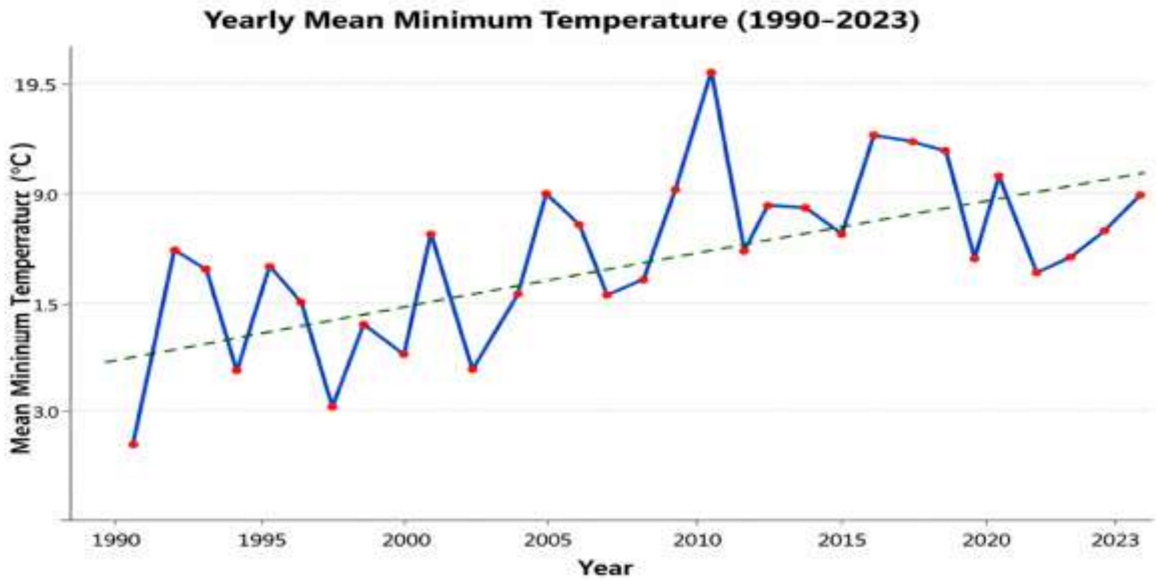


Figure 4: Interannual variation in mean maximum temperature in Gaya city from 1990 to 2023.

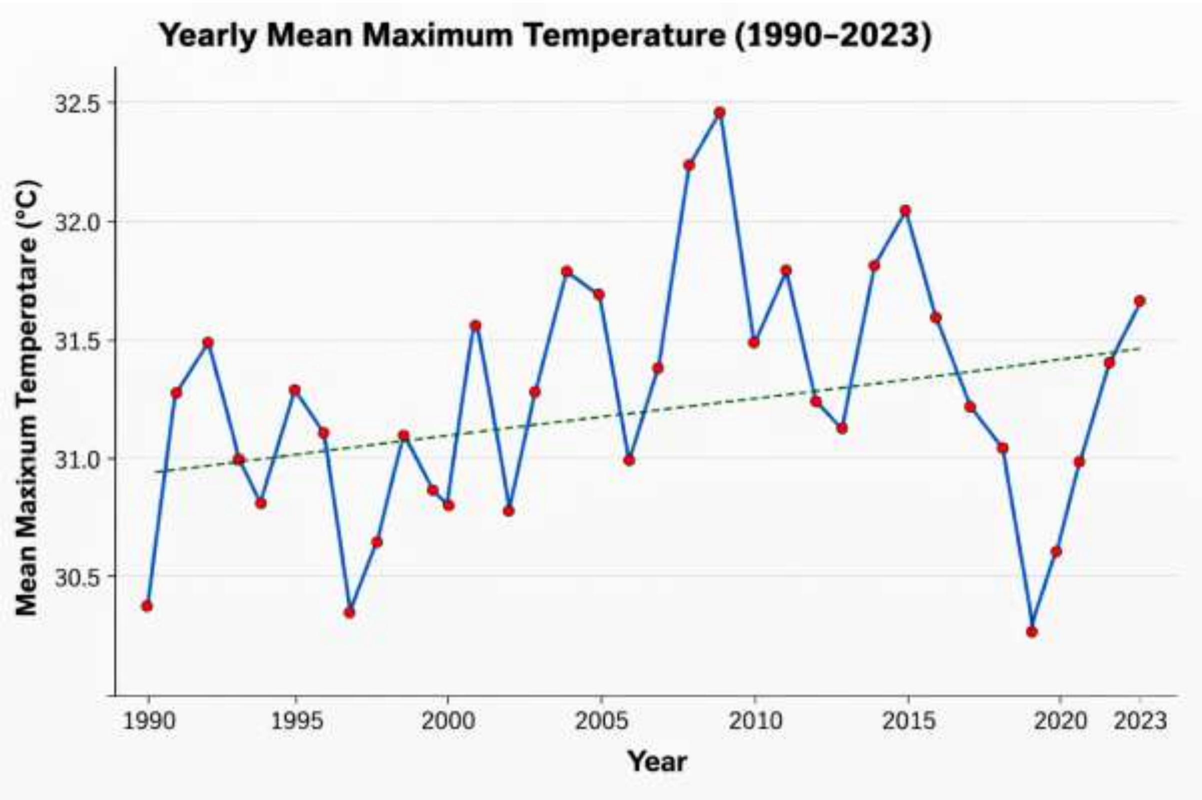


Table 1: Minimum, average and maximum temperature trend over the year (1990 - 2023) in Gaya city

Temperature	Rate of increase °C per year	Approximate temperature increase °C	Periodic pattern	Average Minimum temperature	Average temperature	Average Maximum temperature
Minimum	0.03	1.05	1990 - 2000	~ 18.7°C	~ 24.9°C	~ 31.2°C

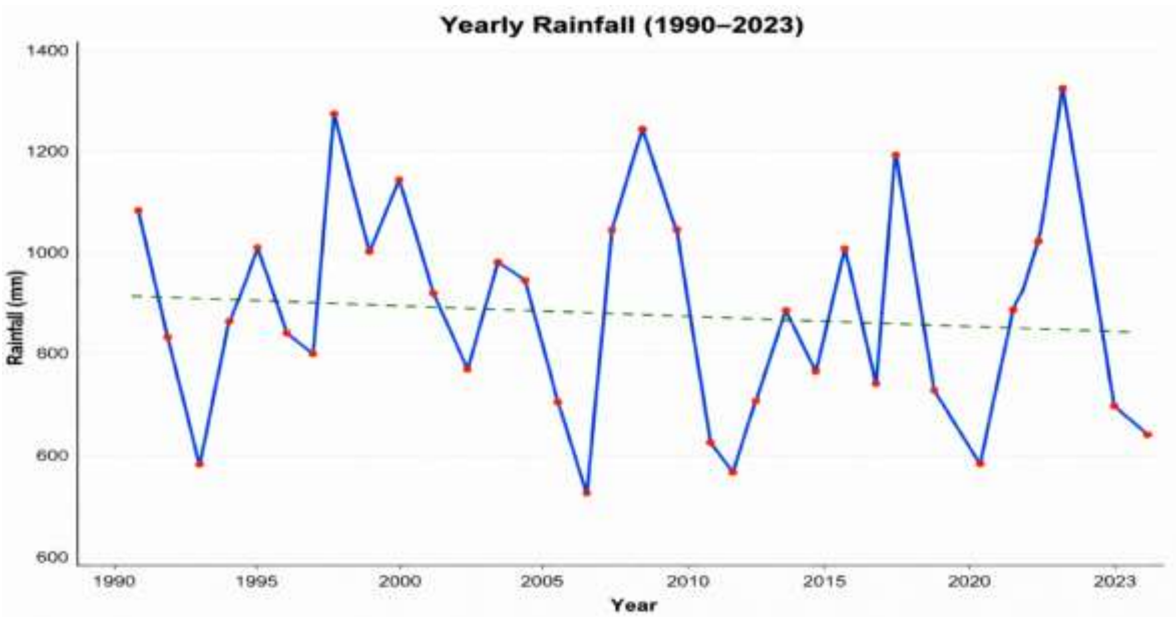
Average	0.02	0.75	**2001 - 2010**	~ 18.9°C	~ 25.2°C	~ 31.4°C
Maximum	0.014	0.48	**2011 - 2020**	~ 19.2°C	~ 25.4°C	~ 31.7°C

The annual minimum temperature data from 1990 to 2023 exhibit a long - term warming trend, despite noticeable interannual variability (Fig. 2). In the early 1990s, minimum temperatures were generally below 18.5 °C, with the lowest value observed in 1990 (17.65 °C). From the mid – 1990s onward, minimum temperature showed a gradual increase, punctuated by short – term declines (Fig. 2).
A marked rise is evident after the year 2000, with minimum temperatures frequently exceeding to 19.0 °C. The highest minimum temperature (~ 19.8 °C) occurred around 2010, indicating increasingly warmer nights. Post – 2010, temperature remain consistently elevated, rarely dropping below 19 °C, suggesting a shift in the baseline minimum temperature regime (Table 1).
This asymmetric warming has resulted in a narrowing diurnal temperature range, a phenomenon widely associated with global climate change (Kabir et al. 2023). Enhanced night-time warming relative to daytime heating may be linked to increased cloud cover, greenhouse gas concentrations, and urban heat retention due to built-up surface (Qian et al. 2022). Rising minimum temperatures can have serious implications for crop phenology, pest populations, and human health. Narrowing of diurnal temperature alter circadian rhythm in plants thus inferencing the plant capability to cope with the temperature fluctuation and cause carbon trade-off particularly in growth and night-time respiration (Sujod et al. 2020). Various studies show an increase in heat-related human mortality due to enhanced exposure to heat in urban areas (Urban et al. 2022). In a study, the urban heat island is considered to affect the population of cicada insects in Okayama City, Japan (Nguyen et al. 2018).

3.2Rainfall Variability

The average annual rainfall over the study period was approximately 981.55 mm, indicating moderate rainfall conditions. However, rainfall exhibits strong interannual variability, with the lowest recorded rainfall of 621.15 mm in 1992 and the highest of 1401.20 mm in 2000 (Fig. 5).

Figure 5: Interannual variation in average rainfal in Gaya city from 1990 to 2023.



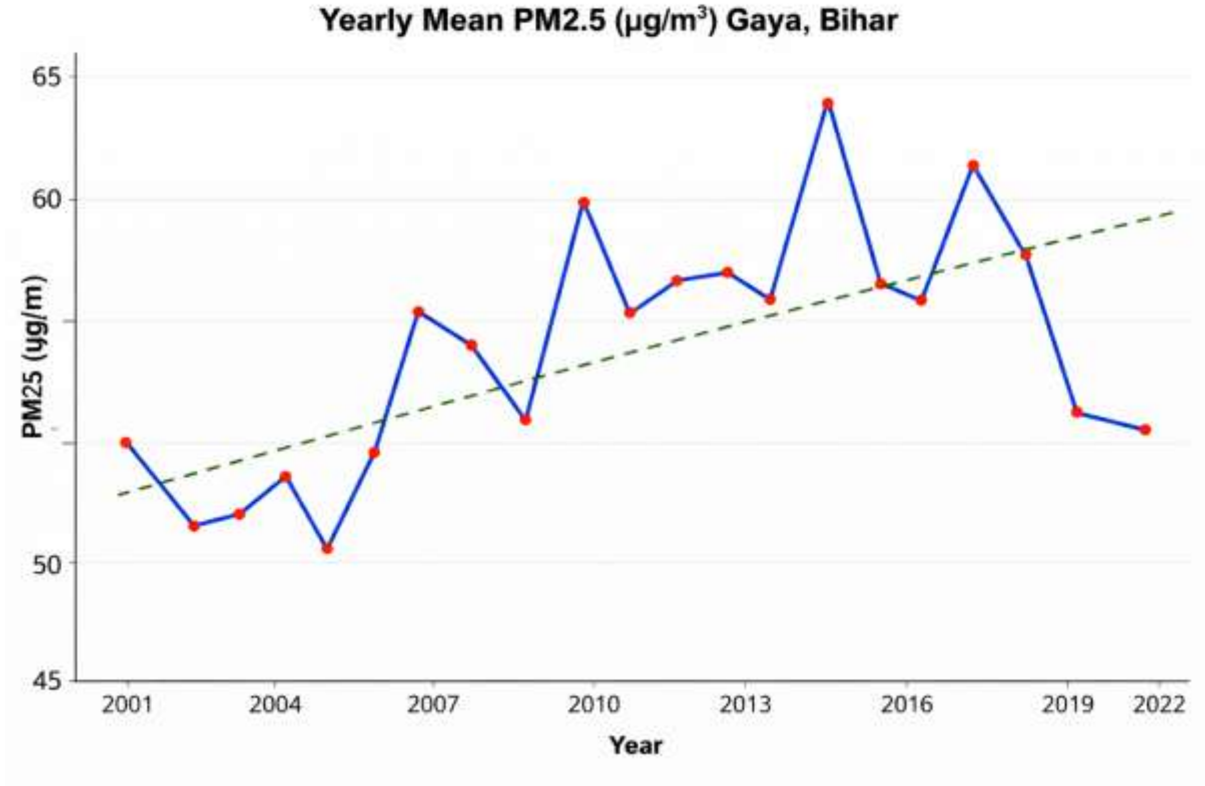
No clear long-term increasing or decreasing trend is evident, suggesting that rainfall in Gaya city is strongly influenced by natural climatic oscillations such as monsoon anomalies, El Niño, and La Niña events as other parts of the Indian Subcontinent (Vishnu et al. 2022). Some of the years experienced rainfall decline exceeding 20%, indicating drought-like conditions, and have severe drought related consequences (Vishnu et al. 2022). While others recorded increases greater than 30%, reflecting intense monsoon episodes leads to flooding causing substantial loss of life and economy (Singh et al. 2019) (Fig. 5). Such variability poses major challenges for agriculture, water resource management, and disaster preparedness (Singh et al. 2019).

3.3 PM 2.5 concentration

3.3.1 Overall Trend

The PM2.5 concentrations over Gaya city showed a long-term increasing trend from 2001 to 2019 (Fig. 6). Average concentrations increased from approximately 46 – 48 µ m^{-3} in the early 2000s to above 60 µ m^{-3} during peak years (Fig. 6).

Figure 6: Interannual variation in mean PM2.5 in Gaya city from 1990 to 2023.



3.3.2 Period-Wise Observations

2001–2006 (Low to Moderate Levels) PM2.5 values remained relatively lower (≈ 45 – 49 µ m^{-3}) (Fig. 6). Minor fluctuations suggest localized emission sources with limited large-scale industrial influence. 2007–2014 (Rapid Increase Phase) a sharp rise is observed, with concentrations exceeding 55 µ m^{-3} (Fig. 6). The increase may be associated with urban expansion, vehicular growth, construction activities, and intensified biomass burning (Zhang et al. 2017). 2015–2019 (Peak Pollution Period) the highest PM2.5 concentration (~ 66 – 67 µ m^{-3}) occurs around 2016 (Fig. 6). This period reflects severe air pollution, likely influenced by regional transport of pollutants, seasonal crop residue burning, and unfavourable meteorological conditions (Zhang et al. 2017, Faisal et al. 2022). 2020–2022 (Recent Decline) a noticeable reduction is seen after 2019, with values falling to ~54 µ m^{-3} by 2022 (Fig. 6). This decline may reflect improved emission controls, reduced activity during COVID-19 lockdowns, and increased awareness, though levels remain critically high.

The long-term upward trend indicates progressive deterioration of air quality in Gaya city over two decades. Despite short-term variability, the overall rise suggests that emission growth has outpaced mitigation measures for most of the study period as compared with standards guideline given for annual

PM2.5 by WHO (5 μ m^{-3}) (WHO 2021) and Indian NAAQS, 2009 (40 μ m^{-3}). Throughout the study period, PM2.5 concentrations in Gaya consistently exceeded both national and international standard, often by a factor of 1.5 – 3, posing serious health concerns (Faisal et al. 2022).

3.3.3. Public Health Implications

Sustained exposure to elevated PM2.5 levels increases the risk of, chronic respiratory diseases (asthma, COPD), cardiovascular disorders, and premature mortality (WHO 2021, Faisal et al. 2022). Vulnerable groups, including children, the elderly, and outdoor workers, are particularly at risk in Gaya city.

3.3.4 Policy and Management Implications

The decline in PM2.5 concentration after 2019 is encouraging but insufficient. The result highlights the need for stronger vehicular emission control, regulation of biomass burning and construction dust, constant district-level air quality monitoring and extensions of urban green spaces.

3.4 Land Use/Land Cover Changes (2001–2023)

Over the past two decades, significant LULC changes have occurred in Gaya City. Built-up areas increased from 64.32 sq km in 2021 to 67.27 sq km in 2023, indicating the steady increase in urbanisation (Table 2, Fig. 7). Although the majority of land is still under cropland, a decline by about 45.19 sq km reflects land conversion for non-agricultural purposes (Table 2, Fig. 8).

The forest cover increased noticeably from 118.93 sq km to 216.78 sq km, implying the impact of afforestation and conservation programmes (Table 2, Fig. 9). In contrast, grassland areas declined sharply, highlighting their vulnerability to land conversion and degradation (Table 2, Fig. 10).

Table 2: Land use land cover classes and transition occurring over the years (2001 - 2023) in Gaya district

LULC	Area 2001 (sq km)	Area 2023 (sq km)	Overall gain (sq km)	Rate of increase or decrease sq km/ year)
Built -up Areas	64.32	67.27	+2.94	+0.49
Cropland	4847.01	4801.82	-45.19	-3.42
Forest Cover	118.93	216.78	+97.84	+4.21
Grassland	104.39	48.80	-55.59	-0.93

Note: Positive (+) sign indicate gain in the area whereas negative (-) sign indicate loss in area

Figure 7: Temporal trend of built-up area and rapid urban expansion in Gaya city from 2001 to 2023.

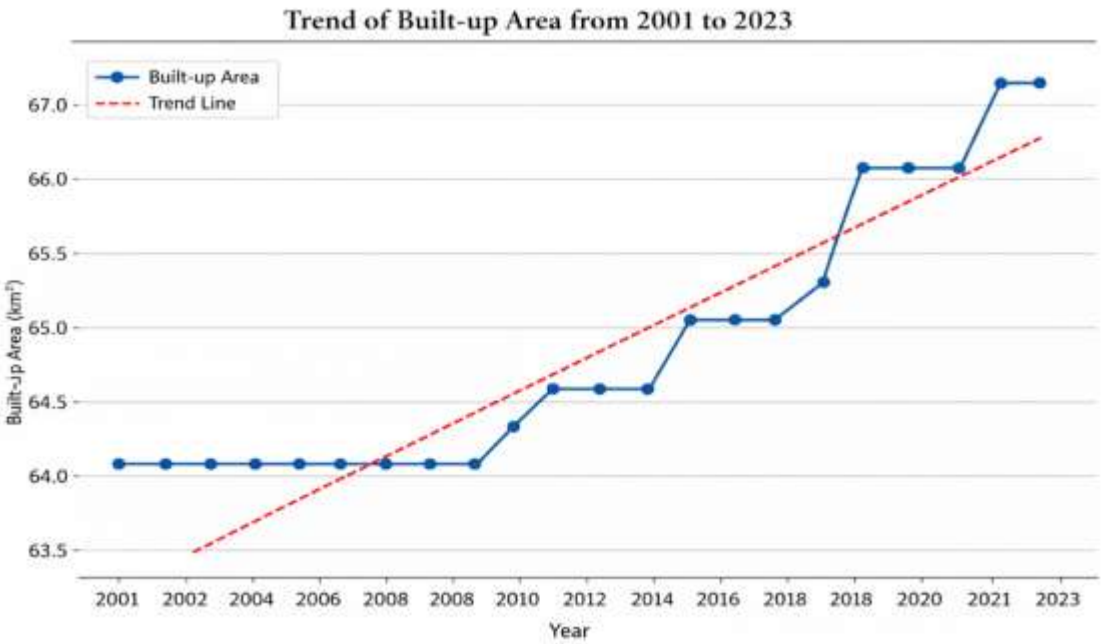


Figure 8: Temporal trend of cropland area in Gaya city from 2001 to 2023.

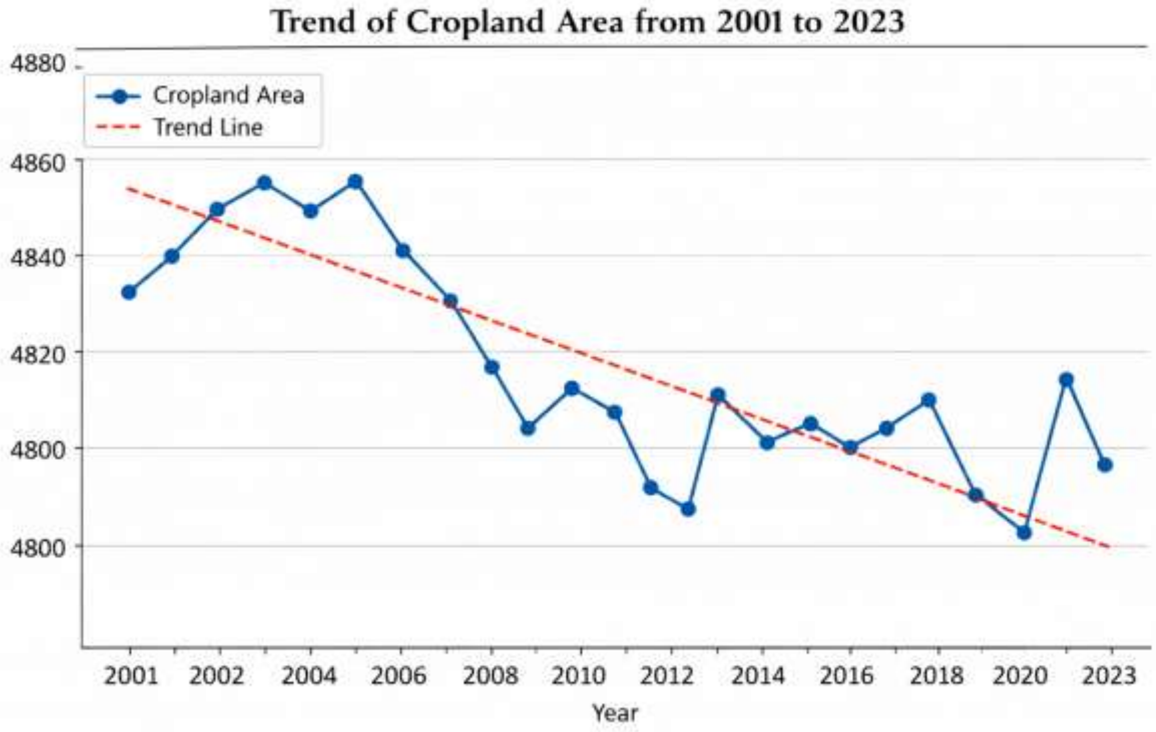


Figure 9: Temporal trend of forest area in Gaya city from 2001 to 2023.

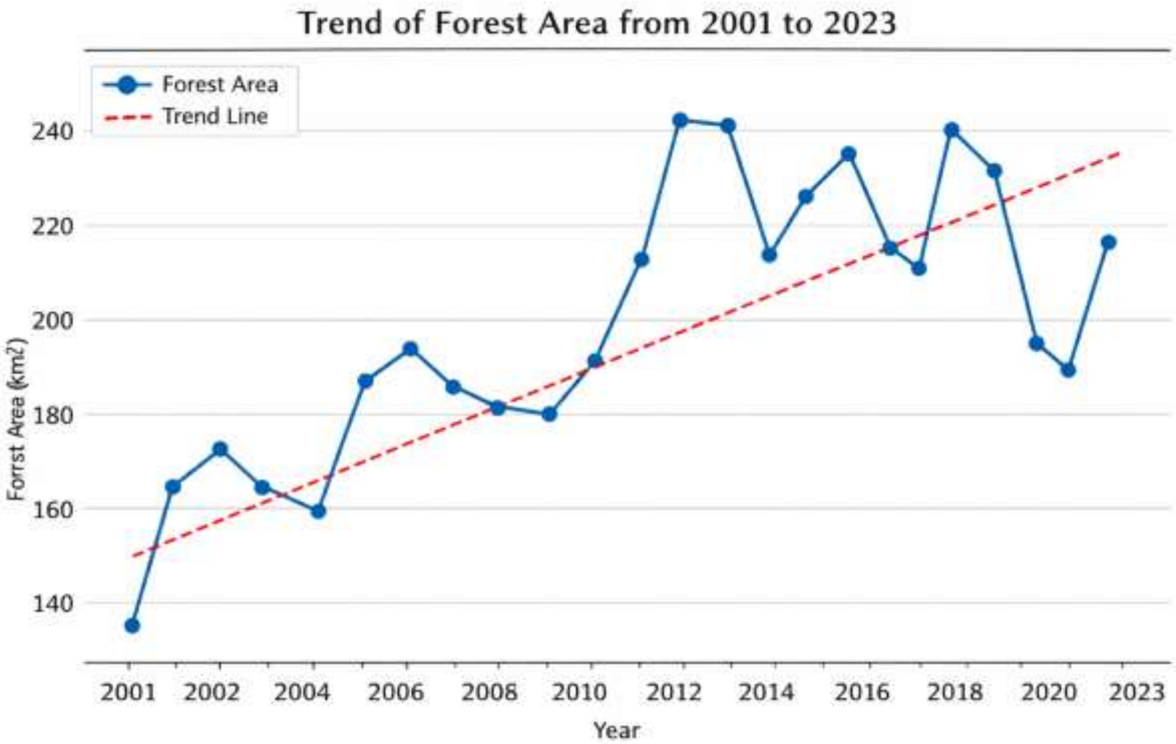
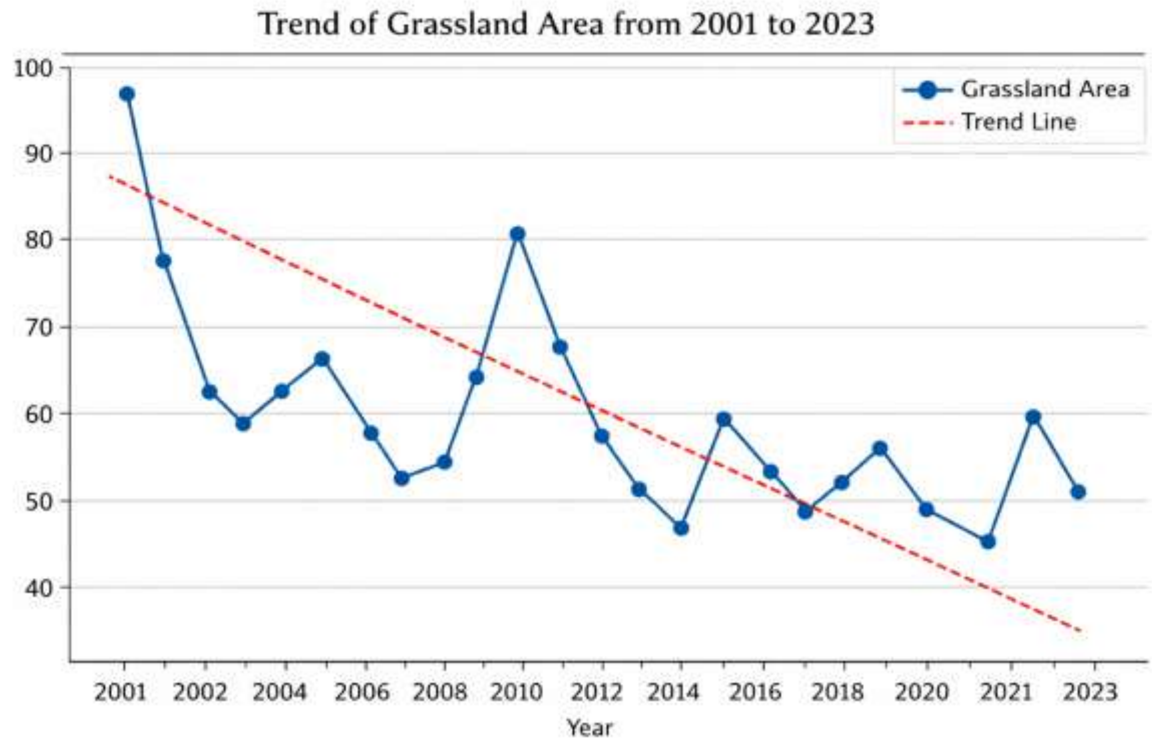


Figure 10: Temporal trend of grassland area in Gaya city from 2001 to 2023.



3.4Urbanization, Climate Interaction, and Pollution Increase

Rapid urbanization in Gaya city has multiple environmental consequences. Expansion of built-up areas contributes to urban heat island effect, particularly by increasing minimum temperature at night. Construction activities, vehicular growth, and industrial development are likely increasing air pollution levels, while changes in land use may exacerbate water pollution through runoff and reduced natural filtration.

The shift of land toward non-agricultural uses in recent decades, reflects growing pressure on natural and agricultural ecosystems. Although afforestation efforts have improved forest cover, rising pollution levels and climatic stress may offset some of these ecological gains if not managed carefully.

4 CONCLUSIONS

This study indicate that Gaya city has experienced significant climatic and environmental changes over the past three decades. Key results include a steady increase in temperature, with a more rapid increase in minimum temperature. No clear long term variation in rainfall was observed, however substantial interannual variability was evident. Further, a surge in PM2.5 concentration was evident with a trajectory of long-term increase from 2001 to 2019. There was an increase in urban built-up areas with a decline in grassland and cropland areas was observed during investigation. Further, afforestation programmes have led to an expansion in forest cover. These interrelated trends have complicated the relationship between land use dynamics, pollution increases, and climate change at the city scale. For long-term environmental assurance and socio-economic resilience in Gaya City, implementing integrated planning that combines sustainable land management, pollution control and climate adaptation is crucial.

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Authors contributions: TM carried out the data collection and did all the calculations, helping to study the LULC over the respective years and providing images. SK wrote the manuscript and did all the corrections as suggested, and SNT and TA generated the main idea, created content, wrote, and finalised the manuscript.

Data availability: All data generated or analysed during this study are included in this published article (and its supplementary information files)

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