

## Linking ambient air pollution to health risk burden: A comparative study across urban and semi-urban regions of Karnataka, India

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### ARTICLE INFORMATION

*Article Chronology:*

Received 28 March 2026

Revised 24 July 2026

Accepted 05 August 2026

Published 29 September 2026

*Keywords:*

Particulate matter; Health risk assessment;  
Mann–Kendall trend test; Karnataka

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### ABSTRACT

**Introduction:** Ambient air pollution poses significant public health challenges across urban and semi-urban India. Karnataka, encompassing coastal, plateau, highland, and semi-arid environments, provides an ideal setting for evaluating regional air quality variability and associated health risks. This study assessed the spatio-temporal characteristics of ten criteria and hazardous air pollutants measured at five Central Pollution Control Board (CPCB) Continuous Ambient Air Quality Monitoring Stations (CAAQMS) across Karnataka during 2024.

**Materials and methods:** Monthly mean concentrations of Particulate Matters (PM<sub>2.5</sub>, PM<sub>10</sub>), Nitrogen dioxide (NO<sub>2</sub>), Sulfur dioxide (SO<sub>2</sub>), Carbon monoxide (CO), Ozone (O<sub>3</sub>), Ammonia (NH<sub>3</sub>), and benzene were analysed across four India Meteorological Department (IMD) seasons. Serial autocorrelation was assessed using the lag-1 Kendall statistic prior to applying the Mann–Kendall test and Sen's slope estimator as an exploratory assessment of intra-annual monotonic tendencies. Spatial variability was evaluated using one-way ANOVA with Tukey's HSD post-hoc test and validated using the Kruskal–Wallis test. Inhalation health risks were assessed using the USEPA Risk Assessment Guidance for Superfund (RAGS) methodology by estimating Hazard Quotient (HQ), Hazard Index (HI), and Lifetime Cancer Risk (LCR).

**Results:** Bengaluru recorded the highest annual mean PM<sub>2.5</sub> (40.2 µg/m<sup>3</sup>) and PM<sub>10</sub> (80.4 µg/m<sup>3</sup>) concentrations, with PM<sub>2.5</sub> equal to the CPCB National Ambient Air Quality Standard (NAAQS) and PM<sub>10</sub> exceeding it by approximately 34%. Annual mean PM<sub>2.5</sub> concentrations at all stations exceeded the WHO 2021 Air Quality Guideline (15 µg/m<sup>3</sup>). The southwest monsoon produced the greatest reduction in particulate concentrations. Exploratory Mann–Kendall analysis yielded negative Sen's slopes for PM<sub>2.5</sub> at all stations, although none were statistically significant ( $p > 0.05$ ). One-way ANOVA confirmed significant spatial heterogeneity among monitoring stations ( $p < 0.001$ ). Screening-level health risk assessment indicated HI values  $> 1.0$  at all stations (1.756–3.290). Estimated PM<sub>2.5</sub> LCR ranged from  $1.76 \times 10^{-3}$  to  $3.34 \times 10^{-3}$  and represents hypothetical upper-bound screening estimates rather than regulatory cancer risk values.

**Conclusion:** Particulate matter remains the dominant air quality concern across Karnataka, particularly in Bengaluru. Strengthened emission control measures, continued multi-year monitoring, and agricultural ammonia management are recommended to support long-term improvements in air quality and public health.

Please cite this article as: D G, KE G. Linking ambient air pollution to health risk burden: A comparative study across urban and semi-urban regions of Karnataka, India. Journal of Air Pollution and Health. 2026;11(3):341-360.

Doi: <https://doi.org/10.18502/japh.v11i3.22624>

## Introduction

Ambient air pollution is widely recognised as one of the most significant global environmental health risks, contributing to approximately 6.7 million premature deaths annually [1, 2]. Fine Particulate Matter (PM<sub>2.5</sub>) and coarse Particulate Matter (PM<sub>10</sub>) are strongly associated with cardiovascular, respiratory, and cancer-related morbidity and mortality [3]. In India alone, PM<sub>2.5</sub> exposure was responsible for an estimated 1.67 million deaths in 2019 [4]. Air quality across Indian cities exhibits pronounced spatial and seasonal heterogeneity, with meteorology-driven PM<sub>2.5</sub> reductions ranging from  $-6.51$  to  $-0.36$   $\mu\text{g}/\text{m}^3$ /year reported for major megacities [5].

Karnataka, located on the southwestern Deccan Peninsula, presents substantial geographic and climatic diversity encompassing the metropolitan hub of Bengaluru, the coastal industrial city of Mangalore, semi-arid inland regions (Belagavi, Yadgir), and the high-altitude Western Ghats terrain of Madikeri. Research gaps persist in linking meteorological controls, multi-pollutant interactions, and quantitative health risk metrics within a unified analytical framework applicable to non-IGP South Indian cities [6, 7]. To address these gaps, this study applies six integrated analytical modules to 2024 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) data: (i) seasonal profiling of ten pollutants across four IMD seasons; (ii) temporal trend analysis including PM-weighted wind rose characterisation; (iii) non-parametric trend detection using the Mann–Kendall test with autocorrelation pre-screening and Sen's slope estimator; (iv) inter-station spatial variability testing using ANOVA and Kruskal–Wallis

statistics; (v) inhalation health risk assessment quantifying non-cancer Hazard Index (HI) and Lifetime Cancer Risk (LCR); and (vi) Pearson correlation-based multi-pollutant interaction analysis.

## Study area

Five CAAQMS operated by the CPCB across Karnataka were selected, representing distinct geographic, climatic, and emission environments spanning coastal, plateau, highland, and semi-arid regions (Fig. 1). Belagavi ( $15.88^\circ\text{N}$ ,  $74.53^\circ\text{E}$ ;  $\sim 747$  m a.s.l.) is a northern Deccan Plateau city with mixed industrial and agri-commercial activities. Bengaluru ( $12.91^\circ\text{N}$ ,  $77.60^\circ\text{E}$ ;  $\sim 920$  m a.s.l.), the state capital, is characterised by high vehicular density and significant PM<sub>2.5</sub> and NO<sub>x</sub> emissions. Madikeri ( $12.41^\circ\text{N}$ ,  $75.73^\circ\text{E}$ ;  $\sim 1,082$  m a.s.l.) is a Western Ghats hill station with dense forest cover and heavy monsoonal rainfall. Mangalore ( $12.89^\circ\text{N}$ ,  $74.85^\circ\text{E}$ ;  $\sim 22$  m a.s.l.) is a coastal industrial-port city along the Arabian Sea. Yadgir ( $16.76^\circ\text{N}$ ,  $77.14^\circ\text{E}$ ;  $\sim 370$  m a.s.l.) is a semi-arid north-eastern district with dominant dust and biomass-burning emissions. These stations span a coastal–plateau–highland gradient with altitudes from  $\sim 22$  m to 1,082 m and annual rainfall from  $\sim 580$  mm to  $>2,500$  mm. Table 1 shows the metadata and site characteristics of the five CAAQMS selected for the study in Karnataka, India.

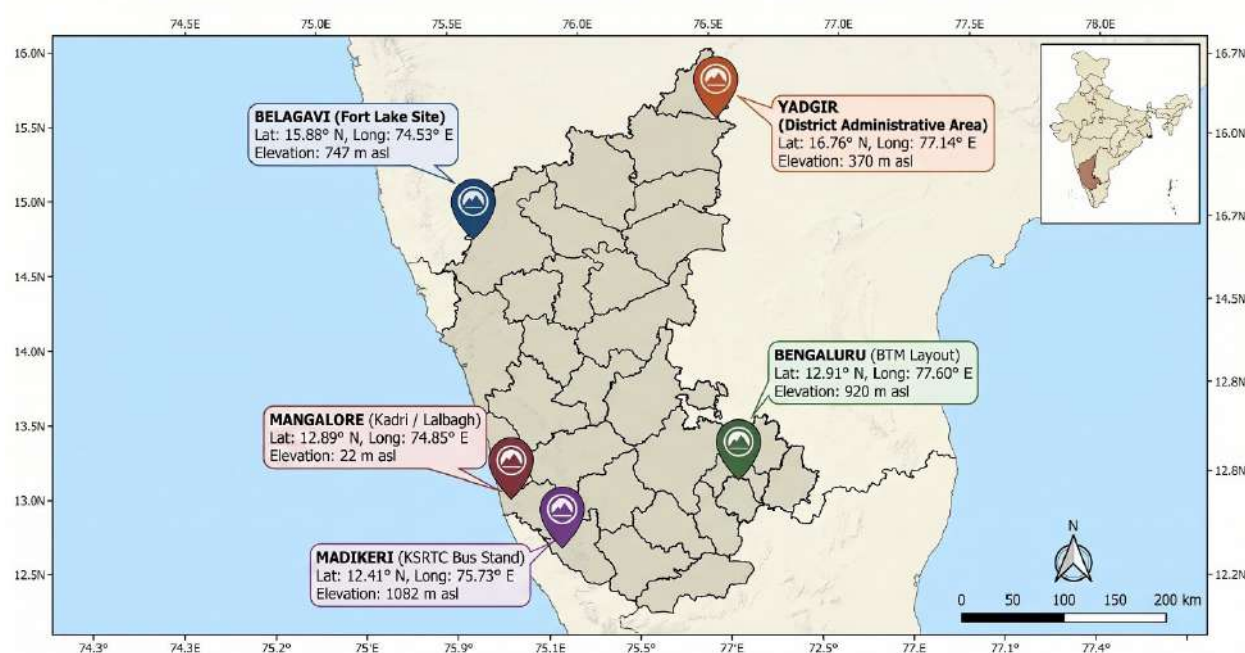


Fig. 1. Geographical location of the five CPCB CAAQMS study stations across Karnataka, India

Table 1. Metadata and site characteristics of the five CAAQMS selected for the study in Karnataka, India

| Station   | Approximate Population<br>(2011 Census) | Elevation<br>(m a.s.l.) | Approximate Distance of<br>CAAQMS from City Centre (km)        | Data<br>Completeness<br>(%) |
|-----------|-----------------------------------------|-------------------------|----------------------------------------------------------------|-----------------------------|
| Belagavi  | ~0.67 million                           | 747                     | ~2.3<br>[15.88° N, 74.53° E]<br>(Fort Lake Site)               | >95                         |
| Bengaluru | ~14.0 million                           | 920                     | ~7.5<br>[12.91° N, 77.60° E]<br>(BTM Layout)                   | >95                         |
| Madikeri  | ~0.04 million                           | 1,082                   | ~1.2<br>[12.41° N, 75.73° E]<br>(KSRTC Bus Stand Area)         | >95                         |
| Mangalore | ~0.75 million                           | 22                      | ~3.1<br>[12.89° N, 74.85° E]<br>(Kadri Monitoring Site)        | >95                         |
| Yadgir    | ~0.17 million                           | 370                     | ~2.0<br>[16.76° N, 77.14° E]<br>(District Administrative Area) | >95                         |

## Materials and methods

### Data source

Monthly averaged concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, NH<sub>3</sub>, SO<sub>2</sub>, CO, O<sub>3</sub>, and benzene, along with four meteorological parameters (temperature, relative humidity, wind speed, wind direction), were obtained from the

CPCB CAAQMS data portal for the calendar year 2024 [8]. Records flagged as instrument malfunction, calibration drift, or anomalous outliers were excluded. Statistical analyses were performed in Python 3.11 [9] using the scipy [9], pymannkendall [10], and pingouin [11] libraries. Table 2 shows the annual mean pollutant concentrations at Karnataka CPCB CAAQMS (2024).

Table 2. Annual mean pollutant concentrations at Karnataka CPCB CAAQMS (2024)

| Station   | PM <sub>2.5</sub><br>(µg/m <sup>3</sup> ) | PM <sub>10</sub><br>(µg/m <sup>3</sup> ) | NO <sub>2</sub><br>(µg/m <sup>3</sup> ) | SO <sub>2</sub><br>(µg/m <sup>3</sup> ) | CO<br>(mg/m <sup>3</sup> ) | O <sub>3</sub><br>(µg/m <sup>3</sup> ) | NH <sub>3</sub><br>(µg/m <sup>3</sup> ) | Benzene<br>(µg/m <sup>3</sup> ) |
|-----------|-------------------------------------------|------------------------------------------|-----------------------------------------|-----------------------------------------|----------------------------|----------------------------------------|-----------------------------------------|---------------------------------|
| NAAQS†    | 40                                        | 60                                       | 40                                      | 50                                      | 2                          | 100                                    | —                                       | 5                               |
| Belagavi  | 22.4                                      | 50.4                                     | 19.7                                    | 6.8                                     | 1.021                      | 22.4                                   | 71.6                                    | 0.90                            |
| Bengaluru | 40.2*                                     | 80.4*                                    | 11.0                                    | 5.2                                     | 0.783                      | 25.2                                   | 4.2                                     | 0.26                            |
| Madikeri  | 21.2                                      | 37.3                                     | 4.5                                     | 3.3                                     | 0.587                      | 26.7                                   | 2.6                                     | 0.03                            |
| Mangalore | 26.4                                      | 68.0*                                    | 4.9                                     | 14.0                                    | 0.754                      | 31.6                                   | 7.1                                     | 0.58                            |
| Yadgir    | 29.0                                      | 60.0‡                                    | 6.6                                     | 15.3                                    | 0.474                      | 15.8                                   | 7.0                                     | 0.13                            |

Note: Benzene reported to two decimal places for consistency with health risk calculations. O<sub>3</sub> and NH<sub>3</sub> are excluded from formal health risk assessment (no applicable chronic RfC available).

Concentrations in µg/m<sup>3</sup> except CO in mg/m<sup>3</sup>, \* NAAQS exceedance; ‡ Yadgir PM<sub>10</sub> equals the NAAQS threshold. † NAAQS annual standards. WHO 2021 annual guideline: PM<sub>2.5</sub> = 15 µg/m<sup>3</sup> (all stations exceeded)

### **Seasonal classification**

Following IMD convention, months were grouped into four climatological seasons: Winter (December–February), Pre-Monsoon (March–May), Monsoon (June–September), and Post-Monsoon (October–November).

### **PM-Weighted wind rose analysis**

Wind directions were classified into eight sectors (45° intervals) and wind speeds into four Beaufort classes. PM-weighted contribution (%) was calculated as: PM-weighted (%) =  $[\Sigma(C_i \times f_i) / \Sigma(C_i \times f_i)_{\text{total}}] \times 100$ , where  $C_i$  is the monthly PM concentration ( $\mu\text{g}/\text{m}^3$ ) and  $f_i$  is the frequency of wind from that sector.

### **Mann–Kendall trend test and sen's slope estimator**

Prior to Mann–Kendall testing, serial autocorrelation was examined using the Lag-1 Kendall autocorrelation statistic [12]. Where significant autocorrelation was detected at  $\alpha = 0.05$ , the modified Mann–Kendall (MMK) test was applied [12]. Monotonic trends in monthly PM<sub>2.5</sub> and PM<sub>10</sub> time series were assessed with the standard MK test [13, 14], and trend magnitude was estimated using Sen's slope estimator [15]. Statistical significance was evaluated at  $\alpha = 0.05$  (\*), 0.01 (\*\*), and 0.001 (\*\*\*). Because only a single calendar year (12 monthly observations) was available, the Mann–Kendall analysis was performed solely as an exploratory assessment of intra-annual monotonic behaviour rather than long-term environmental trend detection. The statistical power of the Mann–Kendall test is inherently limited for such short time series; therefore, the results should not be interpreted as evidence of emission-driven long-term trends.

### **One-Way ANOVA and Kruskal–Wallis test**

Normality of residuals was assessed using the Shapiro–Wilk test [16] and variance homogeneity using Levene's test. One-way ANOVA tested for statistically significant between-station differences, with Kruskal–Wallis as a non-parametric validation. Pairwise post-hoc comparisons used Tukey's HSD (ANOVA) and Dunn's test with Bonferroni correction (Kruskal–Wallis).

### **Inhalation health risk assessment**

Inhalation-based human health risk was evaluated using the United States Environmental Protection Agency (USEPA) Risk Assessment Guidance for Superfund (RAGS) methodology [17, 18]. Annual average pollutant concentrations were assumed to represent chronic exposure conditions. Non-carcinogenic risk was assessed using the Hazard Quotient ( $HQ = C_a/RfC$ ), where  $C_a$  is the annual average concentration and RfC is the reference concentration. The cumulative non-carcinogenic risk was expressed as the Hazard Index ( $HI = \Sigma HQ_i$ ). Carcinogenic risk was estimated as the Lifetime Cancer Risk ( $LCR = C_a \times IUR$ ), where IUR is the inhalation unit risk. Two exposure groups were considered: adults ( $\geq 18$  years; body weight = 60 kg) and children (6–12 years; body weight = 20 kg), using standard exposure parameters recommended by USEPA and the Indian Council of Medical Research (ICMR) [19, 20].

O<sub>3</sub> and NH<sub>3</sub> were excluded from the quantitative health risk assessment because internationally accepted chronic inhalation Reference Concentrations (RfCs) are not available for these pollutants.

For PM<sub>2.5</sub>, no officially established Inhalation Unit Risk (IUR) is available from regulatory

agencies such as the USEPA Integrated Risk Information System (IRIS), the World Health Organization (WHO), or the California Environmental Protection Agency (CalEPA), primarily because PM<sub>2.5</sub> is a chemically heterogeneous pollutant with variable composition and toxicity. Therefore, the IUR value of  $8.3 \times 10^{-5} (\mu\text{g}/\text{m}^3)^{-1}$ , adopted from epidemiological studies linking long-term PM<sub>2.5</sub> exposure with lung cancer mortality, was used solely to provide a conservative, screening-level estimate of potential carcinogenic risk. Accordingly, the calculated PM<sub>2.5</sub> lifetime cancer risks should be interpreted as hypothetical upper-bound screening estimates rather than definitive regulatory cancer risk values.

Similarly, no internationally accepted chronic inhalation Reference Concentration (RfC)

has been established specifically for PM<sub>2.5</sub> by USEPA IRIS or CalEPA. Consequently, the WHO 2021 annual Air Quality Guideline (15  $\mu\text{g}/\text{m}^3$ ) was adopted only as a conservative health-based screening benchmark rather than a toxicological RfC. Therefore, the calculated Hazard Quotient (HQ) and Hazard Index (HI) values should be interpreted as precautionary screening indicators intended to facilitate comparative assessment among monitoring locations, rather than as regulatory risk estimates.

Table 3a illustrates the exposure parameters used in the inhalation health risk assessment and Table 3b shows the screening benchmark concentration and Toxicity reference values (RfC and IUR) used in the health risk assessment.

Table 3a. Exposure parameters used in the inhalation health risk assessment

| Pollutant         | Screening benchmark            | RfC / IUR            | Units                           | Health Endpoint             | Reference                           |
|-------------------|--------------------------------|----------------------|---------------------------------|-----------------------------|-------------------------------------|
| PM <sub>2.5</sub> | Non-cancer (RfC)               | 15                   | $\mu\text{g}/\text{m}^3$        | Cardiovascular, respiratory | WHO [1]                             |
| PM <sub>2.5</sub> | Cancer (IUR)                   | $8.3 \times 10^{-5}$ | $(\mu\text{g}/\text{m}^3)^{-1}$ | Lung cancer                 | Epidemiological studies [21,22, 23] |
| NO <sub>2</sub>   | Non-cancer (RfC)               | 40                   | $\mu\text{g}/\text{m}^3$        | Respiratory inflammation    | CPCB [24]                           |
| SO <sub>2</sub>   | Non-cancer (RfC)               | 40                   | $\mu\text{g}/\text{m}^3$        | Pulmonary function          | CPCB [24]                           |
| CO                | Non-cancer (RfC <sup>†</sup> ) | 4,000                | $\mu\text{g}/\text{m}^3$        | Carboxyhaemoglobin          | WHO [1]                             |
| Benzene           | Cancer (IUR)                   | $2.2 \times 10^{-6}$ | $(\mu\text{g}/\text{m}^3)^{-1}$ | Leukaemia                   | Cal EPA [25]                        |
| Benzene           | Non-cancer (RfC)               | 30                   | $\mu\text{g}/\text{m}^3$        | Haematological effects      | Cal EPA [25]                        |

<sup>†</sup> No chronic IRIS RfC established for CO; WHO 24-hour Air Quality Guideline (4,000  $\mu\text{g}/\text{m}^3$ ) adopted as a conservative chronic surrogate.

## Results and discussion

### Seasonal variation analysis

A consistent seasonal pattern was evident across all monitoring stations, with minimum PM<sub>2.5</sub> and PM<sub>10</sub> concentrations recorded during the monsoon season (June–September), attributable to enhanced wet deposition, precipitation scavenging, and increased atmospheric mixing height [26]. Bengaluru recorded the highest pre-monsoon PM<sub>2.5</sub> (52.0 µg/m<sup>3</sup>), driven by construction activities, road dust resuspension, and reduced boundary layer height [27]. Post-monsoon PM<sub>2.5</sub> peaked at Belagavi (37.6 µg/m<sup>3</sup>), likely reflecting episodic biomass and crop-residue burning across the northern Deccan Plateau [28].

Yadgir exhibited elevated winter PM<sub>2.5</sub> (42.0 µg/m<sup>3</sup>), consistent with cold, dry, low-wind stagnation and enhanced dust mobilisation from semi-arid soils. Ammonia (NH<sub>3</sub>) concentrations at Belagavi were exceptionally high (winter: 133–134 µg/m<sup>3</sup>; pre-monsoon: 133–136 µg/m<sup>3</sup>), indicating persistent agricultural emissions,

with a sharp decline during the monsoon (June: 34.5 µg/m<sup>3</sup>; July: 26.5 µg/m<sup>3</sup>). The annual mean NH<sub>3</sub> at Belagavi (71.6 µg/m<sup>3</sup>) approaches the ATSDR (2004) intermediate-duration inhalation Minimum Risk Level (71 µg/m<sup>3</sup>), warranting targeted epidemiological investigation [29]. SO<sub>2</sub> concentrations at Yadgir (13.8–17.0 µg/m<sup>3</sup>) and Mangalore (10.5–17.0 µg/m<sup>3</sup>) were consistently elevated, implying stable industrial point-source contributions. Table 4 shows the seasonal mean PM<sub>2.5</sub> (µg/m<sup>3</sup>) by station and season (2024). Fig. 2 shows the seasonal average concentrations of ten ambient air pollutants at five Karnataka CPCB CAAQMS (2024). Red dashed lines indicate CPCB NAAQS annual standards. Seasons: Winter (D-J-F), Pre-Monsoon (M-A-M), Monsoon (J-J-A-S), Post-Monsoon (O-N). Fig. 3 illustrates the monthly temporal variation of PM<sub>2.5</sub> (upper panel) and PM<sub>10</sub> (lower panel) at five Karnataka CPCB CAAQMS (2024). Coloured seasonal bands: Winter (blue), Pre-Monsoon (orange), Monsoon (green), Post-Monsoon (purple). Red dashed line = CPCB NAAQS (40 µg/m<sup>3</sup>); purple dashed line = WHO 2021 annual guideline (15 µg/m<sup>3</sup>).

Table 4. Seasonal mean PM<sub>2.5</sub> (µg/m<sup>3</sup>) by station and season (2024)

| Station   | Winter (D-J-F) | Pre-Monsoon (M-A-M) | Monsoon (J-J-A-S) | Post-Monsoon (O-N) |
|-----------|----------------|---------------------|-------------------|--------------------|
| Belagavi  | 28.8           | 21.3                | 10.7              | 37.6               |
| Bengaluru | 49.6*          | 52.0*               | 23.6              | 42.0*              |
| Madikeri  | 26.9           | 23.1                | 13.9              | 24.2               |
| Mangalore | 36.7           | 28.0                | 17.1              | 27.2               |
| Yadgir    | 42.0*          | 33.6                | 15.2              | 30.2               |

\* Equals or exceeds CPCB NAAQS annual standard of 40 µg/m<sup>3</sup>.

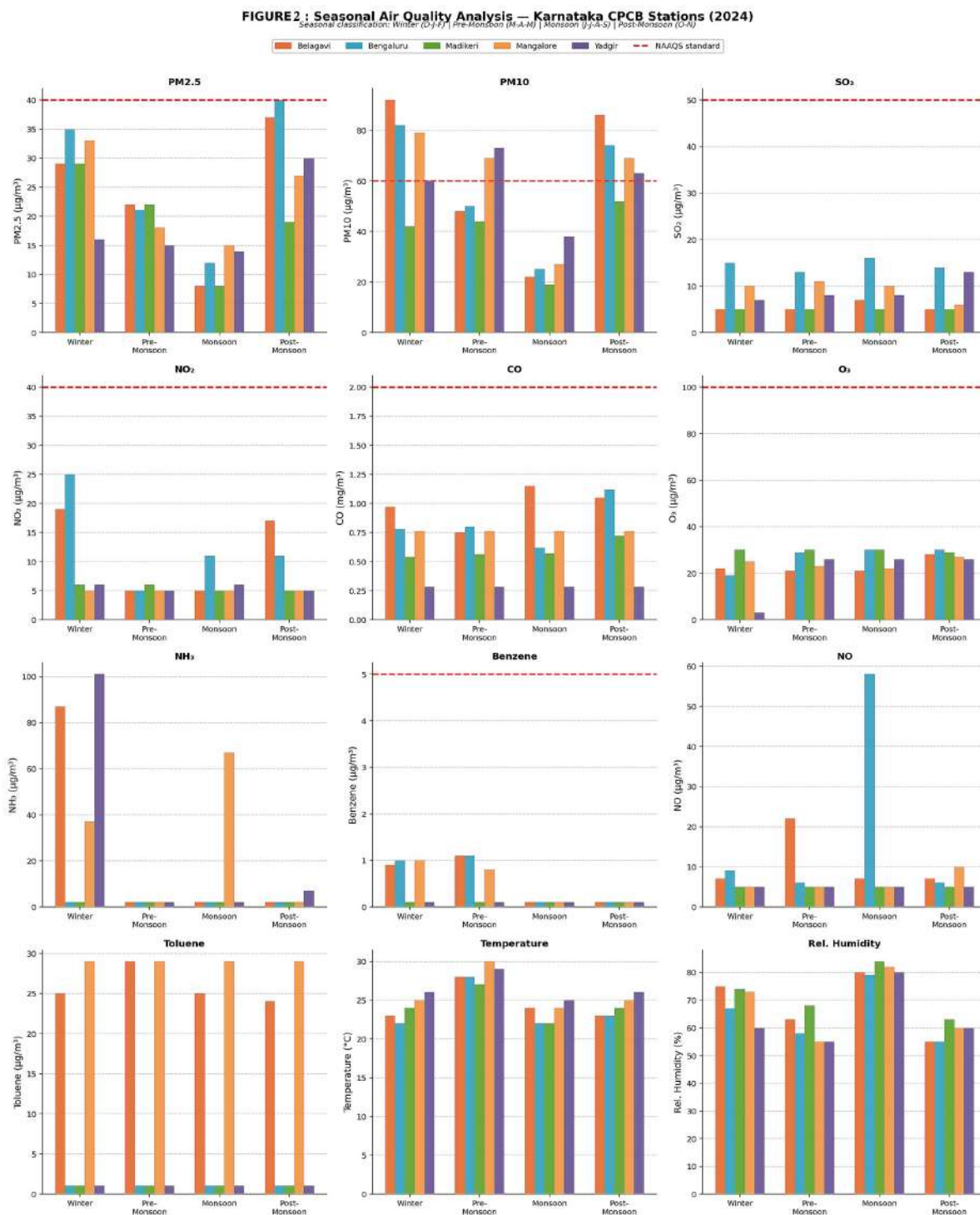


Fig. 2. Seasonal average concentrations of ten ambient air pollutants at five Karnataka CPCB CAAQMS (2024). Red dashed lines indicate CPCB NAAQS annual standards. Seasons: Winter (D-J-F), Pre-Monsoon (M-A-M), Monsoon (J-J-A-S), Post-Monsoon (O-N)

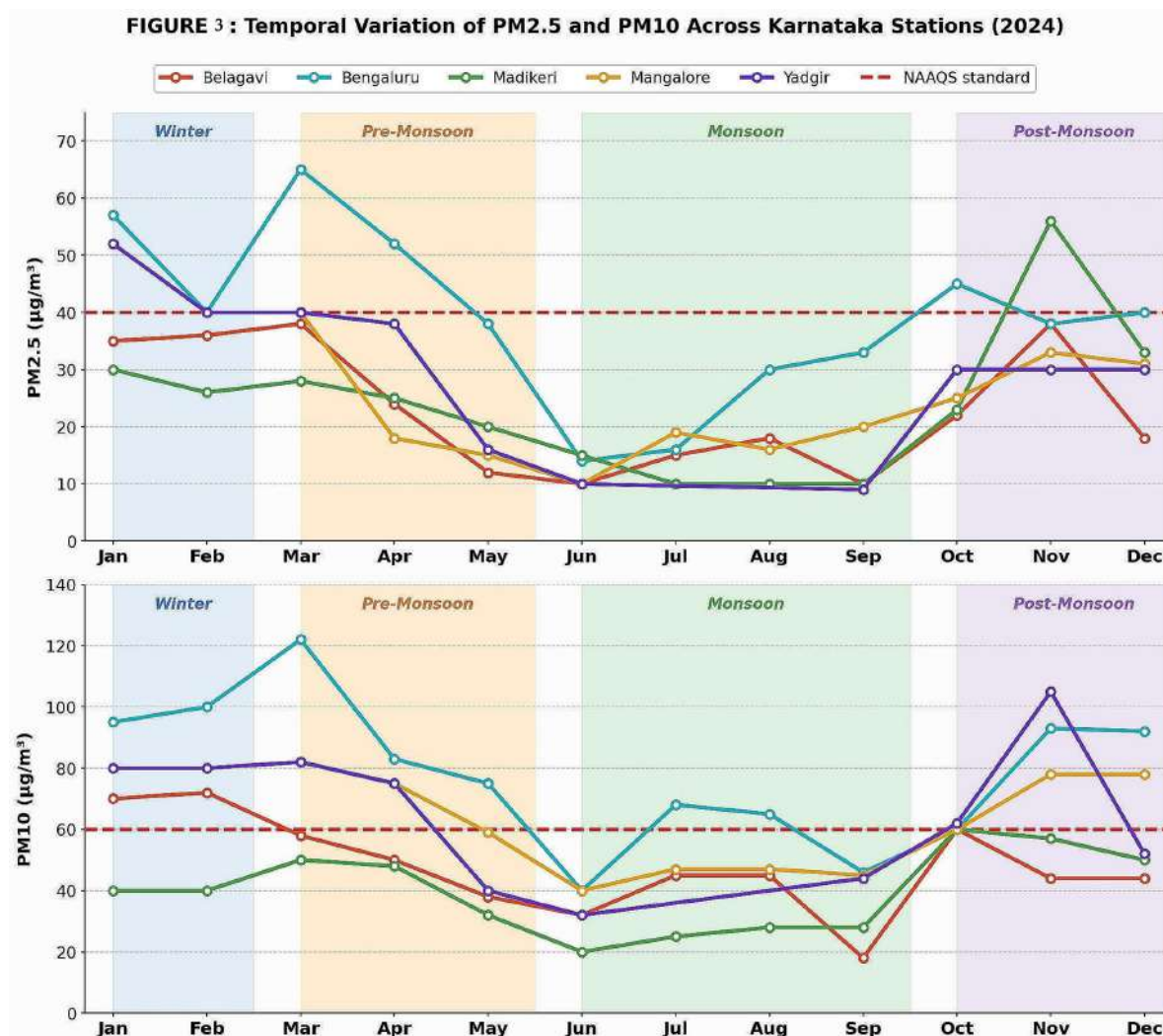


Fig. 3. Monthly temporal variation of PM<sub>2.5</sub> (upper panel) and PM<sub>10</sub> (lower panel) at five Karnataka CPCB CAAQMS (2024). Coloured seasonal bands: Winter (blue), Pre-Monsoon (orange), Monsoon (green), Post-Monsoon (purple). Red dashed line = CPCB NAAQS (40 µg/m<sup>3</sup>); purple dashed line = WHO 2021 annual guideline (15 µg/m<sup>3</sup>)

### ***Mann–Kendall trend analysis and sen's slope***

Autocorrelation pre-screening using the lag-1 Kendall statistic [12] confirmed the absence of significant serial autocorrelation in all 12-month time series ( $p > 0.05$ ), permitting application of the standard Mann–Kendall (MK) test. The exploratory MK analysis yielded negative Sen's slopes for PM<sub>2.5</sub> at all five monitoring stations; however, none of these monotonic tendencies were statistically significant ( $p > 0.14$ ). The only exception was PM<sub>10</sub> at

Madikeri, which exhibited a marginal positive Sen's slope ( $Z = +0.480$ ,  $p = 0.63$ ), although this was likewise statistically non-significant. The MK analysis was performed solely as an exploratory assessment to evaluate whether any monotonic intra-annual tendency was present within the 2024 dataset. Because only twelve-monthly observations were available, the analysis cannot distinguish seasonal variability from genuine long-term changes in ambient pollutant concentrations. Consequently,

the estimated Sen's slopes predominantly reflect seasonal meteorological influences, particularly monsoon-related wet scavenging and associated atmospheric dispersion, rather than changes in anthropogenic emissions.

Among the study locations, Bengaluru exhibited the largest negative PM<sub>2.5</sub> Sen's slope ( $-2.107 \mu\text{g}/\text{m}^3\cdot\text{month}$ ), consistent with the pronounced reduction in concentrations during the southwest monsoon following elevated pre-monsoon levels. Belagavi recorded the largest negative PM<sub>10</sub> Sen's slope ( $-5.342 \mu\text{g}/\text{m}^3\cdot\text{month}$ ), reflecting a similar seasonal response. These negative Sen's slopes should therefore be interpreted only as descriptive measures of within-year variability and not

as evidence of long-term environmental improvement or emission reduction. Robust detection and attribution of temporal trends require continuous multi-year observations (preferably  $\geq 3$ –5 years), consistent with the recommended application of the Mann–Kendall test. Table 5 shows the Mann–Kendall test statistics and Sen's slope estimates for PM<sub>2.5</sub> and PM<sub>10</sub> (2024). Fig. 4 shows the statistical analysis summary. Panel A: Mann–Kendall Z-statistic matrix for all pollutants (blue = -ve monotonic tendency; red = +ve monotonic tendency). Panel B: Sen's slope estimates for PM<sub>2.5</sub> and PM<sub>10</sub> ( $\mu\text{g}/\text{m}^3\cdot\text{month}$ ). Panel C: One-way ANOVA F-statistics (red fill = statistically significant at  $p < 0.05$ ).

Table 5. Mann–Kendall test statistics and Sen's slope estimates for PM<sub>2.5</sub> and PM<sub>10</sub> (2024)

| Station   | Parameter         | S   | Z      | p-value | Trend-direction      | Sen's Slope<br>( $\mu\text{g}/\text{m}^3 \text{ month}^{-1}$ ) | Sig. |
|-----------|-------------------|-----|--------|---------|----------------------|----------------------------------------------------------------|------|
| Belagavi  | PM <sub>2.5</sub> | −16 | −1.029 | 0.304   | Negative Sen's slope | −1.206                                                         | ns   |
| Belagavi  | PM <sub>10</sub>  | −20 | −1.303 | 0.193   | Negative Sen's slope | −5.342                                                         | ns   |
| Bengaluru | PM <sub>2.5</sub> | −22 | −1.440 | 0.150   | Negative Sen's slope | −2.107                                                         | ns   |
| Bengaluru | PM <sub>10</sub>  | −8  | −0.480 | 0.631   | Negative Sen's slope | −1.211                                                         | ns   |
| Madikeri  | PM <sub>2.5</sub> | −6  | −0.343 | 0.732   | Negative Sen's slope | −0.238                                                         | ns   |
| Madikeri  | PM <sub>10</sub>  | +8  | +0.480 | 0.631   | Positive Sen's slope | +0.319                                                         | ns   |
| Mangalore | PM <sub>2.5</sub> | −16 | −1.029 | 0.304   | Negative Sen's slope | −0.933                                                         | ns   |
| Mangalore | PM <sub>10</sub>  | −8  | −0.480 | 0.631   | Negative Sen's slope | −0.716                                                         | ns   |
| Yadgir    | PM <sub>2.5</sub> | −18 | −1.166 | 0.244   | Negative Sen's slope | −1.350                                                         | ns   |
| Yadgir    | PM <sub>10</sub>  | −18 | −1.166 | 0.244   | Negative Sen's slope | −1.775                                                         | ns   |

ns = not significant at  $\alpha = 0.05$ ; all series passed Lag-1 autocorrelation screening.

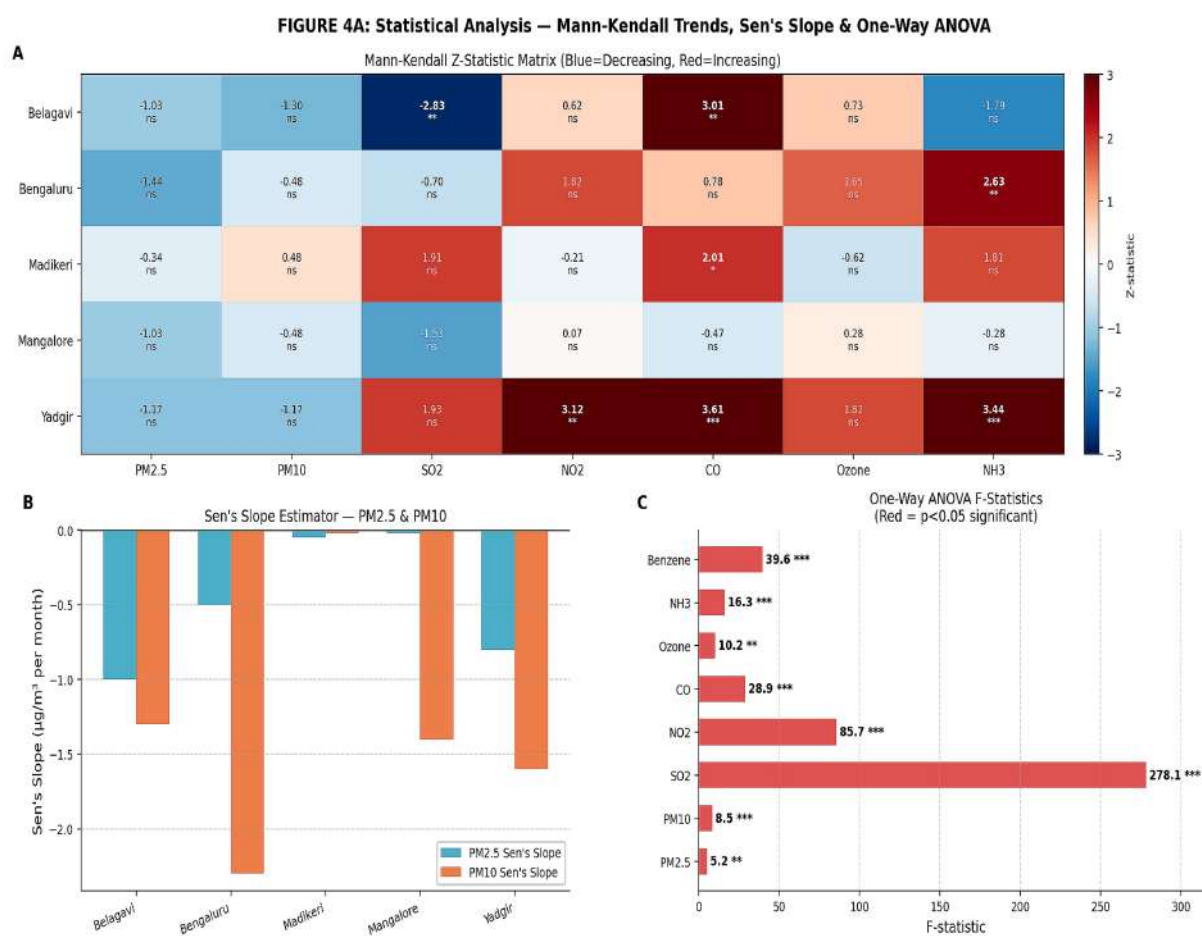


Fig. 4. Statistical analysis summary. Panel A: Mann–Kendall Z-statistic matrix for all pollutants (blue = -ve monotonic tendency; red = +ve monotonic tendency). Panel B: Sen's slope estimates for PM<sub>2.5</sub> and PM<sub>10</sub> ( $\mu\text{g}/\text{m}^3 \text{ month}^{-1}$ ). Panel C: One-way ANOVA F-statistics (red fill = statistically significant at  $p < 0.05$ ).

### One-Way ANOVA and Kruskal–Wallis analysis

One-way ANOVA revealed highly significant between-station differences for all pollutants ( $p < 0.001$ ), with SO<sub>2</sub> recording the highest F-statistic ( $F = 278.1$ ,  $p < 0.001$ ), reflecting extreme spatial heterogeneity driven by the contrast between high-SO<sub>2</sub> industrial stations (Mangalore, Yadgir) and low-SO<sub>2</sub> stations (Bengaluru, Madikeri). NO<sub>2</sub> ( $F = 85.7$ ), benzene ( $F = 39.6$ ), and CO ( $F = 28.9$ )

also showed strong spatial differentiation. Kruskal–Wallis results were fully consistent with ANOVA for all parameters. Tukey HSD post-hoc comparisons identified Bengaluru as significantly different from Madikeri for PM<sub>2.5</sub> ( $p < 0.001$ ), and Yadgir and Mangalore as significantly different from other stations for SO<sub>2</sub> ( $p < 0.001$ ). Table 6 shows the one-way ANOVA and Kruskal–Wallis test results for between-station pollutant variability.

Table 6. One-way ANOVA and Kruskal–Wallis test results for between-station pollutant variability

| Parameter         | F-stat  | p (ANOVA) | Sig. | H (KW) | p (KW)  |
|-------------------|---------|-----------|------|--------|---------|
| PM <sub>2.5</sub> | 5.210   | 0.0012    | **   | 13.816 | 0.0079  |
| PM <sub>10</sub>  | 8.534   | <0.0001   | ***  | 22.836 | 0.0001  |
| SO <sub>2</sub>   | 278.099 | <0.0001   | ***  | 53.155 | <0.0001 |
| NO <sub>2</sub>   | 85.651  | <0.0001   | ***  | 49.805 | <0.0001 |
| CO                | 28.896  | <0.0001   | ***  | 42.979 | <0.0001 |
| O <sub>3</sub>    | 10.165  | <0.0001   | ***  | 25.932 | <0.0001 |
| NH <sub>3</sub>   | 16.317  | <0.0001   | ***  | 37.615 | <0.0001 |
| Benzene           | 39.642  | <0.0001   | ***  | 49.546 | <0.0001 |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$

## Health risk assessment

### Non-Cancer risk

All five stations exhibited cumulative Hazard Index (HI) values exceeding the USEPA safety benchmark of 1.0, ranging from 1.756 at Madikeri to 3.290 at Bengaluru. PM<sub>2.5</sub> was the dominant contributor, accounting for approximately 65–90% of total HI at each station. The observation that even Madikeri—a relatively pristine Western Ghats location—recorded HI > 1 reflects the adoption of the stringent WHO 2021 annual PM<sub>2.5</sub> guideline (15 µg/m<sup>3</sup>) as the reference concentration. In contrast, applying the CPCB NAAQS (40 µg/m<sup>3</sup>) yields HQ(PM<sub>2.5</sub>) = 0.53 for Madikeri, indicating acceptable risk under current national criteria. This divergence between Indian NAAQS and WHO 2021 guidelines

strengthens the public health argument for progressive revision of national standards [4, 30]. Belagavi exhibited the highest NO<sub>2</sub>-related hazard quotient (HQ = 0.492), consistent with elevated agricultural and industrial NO<sub>x</sub> emissions in the northern Karnataka plateau region. Under the conservative WHO-based screening scenario, all stations yielded HI values exceeding unity. When interpreted using the CPCB annual PM<sub>2.5</sub> standard (40 µg/m<sup>3</sup>), the estimated HQ values decrease substantially, illustrating the sensitivity of risk estimates to the selected health benchmark. Table 7 shows the non-cancer hazard quotients (HQ) and hazard index (HI) for adults at all stations (2024). RfC: WHO 2021 for PM<sub>2.5</sub> (15 µg/m<sup>3</sup>) [1]; CPCB NAAQS for NO<sub>2</sub> and SO<sub>2</sub> (40 µg/m<sup>3</sup> each) [24]; WHO 24-h AQG surrogate for CO (4,000 µg/m<sup>3</sup>) [1]; Cal EPA RfC for benzene (30 µg/m<sup>3</sup>) [25].

Table 7. Non-cancer hazard quotients (HQ) and hazard index (HI) for adults at all stations (2024)

| Station   | HQ PM <sub>2.5</sub> | HQ NO <sub>2</sub> | HQ SO <sub>2</sub> | HQ CO | HQ Benzene | HI (Total) | Risk Level        |
|-----------|----------------------|--------------------|--------------------|-------|------------|------------|-------------------|
| Belagavi  | 1.493                | 0.492              | 0.170              | 0.255 | 0.030      | 2.441      | Moderate–<br>High |
| Bengaluru | 2.680                | 0.275              | 0.130              | 0.196 | 0.009      | 3.290      | High              |
| Madikeri  | 1.413                | 0.113              | 0.082              | 0.147 | 0.001      | 1.756      | Moderate          |
| Mangalore | 1.760                | 0.123              | 0.350              | 0.189 | 0.019      | 2.441      | Moderate–<br>High |
| Yadgir    | 1.933                | 0.165              | 0.383              | 0.119 | 0.004      | 2.604      | Moderate–<br>High |

### Lifetime cancer risk

Estimated Lifetime Cancer Risk (LCR) attributable to PM<sub>2.5</sub> inhalation ranged from approximately  $1.76 \times 10^{-3}$  at Madikeri to  $3.34 \times 10^{-3}$  at Bengaluru. These values exceed the conventional USEPA benchmark risk level of  $1 \times 10^{-4}$ ; however, they should be interpreted as hypothetical upper-bound screening estimates rather than regulatory cancer risk values. This is because the PM<sub>2.5</sub> inhalation unit risk (IUR =  $8.3 \times 10^{-5}$  (µg/m<sup>3</sup>)<sup>-1</sup>) adopted in this study was derived from epidemiological evidence linking long-term PM<sub>2.5</sub> exposure with lung cancer mortality rather than from an officially established regulatory IUR [21–23]. Consequently, the calculated LCR values are intended solely for comparative screening purposes.

For benzene, the estimated LCR ranged from

$0.07 \times 10^{-6}$  at Madikeri to  $1.98 \times 10^{-6}$  at Belagavi, with only the Belagavi value marginally exceeding the commonly adopted benchmark of  $1 \times 10^{-6}$ . Furthermore, paediatric Chronic Daily Intake (CDI) values were approximately 1.5 times higher than those for adults (IR/BW ratio: 0.50 vs.  $0.33 \text{ m}^3 \text{ kg}^{-1} \text{ day}^{-1}$ ), indicating a proportionally greater inhalation exposure and, consequently, a higher potential health risk for children under comparable environmental conditions. Table 8 shows the lifetime cancer risk (LCR) from PM<sub>2.5</sub> and benzene for all stations (2024), adults. IUR PM<sub>2.5</sub> =  $8.3 \times 10^{-5}$  (µg/m<sup>3</sup>)<sup>-1</sup> [21–23]; IUR benzene =  $2.2 \times 10^{-6}$  (µg/m<sup>3</sup>)<sup>-1</sup> [25]. USEPA unacceptable risk threshold:  $1 \times 10^{-4}$ . Fig. 5 shows the health risk assessment summary for five Karnataka CPCB CAAQMS (2024). Panel A: Stacked non-cancer hazard quotient components and total HI (dashed line = HI = 1). Panel B: Lifetime

cancer risk from PM<sub>2.5</sub> ( $\times 10^{-6}$ ). Panel C: Monthly PM<sub>2.5</sub> concentrations relative to WHO 2021 (15  $\mu\text{g}/\text{m}^3$ ) and CPCB NAAQS (40  $\mu\text{g}/$

$\text{m}^3$ ) thresholds. Panels D–F: Comparative risk scorecard, NAAQS exceedance months, and cancer risk breakdown by pollutant.

Table 8. Lifetime cancer risk (LCR) from PM<sub>2.5</sub> and benzene for all stations (2024), adults

| Station   | PM <sub>2.5</sub><br>( $\mu\text{g}/\text{m}^3$ ) | Benzene<br>( $\mu\text{g}/\text{m}^3$ ) | LCR PM <sub>2.5</sub><br>( $\times 10^{-6}$ ) | LCR Benzene<br>( $\times 10^{-6}$ ) | Total estimated<br>LCR<br>( $\times 10^{-6}$ ) | Risk Category               |
|-----------|---------------------------------------------------|-----------------------------------------|-----------------------------------------------|-------------------------------------|------------------------------------------------|-----------------------------|
| Belagavi  | 22.4                                              | 0.90                                    | 1859                                          | 1.98                                | 1861                                           | Screening-level<br>estimate |
| Bengaluru | 40.2                                              | 0.26                                    | 3337                                          | 0.57                                | 3337                                           | Screening-level<br>estimate |
| Madikeri  | 21.2                                              | 0.03                                    | 1760                                          | 0.07                                | 1760                                           | Screening-level<br>estimate |
| Mangalore | 26.4                                              | 0.58                                    | 2191                                          | 1.27                                | 2192                                           | Screening-level<br>estimate |
| Yadgir    | 29.0                                              | 0.13                                    | 2407                                          | 0.28                                | 2407                                           | Screening-level<br>estimate |



Fig. 5. Health risk assessment summary for five Karnataka CPCB CAAQMS (2024)

### Correlation analysis and multi-pollutant profiling

Pearson correlation analysis at Bengaluru revealed a strong positive association between PM<sub>2.5</sub> and relative humidity ( $r = +0.83$ ,  $p < 0.001$ ) and a strong negative association with wind speed ( $r = -0.75$ ,  $p < 0.01$ ), consistent with stagnant-air pollutant accumulation and hygroscopic particle growth during fog-prone winter months. At Mangalore, SO<sub>2</sub> was negatively correlated with wind speed ( $r = -0.62$ ,  $p < 0.05$ ), consistent with sea-breeze ventilation of port-area SO<sub>2</sub> plumes. Belagavi showed a strong NH<sub>3</sub>–PM<sub>2.5</sub> anti-correlation ( $r = -0.71$ ,  $p < 0.01$ ), reflecting monsoon suppression of NH<sub>3</sub> coinciding with lowest PM<sub>2.5</sub> months. The PM<sub>2.5</sub>/PM<sub>10</sub> ratio provided a qualitative indicator of emission source type: values 0.5–0.7 at Bengaluru indicate combustion-dominated fine particle sources, while lower ratios at Yadgir and Belagavi

indicate coarser crustal or dust-dominated sources. All Pearson correlations should be interpreted with caution given the small sample size ( $n = 12$  monthly means; critical  $r \approx \pm 0.576$  at  $\alpha = 0.05$ ).

It is important to note that PM<sub>2.5</sub>-related cancer risk estimation remains an area of scientific uncertainty. Unlike established carcinogens such as benzene, regulatory agencies have not defined an official inhalation unit risk for PM<sub>2.5</sub> due to its complex and variable composition. The IUR applied in this study is derived from epidemiological associations and should therefore be interpreted as a conservative upper-bound estimate rather than a definitive measure of carcinogenic risk. Fig. 6 shows the Pearson correlation matrices for each Karnataka station (2024). Correlations with  $p > 0.05$  ( $n = 12$ ) are shown but should be interpreted with caution. Coolwarm colour scale: red = positive, blue = negative.

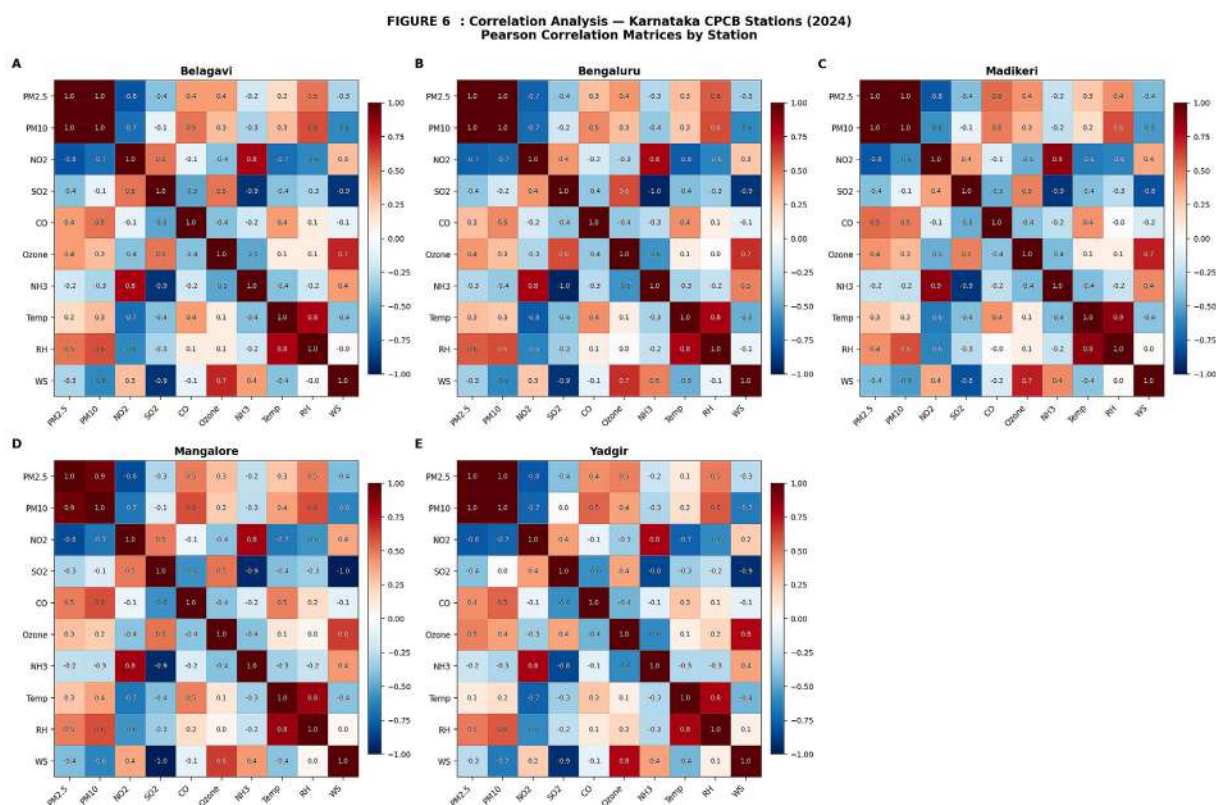


Fig. 6. Pearson correlation matrices for each Karnataka station (2024).

## Limitations

This study has several limitations. The health risk assessment was based on annual mean concentrations from a single CPCB Continuous Ambient Air Quality Monitoring Station (CAAQMS) in each district and may not fully capture intra-urban spatial variability in pollutant exposure. Indoor air pollution, personal activity patterns, and non-inhalation exposure pathways (dermal contact and ingestion) were not considered, potentially underestimating total exposure, particularly among vulnerable populations [1]. For PM<sub>2.5</sub>, the WHO 2021 annual Air Quality Guideline (15 µg/m<sup>3</sup>) was used as a conservative health-based screening benchmark because no internationally accepted chronic inhalation Reference Concentration (RfC) is available. Accordingly, the calculated Hazard Quotient (HQ) and Hazard Index (HI) should be interpreted as precautionary screening indicators rather than regulatory risk estimates. Similarly, PM<sub>2.5</sub> Lifetime Cancer Risk (LCR) estimates were derived using an inhalation unit risk adopted from published epidemiological evidence, as no official regulatory IUR exists for PM<sub>2.5</sub>. Therefore, the reported LCR values represent hypothetical upper-bound screening estimates rather than definitive regulatory cancer risks.

Finally, the analysis was limited to a single year (12 monthly observations), restricting long-term trend detection. Consequently, the Mann–Kendall results reflect intra-annual variability rather than long-term changes in air quality. O<sub>3</sub> and NH<sub>3</sub> were excluded from the quantitative health risk assessment because chronic inhalation reference concentrations are currently unavailable.

## Conclusion

This study presents a comprehensive state-level assessment of ambient air quality, seasonal variability, statistical characteristics, and screening-level inhalation health risks across five CPCB Continuous Ambient Air Quality Monitoring Stations (CAAQMS) in Karnataka during 2024. The principal findings are as follows:

- Among the five monitoring stations Bengaluru exhibited the highest particulate pollution with an annual mean PM<sub>2.5</sub> concentration of 40.2 µg/m<sup>3</sup>, equal to the CPCB National Ambient Air Quality Standard (NAAQS), and an annual mean PM<sub>10</sub> concentration of 80.4 µg/m<sup>3</sup>, exceeding the CPCB standard by approximately 34%. The pronounced pre-monsoon PM<sub>2.5</sub> peak (65.4 µg/m<sup>3</sup> in March) highlights the need for strengthened vehicular emission control, construction dust mitigation, and accelerated adoption of cleaner transportation technologies.
- The southwest monsoon was identified as the dominant meteorological driver of air quality across Karnataka. PM<sub>2.5</sub> concentrations decreased substantially during the monsoon season (10.7–23.6 µg/m<sup>3</sup>), demonstrating the importance of wet scavenging and enhanced atmospheric dispersion in reducing particulate pollution.
- Annual mean PM<sub>2.5</sub> concentrations at all five monitoring stations exceeded the WHO 2021 annual Air Quality Guideline (15 µg/m<sup>3</sup>), with Bengaluru recording exceedances throughout the study period. Seasonal averages were used solely to illustrate intra-annual variability and were not interpreted as

compliance with the WHO annual guideline.

- Exploratory Mann–Kendall analysis yielded predominantly negative Sen's slopes for PM<sub>2.5</sub> and PM<sub>10</sub>, although none were statistically significant ( $p > 0.05$ ). Because only a single year (12 monthly observations) was available, these results primarily reflect seasonal meteorological variability rather than long-term changes in emissions. Robust assessment of temporal trends requires continuous multi-year monitoring.

- One-way ANOVA demonstrated highly significant spatial differences among the monitoring stations for all pollutants (SO<sub>2</sub>:  $F = 278.1$ ; NO<sub>2</sub>:  $F = 85.7$ ; benzene:  $F = 39.6$ ), indicating substantial regional heterogeneity in emission characteristics. Yadgir and Mangalore emerged as the principal SO<sub>2</sub> hotspots, suggesting the need for targeted industrial emission management.

- Under the conservative WHO-based screening benchmark adopted in this study, Hazard Index (HI) values exceeded unity at all five monitoring stations (1.756–3.290), with PM<sub>2.5</sub> contributing the largest proportion of the estimated non-carcinogenic risk. Estimated PM<sub>2.5</sub> lifetime cancer risks ranged from approximately  $1.8 \times 10^{-3}$  to  $3.3 \times 10^{-3}$ . These values represent hypothetical upper-bound screening estimates derived from epidemiological evidence and should not be interpreted as regulatory cancer risk estimates. Children exhibited chronic daily inhalation doses approximately 1.5 times higher than adults, indicating comparatively greater potential vulnerability.

- Although NH<sub>3</sub> exhibited a negative temporal correlation with PM<sub>2.5</sub> at Belagavi during 2024, the elevated annual NH<sub>3</sub> concentrations

indicate substantial agricultural emissions. Consequently, management of agricultural ammonia remains important for limiting nitrogen emissions and reducing the long-term potential for secondary particulate formation, rather than explaining the seasonal PM<sub>2.5</sub> variability observed during the present study.

Overall, the study demonstrates that particulate pollution remains the principal air quality concern across Karnataka, particularly in rapidly urbanising centres such as Bengaluru. The integration of routine monitoring, statistical analysis, and screening-level health risk assessment provides a useful framework for identifying pollution hotspots and supporting evidence-based air quality management. Future studies incorporating multi-year observations, source apportionment, and detailed exposure assessment are recommended to strengthen long-term trend analysis and improve health risk quantification.

### Financial supports

No financial support was utilised.

### Competing interests

The authors declare no competing interests.

### Acknowledgements

The authors gratefully acknowledge the Management and Principal of B.M.S. College of Engineering for their continuous support and encouragement. They also thank the Central Pollution Control Board (CPCB) and the Karnataka State Pollution Control Board (KSPCB) for maintaining the CAAQMS

network and ensuring public access to air quality monitoring data.

### Ethical considerations

Ethical issues (including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.”

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