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

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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 ($PM_{2.5}$, PM_{10}), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Carbon monoxide (CO), Ozone (O_3), Ammonia (NH3), 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 $PM_{2.5}$ (40.2 μg/m³) and PM_{10} (80.4 μg/m³) concentrations, with $PM_{2.5}$ equal to the CPCB National Ambient Air Quality Standard (NAAQS) and PM_{10} exceeding it by approximately 34%. Annual mean $PM_{2.5}$ concentrations at all stations exceeded the WHO 2021 Air Quality Guideline (15 μg/m³). The southwest monsoon produced the greatest reduction in particulate concentrations. Exploratory Mann–Kendall analysis yielded negative Sen's slopes for $PM_{2.5}$ 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 $PM_{2.5}$ LCR ranged from 1.76×10^{-3} to 3.34×10^{-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.

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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 ($PM_{2.5}$) and coarse Particulate Matter (PM_{10}) are strongly associated with cardiovascular, respiratory, and cancer-related morbidity and mortality [3]. In India alone, $PM_{2.5}$ 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 $PM_{2.5}$ reductions ranging from −6.51 to −0.36 µg/m³/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°N, 74.53°E; ~747 m a.s.l.) is a northern Deccan Plateau city with mixed industrial and agri-commercial activities. Bengaluru (12.91°N, 77.60°E; ~920 m a.s.l.), the state capital, is characterised by high vehicular density and significant $PM_{2.5}$ and NO_x emissions. Madikeri (12.41°N, 75.73°E; ~1,082 m a.s.l.) is a Western Ghats hill station with dense forest cover and heavy monsoonal rainfall. Mangalore (12.89°N, 74.85°E; ~22 m a.s.l.) is a coastal industrial-port city along the Arabian Sea. Yadgir (16.76°N, 77.14°E; ~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 ~22 m to 1,082 m and annual rainfall from ~580 mm to >2,500 mm. Table1 shows the metadata and site characteristics of the five CAAQMS selected for the study in Karnataka, India.

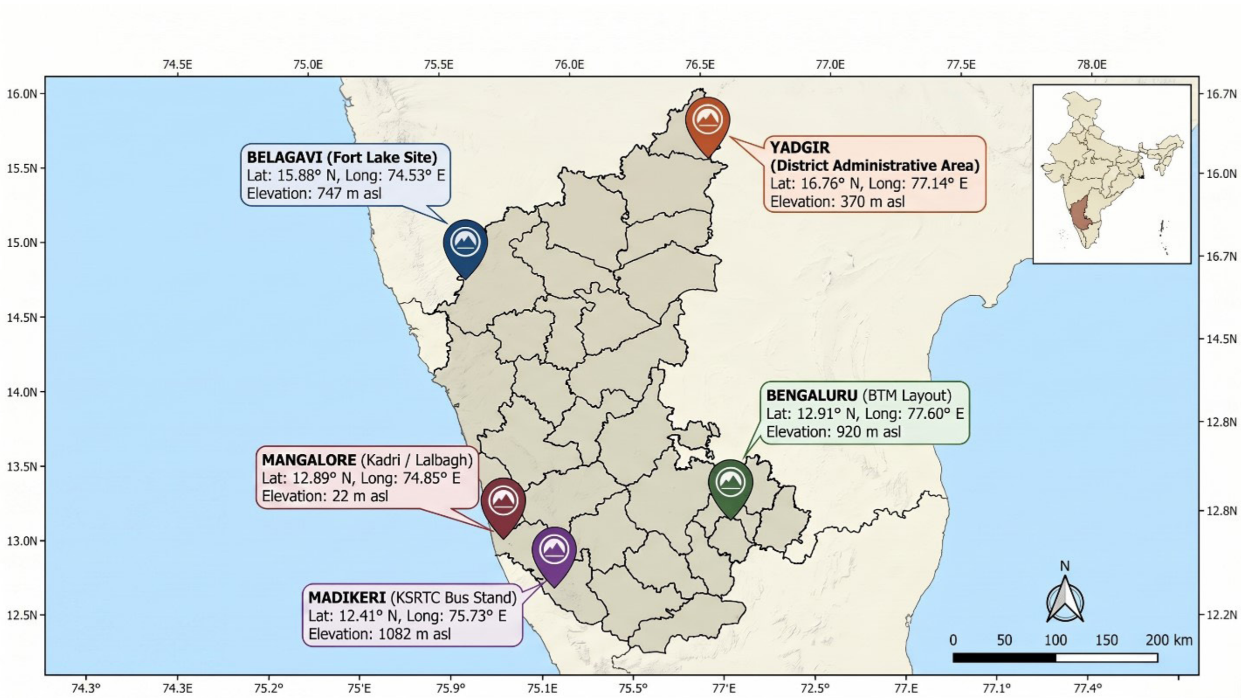

Fig. 1. Geographical location of the five CPCB CAAQMS study stations across Karnataka, India

Table1. Metadata and site characteristics of the five CAAQMS selected for the study in Karnataka, India

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

Materials and methods

Data source

Monthly averaged concentrations of $PM_{2.5}$, PM_{10}, NO_2, NH_3, SO_2, CO, O_3, 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	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	NO_2 (μg/m³)	SO_2 (μg/m³)	CO (mg/m³)	O_3 (μg/m³)	NH_3 (μg/m³)	Benzene (μg/m³)
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_3 and NH_3 are excluded from formal health risk assessment (no applicable chronic RfC available).

Concentrations in μg/m³ except CO in mg/m³, * NAAQS exceedance; ‡ Yadgir PM_{10} equals the NAAQS threshold. † NAAQS annual standards. WHO 2021 annual guideline: $PM_{2.5}$ = 15 μg/m³ (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 (%) = $[\Sigma(C_i \times f_i) / \Sigma(C_i \times f_i)_{total}] \times 100$, where C_i is the monthly PM concentration (µg/m³) 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 $PM_{2.5}$ and PM_{10} 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 (≥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_3 and NH_3 were excluded from the quantitative health risk assessment because internationally accepted chronic inhalation Reference Concentrations (RfCs) are not available for these pollutants.

For $PM_{2.5}$, 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 $PM_{2.5}$ is a chemically heterogeneous pollutant with variable composition and toxicity. Therefore, the IUR value of 8.3×10^{-5} $(\mu g/m^3)^{-1}$, adopted from epidemiological studies linking long-term $PM_{2.5}$ exposure with lung cancer mortality, was used solely to provide a conservative, screening-level estimate of potential carcinogenic risk. Accordingly, the calculated $PM_{2.5}$ 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 $PM_{2.5}$ by USEPA IRIS or CalEPA. Consequently, the WHO 2021 annual Air Quality Guideline (15 $\mu g/m^3$) 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
$PM_{2.5}$	Non-cancer (RfC)	15	$\mu g/m^3$	Cardiovascular, respiratory	WHO [1]
$PM_{2.5}$	Cancer (IUR)	8.3×10^{-5}	$(\mu g/m^3)^{-1}$	Lung cancer	Epidemiological studies [21,22, 23]
NO_2	Non-cancer (RfC)	40	$\mu g/m^3$	Respiratory inflammation	CPCB [24]
SO_2	Non-cancer (RfC)	40	$\mu g/m^3$	Pulmonary function	CPCB [24]
CO	Non-cancer (RfC†)	4,000	$\mu g/m^3$	Carboxyhaemoglobin	WHO [1]
Benzene	Cancer (IUR)	2.2×10^{-6}	$(\mu g/m^3)^{-1}$	Leukaemia	Cal EPA [25]
Benzene	Non-cancer (RfC)	30	$\mu g/m^3$	Haematological effects	Cal EPA [25]

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

Results and discussion

Seasonal variation analysis

A consistent seasonal pattern was evident across all monitoring stations, with minimum $PM_{2.5}$ and PM_{10} 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 $PM_{2.5}$ (52.0 µg/m³), driven by construction activities, road dust resuspension, and reduced boundary layer height [27]. Post-monsoon $PM_{2.5}$ peaked at Belagavi (37.6 µg/m³), likely reflecting episodic biomass and crop-residue burning across the northern Deccan Plateau [28].

Yadgir exhibited elevated winter $PM_{2.5}$ (42.0 µg/m³), consistent with cold, dry, low-wind stagnation and enhanced dust mobilisation from semi-arid soils. Ammonia (NH_3) concentrations at Belagavi were exceptionally high (winter: 133–134 µg/m³; pre-monsoon: 133–136 µg/m³), indicating persistent agricultural emissions, with a sharp decline during the monsoon (June: 34.5 µg/m³; July: 26.5 µg/m³). The annual mean NH_3 at Belagavi (71.6 µg/m³) approaches the ATSDR (2004) intermediate-duration inhalation Minimum Risk Level (71 µg/m³), warranting targeted epidemiological investigation [29]. SO_2 concentrations at Yadgir (13.8–17.0 µg/m³) and Mangalore (10.5–17.0 µg/m³) were consistently elevated, implying stable industrial point-source contributions. Table 4 shows the seasonal mean $PM_{2.5}$ (µg/m³) 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 $PM_{2.5}$ (upper panel) and PM_{10} (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/m³); purple dashed line = WHO 2021 annual guideline (15 µg/m³).

Table 4. Seasonal mean $PM_{2.5}$ (µg/m³) 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/m³.

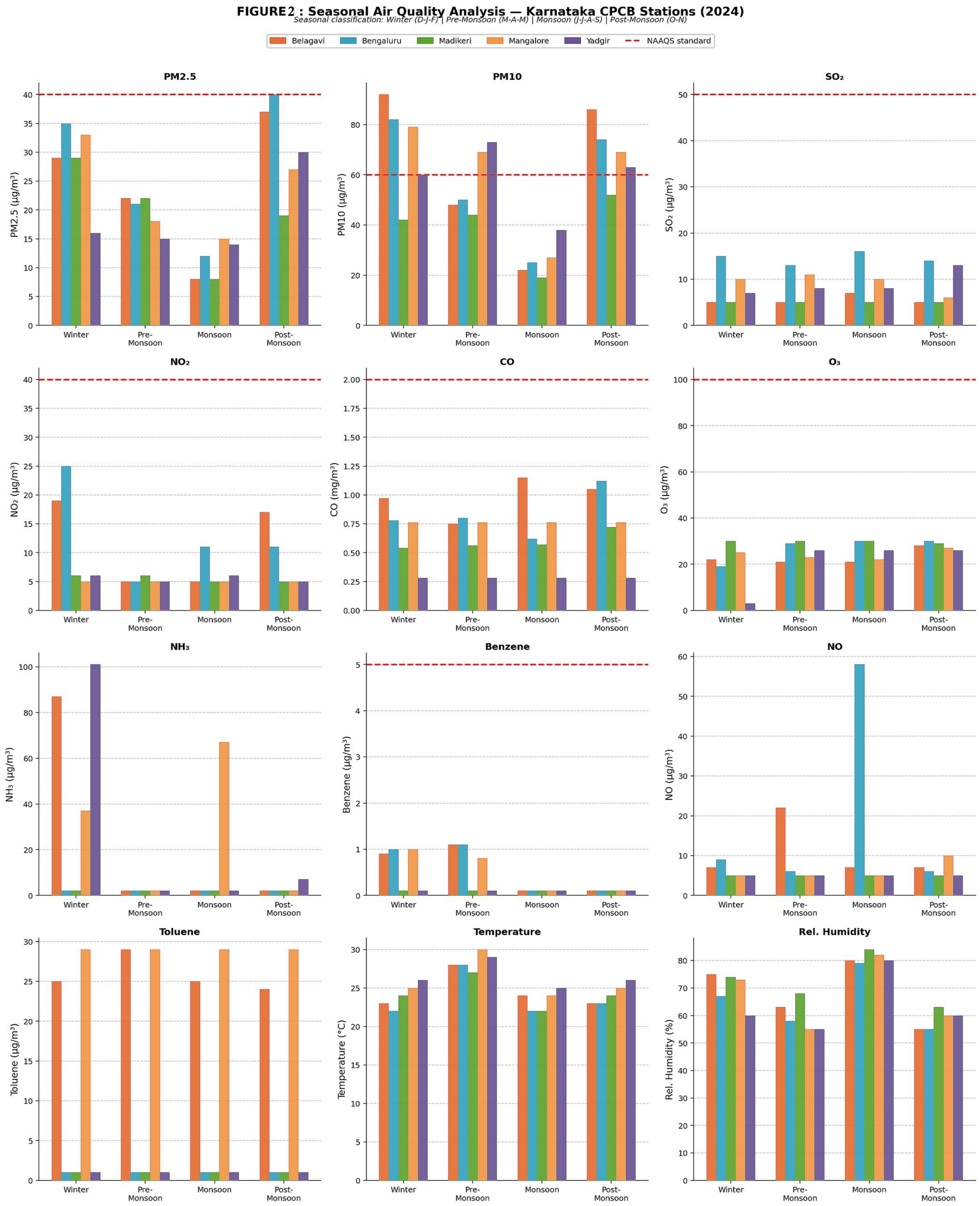

Fig. 2. Seasonal average concentrations of ten ambient air pollutants at five Karnataka CPCB CAAQMS (2024). Red dashed lines indicate CPCB NAAQS annual standards. Seasons: Winter (D-J-F), Pre-Monsoon (M-A-M), Monsoon (J-J-A-S), Post-Monsoon (O-N)

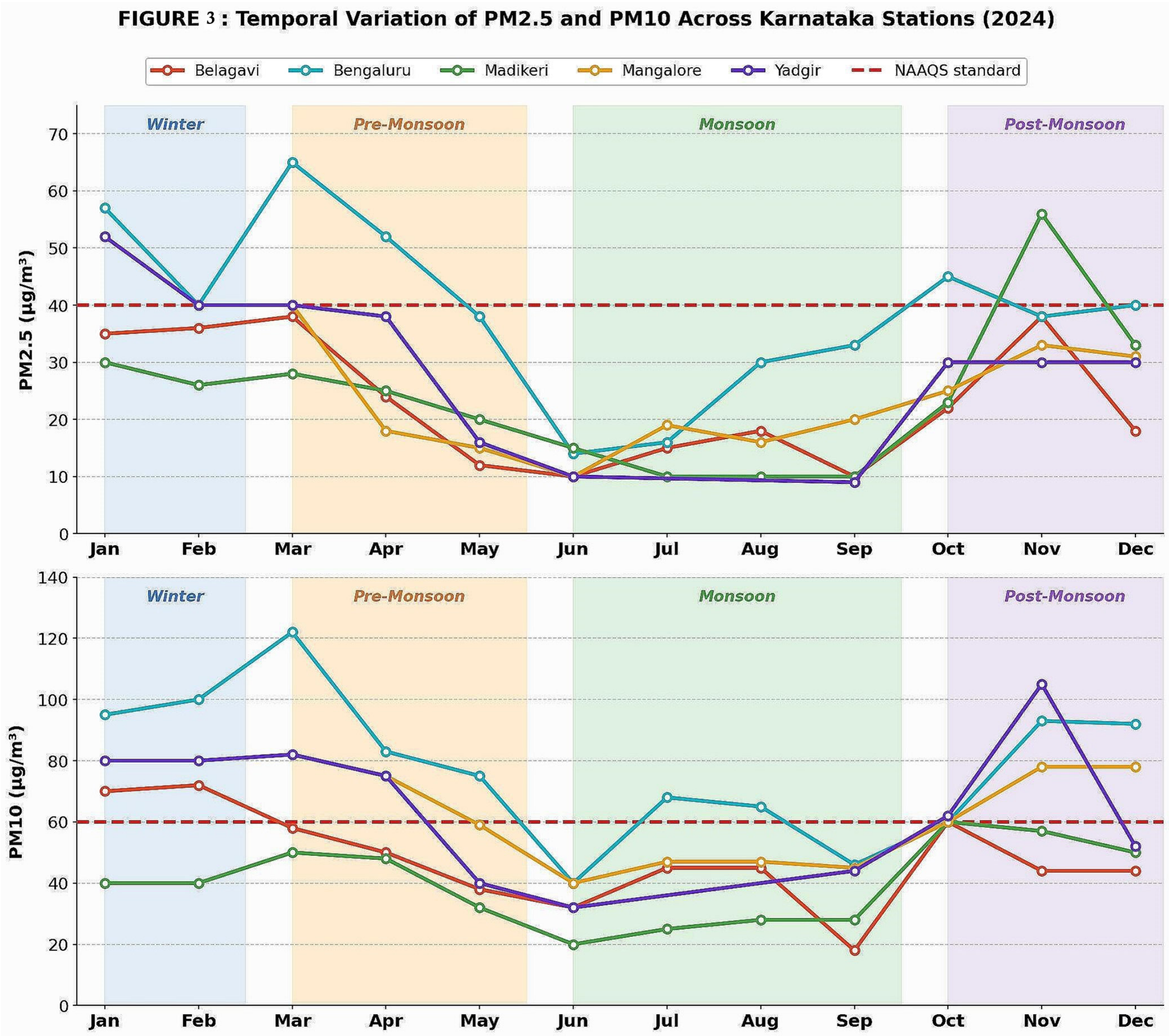

Fig. 3. Monthly temporal variation of $PM_{2.5}$ (upper panel) and PM_{10} (lower panel) at five Karnataka CPCB CAAQMS (2024). Coloured seasonal bands: Winter (blue), Pre-Monsoon (orange), Monsoon (green), Post-Monsoon (purple). Red dashed line = CPCB NAAQS (40 µg/m³); purple dashed line = WHO 2021 annual guideline (15 µg/m³)

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 $PM_{2.5}$ at all five monitoring stations; however, none of these monotonic tendencies were statistically significant ($p > 0.14$). The only exception was PM_{10} 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 $PM_{2.5}$ Sen's slope (−2.107 µg/m³.month), consistent with the pronounced reduction in concentrations during the southwest monsoon following elevated pre-monsoon levels. Belagavi recorded the largest negative PM_{10} Sen's slope (−5.342 µg/m³.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 ≥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 $PM_{2.5}$ and PM_{10} (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 $PM_{2.5}$ and PM_{10} (µg/m³.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 $PM_{2.5}$ and PM_{10} (2024)

Station	Parameter	S	Z	p-value	Trend-direction	Sen's Slope (µg/m³ month¹)	Sig.
Belagavi	$PM_{2.5}$	−16	−1.029	0.304	Negative Sen's slope	−1.206	ns
Belagavi	PM_{10}	−20	−1.303	0.193	Negative Sen's slope	−5.342	ns
Bengaluru	$PM_{2.5}$	−22	−1.440	0.150	Negative Sen's slope	−2.107	ns
Bengaluru	PM_{10}	−8	−0.480	0.631	Negative Sen's slope	−1.211	ns
Madikeri	$PM_{2.5}$	−6	−0.343	0.732	Negative Sen's slope	−0.238	ns
Madikeri	PM_{10}	+8	+0.480	0.631	Positive Sen's slope	+0.319	ns
Mangalore	$PM_{2.5}$	−16	−1.029	0.304	Negative Sen's slope	−0.933	ns
Mangalore	PM_{10}	−8	−0.480	0.631	Negative Sen's slope	−0.716	ns
Yadgir	$PM_{2.5}$	−18	−1.166	0.244	Negative Sen's slope	−1.350	ns
Yadgir	PM_{10}	−18	−1.166	0.244	Negative Sen's slope	−1.775	ns

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

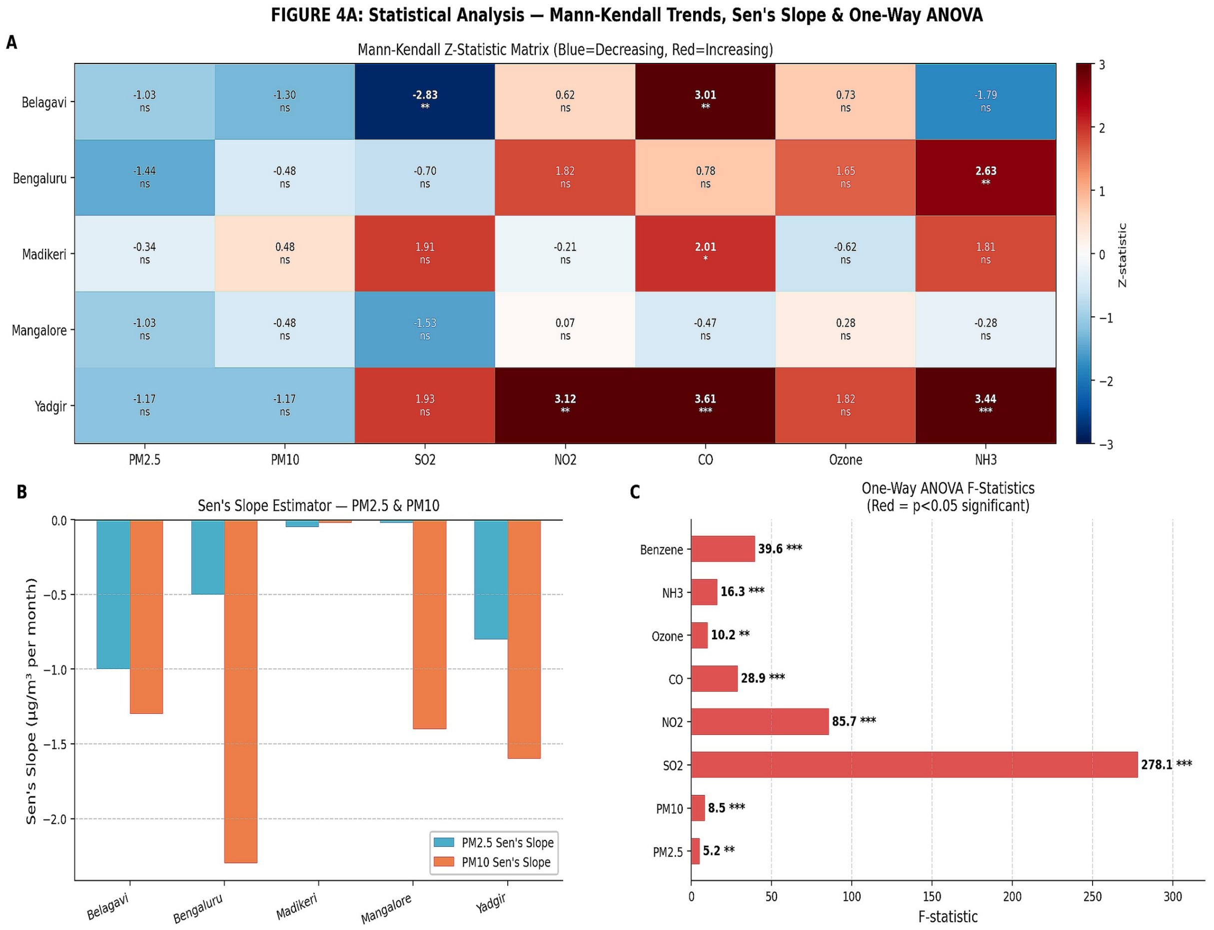

Fig. 4. Statistical analysis summary. Panel A: Mann–Kendall Z-statistic matrix for all pollutants (blue = -ve monotonic tendency; red = +ve monotonic tendency). Panel B: Sen's slope estimates for $PM_{2.5}$ and PM_{10} (μg/m³ month⁻¹). Panel C: One-way ANOVA F-statistics (red fill = statistically significant 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_2 recording the highest F-statistic ($F = 278.1$, $p < 0.001$), reflecting extreme spatial heterogeneity driven by the contrast between high-SO_2 industrial stations (Mangalore, Yadgir) and low-SO_2 stations (Bengaluru, Madikeri). NO_2 ($F = 85.7$), 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 $PM_{2.5}$ ($p < 0.001$), and Yadgir and Mangalore as significantly different from other stations for SO_2 ($p < 0.001$). 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)
$PM_{2.5}$	5.210	0.0012	**	13.816	0.0079
PM_{10}	8.534	<0.0001	***	22.836	0.0001
SO_2	278.099	<0.0001	***	53.155	<0.0001
NO_2	85.651	<0.0001	***	49.805	<0.0001
CO	28.896	<0.0001	***	42.979	<0.0001
O_3	10.165	<0.0001	***	25.932	<0.0001
NH_3	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. $PM_{2.5}$ 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 $PM_{2.5}$ guideline (15 µg/m^3) as the reference concentration. In contrast, applying the CPCB NAAQS (40 µg/m^3) yields HQ($PM_{2.5}$) = 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_2-related hazard quotient (HQ = 0.492), consistent with elevated agricultural and industrial NO_x 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 $PM_{2.5}$ standard (40 µg/m^3), 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 $PM_{2.5}$ (15 µg/m^3) [1]; CPCB NAAQS for NO_2 and SO_2 (40 µg/m^3 each) [24]; WHO 24-h AQG surrogate for CO (4,000 µg/m^3) [1]; Cal EPA RfC for benzene (30 µg/m^3) [25].

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

Station	HQ $PM_{2.5}$	HQ NO_2	HQ SO_2	HQ CO	HQ Benzene	HI (Total)	Risk Level
Belagavi	1.493	0.492	0.170	0.255	0.030	2.441	Moderate–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–High
Yadgir	1.933	0.165	0.383	0.119	0.004	2.604	Moderate–High

Lifetime cancer risk

Estimated Lifetime Cancer Risk (LCR) attributable to $PM_{2.5}$ inhalation ranged from approximately 1.76×10^{-3} at Madikeri to 3.34×10^{-3} at Bengaluru. These values exceed the conventional USEPA benchmark risk level of 1×10^{-4}; however, they should be interpreted as hypothetical upper-bound screening estimates rather than regulatory cancer risk values. This is because the $PM_{2.5}$ inhalation unit risk (IUR = 8.3×10^{-5} $(\mu g/m^3)^{-1}$) adopted in this study was derived from epidemiological evidence linking long-term $PM_{2.5}$ 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 0.07×10^{-6} at Madikeri to 1.98×10^{-6} at Belagavi, with only the Belagavi value marginally exceeding the commonly adopted benchmark of 1×10^{-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 $m^3\ kg^{-1}\ day^{-1}$), 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 $PM_{2.5}$ and benzene for all stations (2024), adults. IUR $PM_{2.5}$ = 8.3×10^{-5} $(\mu g/m^3)^{-1}$ [21-23]; IUR benzene = 2.2×10^{-6} $(\mu g/m^3)^{-1}$ [25]. USEPA unacceptable risk threshold: 1×10^{-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 $PM_{2.5}$ ($\times 10^{-6}$). Panel C: Monthly $PM_{2.5}$ concentrations relative to WHO 2021 (15 µg/m³) and CPCB NAAQS (40 µg/m³) thresholds. Panels D–F: Comparative risk scorecard, NAAQS exceedance months, and cancer risk breakdown by pollutant.

Table 8. Lifetime cancer risk (LCR) from $PM_{2.5}$ and benzene for all stations (2024), adults

Station	$PM_{2.5}$ (µg/m³)	Benzene (µg/m³)	LCR $PM_{2.5}$ ($\times 10^{-6}$)	LCR Benzene ($\times 10^{-6}$)	Total estimated LCR ($\times 10^{-6}$)	Risk Category
Belagavi	22.4	0.90	1859	1.98	1861	Screening-level estimate
Bengaluru	40.2	0.26	3337	0.57	3337	Screening-level estimate
Madikeri	21.2	0.03	1760	0.07	1760	Screening-level estimate
Mangalore	26.4	0.58	2191	1.27	2192	Screening-level estimate
Yadgir	29.0	0.13	2407	0.28	2407	Screening-level estimate

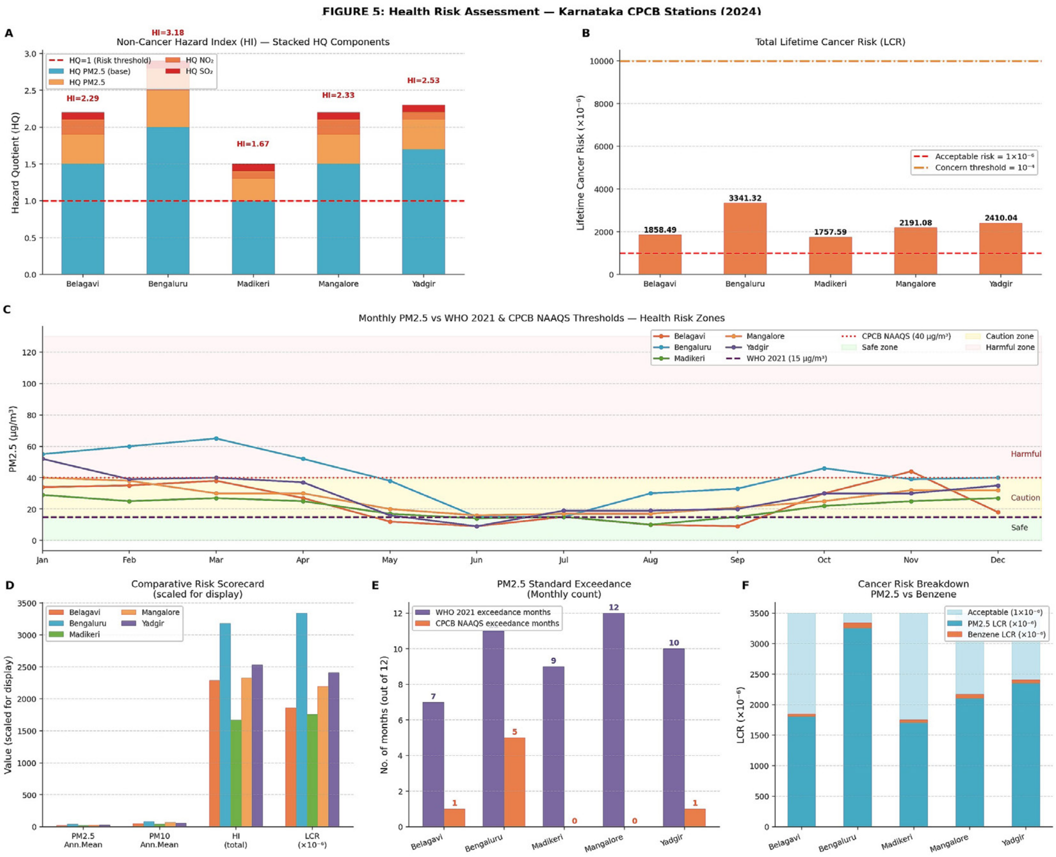

Fig. 5. Health risk assessment summary for five Karnataka CPCB CAAQMS (2024)

Correlation analysis and multi-pollutant profiling

Pearson correlation analysis at Bengaluru revealed a strong positive association between $PM_{2.5}$ 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_2 was negatively correlated with wind speed ($r = −0.62$, $p < 0.05$), consistent with sea-breeze ventilation of port-area SO_2 plumes. Belagavi showed a strong NH_3–$PM_{2.5}$ anti-correlation ($r = −0.71$, $p < 0.01$), reflecting monsoon suppression of NH_3 coinciding with lowest $PM_{2.5}$ months. The $PM_{2.5}/PM_{10}$ 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 $PM_{2.5}$-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 $PM_{2.5}$ 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.

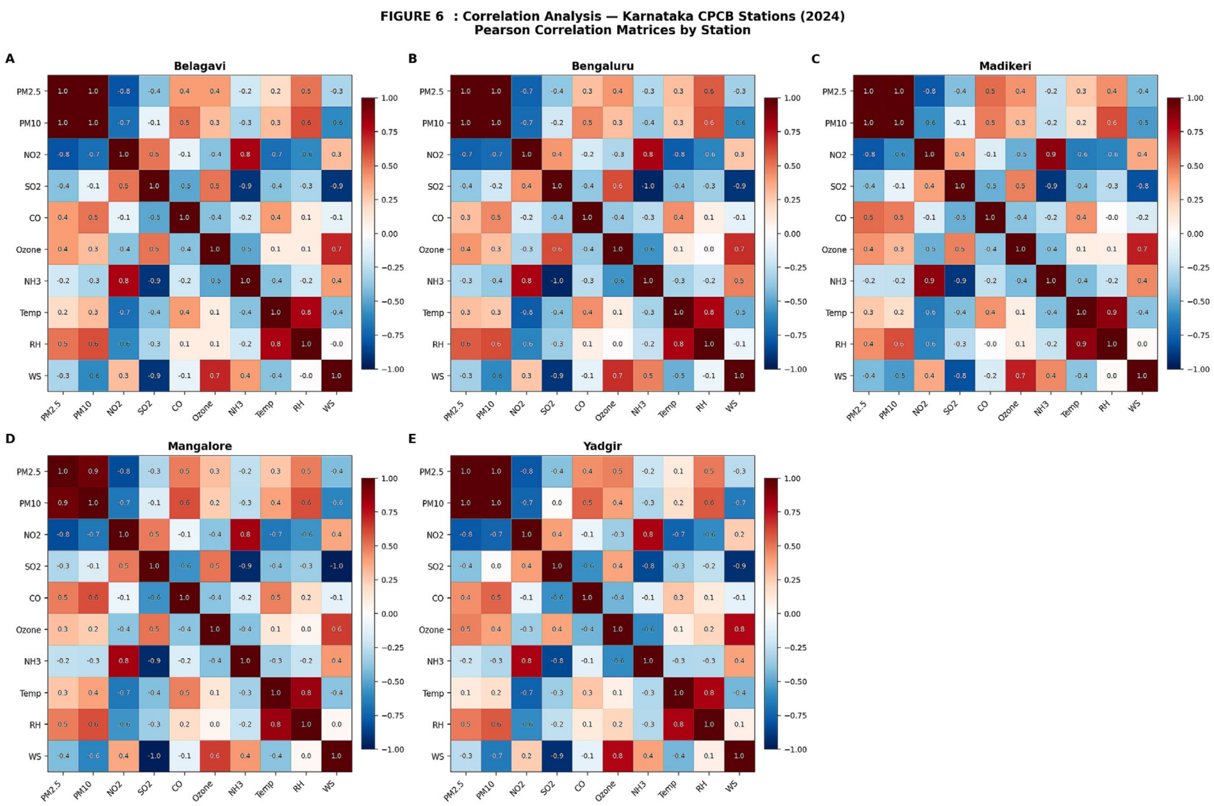

Fig. 6. Pearson correlation matrices for each Karnataka station (2024).

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 $PM_{2.5}$, the WHO 2021 annual Air Quality Guideline (15 µg/m^3) 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, $PM_{2.5}$ Lifetime Cancer Risk (LCR) estimates were derived using an inhalation unit risk adopted from published epidemiological evidence, as no official regulatory IUR exists for $PM_{2.5}$. 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_3 and NH_3 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 $PM_{2.5}$ concentration of 40.2 µg/m^3, equal to the CPCB National Ambient Air Quality Standard (NAAQS), and an annual mean PM_{10} concentration of 80.4 µg/m^3, exceeding the CPCB standard by approximately 34%. The pronounced pre-monsoon $PM_{2.5}$ peak (65.4 µg/m^3 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. $PM_{2.5}$ concentrations decreased substantially during the monsoon season (10.7–23.6 µg/m^3), demonstrating the importance of wet scavenging and enhanced atmospheric dispersion in reducing particulate pollution.

- Annual mean $PM_{2.5}$ concentrations at all five monitoring stations exceeded the WHO 2021 annual Air Quality Guideline (15 µg/m^3), 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 $PM_{2.5}$ and PM_{10}, 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_2: F = 278.1; NO_2: F = 85.7; benzene: F = 39.6), indicating substantial regional heterogeneity in emission characteristics. Yadgir and Mangalore emerged as the principal SO_2 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 $PM_{2.5}$ contributing the largest proportion of the estimated non-carcinogenic risk. Estimated $PM_{2.5}$ lifetime cancer risks ranged from approximately 1.8×10^{-3} to 3.3×10^{-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_3 exhibited a negative temporal correlation with $PM_{2.5}$ at Belagavi during 2024, the elevated annual NH_3 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 $PM_{2.5}$ 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.

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Competing interests

The authors declare no competing interests.

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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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