GMR

The Original

TEMPORAL AND SEASONAL TRENDS OF AMBIENT PM2.5 AND PM10 CONCENTRATIONS IN PUDUCHERRY, INDIA, 2021-2025: A CROSS-SECTIONAL TIME-SERIES ANALYSIS

Balachandar V[1*], Prahankumar R[2], Jayabharathi J[3]

[1]PhD scholar, Department of Community Medicine, Mahatma Gandhi Medical College Research Institute, Sri Balaji Vidyapeeth University, Puducherry, Email ID: srvbala17@gmail.com ORCID id: 0009-0002-6830-1080
[2]Professor & Head, Department of Community Medicine, Mahatma Gandhi Medical College Research Institute, Sri Balaji Vidyapeeth University Puducherry. Email ID: prahankumarr@mgmcri.ac.in
[3]Assistant Professor, Mother Theresa Post Graduate and Research Institute of Health Sciences, Karaikal, Puducherry.
Email id: jayabharathi888.jb@gmail.com
*Corresponding Author: Balachandar V, Email ID: srvbala17@gmail.com ORCID id: 0009-0002-6830-1080

ABSTRACT
Background: Particulate matter is a major ambient air pollutant with important implications for respiratory, cardiovascular and population health. Local evidence on long-term PM2.5 and PM10 trends is needed for air quality surveillance and public health planning in smaller coastal urban settings such as Puducherry.
Objectives: To assess annual, monthly and seasonal trends of 24-hour average PM2.5 and PM10 concentrations in Puducherry from 2021 to 2025, and to quantify exceedance of World Health Organization (WHO) guideline values and Indian National Ambient Air Quality Standards (NAAQS).
Methods: A cross-sectional time-series analysis was conducted using daily 24-hour average PM2.5 and PM10 observations from the Jawahar Nagar, Puducherry monitoring dataset for 1 January 2021 to 31 December 2025. Seasons were classified as winter (January-February), summer (March-May), monsoon (June-September) and post-monsoon (October-December). Descriptive statistics, annual and seasonal comparisons, exceedance analysis, Spearman correlation and Kruskal-Wallis tests were used. Missing observations were excluded by available-case analysis.
Results: Of 1,826 calendar days, valid observations were available for 1,762 PM2.5 days and 1,753 PM10 days. Annual mean PM2.5 ranged from 20.20 ± 13.89 µg/m³ in 2021 to 26.60 ± 19.09 µg/m³ in 2025. Annual mean PM10 ranged from 41.88 ± 19.17 µg/m³ in 2024 to 51.97 ± 21.64 µg/m³ in 2023. All annual means were below Indian annual NAAQS values for PM2.5 and PM10, but daily WHO 2021 guideline exceedance was frequent. PM2.5 exceeded the WHO 24-hour guideline on 52.9% to 68.2% of valid days across years, whereas PM10 exceeded it on 36.1% to 59.2% of valid days. Seasonal variation was significant for both PM2.5 and PM10 (both $p<0.001$), with winter and post-monsoon generally showing higher concentrations and monsoon showing lower concentrations. PM2.5 and PM10 were strongly correlated overall (Spearman $\rho=0.870$, $p<0.001$).
Conclusion: Puducherry showed moderate annual particulate concentrations by Indian annual standards, but substantial daily exceedance of WHO guideline values and clear seasonal peaks. Continuous monitoring, season-specific mitigation and source-oriented control strategies are warranted.

KEYWORDS: Air Pollution; Particulate Matter; PM2.5; PM10; Environmental Monitoring; India.

INTRODUCTION
Ambient air pollution is among the most important environmental determinants of health. Particulate matter (PM) is of particular concern because it represents a complex mixture of solid and liquid particles that can remain suspended in air and enter the respiratory tract. PM2.5 refers to particles with aerodynamic diameter of 2.5 micrometres or less, while PM10 includes particles with aerodynamic diameter of 10 micrometres or less. Because of their size, fine particles can penetrate deeper into the lungs and may contribute to systemic inflammatory, cardiovascular and respiratory effects. The World Health Organization (WHO) has emphasized that a large proportion of the global population breathes air that exceeds recommended guideline levels, making local and regional air quality surveillance an important component of public health action.[1,2]
The 2021 WHO global air quality guidelines recommended substantially lower guideline values for PM2.5 and PM10 than those used in several national regulatory frameworks, reflecting accumulating evidence that adverse health effects can occur even at low concentrations. The WHO 24-hour guideline values are 15 µg/m³ for PM2.5 and 45 µg/m³ for PM10, whereas the corresponding Indian National Ambient Air Quality Standards (NAAQS) 24-hour standards are 60 µg/m³ and 100 µg/m³, respectively. For annual averages, Indian NAAQS values are 40 µg/m³ for PM2.5 and 60 µg/m³ for PM10.[2,3] Interpreting local data against both guideline and regulatory thresholds is therefore useful: the former helps estimate health-protective exceedance, while the latter reflects national compliance requirements.
Indian studies have consistently shown marked temporal and seasonal variability in particulate matter concentrations. Higher winter or post-monsoon levels have often been attributed to lower boundary-layer height, stagnant winds,

temperature inversion, local emissions, biomass burning, traffic-related emissions and secondary aerosol formation. Monsoon periods often show lower concentrations because rainfall and stronger atmospheric mixing can remove or dilute particles. Studies from northern and eastern India have reported particularly high winter PM2.5 and PM10 values, while multi-city analyses have emphasized that exceedance patterns vary by city, season, emission source profile and meteorology.[4-8]

Compared with megacities and northern Indo-Gangetic Plain settings, fewer publication-ready analyses are available from smaller coastal urban centres in South India. Puducherry is a coastal Union Territory with urban traffic, commercial activity, construction-related dust, peri-urban sources and seasonally variable meteorology. Earlier tentative work on Puducherry focused on 2022 and 2023 and highlighted seasonal differences, but the availability of additional annual mastercharts from 2021 to 2025 allowed a broader assessment of medium-term trends. Such an analysis can help identify whether particulate concentrations are increasing, whether exceedances are persistent, and when preventive measures may be most needed.

The present study aimed to assess temporal trends of ambient PM2.5 and PM10 concentrations in Puducherry from 2021 to 2025. The specific objectives were to describe annual and monthly patterns, compare seasonal variation, quantify exceedance of WHO guideline values and Indian NAAQS standards, and evaluate the correlation between PM2.5 and PM10 concentrations.

Methods

1.1 Study design

This was a cross-sectional time-series analysis of routinely recorded ambient particulate matter data. The unit of analysis was the calendar-day 24-hour average concentration for each pollutant. The study was analytical in the sense that temporal and seasonal differences were statistically compared, but it did not include intervention, exposure assignment, participant recruitment or individual-level health outcomes.

1.2 Study setting and duration

The study setting was Puducherry, India, with data derived from the Jawahar Nagar monitoring dataset at Puducherry, a coastal urban region in the Union Territory of Puducherry along the Bay of Bengal. The analytical duration covered five complete calendar years, from 1 January 2021 to 31 December 2025.

1.3 Study population and data source

The study population comprised daily ambient air observations rather than human participants. The data contained date-wise 24-hour average PM2.5 and PM10 concentrations in micrograms per cubic metre (μg/m³). The data were obtained from publicly available Central Pollution Control Board-related air quality data for Jawahar Nagar, Puducherry. The annual data sheets for 2021, 2022, 2023, 2024 and 2025 were used as the source files for the present analysis.

1.4 Eligibility criteria

Inclusion criteria were calendar-day records dated between 1 January 2021 and 31 December 2025 with a valid date entry and a valid PM2.5 or PM10 value. For analyses involving a single pollutant, days with valid data for that pollutant were included. For correlation analysis between PM2.5 and PM10, only paired days with valid values for both pollutants were included. All other data like blank data sheet cells, non-numeric or invalid pollutant values were excluded for the specific analysis. No individual-level inclusion or exclusion criteria were applicable.

1.5 Sample size and sampling technique

The study used complete available secondary monitoring data over a fixed five-year period. The maximum possible sample comprised 1,826 calendar days, including one leap year in 2024. Valid observations were available for 1,762 PM2.5 days and 1,753 PM10 days after excluding missing pollutant values. The sampling technique was complete enumeration of the available daily monitoring dataset for the defined study period.

1.6 Data collection and processing

The five annual data sheets were imported and harmonized into a single dataset. Date fields were converted into calendar dates and used to derive year, month and season. PM2.5 and PM10 values were converted into numeric variables. Data completeness was checked by year and pollutant. Implausible textual entries and blanks were treated as missing. No imputation was performed because the proportion and distribution of missing data could influence seasonal and annual estimates; therefore, available-case analysis was considered the most transparent approach.

1.7 Study variables and operational definitions

The primary variables were daily PM2.5 and PM10 concentrations in μg/m³. The main time variables were year, month and season. Seasons were operationally defined as winter (January-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-December), consistent with common Indian seasonal classifications used in air pollution studies. Exceedance variables were created using two sets of thresholds: WHO 2021 24-hour guideline values of 15 μg/m³ for PM2.5 and 45 μg/m³ for PM10, and Indian NAAQS 24-hour standards of 60 μg/m³ for PM2.5 and 100 μg/m³ for PM10. Annual means were compared with Indian NAAQS annual standards of 40 μg/m³ for PM2.5 and 60 μg/m³ for PM10.[2,3]

1.8 Data quality assurance

Data quality assurance included verification of date ranges in each annual file, confirmation of the number of calendar days by year, assessment of missing observations and comparison of descriptive outputs against visible annual and monthly patterns. Derived variables were generated programmatically to reduce manual transcription error. Summary tables were reviewed for internal consistency, including correspondence between valid-day denominators and exceedance percentages.

1.9 Statistical analysis
Continuous variables were summarized as mean ± standard deviation (SD), 95% confidence interval (CI) for the mean, median with interquartile range (IQR), and minimum-maximum values. Categorical exceedance indicators were summarized as n/N (%), where N represented valid days for the relevant pollutant and year. Normality was not assumed because daily air pollutant concentrations are typically right-skewed and serially structured; therefore, non-parametric tests were used for inferential comparisons. Kruskal-Wallis tests compared pollutant distributions across years and seasons. Spearman rank correlation assessed the monotonic relationship between calendar date and pollutant concentration, and also the relationship between PM2.5 and PM10 on paired days. Exploratory annual mean slopes were estimated using simple linear regression of annual mean concentration on calendar year. A two-sided p value <0.05 was considered statistically significant. The analysis was performed using Python with pandas, SciPy and matplotlib. Missing data were handled by available-case analysis.

1.10 Ethical considerations
The study used secondary, publicly available environmental monitoring data and did not involve patients, human participants, personal identifiers, specimens or clinical interventions. Hence, informed consent was not applicable.

RESULTS
The combined dataset covered 1,826 calendar days from 2021 to 2025. Valid PM2.5 observations were available for 1,762 days, while valid PM10 observations were available for 1,753 days. Data completeness was highest in 2022 and 2023, with no missing PM2.5 values and no missing PM10 values in 2023. The largest missing fraction occurred in 2025, in which 43 daily values were missing for each pollutant.

Annual mean PM2.5 concentrations ranged from 20.20 ± 13.89 µg/m³ in 2021 to 26.60 ± 19.09 µg/m³ in 2025. The highest annual PM2.5 maximum was observed in 2022 (165.14 µg/m³), while the highest annual mean was in 2025. Annual mean PM10 concentrations ranged from 41.88 ± 19.17 µg/m³ in 2024 to 51.97 ± 21.64 µg/m³ in 2023. The maximum PM10 value was also highest in 2022 (178.68 µg/m³). Across all five years, annual mean PM2.5 and PM10 concentrations remained below the Indian NAAQS annual standards of 40 µg/m³ and 60 µg/m³, respectively (Table 1).

Seasonal patterns were evident for both pollutants. PM2.5 was generally higher during winter and post-monsoon periods and lower during monsoon. Winter PM2.5 means were 29.47 µg/m³ in 2021, 28.92 µg/m³ in 2022, 38.15 µg/m³ in 2023, 33.15 µg/m³ in 2024 and 39.40 µg/m³ in 2025. Monsoon PM2.5 means were lower, ranging from 13.72 µg/m³ in 2021 to 16.22 µg/m³ in 2022. PM10 showed a similar but less uniform seasonal distribution, with higher winter or post-monsoon values in most years. The highest seasonal PM10 mean was 67.55 ± 19.55 µg/m³ during winter 2023, followed by 60.75 ± 37.04 µg/m³ during post-monsoon 2022 and 60.14 ± 31.58 µg/m³ during post-monsoon 2025 (Table 2).

Daily exceedance analysis showed a substantial burden of days above the WHO 2021 24-hour guideline values. For PM2.5, the proportion of valid days above 15 µg/m³ was 52.9% in 2021, 62.7% in 2022, 68.2% in 2023, 60.8% in 2024 and 64.3% in 2025. Exceedance of the Indian NAAQS 24-hour PM2.5 standard of 60 µg/m³ was less frequent, ranging from 2.6% in 2021 to 7.5% in 2025. For PM10, days above the WHO 24-hour guideline of 45 µg/m³ ranged from 36.1% in 2024 to 59.2% in 2023, whereas days above the Indian NAAQS 24-hour PM10 standard of 100 µg/m³ ranged from 0.8% in 2024 to 4.4% in 2022 (Table 3).

Inferential analyses confirmed significant variation across years for both pollutants. The Kruskal-Wallis test across years was significant for PM2.5 ($H=25.36$, $p<0.001$) and PM10 ($H=75.15$, $p<0.001$). Spearman correlation with calendar date showed a weak positive monotonic trend for PM2.5 ($\rho=0.068$, $p=0.004$), whereas PM10 did not show a statistically significant monotonic trend ($\rho=-0.033$, $p=0.165$). Exploratory linear regression of annual mean concentration on year suggested a non-significant increase in PM2.5 of 1.07 µg/m³ per year ($p=0.182$) and no meaningful annual mean trend for PM10 (-0.15 µg/m³ per year, $p=0.936$). Seasonal differences were statistically significant for both PM2.5 ($H=366.42$, $p<0.001$) and PM10 ($H=152.03$, $p<0.001$) (Table 4).

On paired days, PM2.5 and PM10 showed a strong positive correlation in every study year. Spearman ρ ranged from 0.845 in 2021 to 0.915 in 2025, with all p values <0.001. The overall correlation for 1,753 paired observations was $\rho=0.870$ ($p<0.001$). The mean PM2.5/PM10 ratio was 0.47 ± 0.15 overall, increasing from 0.44-0.46 in 2021-2023 to 0.51-0.52 in 2024-2025 (Table 5).

Table 1. Annual descriptive statistics of PM2.5 and PM10 concentrations, Puducherry, 2021-2025

Year	PM2.5 n	PM2.5 Mean ± SD	PM2.5 95% CI	PM2.5 Median (IQR)	PM2.5 Min-Max	PM10 n	PM10 Mean ± SD	PM10 95% CI	PM10 Median (IQR)	PM10 Min-Max
2021	350	20.20 ± 13.89	18.74-21.66	15.81 (10.76-25.30)	3.54-107.68	345	43.03 ± 21.22	40.79-45.28	37.89 (27.71-52.36)	10.88-117.58
2022	365	24.74 ± 19.75	22.70-26.77	18.52 (12.28-30.05)	2.80-165.14	361	51.79 ± 24.98	49.20-54.37	47.58 (33.94-62.07)	9.24-178.68
2023	365	24.21 ± 15.97	22.56-25.85	20.21 (12.90-31.02)	3.67-130.39	365	51.97 ± 21.64	49.75-54.20	49.79 (36.07-64.64)	6.66-166.68

2024	360	22.66 ± 15.45	21.06-24.26	16.90 (12.51-29.12)	2.67-112.95	360	41.88 ± 19.17	39.90-43.87	38.33 (28.16-53.02)	10.29-135.43
2025	322	26.60 ± 19.09	24.51-28.70	18.38 (13.39-37.20)	3.56-94.95	322	47.23 ± 23.33	44.67-49.79	41.52 (29.86-62.94)	3.86-126.16

Values are in µg/m³. CI: confidence interval; IQR: interquartile range; PM: particulate matter; SD: standard deviation.

Table 2. Seasonal distribution of PM2.5 and PM10 concentrations by year

Year	Season	PM2.5 n	PM2.5 Mean ± SD	PM2.5 Median (IQR)	PM10 n	PM10 Mean ± SD	PM10 Median (IQR)
2021	Winter	48	29.47 ± 12.90	29.45 (21.28-35.36)	48	57.75 ± 20.02	56.49 (43.99-70.69)
2021	Pre-monsoon	92	18.65 ± 10.21	16.30 (11.47-24.93)	91	42.30 ± 20.68	40.73 (26.09-52.12)
2021	Monsoon	118	13.72 ± 4.99	13.09 (9.83-16.66)	114	37.38 ± 12.08	35.39 (29.42-43.93)
2021	Post-monsoon	92	25.21 ± 19.74	17.61 (10.71-33.40)	92	43.09 ± 27.14	31.62 (22.01-57.73)
2022	Winter	59	28.92 ± 14.27	26.18 (20.25-36.56)	59	55.96 ± 20.96	58.28 (43.17-65.88)
2022	Pre-monsoon	92	20.96 ± 12.82	17.64 (10.40-28.79)	92	49.69 ± 22.35	47.61 (30.48-66.06)
2022	Monsoon	122	16.22 ± 7.64	14.95 (11.72-18.23)	118	44.35 ± 10.77	44.51 (36.95-51.92)
2022	Post-monsoon	92	37.13 ± 30.18	26.82 (15.69-51.66)	92	60.75 ± 37.04	51.50 (32.71-85.74)
2023	Winter	59	38.15 ± 14.41	40.27 (27.82-45.55)	59	67.55 ± 19.55	71.42 (53.84-78.45)
2023	Pre-monsoon	92	21.29 ± 10.77	21.06 (12.08-29.82)	92	47.18 ± 17.43	47.56 (32.46-60.59)
2023	Monsoon	122	16.03 ± 4.65	16.12 (12.22-19.84)	122	49.10 ± 14.02	48.28 (38.47-58.91)
2023	Post-monsoon	92	29.02 ± 22.26	24.40 (12.57-39.80)	92	50.59 ± 29.52	43.47 (29.44-66.26)
2024	Winter	60	33.15 ± 17.36	31.43 (22.48-40.56)	60	54.89 ± 20.23	54.90 (43.95-65.92)
2024	Pre-monsoon	92	18.03 ± 10.98	14.96 (9.78-24.16)	92	38.47 ± 15.83	35.55 (24.78-51.62)
2024	Monsoon	117	15.12 ± 5.44	14.58 (12.20-17.36)	117	34.06 ± 9.38	34.21 (27.62-40.65)
2024	Post-monsoon	91	30.12 ± 19.22	24.42 (13.43-45.19)	91	46.81 ± 24.53	43.08 (25.54-68.88)

2025	Winter	59	39.40 ± 16.00	37.31 (25.93-53.67)	59	59.81 ± 18.42	60.86 (45.22-74.16)
2025	Pre-monsoon	88	17.92 ± 9.62	16.11 (11.60-22.80)	88	35.46 ± 15.03	33.64 (23.97-45.07)
2025	Monsoon	91	14.46 ± 3.83	13.89 (12.11-17.09)	91	38.54 ± 10.64	37.80 (30.62-43.46)
2025	Post-monsoon	84	39.88 ± 24.12	42.28 (15.93-57.38)	84	60.14 ± 31.58	67.06 (32.66-84.57)

Seasons: winter = January-February; pre-monsoon = March-May; monsoon = June-September; post-monsoon = October-December. Values are in µg/m³.

Table 3. Daily exceedance of WHO 2021 24-hour guideline values and Indian NAAQS 24-hour standards

Year	PM2.5 > WHO 24-h guideline n/N (%)	PM2.5 > NAAQS 24-h n/N (%)	PM2.5 annual mean > NAAQS annual	PM10 > WHO 24-h guideline n/N (%)	PM10 > NAAQS 24-h n/N (%)	PM10 annual mean > NAAQS annual
2021	185/350 (52.9)	9/350 (2.6)	No	126/345 (36.5)	6/345 (1.7)	No
2022	229/365 (62.7)	18/365 (4.9)	No	198/361 (54.8)	16/361 (4.4)	No
2023	249/365 (68.2)	10/365 (2.7)	No	216/365 (59.2)	10/365 (2.7)	No
2024	219/360 (60.8)	10/360 (2.8)	No	130/360 (36.1)	3/360 (0.8)	No
2025	207/322 (64.3)	24/322 (7.5)	No	135/322 (41.9)	10/322 (3.1)	No

WHO 2021 24-hour guideline values: PM2.5 >15 µg/m³, PM10 >45 µg/m³. Indian NAAQS 24-hour standards: PM2.5 >60 µg/m³, PM10 >100 µg/m³. Indian annual NAAQS standards: PM2.5 >40 µg/m³, PM10 >60 µg/m³.

Table 4. Statistical assessment of temporal and seasonal variation

Pollutant	Valid daily observations	Kruskal-Wallis H across years (p)	Spearman ρ with calendar date (p)	Annual mean slope, µg/m³/year (p)	Kruskal-Wallis H across seasons (p)
PM2.5	1762	25.36 (<0.001)	0.068 (0.004)	1.07 (0.182)	366.42 (<0.001)
PM10	1753	75.15 (<0.001)	-0.033 (0.165)	-0.15 (0.936)	152.03 (<0.001)

Kruskal-Wallis tests compared distributions across year or season. Spearman correlation assessed monotonic association with calendar date. Annual mean slope was exploratory because only five annual means were available.

Table 5. Correlation between PM2.5 and PM10 and PM2.5/PM10 ratio

Year	Paired observations	Spearman ρ between PM2.5 and PM10 (p)	Mean PM2.5/PM10 ratio ± SD
2021	345	0.845 (<0.001)	0.46 ± 0.15
2022	361	0.860 (<0.001)	0.44 ± 0.14
2023	365	0.850 (<0.001)	0.45 ± 0.14
2024	360	0.905 (<0.001)	0.51 ± 0.14
2025	322	0.915 (<0.001)	0.52 ± 0.15
Overall	1753	0.870 (<0.001)	0.47 ± 0.15

Correlation analyses used paired valid PM2.5 and PM10 observations. All pollutant values were in µg/m³.

Figures

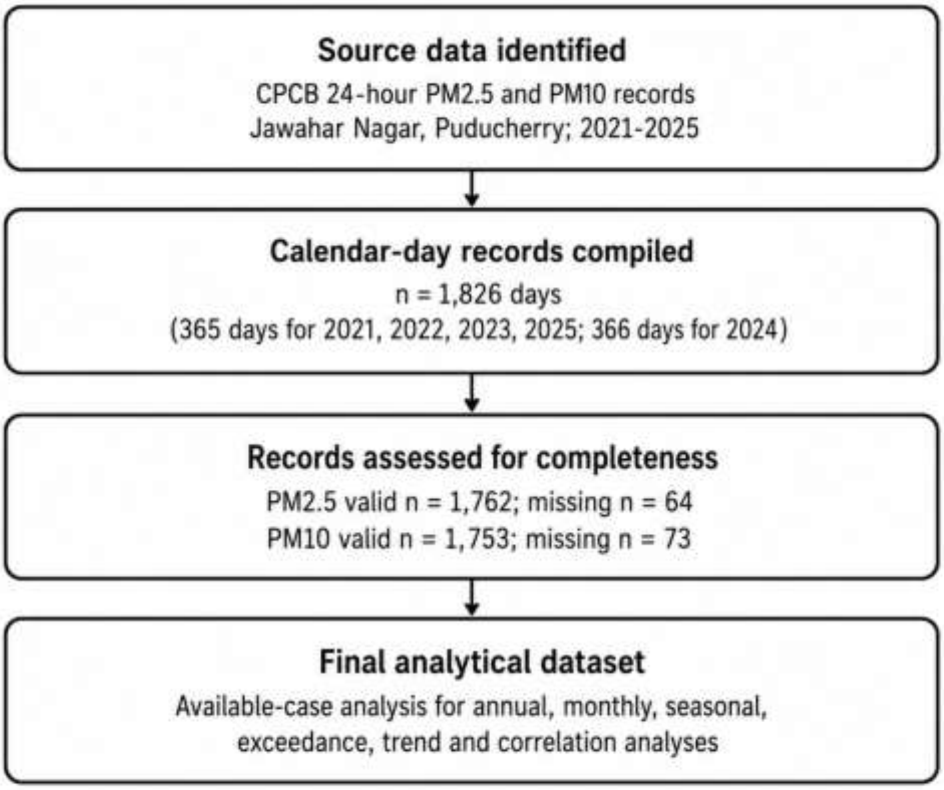

Figure 1. Data flow diagram for the five-year particulate matter dataset. The figure shows calendar days identified, data completeness and final analytical datasets for pollutant-specific and paired analyses.

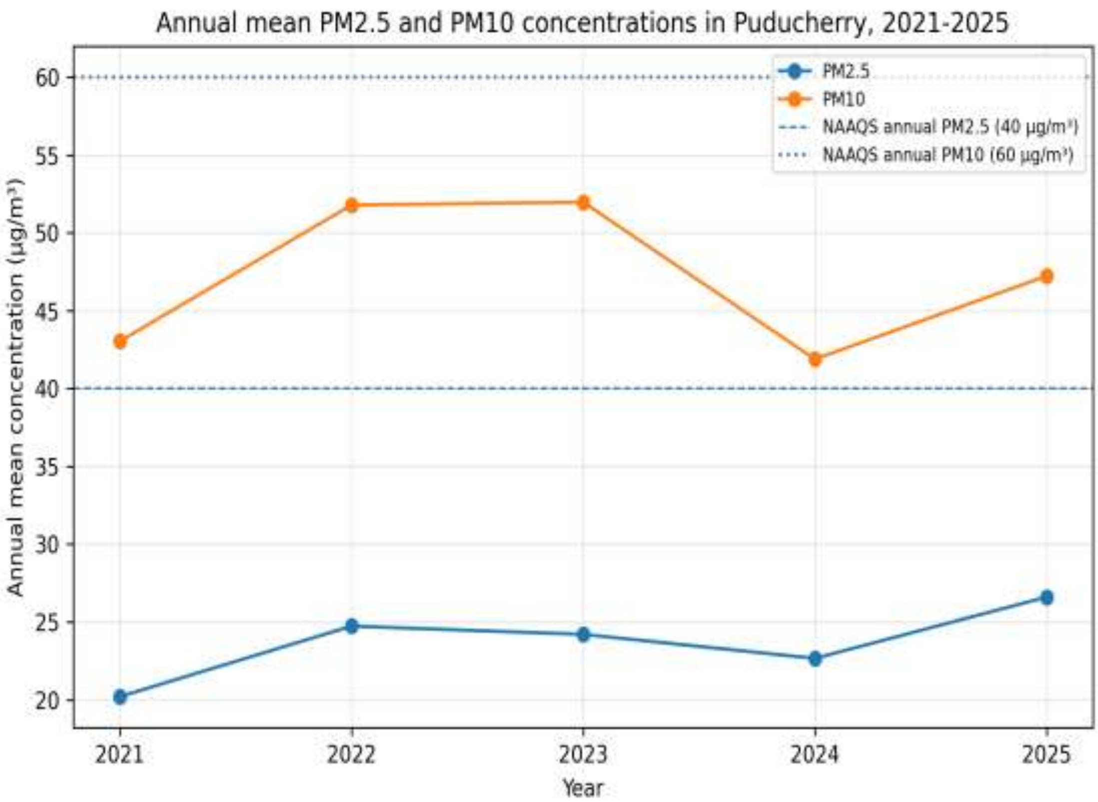

Figure 2. Annual mean PM2.5 and PM10 concentrations in Puducherry from 2021 to 2025, with Indian NAAQS annual thresholds shown for reference.

DISCUSSION

This five-year analysis of daily particulate matter concentrations in Puducherry provides a broader view than the earlier tentative two-year assessment and strengthens local evidence from a smaller coastal urban setting. The principal findings were that annual PM2.5 and PM10 means remained below Indian annual NAAQS standards during 2021-2025, but daily exceedance of WHO 2021 guideline values was common. PM2.5 exceeded the WHO 24-hour guideline on more than half of valid days in every study year, and PM10 exceeded the WHO 24-hour guideline on more than one-third of valid days in every study year. Seasonal variation was marked, with winter and post-monsoon periods generally carrying higher concentrations and monsoon periods showing lower concentrations. PM2.5 and PM10 were strongly correlated, indicating that daily rises in fine and coarse particulate fractions often occurred together. These findings are relevant because ambient particulate pollution remains an important environmental determinant of respiratory, cardiovascular and population health, and guideline-based interpretation is increasingly recommended for public-health-oriented surveillance.[1,2]

The finding that annual means complied with Indian annual NAAQS but frequently exceeded WHO guideline values reflects the difference between regulatory standards and more health-protective guideline values. WHO recommendations identify risk at lower concentrations and therefore capture a larger burden of exposure than national compliance thresholds.[2] In the present analysis, annual PM2.5 means ranged from 20.20 to 26.60 µg/m³ and annual PM10 means from 41.88 to 51.97 µg/m³, values below Indian annual NAAQS but above WHO annual guideline values of 5 µg/m³ for PM2.5 and 15 µg/m³ for PM10.[2,3] This distinction is important for interpretation: absence of annual NAAQS exceedance should not be equated with absence of health-relevant exposure, particularly when short-term guideline exceedances occurred repeatedly.

The seasonal pattern observed in Puducherry was consistent with much of the Indian literature, although concentrations were lower than those reported from more polluted northern urban centres. Singh et al. described PM2.5 exceedances and trends across five Indian megacities and reported substantial city-to-city variation, with monsoon months generally showing lower PM2.5 levels and winter periods showing greater pollution burden in several cities.[4] Chauhan et al. reported high seasonal particulate concentrations over Varanasi, with winter levels exceeding other seasons and monsoon values being lower.[5] Similar seasonal behaviour has been described from Patna and Delhi, where particulate levels were influenced by source mix and meteorological conditions.[6,7] A recent Guwahati study also found highest PM2.5 during winter and lowest values in monsoon, attributing seasonal differences to boundary-layer height, meteorology and transport patterns.[8] The current Puducherry findings support the broader observation that seasonal meteorology strongly influences particulate concentrations even in coastal locations.

Several mechanisms may explain the higher winter and post-monsoon concentrations. Cooler months are often associated with reduced mixing height, lower wind speed during some periods and more stable atmospheric conditions, which limit vertical dispersion. Post-monsoon and winter periods may also coincide with increased combustion-related emissions, regional transport, road dust resuspension under dry conditions, and festival-related or biomass burning contributions in some regions. Conversely, monsoon rainfall can remove particles through wet scavenging, and stronger ventilation can reduce near-surface accumulation. The relatively low monsoon PM2.5 means in Puducherry across all years support the importance of meteorological removal and dilution. This seasonal profile has practical implications because short-term peaks, even within moderate annual averages, can contribute to adverse respiratory and cardiovascular effects.[9,10]

The coastal context deserves specific consideration. The annual particulate levels observed in Puducherry were lower than many reports from the Indo-Gangetic Plain, but they were not negligible. Earlier work from Chennai, another coastal South Indian city, showed seasonal disparity of PM10 and PM2.5, suggesting that coastal ventilation may reduce but does not eliminate particulate exposure when local emissions, traffic and dust sources persist.[11] In contrast, studies from the Indo-Gangetic Plain have highlighted the role of regional transport and potential source locations in sustaining particulate loading across seasons.[12] Thus, Puducherry's pattern may represent a moderate-exposure coastal profile in which local meteorology provides partial dilution, while urban activity and seasonal accumulation still create frequent WHO guideline exceedances.

The health significance of these results is supported by national burden estimates. The India State-Level Disease Burden Initiative estimated substantial mortality, disease burden and reduction in life expectancy attributable to air pollution across Indian states in 2017, and later reported large health and economic losses attributable to air pollution in 2019.[13,14] More recent analyses have reinforced that even concentrations below historically high urban levels remain relevant: annual PM2.5 exposure has been associated with mortality in India, and a multi-city time-series study found daily mortality associations with short-term PM2.5 exposure across ten Indian cities.[15,16] Global modelling has also shown that ambient PM2.5 reduces life expectancy, with larger losses in polluted Asian settings.[17] Therefore, the frequent daily exceedances in Puducherry should be treated as a public health signal rather than merely an environmental monitoring statistic.

The pollutant correlation findings are also relevant. PM2.5 and PM10 were strongly correlated in all years, with an overall Spearman rho of 0.870. This suggests that daily drivers such as traffic intensity, road dust, construction activity, atmospheric stability, long-range transport or meteorological accumulation may influence both fractions simultaneously. However, the PM2.5/PM10 ratio was below 0.5 overall, indicating that coarse particles contributed substantially to total PM10 mass. Indian urban air-pollution reviews have emphasized that particulate sources are mixed and include transport, road dust, construction, waste burning, industries, power generation and residential combustion.[18] Road traffic can contribute both exhaust and non-exhaust particles, including brake, tyre and road-surface abrasion and resuspension, which is particularly relevant when interpreting concurrent PM2.5 and PM10 increases.[19]

The weak positive monotonic trend for PM2.5 over daily dates reached statistical significance, but its magnitude was small. The exploratory annual mean slope suggested an increase of approximately 1.07 µg/m³ per year, but this was not statistically significant because only five annual means were available. PM10 showed significant year-to-year distributional differences but no monotonic trend. These results indicate variability rather than a strong linear increase or decrease over the study period. For policy purposes, the most actionable finding may be the recurrent seasonal and daily exceedance burden rather than a simple long-term linear trend. This supports the need for city-specific clean-air planning, since national programmes require local evidence on source profiles, monitoring gaps, implementation feasibility and seasonal priorities.[20]

Public health implications include the need for seasonal preparedness and targeted emission reduction. Sensitive groups, including children, older adults, pregnant women and people with chronic respiratory or cardiovascular disease, may be affected by repeated short-term peaks. Local authorities can use daily and seasonal monitoring to strengthen advisories, construction dust control, road cleaning, traffic management, public awareness and emission controls during higher-risk months. The post-monsoon and winter peaks observed in Puducherry suggest that pre-season planning may be more effective than reactive action after exceedances occur. Integration of PM data with meteorological variables, hospital morbidity data and episode-based alerts would further strengthen local health-risk assessment.

The study has important strengths, including use of five complete calendar years of date-wise data, consistent definitions, assessment of both PM2.5 and PM10, reporting of data completeness, and comparison with both WHO guideline values and Indian regulatory standards. Avoidance of imputation and use of valid denominators improved transparency, while non-parametric methods were suitable for skewed pollutant data. It also adds evidence from a smaller coastal urban setting. Limitations include reliance on a single monitoring site, missing observations, absence of meteorological and source data, no chemical characterization, possible serial autocorrelation, and lack of linked health outcome data for impact estimation.

CONCLUSION

In this five-year analysis of ambient particulate matter in Puducherry, annual mean PM2.5 and PM10 concentrations were below Indian annual NAAQS standards but exceeded WHO annual guideline values and showed frequent daily exceedance of WHO 24-hour guideline values. Seasonal variation was pronounced, with higher concentrations during winter and post-monsoon periods and lower concentrations during monsoon. PM2.5 and PM10 were strongly correlated, suggesting common temporal drivers or shared meteorological influences. The findings indicate that Puducherry may not show severe annual regulatory exceedance by Indian standards, but it experiences repeated health-relevant particulate matter exposure. Continuous surveillance, local source assessment and season-specific control strategies are recommended to prevent worsening air quality and reduce population exposure.

Acknowledgement:

The authors would like to acknowledge the Pondicherry Pollution Control Committee (PPCC) for its encouragement in this study. The authors would also like to acknowledge the members of the Research Advisory Committee for their academic oversight and association with the research program.

REFERENCES

1. 1. World Health Organization. Ambient (outdoor) air pollution. Geneva: World Health Organization; 2024.
2. World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: World Health Organization; 2021.
3. Central Pollution Control Board. National Ambient Air Quality Standards. New Delhi: Central Pollution Control Board, Ministry of Environment, Forest and Climate Change, Government of India; 2009.
4. Singh V, Sokhi RS, Kukkonen J. PM2.5 exceedances and trends in five Indian megacities. Sci Total Environ. 2020;750:141461.
5. Chauhan PK, Kumar A, Pratap V, Singh AK. Seasonal characteristics of PM1, PM2.5, and PM10 over Varanasi during 2019-2020. Front Sustain Cities. 2022;4:909351.
6. Kumar A, Yadav IC, Shukla A, Devi NL. Seasonal variation of PM2.5 in the central Indo-Gangetic Plain (Patna) of India: chemical characterization and source assessment. SN Appl Sci. 2020;2:1366.
7. Singh BP, Singh D, Kumar K, Jain VK. Study of seasonal variation of PM2.5 concentration associated with meteorological parameters at residential sites in Delhi, India. J Atmos Chem. 2021;78(3):161-176.
8. Chaudhry SK, Tripathi SN, Reddy TVR, Kumar A, Madhwal S, Yadav AK, et al. Influence of seasonal variation on spatial distribution of PM2.5 concentration using low-cost sensors. Environ Monit Assess. 2024;196(12):1234.
9. Anderson JO, Thundiyil JG, Stolbach A. Clearing the air: a review of the effects of particulate matter air pollution on human health. J Med Toxicol. 2012;8(2):166-175.
10. Kaur R, Pandey P. Air pollution, climate change, and human health in Indian cities: a brief review. Front Sustain Cities. 2021;3:705131.
11. Prabagaran P, Krishnasamy V, Ayyar D, Rambabu V. Quantification and seasonal disparity of PM10, PM2.5 and lead in Chennai city atmospheric air. Indian J Environ Prot. 2017;37(2):117-131.
12. Rahman MH, Sharma VP, Kundu S, Datta A. Seasonal variation of potential source locations of atmospheric particulates over the Indo-Gangetic Plain of India. Open J Air Pollut. 2020;9(1):1-10.
13. India State-Level Disease Burden Initiative Air Pollution Collaborators. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. Lancet Planet Health. 2019;3(1):e26-e39.
14. India State-Level Disease Burden Initiative Air Pollution Collaborators. Health and economic impact of air pollution in the states of India: the Global Burden of Disease Study 2019. Lancet Planet Health. 2021;5(1):e25-e38.
15. Jaganathan S, Stafoggia M, Rajiva A, Mandal S, Dixit S, de Bont J, et al. Estimating the effect of annual PM2.5 exposure on mortality in India: a difference-in-differences approach. Lancet Planet Health. 2024;8(12):e987-e996.

16. de Bont J, Krishna B, Stafoggia M, Banerjee T, Dholakia H, Garg A, et al. Ambient air pollution and daily mortality in ten cities of India: a causal modelling study. Lancet Planet Health. 2024;8(7):e433-e440.
17. Apte JS, Brauer M, Cohen AJ, Ezzati M, Pope CA III. Ambient PM2.5 reduces global and regional life expectancy. Environ Sci Technol Lett. 2018;5(9):546-551.
18. Guttikunda SK, Goel R, Pant P. Nature of air pollution, emission sources, and management in the Indian cities. Atmos Environ. 2014;95:501-510.
19. Pant P, Harrison RM. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. Atmos Environ. 2013;77:78-97.
20. Ganguly T, Kurinji LS, Guttikunda SK. National Clean Air Programme (NCAP) for Indian cities: review and outlook of clean air action plans. Atmos Pollut Res. 2020;11(11):2048-2061.