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Ambient Air Quality Assessment of Nitrogen Dioxide and Sulphur Dioxide in Agra India Spatial Distribution, Seasonal Variation and Year on Year Trends (2024–2026)

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Abstract

This study analyses twenty-five months of ambient air quality monitoring data (March 2024–March 2026) collected at four Central Pollution Control Board (CPCB) National Ambient Air Quality Monitoring Programme (NAMP) stations in Agra India: Taj Mahal (heritage monument zone), Itmad-ud-Daulah (secondary heritage zone), Rambagh (residential/traffic corridor) and Nunhai (industrial estate). Monthly mean concentrations of nitrogen dioxide (NO₂) and sulphur dioxide (SO₂) are analysed for seasonal patterns, inter-station spatial gradients and year on year trends. Results reveal a consistent spatial hierarchy (Nunhai > Rambagh ≈ Itmad-ud-Daulah > Taj Mahal) and robust seasonal cycling with NO₂ peaking in the post monsoon and winter seasons and reaching minima during the southwest monsoon. All four stations remain compliant with NAAQS 2009 annual limits for NO₂ (40 µg/m³) but persistently exceed the WHO 2021 annual guideline of 10 µg/m³ indicating a significant public health protection gap. SO₂ concentrations were overwhelmingly below the instrument detection limit (< 4 µg/m³) throughout the study period reflecting the effectiveness of BS-VI fuel standards and Taj Trapezium Zone (TTZ) deindustrialisation policies. A modest year on year improvement in NO₂ was observed at three of four stations between 2024–25 and 2025–26, tentatively attributed to the cumulative impact of progressive vehicle emission norms. Findings carry important implications for heritage conservation, urban public health policy and the alignment of Indian ambient air quality standards with contemporary WHO evidence.

Keywords; Nitrogen dioxide · Sulphur dioxide · Agra · Taj Mahal · NAAQS · WHO air quality guidelines · Taj Trapezium Zone · Seasonal variation · Indo-Gangetic Plain.

INTRODUCTION

Air pollution is the contamination of indoor or outdoor air by a range of gases and solids that modify its natural characteristics. Key health harmful pollutants include particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), ozone (O₃), black carbon (BC), sulphur dioxide (SO₂) and nitrogen oxides (NO_x) [27]. Ambient air pollution has emerged as one of the defining environmental and public health challenges of the twenty first century, cutting across borders, income levels and governance systems [2]. It is no longer confined to a handful of industrialised regions; it is now a pervasive planetary risk factor that shapes mortality, morbidity and economic productivity on a global scale [21, 23].

Urban areas already host more than half of the global population and are projected to absorb most future population growth, with a corresponding escalation in material consumption [9, 22]. This demographic pressure is sharpest in low and middle income countries where 1 Agra Air Quality Assessment · NO₂ and SO₂ in Agra (2024–2026) urbanisation has frequently outpaced both environmental regulation and infrastructure, amplifying local pollution burdens [2, 22].

Megacities such as Delhi, Mumbai and Kolkata have experienced explosive growth in population, vehicle fleets, energy demand and industrial capacity all tightly coupled to elevated emissions of criteria pollutants [9, 22]. The emission profile of nitrogen oxides fundamentally shapes the toxicity of a region's overall air pollution mixture while SO₂ undergoes atmospheric transformation into sulphate

aerosols that contribute to fine particulate matter, acid deposition and radiative forcing [7, 19].

Over the past two decades global evidence has revealed that trajectories for particulate and gaseous pollutants are not uniform [23]. Reanalysis and observational syntheses indicate that average PM_{2.5} exposure in urban areas has declined modestly at the global scale, while many cities particularly in South Asia, the Middle East and parts of Africa have experienced rising concentrations [23]. These differentiated trends underscore the need for region specific syntheses [9, 22].

Agra presents an especially compelling case for such a study. As home to the Taj Mahal a UNESCO World Heritage Site Agra occupies a unique intersection of urban air quality, heritage conservation and public health governance. The Taj Mahal's Makrana marble surfaces are acutely sensitive to acidic gaseous pollutants: sulphurous and nitrous acids derived from ambient SO₂ and NO₂ react with the calcium carbonate matrix to produce soluble gypsum crusts, a deterioration process colloquially termed 'marble cancer' [12]. In direct response the Government of India established the Taj Trapezium Zone (TTZ) a 10,400 km² pollution control area subject to stringent regulatory restrictions on industrial activity and vehicular emissions.

Despite the TTZ's regulatory significance relatively few studies have used long term continuous monitoring data to simultaneously characterise NO₂ and SO₂ concentrations across multiple land use zones within Agra. This study addresses that gap by analysing twenty five months of CPCB NAMP data (March 2024-March 2026) from four monitoring stations. The primary objectives are to: (i) characterise the spatial distribution of NO₂ and SO₂ across contrasting land use zones (ii) analyse seasonal and inter annual variation (iii) assess compliance with NAAQS 2009 and WHO 2021 air quality guidelines (iv) discuss implications for public health, heritage conservation and policy.

LITERATURE REVIEW

Gurjar et al. [9] examined long term air pollution trends in Delhi, Mumbai and Kolkata, documenting that SO₂ levels have generally declined across the three megacities linked to reductions in sulphur content in fuels while nitrogen oxides have tended to rise primarily because of growing vehicle numbers. This asymmetry demonstrates that progress in one pollutant category does not necessarily translate into progress across the board.

Shrivastava et al. [22] framed rapid industrialisation, urbanisation, rising vehicular fleets and unplanned development as key drivers of Indian urban pollution. India's urban population increased nearly fivefold from approximately 60 million at independence to roughly 400 million with projections of another 700 million in cities by 2050 [22].

Kumar and Maharana [14] provided a detailed case study of Delhi demonstrating that black carbon extinction coefficients peak in winter due to biomass burning, crop residue burning, vehicular emissions, shallow mixing heights and stable atmospheric conditions a framework directly applicable to the Agra airshed.

At the local level Kumar et al. [13] evaluated air quality and public perceptions of pollution in Agra situating the city within the broader Indo Gangetic Basin context. Rajouriya et al. [18] investigated size segregated particulate matter, black carbon and gases (NO₂, O₃) at multiple Agra sites finding highest concentrations at high traffic roadside locations.

Globally Sicard et al. [23] analysed population weighted urban exposure trends for ozone, PM_{2.5} and NO₂ between 2000 and 2019 finding that NO₂ concentrations increased in most cities with particularly pronounced rises in South Asia. Mandal et al. [16] documented through OMI satellite retrievals that NO₂ column densities reach their annual minimum during the monsoon and peak during the post monsoon season consistent with the surface level observations in this study.

Regarding SO₂ Kuttippurath et al. [15] analysed four decades of SO₂ pollution over India finding that concentrations began declining in the 2010s linked to stricter emission standards and growth in renewable energy. The WHO Global Air Quality Guidelines (2021) [28] revised the annual mean NO₂ guideline downward from 40 to 10 µg/m³ creating a stark policy challenge for Indian cities where the NAAQS annual limit for NO₂ remains at 40 µg/m³ [10].

METHODOLOGY

Study Area

The study was conducted in Agra a historically significant urban centre in the western region of Uttar Pradesh northern India. Agra occupies the western margins of the Indo Gangetic Plain on the banks of the Yamuna River approximately 200 km south east of New Delhi at coordinates 27.18°N 78.02°E and an elevation of approximately 171 m above mean sea level. The city

experiences a semi arid climate (Köppen BSh) with four climatically distinct seasons: hot and dry summer, south west monsoon , post monsoon and cool dry winter. Mean monthly temperatures range from approximately 8°C in January to 45°C in May-June.

MONITORING STATIONS

Taj Mahal (Heritage Monument Zone)

Located at 27.1751°N 78.0421°E on the southern bank of the Yamuna River the Taj Mahal was inscribed on the UNESCO World Heritage List in 1983. This site is the most ecologically sensitive monitoring location in the study functioning as both a receptor of air pollution and a physical indicator of long-term exposure. The Government of India established the TTZ (10,400 km²) in direct response to the threat of gaseous pollutant damage to the monument's marble fabric [12].

Itmad-ud-Daulah (Secondary Heritage Zone)

The Tomb of Itmad-ud-Daulah is situated on the eastern bank of the Yamuna River constructed between 1622 and 1628 CE. Commonly referred to as the 'Baby Taj', this white marble mausoleum occupies a position within the TTZ and is subject to the same regulatory framework as the Taj Mahal. Its designation as a CPCB monitoring station enables cross site comparative analysis within the heritage corridor.

Rambagh (Residential and Traffic-Dominated Zone)

Rambagh is a densely populated residential locality along the northern bank of the Yamuna River and a major traffic artery, experiencing high volumes of two wheelers, three wheelers and commercial vehicles. Road dust resuspension from unpaved margins and construction activity further contributes to the particulate fraction. This site provides a baseline for assessing residential air quality against heritage zone concentrations.

Nunhai (Industrial Zone)

Nunhai is a prominent industrial estate in the eastern precincts of Agra encompassing small to medium scale

manufacturing units, diesel generator sets and associated ancillary operations. Agra generates approximately 37 tonnes per day of PM₁₀ and 15 tonnes per day of PM_{2.5} from combined anthropogenic sources of which industrial zones such as Nunhai constitute a substantial component [3].

DATA COLLECTION AND ANALYSIS

This study employs a secondary data research design drawing exclusively on air quality monitoring records obtained from the CPCB NAMP the statutory authority responsible for continuous ambient air quality monitoring across Indian cities [4]. The temporal scope spans March 2024 to March 2026 capturing two complete seasonal cycles. Seasonal classification follows the India Meteorological Department (IMD) four season framework: Pre monsoon or Summer (March to May), Southwest Monsoon (June to September), Post monsoon (October to November) and Winter (December to February).

Monthly mean concentrations of NO₂ and SO₂ were sourced for all four stations. Values recorded as BDL (Below Detection Limit) indicate concentrations below the instrument detection threshold of 4 µg/m³ for SO₂ and 9 µg/m³ for NO₂ per CPCB monitoring protocol [3]. Annual means were computed as 12-month arithmetic means for the April to March cycles 2024-25 and 2025-26. Results were assessed against NAAQS (2009) annual permissible limits (NO₂: 40 µg/m³; SO₂: 50 µg/m³) and the WHO Global Air Quality Guidelines (2021) annual mean NO₂ guideline (10 µg/m³) [28].

Observational Data

Tables 1-4 present the monthly mean concentrations of NO₂ and SO₂ (in µg/m³) recorded at the four CPCB NAMP monitoring stations from March 2024 to March 2026. Monthly observations are organised into seasonal groupings consistent with the IMD meteorological framework. The NAAQS applicable to monitoring sites classified under the 'Sensitive Area' category are: SO₂ 15 µg/m³ (annual mean) and NO₂ 15 µg/m³ (annual mean).

Table 1 Monthly mean concentrations of NO₂ and SO₂ at four monitoring stations, Agra (March 2024–March 2026)

Month/Year	NO ₂ Taj Mahal	NO ₂ Itmad-ud-Daulah	NO ₂ Rambagh	NO ₂ Nunhai	SO ₂ Taj Mahal	SO ₂ Itmad-ud-Daulah	SO ₂ Rambagh	SO ₂ Nunhai
Mar 2024	16.15	20.85	16.14	25.28	4.50	BDL	BDL	BDL
Apr 2024	12.61	15.66	15.00	24.18	4.62	BDL	BDL	BDL
May 2024	14.43	17.62	18.00	25.70	BDL	BDL	BDL	BDL
Jun 2024	11.93	16.43	16.00	21.67	BDL	BDL	BDL	BDL
Jul 2024	13.50	17.00	12.86	18.12	BDL	BDL	5.33	BDL
Aug 2024	9.65	9.17	12.45	19.00	4.09	4.27	BDL	BDL

Sep 2024	9.50	14.22	12.33	17.00	4.50	4.89	4.56	BDL
Oct 2024	15.36	21.11	17.11	33.60	4.04	4.13	BDL	BDL
Nov 2024	18.80	26.12	30.07	31.40	BDL	BDL	BDL	BDL
Dec 2024	16.65	16.28	21.58	31.43	4.42	4.36	BDL	BDL
Jan 2025	15.91	15.27	28.40	23.40	4.04	4.27	BDL	BDL
Feb 2025	17.86	25.22	15.44	23.36	4.11	BDL	BDL	BDL
Mar 2025	13.79	14.80	13.11	24.30	4.45	4.25	4.20	BDL
Apr 2025	11.04	17.14	21.11	15.70	4.06	4.50	4.85	4.37
May 2025	10.04	12.11	14.89	26.80	4.36	4.78	4.60	BDL
Jun 2025	9.79	11.44	19.33	16.30	4.10	BDL	BDL	BDL
Jul 2025	9.36	12.56	11.82	10.80	BDL	BDL	BDL	BDL
Aug 2025	9.61	11.20	13.10	13.85	4.30	4.20	4.28	BDL
Sep 2025	9.54	9.92	10.43	15.70	3.88	4.57	BDL	BDL
Oct 2025	13.50	10.75	19.35	20.44	4.50	4.31	BDL	BDL
Nov 2025	17.88	23.17	16.43	34.38	5.04	5.13	4.75	BDL
Dec 2025	15.23	31.50	26.30	24.00	4.38	4.70	4.10	4.33
Jan 2026	15.08	19.40	15.90	17.55	4.19	4.50	4.60	BDL
Feb 2026	15.50	27.56	19.90	20.11	4.67	5.67	4.30	BDL
Mar 2026	12.22	19.56	14.87	19.00	4.09	4.36	BDL	BDL

All values in $\mu\text{g}/\text{m}^3$. BDL = Below Detection Limit ($< 4 \mu\text{g}/\text{m}^3$ for SO_2 ; $< 9 \mu\text{g}/\text{m}^3$ for NO_2). Row shading: premonsoon (Mar–May); monsoon (Jun–Sep); post-monsoon (Oct–Nov); winter (Dec–Feb). Source: CPCB NAMP, 2024–2026.

Table 2 Seasonal mean concentrations of NO_2 by station and year

Season	Year	Taj Mahal ($\mu\text{g}/\text{m}^3$)	Itmad-ud-Daulah ($\mu\text{g}/\text{m}^3$)	Rambagh ($\mu\text{g}/\text{m}^3$)	Nunhai ($\mu\text{g}/\text{m}^3$)
Pre-monsoon (Mar–May)	2024	14.40	18.04	16.38	25.05
Pre-monsoon (Mar–May)	2025	11.62	14.68	16.37	22.27
Monsoon (Jun–Sep)	2024	11.15	14.21	13.41	18.95
Monsoon (Jun–Sep)	2025	9.58	11.28	13.67	14.16
Post-monsoon (Oct–Nov)	2024	17.08	23.62	23.59	32.50
Post-monsoon (Oct–Nov)	2025	15.69	16.96	17.89	27.41
Winter (Dec–Feb)	2024–25	16.81	18.92	21.81	26.06

Winter (Dec–Feb)	2025–26	15.27	26.15	20.70	20.55
Annual (Apr–Mar)	2024–25	14.36	17.91	17.95	24.51
Annual (Apr–Mar)	2025–26	12.53	16.80	16.81	19.99

Seasons per IMD: pre-monsoon = Mar–May; monsoon = Jun–Sep; post-monsoon = Oct–Nov; winter = Dec–Feb. Annual figures are April–March 12-month arithmetic means. NAAQS annual standard for $\text{NO}_2 = 40 \mu\text{g}/\text{m}^3$; WHO 2021 annual guideline = $10 \mu\text{g}/\text{m}^3$.

Table 3 Seasonal profile of SO_2 concentrations by station (range of detected values, $\mu\text{g}/\text{m}^3$)

Season	Taj Mahal	Itmad-ud-Daulah	Rambagh	Nunhai
Pre-monsoon 2024 (Mar–May)	4.50–4.62 (Mar–Apr only)	BDL	BDL	BDL
Monsoon 2024 (Jun–Sep)	4.09–4.50 (Aug–Sep)	4.27–4.89	4.56 (Sep)	BDL
Post-monsoon 2024 (Oct–Nov)	4.04	4.13	BDL	BDL
Winter 2024–25 (Dec–Feb)	4.04–4.42	4.27–4.36	BDL	BDL

Pre-monsoon 2025 (Mar–May)	4.06–4.45	4.25–4.78	4.20–4.85	4.37 (Apr only)
Monsoon 2025 (Jun–Sep)	4.10 (Jun)	4.20–4.57	4.28 (Aug)	BDL
Post-monsoon 2025 (Oct–Nov)	4.50–5.04	4.31–5.13	4.75 (Nov)	BDL
Winter 2025–26 (Dec–Feb)	4.19–4.67	4.50–5.67	4.10–4.60	4.33 (Dec only)

Range notation (x.xx–x.xx) indicates minimum and maximum detected values within that season. BDL = Below Detection Limit ($< 4 \mu\text{g}/\text{m}^3$). Source: CPCB NAMP.

Table 4 Annual mean NO₂ compliance with NAAQS 2009 and WHO AQG 2021

Station	NO ₂ 2024–25 ($\mu\text{g}/\text{m}^3$)	NO ₂ 2025–26 ($\mu\text{g}/\text{m}^3$)	NAAQS Limit ($\mu\text{g}/\text{m}^3$)	WHO 2021 ($\mu\text{g}/\text{m}^3$)	Annual SO ₂ Status
Taj Mahal	14.17	12.40	40	10	BDL/Low ✓ Within NAAQS
Itmad-ud-Daulah	17.41	17.19	40	10	BDL/Low ✓ Within NAAQS
Rambagh	17.70	16.95	40	10	BDL/Low ✓ Within NAAQS
Nunhai	24.43	19.55	40	10	BDL/Low ✓ Within NAAQS

Highlighted NO₂ cells exceed the WHO 2021 annual guideline of $10 \mu\text{g}/\text{m}^3$. ✓ = within NAAQS limits. SO₂ annual averages not computed due to widespread BDL observations; all detected values are within the NAAQS annual standard of $50 \mu\text{g}/\text{m}^3$.

RESULTS AND DISCUSSION

The results derived from twenty-five months of continuous ambient air quality monitoring (March 2024–March 2026) at the four CPCB NAMP stations in Agra reveal distinct spatial heterogeneity and consistent seasonal cycling in both NO₂ and SO₂ concentrations. The findings are structured around the four IMD meteorological seasons, with inter-annual comparisons drawn between the 2024 and 2025 cycles.

Spatial Distribution of NO₂

Across the full study period a consistent spatial hierarchy in NO₂ concentrations was observed: Nunhai $>$ Rambagh \approx Itmad-ud-Daulah $>$ Taj Mahal. The Nunhai station recorded

the highest annual mean of $24.51 \mu\text{g}/\text{m}^3$ in 2024-25 and $19.99 \mu\text{g}/\text{m}^3$ in 2025-26 reflecting intense vehicular activity on the arterial NH-19 corridor and proximity to the Nunhai marshalling yard. The Taj Mahal station consistently recorded the lowest concentrations — $14.36 \mu\text{g}/\text{m}^3$ in 2024-25 and $12.53 \mu\text{g}/\text{m}^3$ in 2025-26 attributable to the Supreme Court's 2000 mandate restricting polluting traffic within the 50 km TTZ buffer [11]. This spatial gradient corroborates findings by Kumar and Shukla [12] who reported NO₂ concentrations of 17-23 $\mu\text{g}/\text{m}^3$ from a decade long monitoring record at the Taj Mahal site.

The Rambagh and Itmad-ud-Daulah stations recorded comparable annual means 17.95 and 17.91 $\mu\text{g}/\text{m}^3$ respectively in 2024-25, narrowing marginally to 16.81 and 16.80 $\mu\text{g}/\text{m}^3$ in 2025-26. These concentrations remain substantially below the NAAQS (2009) annual permissible limit of $40 \mu\text{g}/\text{m}^3$. However, when assessed against the WHO 2021 guidelines [28] — which recommend an annual mean NO₂ not exceeding $10 \mu\text{g}/\text{m}^3$ all four stations exceeded this threshold in both annual cycles highlighting a significant public health protection gap consistent with findings across South Asian urban centres [1].

Seasonal Variation: Pre-Monsoon Season

The pre monsoon season (March–May) is characterised by rising temperatures, low relative humidity and increasing north westerly winds that facilitate moderate pollutant dispersion. In 2024 pre monsoon NO₂ means were 14.40, 18.04, 16.38 and 25.05 $\mu\text{g}/\text{m}^3$ at Taj Mahal, Itmadud Daulah, Rambagh and Nunhai respectively. In 2025 corresponding values declined to 11.62, 14.68, 16.37 and 22.27 $\mu\text{g}/\text{m}^3$ representing decreases of approximately 19.3%, 18.6%, 0.1% and 11.1%. The marked decline at Taj Mahal and Itmad-ud-Daulah suggests an improving micro environmental trajectory at the heritage sensitive sites may be possibly linked to enhanced traffic management around the Agra Fort-Taj Mahal corridor implemented in early 2025. The near stagnant value at Rambagh across both years suggests emissions in that residential commercial zone remained structurally unchanged.

Seasonal Variation: Southwest Monsoon

The southwest monsoon season (June–September) invariably produces the lowest NO₂ concentrations of the year at all four stations. In monsoon 2024 station means were 11.15 (Taj Mahal), 14.21 (Itmad-ud-Daulah), 13.41 (Rambagh) and 18.95 $\mu\text{g}/\text{m}^3$ (Nunhai). By monsoon 2025 these values had declined further to 9.58, 11.28, 13.67 and 14.16 $\mu\text{g}/\text{m}^3$ respectively. Notably the Taj Mahal station achieved a monsoon mean of 9.58 $\mu\text{g}/\text{m}^3$ in 2025 the closest

any station came to the $10 \mu\text{g}/\text{m}^3$ WHO threshold during the entire study period.

The mechanistic basis for pronounced monsoon minima is well established precipitation driven wet deposition efficiently scavenges both NO_2 and its oxidation products while the deeper daytime planetary boundary layer characteristic of the convective monsoon period facilitates greater vertical mixing and dilution [20]. Mandal et al. [16] documented through long term OMI satellite retrievals over the Upper IGP that NO_2 column densities reach their annual minimum during the monsoon consistent with the surface level observations recorded here. The year on year comparison reveals that monsoon 2025 was markedly cleaner than monsoon 2024 with reductions of 14.1% at Taj Mahal, 20.6% at Itmad-ud-Daulah, 1.8% at Rambagh and 25.3% at Nunhai.

Seasonal Variation: Post-Monsoon Season

The post monsoon season (October-November) represents the period of sharpest rise in NO_2 concentrations transitioning from monsoon minima to near annual maxima within six to eight weeks. In post monsoon 2024 the four stations recorded means of 17.08, 23.62, 23.59 and $32.50 \mu\text{g}/\text{m}^3$ for Taj Mahal, Itmad-ud-Daulah, Rambagh and Nunhai respectively. In post monsoon 2025 corresponding seasonal means declined to 15.69, 16.96, 17.89 and $27.41 \mu\text{g}/\text{m}^3$ respectively, representing reductions of 8.2%, 28.2%, 24.2% and 15.7%.

This post monsoon deterioration is driven by a convergence of well documented factors across the Upper IGP: (a) rapid shallowing of the planetary boundary layer as land cools following monsoon withdrawal, leading to nocturnal temperature inversions (b) episodic crop residue burning in Punjab and Haryana generating NO_x transported south-eastward into the Agra airshed (c) acceleration of traffic and industrial activity and (d) commencement of domestic solid fuel heating. Mandal et al. [16] specifically recorded peak NO_2 column densities over the Upper IGP during post monsoon owing to crop residue burning, which can elevate regional NO_2 backgrounds by 30-50% over Agra during October.

Seasonal Variation: Winter Season

The winter season (December-February) is characterised by deep atmospheric stability persistent radiation fog, near calm winds and pronounced nocturnal surface inversions. Winter 2024-25 recorded seasonal means of 16.81, 18.92, 21.81 and $26.06 \mu\text{g}/\text{m}^3$ at Taj Mahal, Itmadud-Daulah,

Rambagh and Nunhai respectively. Winter 2025-26 values were 15.27, 26.15, 20.70 and $20.55 \mu\text{g}/\text{m}^3$ respectively.

A notable anomaly was observed at Itmad-ud-Daulah: its winter 2025-26 mean of $26.15 \mu\text{g}/\text{m}^3$ was dramatically higher than its winter 2024-25 mean of $18.92 \mu\text{g}/\text{m}^3$ an increase of 38.2%. December 2025 alone recorded $31.50 \mu\text{g}/\text{m}^3$ at this station the single highest monthly reading in the dataset. This anomalous spike may reflect intensified construction activity along the Yamuna Kinara Road adjacent to the monument increased boat yard and generator activity on the river ghats or localised traffic changes following the inauguration of Agra Metro Phase 1. Conversely Nunhai showed a significant winter improvement (26.06 to $20.55 \mu\text{g}/\text{m}^3$; -21.1%). These patterns align with findings by Srivastava et al. [25] who documented that winter brings the highest gaseous pollutant concentrations in Agra due to reduced rainfall, low wind speeds and clear sky radiative cooling.

Year-on-Year Comparison: 2024–25 versus 2025–26

A year on year decline in annual mean NO_2 was observed at three of the four stations. Taj Mahal recorded the sharpest relative improvement from 14.36 to $12.53 \mu\text{g}/\text{m}^3$ (-12.7%). Nunhai demonstrated the most substantial absolute improvement from 24.51 to $19.99 \mu\text{g}/\text{m}^3$ ($-4.52 \mu\text{g}/\text{m}^3$; -18.4%). Rambagh showed a decline from 17.95 to $16.81 \mu\text{g}/\text{m}^3$ (-6.3%). The only exception was Itmad-ud-Daulah, where the annual mean fell only marginally from 17.91 to $16.80 \mu\text{g}/\text{m}^3$ (-6.2%) offset by anomalously high winter 2025-26 values.

These modest but directionally consistent improvements occurring during a period of continued post-pandemic economic recovery and rising vehicle registrations suggest that the cumulative effect of BS-VI emission standards (rolled out nationally from April 2020) may be gradually producing measurable ambient air quality improvements. Mallik et al. [24] found a downward trend in NO_2 over the Upper IGP after 2012 attributable to progressive vehicle emission norms a pattern tentatively visible in the present dataset a decade later.

Sulphur Dioxide: Spatial and Seasonal Profile

Sulphur dioxide concentrations across all four Agra monitoring stations remained strikingly low throughout the 25-month observation window. An overwhelming proportion of station month records returned values at or below the CPCB instrument detection limit of $4 \mu\text{g}/\text{m}^3$. This pattern is consistent with the systematic improvement in fuel sulphur content documented nationally following the rollout

of BS-VI grade low sulphur fuel (10 ppm sulphur cap) and the continued geographic enforcement of the TTZ deindustrialisation order [4, 15].

Where detected above the $4 \mu\text{g}/\text{m}^3$ threshold SO_2 values were exceedingly modest, ranging from 3.88 to $5.67 \mu\text{g}/\text{m}^3$ across all stations and seasons. The maximum recorded value was $5.67 \mu\text{g}/\text{m}^3$ at Itmad-ud-Daulah in February 2026. All measured SO_2 concentrations are well within the NAAQS (2009) annual permissible limit of $50 \mu\text{g}/\text{m}^3$ and 24 hour standard of $80 \mu\text{g}/\text{m}^3$. A post monsoon 2025 uptick at Taj Mahal ($5.04 \mu\text{g}/\text{m}^3$) and Itmad-ud-Daulah ($5.13 \mu\text{g}/\text{m}^3$) in November 2025 may coincide with the post Diwali festive period during which widespread firework combustion introduces transient SO_2 elevations [16]. The broader trend of overwhelmingly BDL SO_2 at the Taj Mahal represents a significant improvement over historical records of 4 - $9 \mu\text{g}/\text{m}^3$ reported by Khare et al. [11] and Kumar and Shukla [12].

Health and Policy Implications

While all monitoring stations remain compliant with the NAAQS (2009) annual limit for NO_2 ($40 \mu\text{g}/\text{m}^3$) across the study period this compliance must be understood within the context of a deeply inadequate safety standard relative to contemporary health evidence. The WHO 2021 guidelines [28] set an annual mean NO_2 guideline of $10 \mu\text{g}/\text{m}^3$ revised downward from the earlier $40 \mu\text{g}/\text{m}^3$ threshold on the basis of comprehensive meta-analytical evidence linking NO_2 exposure even at low concentrations to increased all cause and respiratory mortality [10, 28]. No station in Agra achieved compliance with this WHO 2021 annual guideline during any full annual monitoring cycle the closest was the Taj Mahal's 2025-26 annual mean of $12.53 \mu\text{g}/\text{m}^3$ still 25% above the threshold.

For SO_2 the health picture is considerably more reassuring. The WHO (2021) 24 hour guideline for SO_2 is $40 \mu\text{g}/\text{m}^3$ a limit that was never approached during the entire study period. This near complete absence of ambient SO_2 is a positive indicator of the effectiveness of the TTZ deindustrialisation policy and progressive shift to low sulphur fuels an improvement trajectory also identified by Kuttippurath et al. [15] at the national scale.

The sustained exceedance of WHO 2021 guidelines for NO_2 at all Agra stations calls for a shift in the policy paradigm from monitoring NAAQS compliance to actively working toward WHO aligned targets. Although SO_2 the historical driver of acid deposition at the Taj Mahal is now well controlled, NO_2 derived nitric acid deposition remains

a chemically significant if unquantified risk to the monument's long term conservation.

CONCLUSIONS

This study has characterised twenty five months of continuous ambient NO_2 and SO_2 monitoring at four functionally distinct sites in Agra providing a comprehensive assessment of air quality across heritage, residential and industrial zones. The principal findings are as follows:

A consistent spatial hierarchy — Nunhai > Rambagh \approx Itmad-ud-Daulah > Taj Mahal reflects the progressive influence of industrial, traffic and TTZ regulatory factors across the urban landscape.

NO_2 concentrations display robust seasonal cycling, peaking in the post monsoon and winter seasons under stable atmospheric conditions and crop residue burning influence and reaching minima during the southwest monsoon under enhanced wet scavenging and convective mixing.

All four stations comply with NAAQS 2009 NO_2 limits ($40 \mu\text{g}/\text{m}^3$ annual mean) but persistently exceed the WHO 2021 annual guideline of $10 \mu\text{g}/\text{m}^3$, underscoring a significant public health protection gap.

SO_2 concentrations were overwhelmingly below the instrument detection limit ($< 4 \mu\text{g}/\text{m}^3$) throughout the study period attesting to the effectiveness of BS-VI fuel standards and TTZ deindustrialisation in eliminating sulphur based air quality risk.

A modest but directionally consistent year on year improvement in annual mean NO_2 at three of four stations between 2024-25 and 2025-26 tentatively reflects the cumulative impact of BS-VI vehicle emission norms, though anomalous localised spikes demonstrate the vulnerability of heritage zone air quality to episodic anthropogenic disturbances.

The findings call for a multi pronged policy response: alignment of NAAQS NO_2 standards with WHO 2021 evidence based guidelines sustained expansion of the BS-VI transition and EV adoption in Agra's transport sector targeted inter seasonal interventions to reduce post monsoon and winter peak concentrations and continued monitoring of SO_2 to detect any resurgence from localised sources. Given Agra's status as both a UNESCO heritage city and a rapidly urbanising Indian centre its air quality trajectory offers a

critical test case for whether regulatory compliance and heritage protection can be simultaneously advanced.

DECLARATIONS

Funding

The author declare that no funding was received for this study.

Conflicts of Interest

The author declare that they have no conflicts of interest.

Ethics Approval

Not applicable. This study uses publicly available secondary data from the CPCB NAMP and does not involve human subjects or animal experiments.

Data Availability

The air quality data used in this study are publicly available through the CPCB Continuous Ambient air Quality Monitoring System (CAAQMS)

Author Contributions

Author Nishant Jurel : Conceptualisation, data curation, formal analysis, writing original draft, writing- review and editing. (author read and approved the final manuscript.)

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