Long-Term Spatiotemporal Trends and Seasonal Dynamics of SO_2, NO_2, and CO Concentrations in Two Contrasting Urban-Industrial Districts of the Dhaka Metropolitan Area, Bangladesh: A 13-Year Continuous Monitoring Analysis (2012–2025)

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Abstract: - Station-level records of gaseous air pollutants remain scarce for Bangladesh. This study analyzes hourly SO_2, NO_2, and CO concentrations recorded from November 2012 to December 2025 at the Gazipur and Narayangonj Continuous Air Monitoring Stations (CAMS) of the Department of Environment (DoE) in the Dhaka Metropolitan Area (DMA). A documented quality-control (QC) procedure, validated against the original DoE archive for 2022–2024, showed that 50–70% of the hourly values in the compiled record were gap-filled, flat-lined, or otherwise invalid; data completeness after QC was 29.9–50.5% per series. Trends were tested on monthly means with the seasonal Kendall test, corrected for serial dependence (Hirsch–Slack) and multiple comparisons (Holm), with Sen's slope and the Pettitt change-point test. No series showed a significant monotonic trend after correction (all adjusted $p \geq 0.91$), whereas abrupt shifts occurred in four series, including a fall in Narayangonj NO_2 from 13.8 to 1.7 ppb after May 2019 that is more consistent with an instrumental discontinuity than with an emission change. Seasonal differences (Kruskal–Wallis tests on daily means with Dunn post-hoc tests and effect sizes) were large at Narayangonj ($\varepsilon^2 = 0.09$–0.37; winter/monsoon ratios 3.3–4.0) but small at Gazipur ($\varepsilon^2 = 0.04$–0.12). The strongest inter-pollutant association, SO_2–CO at Narayangonj (Spearman $\rho = 0.59$, 95% CI 0.44–0.70), weakened to 0.22 after removing the seasonal cycle. Daily means exceeded the WHO 24-h guideline levels on 10.0–34.5% of valid days. A matched-window comparison (26 March–30 May) was possible only for Narayangonj CO, which was 48.8% lower in 2020 than in 2019 (95% CI −72.3% to −36.1%). Trend and source claims for the DMA require rigorous screening of the monitoring record.

Key-Words: - air quality monitoring; data quality control; seasonal Kendall test; serial correlation; seasonal variation; WHO air quality guidelines; COVID-19 lockdown; Bangladesh.

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1 Introduction

Ambient air pollution is a leading environmental risk to health, with the heaviest burden in South and Southeast Asia [1], [2]. SO_2, NO_2, and CO are regulated nationally and internationally because of their direct health effects, their role as precursors of O_3 and sulfate particles, and their origin in fuel combustion by industry, vehicles, and energy production. The Dhaka Metropolitan Area (DMA) is affected by fast-growing industry in the satellite districts of Gazipur and Narayangonj, an ageing vehicle fleet, brick kilns, and a tropical monsoon climate [3], [4]. Gazipur, about 30 km north of Dhaka, hosts garment, dyeing, chemical, and logistics industries; Narayangonj, 16 km southeast on the Buriganga and Shitalakhya rivers, is known for textile dyeing and finishing factories whose boilers burn heavy fuel oil, natural gas, and coal.

Ground-based analyses of DoE records have focused mainly on central Dhaka: [3] described

spatial gradients and time trends, and [5] reported increasing CO, NO_2, and SO_2 over 2003–2019. Sentinel-5P analyses for Dhaka (2020–2024) found clear seasonal cycles but mostly non-significant trends [6]. In Indian megacities, ground networks show winter maxima, monsoon minima, and declining trends in most cities [7], while satellite records indicate rising NO_2 over Delhi and Kanpur [8]. Station-level analyses of the industrial districts around Dhaka remain few, and published analyses of DoE data seldom report how missing, imputed, or malfunction-affected data were handled, although gap-filled values can create apparent trends and contrasts. Members of the present team previously applied univariate time-series models to national maximum temperature [9] and CO_2 emissions [10]; those studies used different data, addressed forecasting rather than trend detection, and share no data, figures, or conclusions with this work. The station-level records analyzed here have not been published previously.

The Mann–Kendall (MK) test and Sen's slope are standard non-parametric tools for environmental trends [11], [12], [13]. Because the MK test assumes serial independence, seasonal and autocorrelated data require the seasonal Kendall (SK) test [14] with serial-dependence correction [15] or variance corrections [16], [17]. The objectives are to: (i) document a reproducible QC of the DoE hourly SO_2, NO_2, and CO records at Gazipur and Narayangonj; (ii) test for monotonic trends and abrupt shifts with dependence-corrected methods; (iii) quantify seasonal differences with effect sizes and confidence intervals (CI); (iv) estimate inter-pollutant correlations accounting for temporal dependence; (v) compare daily means with the WHO 24-h air quality guideline (AQG) levels; and (vi) assess the COVID-19 lockdown with matched calendar windows.

2 Study Area and Monitoring Infrastructure

The DMA (about 23.6°N–24.1°N, 90.2°E–90.6°E) has a tropical monsoon climate (Köppen Aw) with four seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–August), and post-monsoon (September–November); annual rainfall is 1,500–2,000 mm, mostly in the monsoon. The Gazipur CAMS (23.99°N, 90.41°E) is a mixed urban-industrial receptor near National Highway N2. The Narayangonj CAMS (23.62°N, 90.50°E) is an industrial-urban receptor in a river port dominated by textile dyeing, with boat and cargo-vessel traffic. Both stations belong to the DoE national network; SO_2, NO_2, and CO are measured with UV-fluorescence, chemiluminescence, and non-dispersive infrared analyzers and stored as hourly averages.

3 Data and Analytical Methods

3.1 Dataset Description and Quality Control

The compiled hourly record covers 1 November 2012 to 31 December 2025 (115,416 hours per station; SO_2 and NO_2 in ppb, CO in ppm). Gaps in this record had been filled before release, either with constants (e.g., 0.52 ppb for Gazipur SO_2 throughout 2020) or with recursive moving averages. For 2022–2024 the original DoE archive, in which missing hours are blank, was used directly. The following steps were applied in sequence to each pollutant–site series: (1) *Missing and gap-filled values*: archive-blank hours (2022–2024) and, in other years, values satisfying $|x_t - (1/k)\Sigma_{j=1}^{k} x_{t-j}| < 5\times10^{-4}$ for some $k \in \{2,\ldots,6, 8, 12, 24\}$ while $x_t \neq x_{t-1}$; the Gazipur SO_2 value 0.52 ppb (always archive-blank in 2022–2024) was treated as a fill code. Against the archive, this rule detected 99.0% of blank hours and flagged 7.0% of genuine non-flat hours. (2) *Flat-lines*: runs of ≥6 identical consecutive hours (stuck analyzer or constant fill). (3) *Negative values*. (4) *Malfunction months*: months with ≥80% of values below the lower detection limit (LDL: 0.4 ppb SO_2 and NO_2 ; 0.04 ppm CO). (5) *Outliers*: values above $T = P_{99} + 3s$, where P_{99} is the 99th percentile and s the standard deviation of the series, which removes isolated spikes but keeps pollution episodes. (6) Remaining values below the LDL were set to LDL/2 [13]. No gap-filling was applied. Table 1 (Appendix) gives the hours removed at each step.

3.2 Temporal Aggregation and Seasonality Classification

Daily means required ≥18 valid hours, monthly means ≥50% valid hours, and annual means ≥50% valid hours in the calendar year. The partial year 2012 (November–December) was excluded from annual and trend analyses, so the annual series covers 2013–2025 (at most 13 values; Table 3, Appendix). Seasons follow Section 2 [5].

3.3 Trend Detection

The primary test was the SK test on monthly means [14]. For calendar month g with values x_{ig} in years $i = 1,\ldots,n$,

$$S_g = \Sigma_{i<j}\, \mathrm{sgn}(x_{jg} - x_{ig}), \quad (1)$$

where sgn(θ) = +1, 0, −1 for θ > 0, = 0, < 0 and missing pairs contribute zero; $S = \Sigma_g S_g$. The tie-corrected variance is:

$$\mathrm{Var}(S_g) = [n_g(n_g-1)(2n_g+5) - T_g]/18, \quad (2)$$

with n_g valid values, $T_g = \Sigma_p\, t_p(t_p-1)(2t_p+5)$, and t_p the size of the p-th tie group. Serial dependence between months was handled with the Hirsch–Slack variance, $\mathrm{Var}(S) = \Sigma_g \mathrm{Var}(S_g) + \Sigma_{g\neq h}\mathrm{Cov}(S_g,S_h)$, with covariances estimated from within-month ranks [15]; the test statistic is:

$$Z = (S - \mathrm{sgn}(S))/\sqrt{\mathrm{Var}(S)}, \quad (3)$$

referred to the standard normal distribution; Kendall's $\tau = S/D$, with D the number of non-missing pairs. The seasonal Sen slope [12], [14] is:

$$\beta = \mathrm{median}[(x_{jg} - x_{ig})/(j - i)], \quad (4)$$

over all months g and pairs $i < j$ (units yr^{-1}). As secondary analyses, the MK test was applied to valid annual means when ≥6 valid years existed, with the Hamed–Rao correction [16] and trend-free pre-whitening [17] when ≥8 existed, and abrupt shifts in deseasonalized monthly means were tested with the Pettitt test [18]. P-values for the six series were Holm-adjusted [19] (α = 0.05).

3.4 Seasonal Differences

For each series, seasons were compared with the Kruskal–Wallis test [20] on daily means:

$$H = [12/(N(N+1))]\, \Sigma_{i=1}^{k} R_i^2/n_i - 3(N+1), \quad (5)$$

where $k = 4$ seasons, n_i valid days in season i, $N = \Sigma n_i$, and R_i the rank sum of season i; H was tie-corrected and referred to χ^2 with 3 degrees of freedom. The effect size $\varepsilon^2 = (H - k + 1)/(N - k)$ [21] and Holm-adjusted Dunn tests [22] are reported. Because daily means are autocorrelated, the test was repeated on monthly means, and the winter–monsoon contrast was tested with Welch's t-test [23] on monthly means,

$$t = (\bar{x}_W - \bar{x}_M)/\sqrt{(s_W^2/n_W + s_M^2/n_M)}, \quad (6)$$

with Welch–Satterthwaite degrees of freedom, 95% CI, and Hedges' g.

3.5 Spearman Rank Correlation

Spearman's ρ was computed from daily means, with effective sample size $n_{eff} = n(1 - r_x r_y)/(1 + r_x r_y)$, where r_x, r_y are lag-1 autocorrelations [24]; the 95% CI is $\tanh[\mathrm{arctanh}(\rho) \pm 1.96\times1.03/\sqrt{(n_{eff} - 3)}]$. The analysis was repeated on deseasonalized daily anomalies (daily mean minus the calendar-month mean) to separate shared seasonality from day-to-day co-variation.

3.6 Comparison with WHO Air Quality Guideline Levels

Daily means were compared with the WHO AQG 2021 24-h levels [1] (SO_2 40 μg m^{-3} = 15.3 ppb; NO_2 25 μg m^{-3} = 13.3 ppb; CO 4 mg m^{-3} = 3.5 ppm; 25 °C, 1 atm), and valid annual means with the annual NO_2 level (10 μg m^{-3} = 5.3 ppb). Hourly values were not compared with any guideline. The exceedance frequency is the percentage of valid days above the level; the comparison is exploratory, and the WHO short-term SO_2 and CO levels were not assessed.

3.7 COVID-19 Lockdown Analysis

Daily means in the lockdown window (26 March–30 May 2020, 66 days) were compared with the same window in 2019 when both windows had ≥33 valid days, using the Mann–Whitney U test [25], Welch's t-test on log daily means with n_{eff}, a moving-block bootstrap CI for the percentage change (7-day blocks, 5,000 resamples) [26], and Cliff's δ [27]. Meteorological data for 2019–2020 were unavailable, so no meteorological adjustment was possible. Analyses used Python 3.13 (NumPy, pandas, SciPy, pymannkendall, scikit-posthocs, Matplotlib); scripts and QC'd data are available from the corresponding author.

4 Results

4.1 Data Completeness and Descriptive Statistics

QC removed 49.5–70.1% of hourly values (Table 1, Appendix), mostly gap-filled values and flat-line runs (>95% of removals). No valid Gazipur data exist for the 2020 lockdown period (the 2020 SO_2 record consists entirely of the fill value 0.52 ppb), Narayangonj SO_2 is essentially absent after 2019 (≤5.6% completeness), and Gazipur NO_2 after 2021 consists mostly of sub-LDL values. All series are right-skewed (Table 2, Appendix). On days when both sites were valid, NO_2 was higher at Narayangonj by 3.66 ppb (95% CI 1.14–6.19; 936 days) and CO lower by 1.47 ppm (0.32–2.62; 1143 days); the SO_2 difference (3.11 ppb, CI -1.96 to 8.18) was not significant. The threefold SO_2 contrast in the earlier version was an artifact of the 0.52 ppb fill value.

4.2 Long-Term Trends and Abrupt Shifts

Under the independence assumption, the SK test indicated trends in Gazipur CO (p = 0.016), Narayangonj NO_2 (p = 0.003), and Narayangonj CO (p = 0.002), but none remained significant after the Hirsch–Slack correction (p = 0.24, 0.16, 0.15); all Holm-adjusted $p \geq 0.91$ (Table 4, Figure 1 in Appendix). The annual MK test was possible for three series and was significant only for Narayangonj CO (τ = 1.00, 7 years, Holm-adjusted p = 0.008); since these years end in 2021, before the low (incomplete) 2023–2025 values, this indicates a 2015–2021 rise rather than a sustained trend. The Pettitt test found four shifts. Narayangonj NO_2 fell from 13.8 to 1.7 ppb after May 2019 ($p < 0.001$); a persistent 88% drop at an industrial port, not seen at Gazipur, more plausibly reflects an analyzer or calibration change than an emission change. Gazipur CO rose after August 2020, driven by a suspect 2021 mean of 10.2 ppm (6–8 times the 2013–2016 level). The Gazipur NO_2 decline and CO increase of the earlier version are therefore not supported: the former was produced by flat-lined ≈0.2 ppb values in 2022–2025.

4.3 Seasonal Variation

All Kruskal–Wallis tests on daily means were significant (Table 5, Appendix), but effect sizes differed. At Narayangonj, effects were large for SO_2 (ε^2 = 0.32) and CO (0.37) and moderate for NO_2 (0.09); all pairwise comparisons and the monthly-mean tests were significant ($p \leq 0.008$). Winter exceeded monsoon monthly means by 12.1 ppb SO_2 (95% CI 7.2–17.0; g = 1.80), 10.7 ppb NO_2 (6.0–15.4; g = 1.16), and 1.92 ppm CO (1.14–2.70; g = 1.33), i.e., ratios of 3.3–4.0. At Gazipur, effects were small (ε^2 = 0.04–0.12); on monthly means only NO_2 differed (H = 7.92, p = 0.048; winter–monsoon 6.6 ppb, CI 1.8–11.4). Figure 2 (Appendix) shows little overlap of seasonal interquartile ranges at Narayangonj but strong overlap at Gazipur; Figure 3 (Appendix) shows a U-shaped cycle (minima June–August, maxima December–February) at Narayangonj with narrow dry-season CIs, and flatter, uncertain cycles at Gazipur, where 1–10 years contribute per month. The pattern is consistent across sites only for NO_2.

4.4 Inter-Pollutant Spearman Correlations

At Narayangonj, SO_2 correlated with CO (ρ = 0.59, 95% CI 0.44–0.70) and NO_2 (ρ = 0.43); NO_2–CO was not correlated. At Gazipur, NO_2–CO was moderate (ρ = 0.43, CI 0.22–0.60), while CIs of both SO_2 pairs included zero (Table 6, Figure 4 in Appendix). Deseasonalization weakened most correlations (Narayangonj SO_2–CO to 0.22; Gazipur SO_2–NO_2 became weakly negative, -0.26), so much of the daily correlation reflects shared seasonal meteorology. Correlation does not establish a common or an independent source: shared meteorology can correlate unrelated sources, and different emission timing and NO_2 photochemistry can decouple co-emitted gases. The residual SO_2 – CO association at Narayangonj is consistent with, but does not demonstrate, common combustion sources such as boilers.

4.5 Comparison with WHO 24-h Guideline Levels

Daily means exceeded the 24-h levels on 26.9% (SO_2), 34.5% (NO_2), and 10.0% (CO) of valid days at Narayangonj and 15.6%, 33.2%, and 19.8% at Gazipur (Table 7, Appendix). The annual NO_2 level was exceeded in 6 of 7 valid years at Narayangonj and 3 of 4 at Gazipur. In Figure 5 (Appendix), Narayangonj NO_2 exceedances were 30–67% of valid days in 2013–2019; Gazipur CO reached 67–97% in 2020–2021, reflecting the suspect CO levels, and the 100% SO_2 value for Gazipur in 2017 rests on 37% completeness.

4.6 COVID-19 Lockdown: Matched-Window Comparison

Only Narayangonj CO had sufficient data in both windows (Table 8, Appendix): it was 48.8% lower in 2020 (0.38 ppm, 39 days) than in 2019 (0.75 ppm, 37 days; bootstrap 95% CI -72.3% to -36.1%; Mann–Whitney $p < 0.001$; dependence-adjusted Welch p = 0.003; Cliff's δ = -0.80), consistent with reduced combustion during lockdowns elsewhere [28], [29], although weather effects cannot be excluded. The other five series had no valid days in the 2020 window; the earlier whole-year changes (−73.1% Gazipur SO_2 , −61.3% Narayangonj NO_2) arose from the fill value and the 2019 NO_2 shift and are withdrawn.

5 Discussion

The main finding concerns the data: after removing gap-filled, flat-lined, and malfunction-affected values, half or more of each series was lost, and the site contrast in SO_2, the Gazipur NO_2 decline and CO increase, and the large lockdown changes disappeared. Analyses of DoE records, including published trends [3], [5], therefore depend strongly on the handling of missing data and instrument changes, which should be reported explicitly. After QC and corrections for dependence and multiple

testing, no series shows a significant monotonic trend over 2013–2025. This is not evidence of stability: long gaps reduce power, and step changes violate the monotonic-trend assumption. The result agrees with mostly non-significant satellite-based trends for Dhaka [6] and contrasts with increases reported for central Dhaka over 2003–2019 [5]. Explanations such as CNG adoption or brick-kiln expansion remain hypotheses that these data cannot test.

The most robust signal is the seasonal cycle at Narayangonj (winter 3.3–4.0 times monsoon), typical of Dhaka and the Indo-Gangetic region [5], [7] and usually explained by shallow winter mixing, dry-season kiln operation, and monsoon wet scavenging; as meteorology was not analyzed here, this remains an interpretation. NO_2 exceeded the WHO 24-h level on about one-third of valid days at both sites, so NO_2 exposure is likely frequent, although uneven coverage makes these frequencies indicative only. Limitations: completeness of 30–51%; an imperfect (though validated) gap-fill detector for years without the archive; unverified instrument changes (Narayangonj NO_2 2019, Gazipur CO 2020–2021) that should be checked against DoE logs; no meteorological normalization; and two stations only. Future work should use the full DoE archive with instrument logs and co-located meteorology, and the DoE should release data with validity flags rather than gap-filled values.

6 Conclusion

- 49.5–70.1% of hourly values were gap-filled, flat-lined, or invalid; completeness after QC was 29.9–50.5%. Gap-filled DoE records can produce artificial trends, contrasts, and lockdown effects.
- No series showed a significant monotonic trend after dependence and multiple-testing corrections (adjusted $p \geq 0.91$); four abrupt shifts were found, the Narayangonj NO_2 fall in 2019 most likely being instrumental.
- Seasonality was strong at Narayangonj (ε^2 = 0.09–0.37; winter/monsoon 3.3–4.0) and weak at Gazipur (ε^2 = 0.04–0.12).
- Correlations were at most moderate (SO_2–CO at Narayangonj, $\rho = 0.59$) and weakened after deseasonalization; they do not identify sources.
- Daily means exceeded WHO 24-h levels on 10.0–34.5% of valid days, most often for NO_2; annual NO_2 exceeded its level in 9 of 11 valid site-years.
- Narayangonj CO was 48.8% lower (95% CI −72.3% to −36.1%) during the 2020 lockdown window than in 2019; other series could not be assessed.
- Priorities: quality-flagged DoE data with instrument metadata, co-located meteorology for deweathered trends, and continued control of combustion sources given frequent NO_2 exceedances.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the revision, the authors used an AI assistant (Claude, Anthropic) for statistical code and language editing. The authors reviewed and edited all code, results, and text and take full responsibility for the content.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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APPENDIX

Table 1. Quality-control (QC) results per pollutant–site series (hourly values affected at each step, applied in sequence)

Quantity (hours)	Gazi. SO_2	Gazi. NO_2	Gazi. CO	Nara. SO_2	Nara. NO_2	Nara. CO
Total hourly time stamps	115,416	115,416	115,416	115,416	115,416	115,416
(1) Missing or gap-filled	62,350	34,054	29,900	32,348	29,122	18,724
(2) Flat-line runs ≥ 6 h	0	39,884	38,502	48,458	26,436	40,168
(3) Negative values	0	5	85	0	0	0
(4) Malfunction months (≥80% < LDL)	0	2,734	0	5	1,581	0
(5) Outlier threshold T (ppb/ppm)	102.63	79.50	25.40	109.55	84.31	12.64
(5) Outliers removed (> T)	136	12	191	79	43	44
(6) Values < LDL set to LDL/2	3,064	5,563	312	1,711	2,861	117
Valid hours after QC	52,930	38,727	46,738	34,526	58,234	56,480
Completeness after QC (%)	45.9	33.6	40.5	29.9	50.5	48.9

Note: Gaz. = Gazipur; Nara. = Narayangonj; LDL = lower detection limit. Step (1) uses the DoE archive for 2022–2024 and the gap-fill rule of Section 3.1 otherwise. Values set to LDL/2 remain valid.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 2. Descriptive statistics of quality-controlled hourly concentrations, November 2012–December 2025

Statistic	Gazi. SO_2 (ppb)	Gazi. NO_2 (ppb)	Gazi. CO (ppm)	Nara. SO_2 (ppb)	Nara. NO_2 (ppb)	Nara. CO (ppm)
Valid hours (n)	52,930	38,727	46,738	34,526	58,234	56,480
Completeness (%)	45.9	33.6	40.5	29.9	50.5	48.9
Valid days	2,061	1,243	1,910	1,292	2,216	2,146
Mean	9.62	9.23	2.81	10.59	10.78	1.53
Median	6.66	5.60	1.60	6.55	6.83	0.94
Std. dev.	11.19	10.54	3.28	12.52	11.60	1.59
95th percentile	34.48	30.90	11.75	33.73	34.72	5.10
Maximum	102.62	78.60	25.25	108.53	83.27	12.40

Note: The sites cover different valid periods; site differences are assessed on matched days (Section 4.2). Valid days: ≥18 valid hours.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 3. Annual mean concentrations (SO_2, NO_2 in ppb; CO in ppm) with hourly completeness (%) in curly braces { }

Year	Gazi. SO_2	Gazi. NO_2	Gazi. CO	Nara. SO_2	Nara. NO_2	Nara. CO
2012	(1.21) {23}	(7.69) {94}	(1.16) {92}	(6.32) {81}	(1.69) {32}	(1.20) {80}
2013	**8.26 ± 3.10** {95}	**10.35 ± 1.67** {82}	**1.49 ± 0.23** {71}	**9.71 ± 4.70** {89}	**10.29 ± 4.22** {78}	**0.80 ± 0.28** {81}
2014	**4.89 ± 1.58** {57}	(9.20) {50}	**1.62 ± 0.63** {92}	**9.75 ± 5.16** {67}	**15.52 ± 5.37** {54}	**0.94 ± 0.42** {74}
2015	**10.50 ± 2.93** {71}	**4.82 ± 1.58** {57}	**1.59 ± 0.37** {88}	(9.49) {34}	**11.21 ± 4.51** {88}	**1.04 ± 0.22** {80}
2016	**8.64 ± 3.72** {55}	**8.17 ± 3.26** {52}	**1.31 ± 0.27** {64}	(5.67) {36}	**11.59 ± 4.35** {90}	– {0}
2017	(36.46) {37}	(3.56) {26}	(2.69) {20}	(11.05) {33}	**20.75 ± 7.14** {58}	(0.57) {13}
2018	(4.70) {47}	**12.25 ± 6.75** {63}	(1.20) {15}	**13.01 ± 4.49** {54}	**15.39 ± 5.49** {90}	**1.19 ± 0.74** {53}
2019	(5.59) {28}	(12.92) {30}	(2.03) {46}	**14.24 ± 5.78** {54}	(14.45) {41}	**2.05 ± 1.14** {85}
2020	– {0}	(14.23) {21}	(4.12) {26}	(15.82) {4}	(6.30) {9}	**2.44 ± 1.97** {60}
2021	(3.66) {18}	(11.31) {34}	**10.20 ± 2.34** {66}	(27.15) {3}	**1.15 ± 0.70** {72}	**3.30 ± 1.57** {62}
2022	(6.05) {15}	(0.35) {9}	– {0}	– {0}	(0.69) {18}	(4.10) {14}
2023	(10.77) {47}	(0.69) {1}	(6.45) {1}	(9.80) {6}	(1.24) {19}	(0.91) {29}
2024	**11.05 ± 1.63** {58}	– {0}	(1.60) {30}	– {0}	(3.05) {36}	(0.81) {49}
2025	**6.70 ± 0.43** {72}	– {0}	– {0}	(4.63) {0}	(1.70) {6}	(0.99) {32}

Note: Bold: years with ≥50% valid hours (2013–2025), used in the annual MK test; shown as mean ± 95% CI half-width (from daily means, autocorrelation-corrected effective sample size). Parentheses: years with <50% valid hours, not tested. 2012 covers November–December only; – = no valid data. Numbers in curly braces { } are hourly completeness percentages, not references.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 4. Seasonal Kendall tests on monthly means (2013–2025), annual MK tests, and Pettitt change-point tests

Site – pollutant	n months	S	Z (indep.)	τ	Seasonal Sen slope (yr^{-1})	p (indep.)	p (H–S)	p (H–S, Holm)	Annual MK: n, τ, p	Pettitt: date, p (mean before → after)
Gazipur – SO_2	77	+25	+1.02	+0.105	+0.161 ppb	0.31	0.54	1.00	6, 0.20, 0.71	2015-02, 0.23 (6.89 → 10.72)
Gazipur – NO_2	57	+17	+0.96	+0.124	+0.545 ppb	0.34	0.57	1.00	4 yrs; not tested	2018-01, 0.007 (7.54 → 13.39)
Gazipur – CO	68	+44	+2.41	+0.265	+0.178 ppm	0.02	0.24	0.97	5 yrs; not tested	2020-08, 0.001 (1.66 → 6.77)
Narayangonj – SO_2	45	+8	+0.64	+0.108	+0.202 ppb	0.53	0.54	1.00	4 yrs; not tested	2017-12, 0.06 (9.77 → 13.78)
Narayangonj – NO_2	83	-71	-2.93	-0.276	-0.681 ppb	0.003	0.16	0.91	7, 0.05, 1.00	2019-05, <0.001 (13.79 → 1.66)
Narayangonj – CO	84	+78	+3.12	+0.291	+0.038 ppm	0.002	0.15	0.91	7, 1.00, 0.003	2018-06, 0.002 (0.90 → 1.92)

Note: "p (indep.)" assumes independence between months; "p (H–S)" uses the Hirsch–Slack correction; "Holm" adjusts for six series. Annual MK uses years with ≥50% completeness when ≥6 exist (Holm-adjusted p for Narayangonj CO = 0.008). Pettitt: first month after the change; monthly means before → after.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 5. Kruskal–Wallis tests of seasonal differences (one test per series), effect sizes, post-hoc tests, and winter–monsoon contrasts

Site – pollutant	N days	Median W / Pre / M / Post	H (df = 3)	p	ε²	Dunn pairs not significant	H, p (monthly means)	Winter − monsoon, Welch (95% CI)	Hedges g
Gazipur – SO_2	2061	8.26 / 7.65 / 5.98 / 6.80	77.8	<0.001	0.036	W–Pre, M–Post	4.10, 0.25	+2.20 (-4.52, +8.92), p = 0.51	0.21
Gazipur – NO_2	1243	11.94 / 6.65 / 5.61 / 10.32	147.1	<0.001	0.116	none	7.92, 0.05	+6.60 (+1.78, +11.43), p = 0.01	0.96
Gazipur – CO	1910	2.02 / 1.52 / 1.25 / 1.65	94.3	<0.001	0.048	Pre–M	5.74, 0.12	-0.45 (-2.64, +1.74), p = 0.67	-0.14
Narayangonj – SO_2	1292	15.17 / 7.45 / 2.53 / 5.16	415.1	<0.001	0.320	none	20.09, <0.001	+12.09 (+7.20, +16.97), p = <0.001	1.80
Narayangonj – NO_2	2216	14.56 / 8.00 / 4.48 / 9.23	204.7	<0.001	0.091	none	11.89, 0.008	+10.66 (+5.95, +15.38), p = <0.001	1.16
Narayangonj – CO	2146	1.85 / 0.81 / 0.50 / 1.05	798.8	<0.001	0.372	none	35.64, <0.001	+1.92 (+1.14, +2.70), p = <0.001	1.33

Note: H on daily means; medians in ppb (SO_2, NO_2) or ppm (CO). ε² benchmarks: 0.01 small, 0.08 moderate, 0.26 large. Dunn tests Holm-adjusted. Monthly-mean test and Welch contrast use monthly means (≥50% valid hours). W/Pre/M/Post = winter/pre-monsoon/monsoon/post-monsoon.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 6. Spearman correlations of daily means and deseasonalized anomalies, with dependence-adjusted CIs.

Site	Pair	n days	n_{eff}	ρ (daily means) [95% CI]	p (n_{eff})	ρ (deseasonalized) [95% CI]	p (n_{eff})
Gazipur	SO_2–NO_2	791	104	-0.08 [-0.28, +0.12]	0.40	-0.26 [-0.41, -0.08]	0.003
Gazipur	SO_2–CO	982	51	+0.08 [-0.21, +0.36]	0.58	-0.07 [-0.33, +0.19]	0.58
Gazipur	NO_2–CO	803	79	+0.43 [+0.22, +0.60]	<0.001	+0.33 [+0.14, +0.50]	<0.001
Narayangonj	SO_2–NO_2	960	126	+0.43 [+0.27, +0.57]	<0.001	+0.15 [+0.01, +0.28]	0.03
Narayangonj	SO_2–CO	964	108	+0.59 [+0.44, +0.70]	<0.001	+0.22 [+0.08, +0.36]	0.002
Narayangonj	NO_2–CO	1347	77	+0.04 [-0.19, +0.27]	0.70	-0.10 [-0.29, +0.10]	0.31

Note: neff = n(1 − rxry)/(1 + rxry) from lag-1 autocorrelations; CIs via Fisher transformation. Correlation does not establish a common or independent source.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

Table 7. Comparison of daily and annual means with WHO AQG 2021 levels.

Pollutant	WHO AQG 2021 level (averaging time)	Gazipur: % valid days above (valid days)	Narayangonj: % valid days above (valid days)
SO_2	40 μg m^{-3} (15.3 ppb) (24 h)	15.6 (2,061)	26.9 (1,292)
NO_2	25 μg m^{-3} (13.3 ppb) (24 h)	33.2 (1,243)	34.5 (2,216)
CO	4 mg m^{-3} (3.5 ppm) (24 h)	19.8 (1,910)	10.0 (2,146)
NO_2	10 μg m^{-3} (5.3 ppb) (annual)	3 of 4 valid years (2013, 2016, 2018)	6 of 7 valid years (2013–2018)

Note: Denominator = valid days (≥18 valid hours); valid years have ≥50% completeness. Conversion at 25 °C, 1 atm (SO_2 2.62, NO_2 1.88 μg m^{-3} per ppb; CO 1.145 mg m^{-3} per ppm). Exploratory comparison with non-binding guideline levels.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh and WHO AQG 2021 levels [1]

Table 8. COVID-19 lockdown: daily means, 26 March–30 May 2020 versus the same window in 2019.

Site – pollutant	Valid days 2019	Valid days 2020	Mean 2019	Mean 2020	Change (%) [95% CI]	Mann–Whitney p	Welch p (n_{eff})	Cliff's δ
Gazipur – SO_2	11	0	–	–	not assessable	–	–	–
Gazipur – NO_2	29	0	–	–	not assessable	–	–	–
Gazipur – CO	8	0	–	–	not assessable	–	–	–
Narayangonj – SO_2	32	0	–	–	not assessable	–	–	–
Narayangonj – NO_2	34	0	–	–	not assessable	–	–	–
Narayangonj – CO	37	39	0.746	0.382	-48.8 [-72.3, -36.1]	<0.001	0.003	-0.80

Note: 66-day windows; ≥33 valid days required in both years. Welch test on log daily means with neff = 10.3 and 8.5 days; CI from moving-block bootstrap. No meteorological adjustment.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

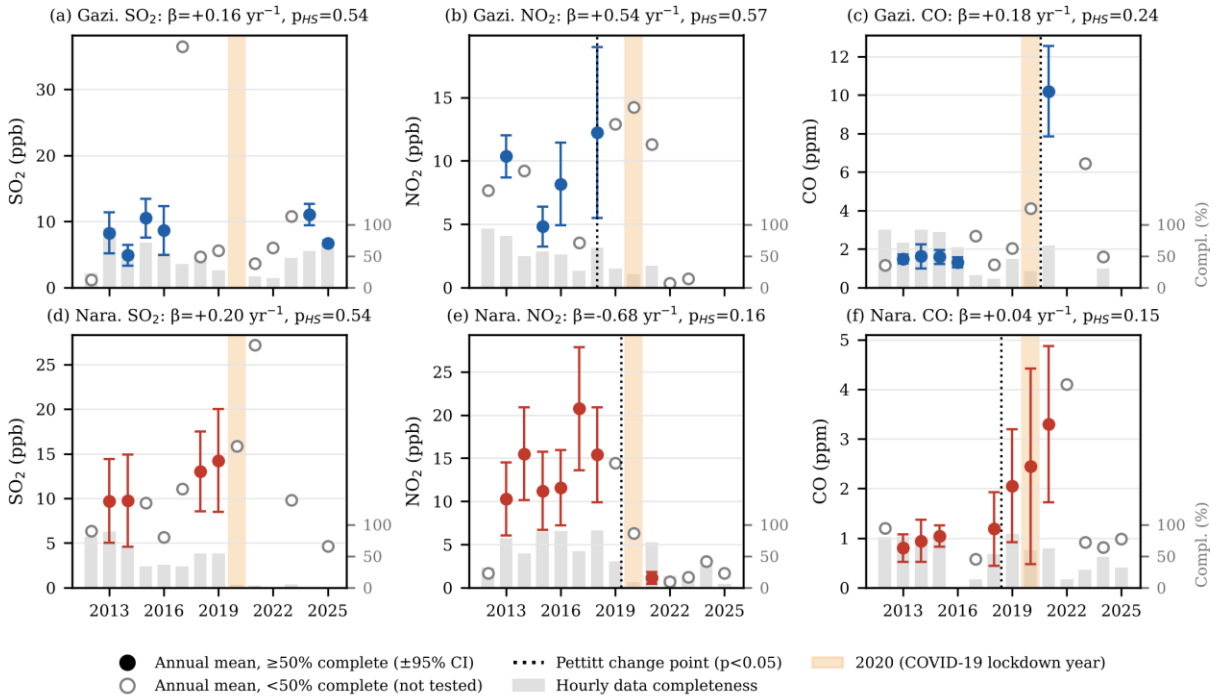

Fig. 1: Annual means at Gazipur (a–c) and Narayangonj (d–f). Filled circles: years with ≥50% valid hours, with 95% CI (from daily means, autocorrelation-corrected); hollow: <50% valid (not tested). Grey bars (right axis): hourly completeness (%). Dotted line: Pettitt change point ($p < 0.05$). Orange: 2020. Titles: seasonal Sen slope β and Hirsch–Slack p-value (p_{HS}).

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

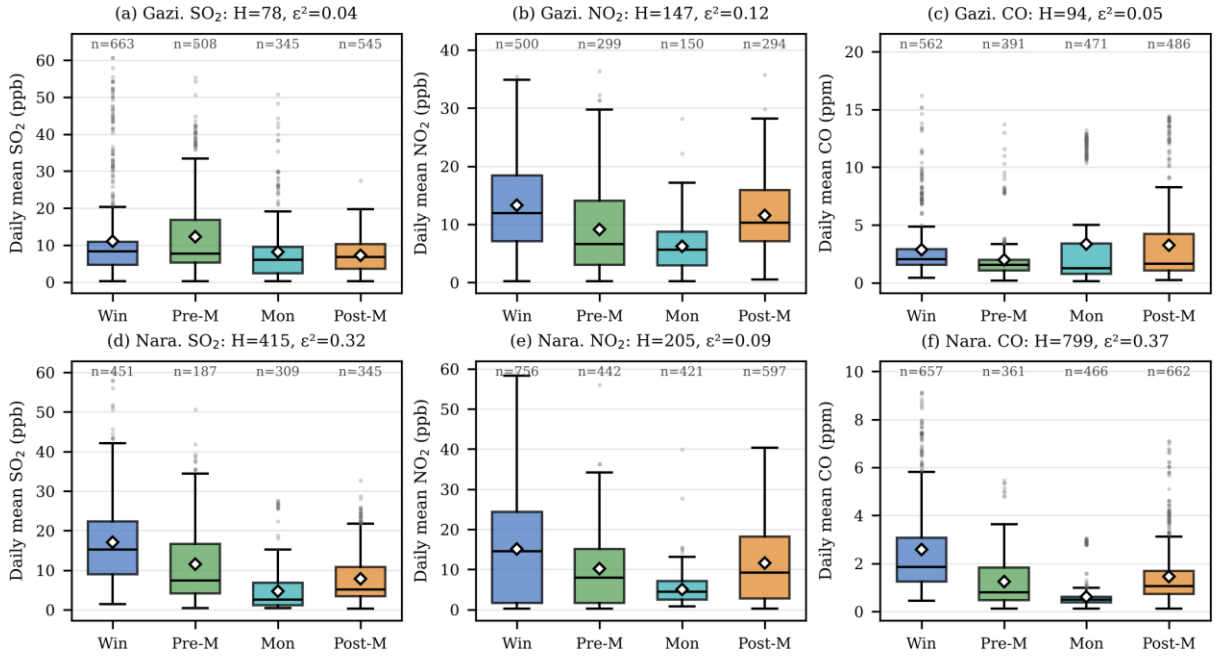

Fig. 2: Daily means by season at Gazipur (a–c) and Narayangonj (d–f). Boxes: interquartile range; line: median; diamond: mean; whiskers: 1.5×IQR; dots: days beyond whiskers; n: valid days. Titles: Kruskal–Wallis H (df = 3, all $p < 0.001$) and ε^2. Win = Dec–Feb; Pre-M = Mar–May; Mon = Jun–Aug; Post-M = Sep–Nov.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

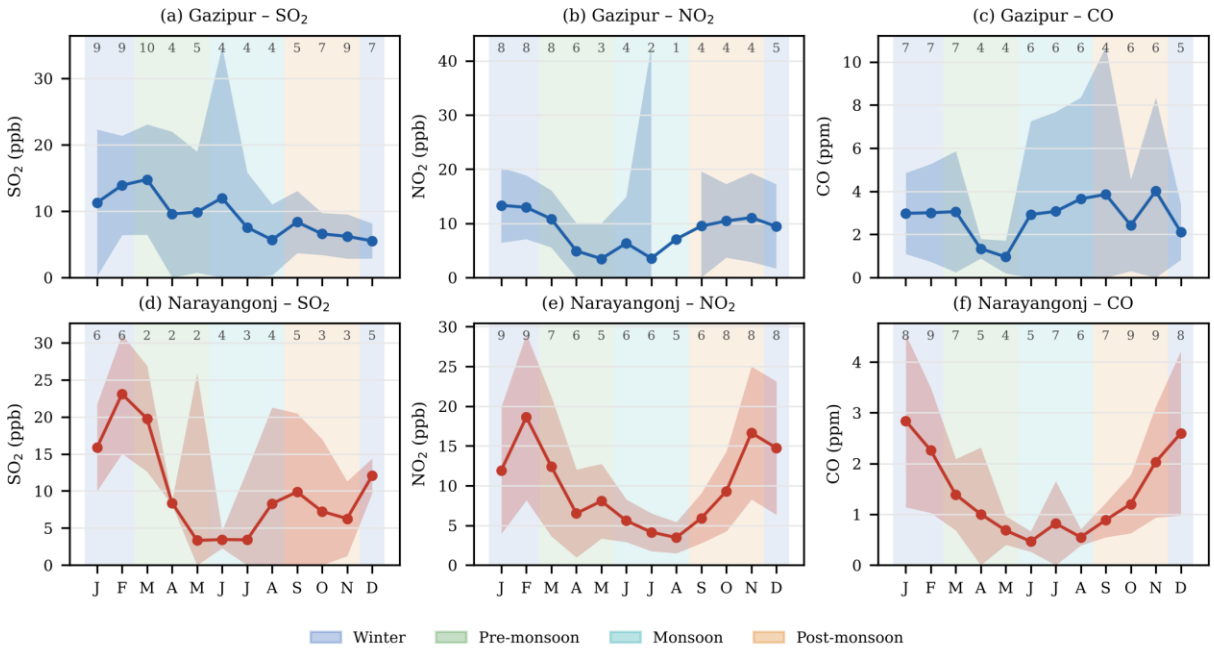

Fig. 3: Monthly climatology at Gazipur (a–c) and Narayangonj (d–f): mean of valid monthly means of each calendar month pooled across 2013–2025; band: 95% CI across years (t-distribution); top numbers: years contributing; background: seasons.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

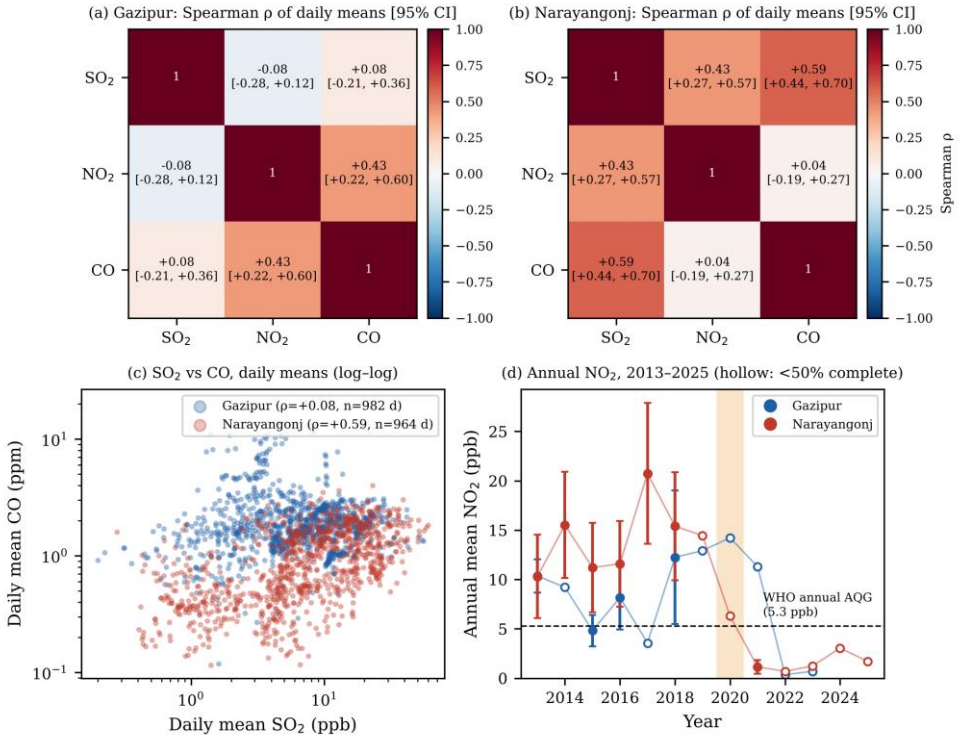

Fig. 4: (a, b) Spearman ρ [95% CI] of daily means (color: −1 blue to +1 red). (c) Daily SO_2 versus CO (log axes). (d) Annual NO_2, 2013–2025 (2012 omitted as only Nov–Dec); filled: ≥50% complete with 95% CI; hollow: incomplete; dashed: WHO annual level (5.3 ppb).

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh

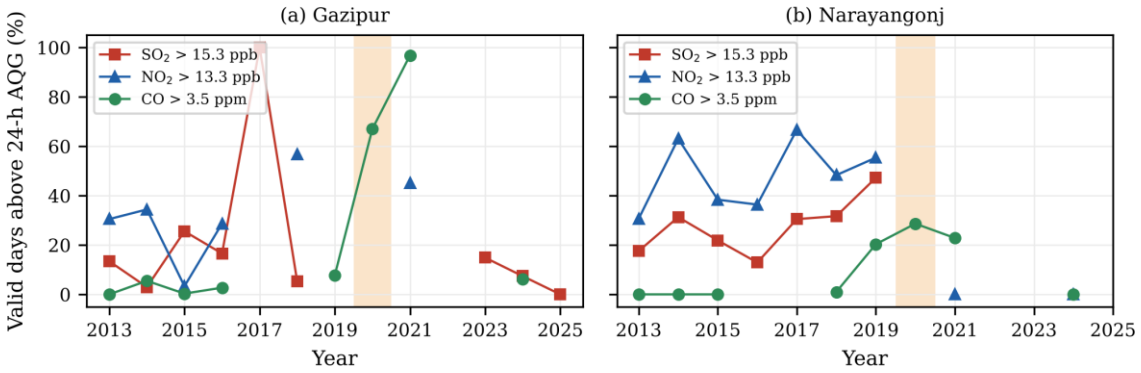

Fig. 5: Annual percentage of valid days with daily means above the WHO 24-h levels (SO_2 15.3 ppb, NO_2 13.3 ppb, CO 3.5 ppm). Denominator: valid days per year; only years with ≥90 valid days are plotted; lines break across excluded years. Orange: 2020.

Source: created by the authors using data from the Department of Environment (DoE), Government of the People's Republic of Bangladesh and WHO AQG 2021 levels [1]