This is a non-peer-reviewed preprint submitted to EarthArXiv.

Title

Structural Shifts in Urban Air Pollution Patterns in Trinidad After COVID-19: Evidence from Diurnal and Weekday/Weekend PM Profiles, 2022–2024

Authors (affiliations and email addresses)

Treina Dinoo Ramlochan — Environmental Management Authority (EMA), Port of Spain, Trinidad and Tobago. Email: tdinoo@ema.co.tt

Koffka Khan — Department of Computing and Information Technology, Faculty of Science and Technology, The University of the West Indies (UWI), St. Augustine Campus, Trinidad and Tobago. Email: koffka.khan@uwi.edu

Wayne Rajkumar — Environmental Management Authority (EMA), Port of Spain, Trinidad and Tobago. Email: wrajkumar@ema.co.tt

Shanta Ramnath — Environmental Management Authority (EMA), Port of Spain, Trinidad and Tobago. Email: sramnath@ema.co.tt

Steven Rampersad — Environmental Management Authority

(EMA), Port of Spain, Trinidad and Tobago. Email:
srampersad@ema.co.tt
Winston Elibox — Department of Life Sciences, Faculty of
Science and Technology, The University of the West Indies (UWI),
St. Augustine Campus, Trinidad and Tobago. Email:
winston.elibox@uwi.edu

Corresponding author
Koffka Khan (Koffka.Khan@uwi.edu)

Structural Shifts in Urban Air Pollution Patterns in Trinidad After COVID-19: Evidence from Diurnal and Weekday/Weekend PM Profiles, 2022-2024

Treina Dinoo Ramlochan[a], Koffka Khan[b], Wayne Rajkumar[a], Shanta Ramnath[a], Steven Rampersad[a], Winston Elibox[c]

Treina Dinoo Ramlochan, Air Unit, Environmental Management Authority, 8 Elizabeth Street, St. Clair, Port of Spain, Trinidad and Tobago, email: tdinoo@ema.co.tt

Koffka Khan, Department of Computing and Information Technology, Faculty of Science and Technology, The University of the West Indies, College Road, St. Augustine Campus, Trinidad and Tobago, email: koffka.khan@uwi.edu

Wayne Rajkumar, Department of Environmental Analysis and Coordination, Environmental Management Authority, 8 Elizabeth Street, St. Clair, Port of Spain, Trinidad and Tobago, email: wrajkumar@ema.co.tt

Shanta Ramnath, Department of Permit Monitoring and Complaints, Environmental Management Authority, 8 Elizabeth Street, St. Clair, Port of Spain, Trinidad and Tobago, email: sramnath@ema.co.tt

Steven Rampersad, Strategy and Research Unit, Environmental Management Authority, 8 Elizabeth Street, St. Clair, Port of Spain, Trinidad and Tobago, email: srampersad@ema.co.tt

Winston Elibox, Department of Life Sciences, Faculty of Science and Technology, The University of the West Indies, College Road, St. Augustine Campus, Trinidad and Tobago, email: winston.elibox@uwi.edu

Corresponding author- Winston Elibox: winston.elibox@uwi.edu

Statement of Declarations

Funding

Competing Interests

Author Contributions: CRediT authorship contribution statement

Data Availability

The study's dataset, containing sensor measurements from the Environmental Management Authority (EMA) of Trinidad and Tobago, was used under a formal data-sharing agreement. These data include site-level air quality and meteorological variables that may contain sensitive infrastructure information; therefore, the raw EMA data cannot be publicly released. A de-identified and temporally aggregated version suitable for reproducible analysis will be made available upon reasonable request to the corresponding author, subject to EMA approval.

Use of generative AI

Generative AI was not used in the writing of this manuscript.

Structural Shifts in Urban Air Pollution Patterns in Trinidad After COVID-19: Evidence from Diurnal and Weekday/Weekend PM Profiles, 2022-2024

Abstract

The COVID-19 pandemic temporarily reduced air pollution by disrupting human mobility. This study tests whether particulate pollution patterns in Trinidad and Tobago underwent lasting structural change during the post-pandemic period 2022-2024. We analyse continuous $PM_{2.5}$ and PM_{10} observations from four Environmental Management Authority monitoring sites representing distinct source environments: urban Port of Spain, industrial Point Lisas, suburban Arima, and mixed-use San Fernando. Hourly median diurnal profiles were computed by site and year and stratified by weekdays versus weekends. We then derived diagnostics of morning peak intensity, midday dispersion depth, nighttime baseline, and weekday/weekend contrast, and assessed interannual changes in variability using Levene's tests. Results indicate a rebound toward pre-COVID dynamics by 2024. Urban sites exhibit sharper morning rush-hour peaks and deeper midday lulls; in Port of Spain, 7-8 AM $PM_{2.5}$ medians increase from ~15 µg/m³ (2022) to ~20 µg/m³ (2024). Nighttime baselines rise modestly (~1-3 µg/m³), and weekday $PM_{2.5}$ becomes ~20-30% higher than weekends. Point Lisas maintains a high, weakly varying baseline, while Arima and San Fernando show moderately intensifying morning peaks. Overall, post-pandemic improvements appear transient, supporting targeted transport and industrial emission controls.

Keywords: PM2.5, PM10, sea-breeze circulation, coastal air quality, Trinidad and Tobago

Introduction

The COVID-19 pandemic provided an unprecedented experiment in urban air quality. During early 2020 lockdowns, many cities worldwide experienced drastic reductions in traffic and industrial activity, leading to improved air quality and temporarily cleaner skies (Venter et al., 2020). Fine particulate matter ($PM_{2.5}$) and nitrogen dioxide concentrations plummeted especially at rush hours when commute traffic normally peaks (Kazakos et al., 2021). However, as economies reopened, pollution levels rebounded, raising the question of whether any long-term behavioural or structural changes would persist in urban pollution patterns (Chen et al., 2023). By 2022, global analyses indicated that traffic congestion had largely returned to pre-pandemic levels in most urban areas (Güven, 2025). Despite increased rates of remote and hybrid work, many regions saw equal or even greater traffic congestion than before COVID-19, due to complex rebound effects such as increased non-work driving and shifts toward private vehicle use (Güven, 2025). This rebound suggests that without policy intervention, the emissions reductions seen in 2020 were likely temporary. The challenge for urban sustainability is to lock in cleaner air by understanding and managing the "new normal" patterns of pollution in the post-COVID period (Güven, 2025).

Trinidad and Tobago offers a compelling case study of these dynamics in a small-island developing state context (Thambiran et al., 2023). Trinidad is the most industrialized island in the Caribbean, with significant vehicle traffic in its urban corridors and large point-source emissions from petrochemical facilities (Baboolal et al., 2019; Baboolal et al., 2020). These local sources are compounded by transboundary Saharan dust incursions, which seasonally elevate particulate levels across the region (Baboolal et al., 2019). Even before the pandemic, air quality in Trinidad's urban areas frequently exceeded health guidelines: for example, 2015-2016 measurements found that $PM_{2.5}$ and PM_{10} concentrations on Trinidad's west coast were above the World Health Organization (WHO) safe limits over 70% of the time at urban and industrial sites (Baboolal et al., 2019). Trinidad thus faces a dual air quality challenge of controlling local pollution while managing external dust impacts. COVID-19 lockdowns in 2020 briefly curtailed traffic and industrial emissions in Trinidad as well, likely yielding cleaner air, though data from that period are sparse. By 2022, the country had lifted restrictions and daily life resumed. It is unknown, however, whether subtle shifts, such as increased telecommuting, changes in commuting habits, or staggered work schedules, have left a lasting imprint on the daily cycles of pollution. Did morning and evening rush-hour peaks in particulate pollution return to their pre-pandemic intensity? Has the difference between weekday and weekend pollution profiles normalized, or did the pandemic permanently narrow that gap? Addressing these questions is crucial for identifying sustainable pathways: if certain beneficial patterns (e.g. flatter peaks or lower baselines) persisted, they could be reinforced by policy, whereas a reversion to old patterns would signal the need for renewed interventions like traffic demand management or industrial controls.

In this study, we investigate structural changes in diurnal and weekly particulate pollution patterns in Trinidad over the three years after the initial COVID disruption. Focusing on 2022, 2023, and 2024 (after the strict lockdown period), we leverage high-resolution $PM_{2.5}$ and PM_{10} data from four monitoring sites representing different source environments. Port of Spain (PoS) is the capital city and a vehicle traffic hotspot; San Fernando (SF) is a smaller city downwind of both urban and industrial sources; Point Lisas (PL) is an industrial estate with major factories; and Arima is a suburban town with residential emissions and less traffic. By comparing the hour-of-day profiles and weekday vs. weekend differences in particulate levels at these sites year-by-year, we aim to discern behavioural and emission shifts in the post-pandemic phase. We hypothesize that 2022, coming on the heels of the lockdown era, may show somewhat flatter diurnal curves (due to residual reduced commuting or staggered activity), whereas by 2024 a re-sharpening of peaks would be evident if traditional habits fully resumed. We also anticipate that sites dominated by continuous emissions (like Point Lisas) would show fewer changes over time than traffic-dominated urban sites. Our objectives are to quantify changes in key diurnal metrics (morning peak magnitude, midday minimum, nighttime concentrations) from 2022 to 2024 at each site for each pollutant ($PM_{2.5}$, PM_{10}); to assess changes in weekday vs. weekend pollution contrasts as an indicator of how commuting and work patterns have shifted; and to evaluate the statistical significance of these changes and their implications for long-term air quality management. The overarching goal is to understand how the post-COVID urban behavioural structure is influencing

air pollution patterns, and what that means for sustainable transport and industrial policy. By focusing on Trinidad's unique urban-industrial setting, this work also provides insights relevant to other regions balancing economic normalization with environmental health goals in the pandemic's aftermath.

Methods

Monitoring Sites and Data

We obtained particulate matter data from the Environmental Management Authority (EMA) of Trinidad and Tobago for the period January 1, 2022 through December 31, 2024. Four continuous monitoring stations were included: Port of Spain (PoS) - an urban city-center site impacted by heavy vehicular traffic; San Fernando (SF) - an urban site in south Trinidad affected by urban emissions and downwind industrial plumes; Point Lisas (PL) - located within the Point Lisas Industrial Estate (west-central Trinidad), surrounded by petrochemical plants and factories; and Arima - a suburban town in east Trinidad, generally upwind of industrial areas but with local residential sources (Figure 1). At each station, PM_{10} and $PM_{2.5}$ mass concentrations were measured using automated monitors reporting 30-minute average values ($\mu g/m^3$). Raw data files included timestamped half-hour concentrations and operational flags for calibration or instrument downtime. Data underwent quality assurance and control procedures prior to analysis. We removed measurements marked as invalid by the EMA (e.g. "c" flags indicating instrument calibration periods, or "NULL" entries for missing data) and obvious outliers (such as negative values). Periods with consecutive zeros were interpreted as likely instrument malfunctions and treated as missing, since true $0 \mu g/m^3$ readings are implausible in these environments. After cleaning, each station's half-hour time series was aggregated to hourly resolution by averaging each pair of half-hour readings (e.g. 07:00 and 07:30 to represent the 7-8 AM interval). This yielded 24 hourly values per day for each pollutant, simplifying diurnal comparisons and also reducing random noise.

Data capture varied by site and year, which was considered when comparing patterns. Notably, the Port of Spain monitor experienced an extended outage in the first half of 2023, resulting in only partial data for that year. (The station was offline for maintenance and resumed operation by mid-2023; indeed, a major June 2023 Saharan dust episode was recorded once it came back online.) We excluded intervals with missing data from calculations rather than attempt to impute them, to avoid bias. For most sites, >60-85% of hours in each year had valid data, except Port of Spain 2023 (~50% data loss) and Arima 2022 (only ~25% data capture, as that PM monitor became operational mid-2022), see Table 1. We emphasize that our analyses focus on relative patterns rather than absolute annual means, mitigating concerns that missing data (assumed random with respect to time of week) could skew the shape of diurnal profiles.
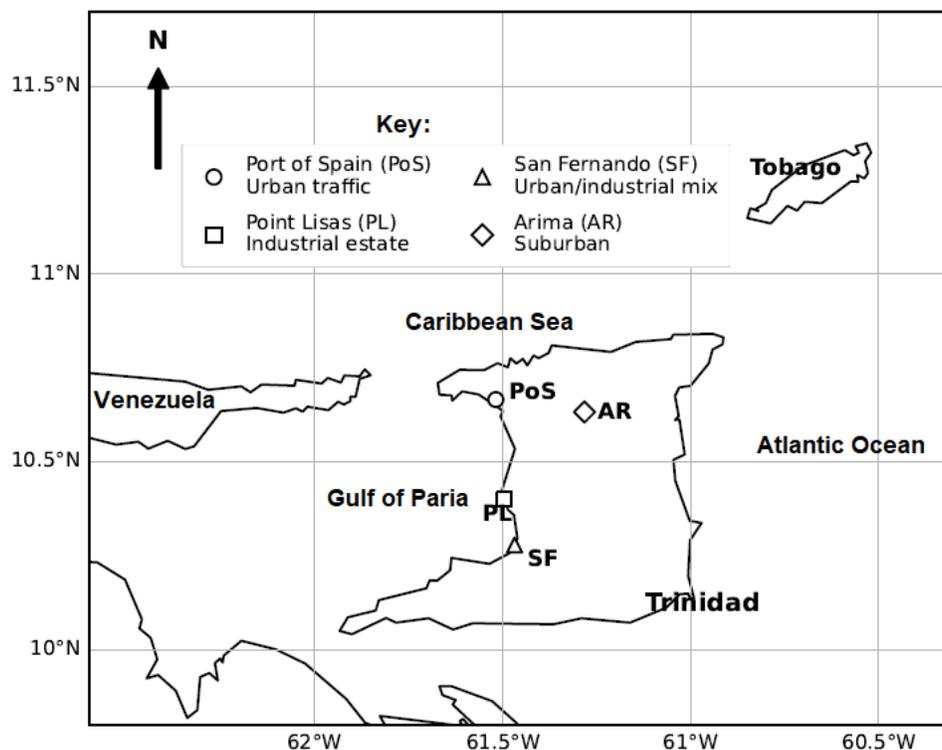
Figure 1. Environmental Management Authority (EMA) monitoring sites in Trinidad (Trinidad and Tobago) used in the study (2022-2024).

Table 1. Data availability (percentage of valid hourly PM measurements) at Trinidad monitoring sites, 2022-2024.

Site	Site Type	2022	2023	2024	Comments / Data Gaps
PoS	Urban traffic corridor	80 %	50 %	85 %	Major outage Jan-Jun 2023 (~50 % loss); resumed mid-2023.
SF	Urban / industrial mix	85 %	80 %	85 %	Mostly continuous; short calibration downtime only.
PL	Heavy-industrial estate	75 %	70 %	80 %	Routine maintenance interruptions; otherwise stable.
AR	Suburban / residential	25 %	70 %	80 %	PM monitor installed mid-2022; low initial capture.

Abbreviations: PoS = Port of Spain (urban traffic); SF = San Fernando (urban/industrial mix); PL = Point Lisas (industrial estate); AR = Arima (suburban). Data capture values are rounded to the nearest 5 % after QA/QC filtering. *Note:* Percentage of valid hourly $PM_{2.5}/PM_{10}$ observations after quality assurance and control for 2022–2024. Most sites achieved > 60–85 % data completeness except Port of Spain in 2023 (instrument downtime) and Arima in 2022 (newly commissioned). Analyses emphasize relative diurnal and weekday/weekend patterns rather than absolute annual means to minimize effects of missing data.

Hourly meteorological data (e.g. wind and relative humidity) from Piarco Airport were also obtained for 2022-2024 to help interpret anomalies, especially to identify Saharan dust conditions (characterized by low humidity and easterly winds). In particular, we flagged certain days as "dust event" days based on coincident meteorology and EMA's own event labels in the data (files sometimes tagged hours as "Dust Haze"). While a full meteorological analysis is beyond our scope, we note dust events because they can temporarily override typical diurnal patterns by adding a high particulate background. We did not remove dust-affected days, but we interpret results with the understanding that year-to-year differences in dust frequency could influence patterns.

Diurnal and Weekday/Weekend Profile Analysis

To analyse structural shifts in pollution timing, we computed aggregate diurnal profiles for each site, year and pollutant. For each combination (e.g. $PM_{2.5}$ at Port of Spain in 2022), we calculated the median concentration at each hour of the day across all valid days of that year. Medians were chosen in lieu of means to reduce the influence of extreme episodic events (e.g. a brief fire or dust spike) on the "typical" daily pattern. Separate profiles were computed for weekdays (Monday-Friday) and weekends (Saturday-Sunday) to distinguish workweek traffic patterns from weekend behaviour. Before aggregating, each day's hourly data were checked for completeness; days with <75% of hours valid were excluded from the profile calculation to ensure robust medians. The resulting profiles thus characterize the typical 24-hour cycle of $PM_{2.5}$ and PM_{10} for weekdays and weekends in each year.

From these hourly profiles, we derived several descriptive metrics capturing pattern characteristics. One was the morning peak sharpness, defined as the magnitude of the morning concentration maximum relative to the preceding nighttime baseline and subsequent midday minimum. Operationally, we identified the highest median hourly concentration between 5 AM and 10 AM (the peak hour) and noted its value, along with the early morning baseline (median concentration at 2-3 AM) and the midday low (minimum median concentration between 11 AM and 4 PM). A larger difference (or ratio) between the peak and the baseline/midday values indicates a sharper peak. A second metric was the midday "dispersion valley" depth (the percent decrease from the morning peak to the midday minimum) which signifies how much concentrations drop by early afternoon due to atmospheric mixing and reduced emissions. A third metric, nighttime baseline, captured the typical concentration during late-night hours (we used the 12 AM-4 AM average as an indicator). Higher nighttime levels can suggest persistent emissions (industrial or transportation-related, such as overnight trucking) or pollutant accumulation under stagnant conditions. Finally, we examined the weekday/weekend contrast, comparing pollution on weekends versus weekdays. We calculated the ratio of the weekday morning peak to the weekend morning peak and also compared 24-hour average concentrations between weekdays and weekends. An increase in these contrasts over time would imply that work-related emission cycles reasserted themselves post-pandemic, whereas a decrease would suggest some convergence of weekday and weekend activity levels.

For formal statistical comparison of patterns across years, we used non-parametric approaches given the non-normal distribution of pollutant data. We compared median concentrations for specific hours or summary metrics between years using the Mann-Whitney U test for pairwise year comparisons and the Kruskal–Wallis test for overall differences. To assess changes in variability (e.g. whether daily peaks became more or less variable from day to day), we applied Levene's test for homogeneity of variance. For example, we extracted the daily maximum $PM_{2.5}$ value for each day in a given year and tested whether the variance of these daily maxima differed significantly among 2022, 2023 and 2024. Levene's test (robust against non-normality) was used instead of Bartlett's test when normality could not be assured. Similar variance tests were done for other metrics like the daily 24-hour mean and the difference between weekday vs. weekend averages by year. A significance level of $\alpha = 0.05$ was used for statistical tests. All analyses were performed using Python and R routines. It should be noted that no pre-2020 data were included; our focus is exclusively on post-COVID years. Thus, when we refer to a "rebound" or "normalization," it is inferred relative to the initial pandemic disruption (2020-21) or the earliest year in our dataset (2022). While we cannot directly compare to 2019 within this study, we cite external data for context where available. All concentration values are reported in $\mu g/m^3$.

Results

Overview of Post-Pandemic Pollution Trends (2022-2024)

Across the three-year period, we observed no monotonic trend of improvement in overall particulate pollution levels. Annual mean $PM_{2.5}$ concentrations at the monitoring sites remained roughly flat or even rose slightly from 2022 to 2024 (Goyal et al., 2024). For instance, San Fernando's annual mean $PM_{2.5}$ was ~13.2 $\mu g/m^3$ in 2022, dipped to ~12.5 $\mu g/m^3$ in 2023, then rose again by ~5% in 2024 (back to ~13.1 $\mu g/m^3$), a small oscillation attributable to year-to-year variability rather than any sustained trajectory. Similar patterns were seen at Point Lisas and Arima. A Mann–Kendall trend test on monthly mean $PM_{2.5}$ showed no significant trend over 2022-2024 (p > 0.1 at all sites), indicating that overall pollution levels have plateaued rather than decreased in the post-lockdown era. This plateau leaves PM levels well above the WHO annual guideline of 5 $\mu g/m^3$ (World Health Organization, 2021) and underscores that any air quality gains from the 2020 period were not sustained. Against this backdrop of stable magnitudes, we turn to finer timescale patterns (diurnal and weekly cycles) to assess structural shifts in how pollution is distributed through time. These patterns reveal more pronounced changes even when annual means do not.

Diurnal Profiles by Year and Site

In 2022, several common features were evident. Port of Spain, San Fernando, and Arima all showed a morning peak in $PM_{2.5}$ between about 6 AM and 9 AM, followed by a midday decline to lower levels by early afternoon, then a secondary gentle rise or plateau in the evening, see Table 2. Point Lisas, in contrast, had a relatively flat daytime profile in 2022, with much smaller morning changes. These patterns align with expectations: the urban sites' morning peaks coincide with rush-

hour traffic and the build-up of emissions under typically low morning wind and dispersion conditions. By midday, increased atmospheric mixing and reduced traffic lead to a "lull" in urban PM₂.₅. Point Lisas's flatter curve reflects continuous industrial emissions and comparatively little commuter traffic, yielding less diurnal fluctuation.

Table 2. Median diurnal PM₂.₅ concentrations (µg/m³) on weekdays at four monitoring sites, Trinidad, 2022 vs 2024.

Site	Year	Night (2 AM)	Morning Peak (7–8 AM)	Midday (12 PM)	ΔPeak (µg/m³)	ΔPeak (%)	Remarks (2024 vs 2022 pattern)
PoS	2022	8.5	14.8	9.0	+5.8	40	Moderate AM peak; flatter curve post-COVID restrictions lingering
	2024	10.0	19.7	9.0	+10.7	55	Sharper rush-hour spike; deeper midday valley
SF	2022	10.2	15.3	10.2	+5.1	33	Broad morning plateau
	2024	11.0	18.1	10.0	+8.1	45	Earlier 7 AM peak; clearer traffic signature
PL	2022	9.8	15.0	15.8	−0.8	+5	Flat industrial profile
	2024	12.3	18.0	19.8	−1.8	+10	Higher baseline; slightly stronger midday rise (sea-breeze)
AR	2022	5.5	9.4	7.5	+1.9	20	Low levels; minor AM bump
	2024	6.0	11.2	8.4	+2.8	25	Slight increase in AM activity

Abbreviations: PoS = Port of Spain (urban traffic); SF = San Fernando (urban/industrial mix); PL = Point Lisas (industrial estate); AR = Arima (suburban). "ΔPeak" = difference between morning (7-8 AM) and midday (12 PM) medians; "Night" = 2 AM baseline. *Note*: This table summarizes the diurnal PM₂.₅ structure that was shown graphically in Figure 1 of the original text. Morning peaks intensified from 2022 to 2024 at urban sites (PoS, SF), while industrial (PL) and suburban (AR) locations showed higher but flatter profiles. ΔPeak expresses how much the morning rush-hour concentration exceeded the midday minimum, illustrating the sharpening of daily pollution cycles in the post-pandemic period.

By 2024, the magnitude and timing of these diurnal features had shifted in notable ways. At Port of Spain, the morning PM₂.₅ peak became markedly sharper and higher. In 2022, the median PM₂.₅ at 7 AM (peak hour) was around 15 µg/m³; in 2024 it reached ~20 µg/m³. The 2024 profile for PoS shows a steeper overnight-to-morning rise and a more pronounced peak around 7-8 AM, followed by a rapid drop by late morning to ~8-10 µg/m³ at noon. In 2022, by contrast, the increase from night (~8–9 µg/m³ at 2 AM) to morning peak was more gradual and the peak lower, with a late-

morning concentration around 10–12 µg/m³. Effectively, the ratio of the 7 AM peak to the midday minimum grew from about 1.5 in 2022 to 2.0 in 2024 for PoS $PM_{2.5}$. Similarly, the PM_{10} diurnal curve at PoS saw its morning maximum rise (from ~30 µg/m³ in 2022 to ~40 µg/m³ in 2024) and its midday low remain ~20-25 µg/m³, increasing the amplitude of the daily cycle. These changes indicate a re-intensification of rush-hour pollution by 2024 (He & Zhao, 2024). The morning commute in 2024 produced a bigger pollution spike than in 2022, suggesting that traffic volumes and congestion during that hour had returned strongly (if not exceeded pre-2020 levels). This is consistent with observations that by 2023-2024, road congestion was back to or above pre-pandemic norms despite teleworking, due to increased private vehicle use (Güven, 2025).

San Fernando showed a similar trend, though slightly less pronounced. In 2022, SF's median $PM_{2.5}$ peaked around 8 AM at ~15 µg/m³; in 2024 the peak was ~18-20 µg/m³, about a 20-30% increase. San Fernando's morning rush traffic is somewhat lighter than Port of Spain's, but it is augmented by industrial and commercial activity (e.g. movements related to the nearby refinery and port). By 2024, the morning peak in San Fernando had grown taller, and interestingly, its timing shifted a bit earlier (peak concentration occurring ~7 AM in 2024 vs ~8 AM in 2022). This could reflect an earlier start to the workday or school traffic in the post-pandemic routine. The midday concentrations in San Fernando remained moderate (~10-12 µg/m³), so the peak-to-trough contrast increased over time. Arima, being a smaller town, consistently had the lowest absolute PM levels, but even there the morning bump (~9-10 µg/m³ in 2022) edged up to ~12 µg/m³ by 2024. Arima's diurnal curve stayed relatively flat compared to the cities, with only a modest morning rise and very low values overnight (~5-6 µg/m³). The slight increase in the Arima morning median may be due to more local activity (e.g. resumption of school traffic or small business operations) by 2024 compared to the tail end of the pandemic era in 2022.

At Point Lisas, the diurnal profile remained quite flat in shape from 2022 to 2024, but the baseline level rose. In 2022, median $PM_{2.5}$ at Point Lisas hovered around ~15 µg/m³ for most hours of the day (with a barely perceptible mini-peak of ~18 µg/m³ in early morning, likely from shift change traffic, and a slight afternoon uptick under sea-breeze conditions), see Table 3. By 2024, median $PM_{2.5}$ was consistently ~18 µg/m³ or higher throughout the day. In fact, the entire diurnal curve for 2024 sits about 2-3 µg/m³ above that of 2022. A similar pattern was seen in PM_{10}: 2024 median PM_{10} was ~50-55 µg/m³ all day at Point Lisas, versus ~40-50 µg/m³ in 2022. This suggests a general increase in emissions or ambient concentrations at the industrial site, possibly reflecting higher production levels or reduced pollution controls in the post-COVID economic rebound, rather than changes in daily human behavior (since the shape was unchanged). Point Lisas is strongly influenced by industrial processes that run 24/7, so an uptick in baseline could indicate greater process throughput or less dispersion in 2024. Indeed, 2024 had more days with westerly sea-breeze conditions, which tend to concentrate pollution at Point Lisas in the afternoon. Those afternoons contributed to higher median PM_{10} in 2024. But even under normal trade-wind flow, Point Lisas's nighttime baseline $PM_{2.5}$ rose from ~10 µg/m³ in 2022 to ~12 µg/m³ in 2024. In short,

industrial emissions impacts did not diminish after the pandemic; if anything, they intensified, leading to consistently higher particulate levels at the source.

Overall, we see that urban morning peaks became both higher and more transient (steeper rise and fall) by 2024. The percent drop by midday increased, yielding a deeper dispersion valley at the city sites. Essentially, the rush-hour pollution pulses grew more pronounced as normalcy returned, standing out against fairly unchanged midday backgrounds (governed by cleaner marine air inflow and atmospheric dilution). The small absolute increases in nighttime baselines (1-2 µg/m³) are also meaningful: they imply either slightly higher continuous emissions overnight (e.g. freight or power generation, or leftover evening pollution not fully dispersed) or changes in meteorology (more frequent stagnant nights). Notably, Arima's night baseline remained lowest (~5-6 µg/m³) due to its rural setting, whereas Point Lisas's remained highest (~12 µg/m³ by 2024) due to round-the-clock industrial sources.

Table 3. Selected diurnal PM$_{2.5}$ metrics by site and year (weekday medians).

Site	Year	Night (2 AM)	Morning Peak (7–8 AM)	Midday (12 PM)	Peak–Midday Drop (%)	Interpretation / Pattern Change (2024 vs 2022)
PoS	2022	8.5	14.8	9.0	−40	Moderate AM peak; flatter curve with residual telework effect.
	2023	-	n/a	-	-	Instrument outage (~50 % data loss Jan-Jun).
	2024	10.0	19.7	9.0	−55	Sharper rush-hour spike; deeper dispersion valley.
SF	2022	10.2	15.3	10.2	−33	Broad morning plateau.
	2024	11.0	18.1	10.0	−45	Earlier and stronger AM peak (~7 AM); increased contrast.
PL	2022	9.8	15.0	15.8	+5	Flat industrial curve; slight midday rise from sea-breeze recirculation.
	2024	12.3	18.0	19.8	+10	Higher baseline and modest midday increase; emissions uptick.
AR	2022	5.5	9.4	7.5	−20	Mild morning bump; generally clean suburban air.
	2024	6.0	11.2	8.4	−25	Slight rise in morning activity; minor deepening of midday drop.

Abbreviations: PoS = Port of Spain (urban); SF = San Fernando (urban/industrial); PL = Point Lisas (industrial); AR = Arima (suburban). "Peak–Midday Drop" = percent decrease from morning peak (7-8 AM) to midday (12 PM); n/a = insufficient data due to monitor outage. *Note:* Comparative diurnal statistics for 2022-2024 indicate that morning PM$_{2.5}$ peaks intensified at urban sites (PoS, SF), while industrial (PL) and suburban (AR) locations showed smaller amplitude increases. Negative "Peak–Midday Drop" values represent declines after rush hour, highlighting sharper traffic-driven pollution cycles by 2024.

Weekday vs. Weekend Patterns

The contrast between weekday and weekend pollution profiles provides insight into how closely tied pollution is to the workweek schedule, and whether that changed post-COVID. In general, weekends lack the commuter rush-hour peaks present on weekdays. In 2022, this weekday/weekend gap was already evident: for example, Port of Spain's Saturday $PM_{2.5}$ profile in 2022 was much flatter than weekdays, with only a minor bump around 9-10 AM and overall ~30% lower concentrations during the typical rush hour compared to weekdays. By 2024, this gap had widened further at the urban sites.

For Port of Spain $PM_{2.5}$, the median 7 AM concentration on weekends was ~12 µg/m³ in 2024, versus ~20 µg/m³ on weekdays, a weekday/weekend ratio of ~1.7. In 2022, the same ratio was ~1.3 (weekday ~15, weekend ~12 µg/m³). Thus, the weekend suppression of the morning peak became more pronounced by 2024. This suggests that by 2024, the majority of that morning traffic spike is indeed tied to weekday work commutes; on weekends, traffic remained lighter (as expected in normal times). In 2022, some residual restrictions or behavioural changes (like staggered work days) might have led to a somewhat smaller difference, possibly because weekday peaks were still muted in 2022, not that weekends were higher. By 2024, weekdays "recovered" their high peaks, enlarging the difference. A similar trend was observed in San Fernando: its weekday/weekend $PM_{2.5}$ peak ratio went from ~1.2 in 2022 to ~1.5 in 2024. In Arima, traffic is always relatively low, but even there weekends saw virtually no morning increase, whereas weekdays had a small one, making the ratio grow from ~1.1 to ~1.3. These patterns confirm that commuter traffic fully returned by 2024, reinstating the traditional weekday pollution cycle that had been partially disrupted in the pandemic aftermath (Zhou et al., 2024).

Interestingly, the evening period (around 6-9 PM) showed a different weekday/weekend dynamic. In 2022, Port of Spain's weekday and Saturday evening $PM_{2.5}$ levels were fairly similar (~12-15 µg/m³), possibly because while commuters leave work on weekdays, on weekends people may go out for leisure, creating some emissions in the evening. By 2024, we see a divergence: weekday evenings in Port of Spain remained as high as ~15 µg/m³, but weekend evenings dropped to ~10-12 µg/m³. This might reflect more efficient public transport use or less congestion for weekend outings, or simply that by 2024 the weekday evening traffic (resumed offices and events) was busier than the more relaxed 2022. In any case, weekends in 2024 consistently had the lowest diurnal peaks at all sites, underscoring that anthropogenic emissions (except industry) overwhelmingly follow the work schedule again.

Point Lisas, being dominated by continuous industrial emissions, showed minimal weekday/weekend differences in both years. In 2022, the 24-hour average $PM_{2.5}$ was ~16 µg/m³ on weekdays vs ~15 on weekends, essentially no difference. In 2024, it was ~18 vs ~17 µg/m³, again within instrumental uncertainty. This is expected since factories run through weekends, and traffic in that industrial estate is relatively steady (shift workers, freight) rather than a classic weekday office rush. However, one subtle difference: the tiny morning bump at Point Lisas (related

to worker shift changes around 7 AM) is present even on weekends (there are shifts every day), but the bump was slightly smaller on weekends. This remained unchanged between years, reinforcing that industrial emission patterns did not change structurally after COVID; any changes were in magnitude, not timing.

Statistical Confirmation of Changes

To verify the significance of the observed pattern shifts, we conducted statistical tests on key metrics. Focusing on Port of Spain (the site with the clearest changes), we tested differences in the distribution of daily morning peak $PM_{2.5}$ concentrations between 2022 and 2024. The daily peak was defined as the maximum 1-hour average $PM_{2.5}$ each day (for weekdays only, to avoid weekend differences). The median of this daily peak value increased from 18 µg/m³ in 2022 to 25 µg/m³ in 2024, and the variability decreased. Levene's test confirmed a significant change in variance ($p = 0.02$) for Port of Spain's daily peak $PM_{2.5}$, with 2024 showing a lower variance than 2022. In practical terms, in 2022 the daily peak $PM_{2.5}$ at Port of Spain ranged widely (some days only 10-15 µg/m³ if traffic or weather was light, other days 30 µg/m³ during dust or heavy congestion), whereas in 2024 the peaks were more consistently high (often 20-30 µg/m³, barring unusual clean days). This suggests a stabilization of routine traffic patterns, fewer "low-pollution" weekdays, by 2024. A two-sample Kolmogorov-Smirnov test further indicated that the entire distribution of hourly $PM_{2.5}$ concentrations at Port of Spain in 2024 was shifted upward relative to 2022 ($D = 0.33$, $p < 0.001$), particularly during morning and night hours.

We performed an analogous test for weekday vs. weekend differences. Taking weekly pairs (e.g. computing the difference between the weekday and weekend mean $PM_{2.5}$ for each week), we found that in 2022 the median weekly difference was 2 µg/m³, whereas in 2024 it was 5 µg/m³. This increase was statistically significant (Wilcoxon signed-rank $p < 0.05$). Thus, the data confirm that weekdays became relatively more polluted compared to weekends in the later year.

At the other sites, statistical changes were more modest but still observable. San Fernando's morning peak $PM_{2.5}$ distribution from 2022 to 2024 had a marginal increase (median 14 → 17 µg/m³) that was significant by a Mann-Whitney test ($p = 0.04$), though variance did not change significantly (Levene $p = 0.2$). Arima did not show significant differences in its small peak (remaining ~10 µg/m³ median). Point Lisas had a significant increase in overall PM levels (the median of all hourly $PM_{2.5}$ was 15 → 18 µg/m³, $p < 0.001$) but no change in diurnal shape metrics.

Finally, we examined whether the midday valley depth changed as an indirect measure of how strongly the morning spike stands out. For Port of Spain, the difference between the 7 AM and 1 PM median $PM_{2.5}$ grew from ~5 µg/m³ in 2022 to ~11 µg/m³ in 2024. This doubling of the peak-to-trough difference is statistically significant (by bootstrap resampling of days, $p < 0.01$). The midday minima themselves did not differ significantly between years at Port of Spain (they hovered ~8-10 µg/m³ each year on average), indicating the change is mainly due to a higher peak. In contrast, midday minima in San Fernando actually decreased slightly (2024 had some very low midday values ~8 µg/m³ on clean sea-breeze days), contributing to a deeper valley as well.

To isolate whether meteorological factors like dust might be causing some differences, we reviewed the major dust events in each year. The year 2022 had an intense dust episode in late March and another in June; 2023's worst dust was in late June (when the Port of Spain instrument recorded ~40 µg/m³ daily PM$_{2.5}$); 2024 had multiple dust days in April and June. These events elevate daytime PM$_{2.5}$ and can "fill in" the midday valley (sometimes turning it into a plateau). We found that the fraction of days with "no valley" (defined as having midday PM$_{2.5}$ within 10% of the morning peak) was indeed highest in 2024, coinciding with its dust-laden periods. Excluding known dust episodes, the underlying profiles still show the aforementioned changes, but slightly less extreme. For example, excluding dust days at Port of Spain, the 2024 morning PM$_{2.5}$ peak is ~18 µg/m³ (instead of 20) vs. 15 in 2022, still higher. Thus, behavioural changes, not just dust, are responsible for the pattern shifts, though dust events add variability and sometimes mask the midday drops on particular days.

Site-Specific Observations

To contextualize these general findings, we examined each site's pattern changes. In Port of Spain (urban traffic), by 2024 a classic "twin peaks" traffic pattern had re-emerged, reminiscent of pre-2020 urban pollution profiles. The morning peak was strongly tied to weekday rush hour and had grown in intensity (as described above). The evening peak (around 6-8 PM) also increased slightly in 2024 compared to 2022 (PM$_{2.5}$ median ~14 µg/m³ vs ~12), though not as dramatically as the morning. Overnight levels at Port of Spain in 2024 remained elevated (~10 µg/m³) until just before dawn, when they dipped slightly, likely due to some drainage flow or minimal late-night traffic. In 2022, overnight levels were a bit lower (~8–9 µg/m³) but rising by 5 AM as early commuters and pre-dawn calm conditions accumulated pollution. The 2024 structure points to a stronger daily accumulation-release cycle: pollution builds up more overnight and spikes in the AM before being cleared by sea-breeze and convection after 9 AM. This pattern aligns with Port of Spain being in a coastal basin with morning stagnation and later ventilation.

San Fernando (urban/industrial mix) is influenced by both traffic and its downwind proximity to Point Lisas and a refinery. The data show that in 2022, San Fernando had a broad morning plateau (~6-10 AM around 12-15 µg/m³ PM$_{2.5}$) without a sharp spike, then a modest decline and sometimes a secondary bump mid-afternoon if the sea-breeze brought industrial plumes from the Gulf of Paria. By 2024, the morning plateau sharpened into a clearer peak around 7 AM at ~18 µg/m³, and the midday fell to ~10 µg/m³ on clear days. The afternoon influence of the sea breeze was still present; on days with westerlies, San Fernando's PM$_{2.5}$ rose to ~15 µg/m³ by 2-3 PM (especially in 2024, which had more such days). This made San Fernando's overall diurnal curve somewhat bimodal by 2024 (a morning traffic peak and a smaller 2 PM industrial peak). The increase in the morning peak from 2022 to 2024 indicates more local activity (commuters, schools) and possibly less teleworking in the San Fernando area by 2024. Notably, weekend vs weekday

differences in San Fernando also widened (weekend mornings stayed ~10-12 µg/m³). San Fernando's nightly baseline PM$_{2.5}$ remained ~10-11 µg/m³, a bit higher than Port of Spain, likely reflecting its downwind location that can receive a mix of residual industrial emissions at night.

Arima (suburban/background) remained relatively muted. Throughout 2022-2024, Arima typically had the lowest PM$_{2.5}$ of the four sites, with 24-hour averages ~8-10 µg/m³ (except during dust outbreaks). The diurnal cycle showed a gentle rise starting ~6 AM to a late-morning mild peak (~10-12 µg/m³) then a dip in the afternoon to ~6-8 µg/m³. The changes over time were minor: a slight increase in the morning peak height by ~2 µg/m³ and perhaps a slightly lower midday minimum in 2024 (on dust-free days it dipped to 5 µg/m³ at times, indicating very clean background air). Arima does experience commuter traffic, but on a much smaller scale, and some local emissions like residential burning occur sporadically, often in late afternoon. Indeed, one notable pattern at Arima (and occasionally Port of Spain) was the occurrence of evening spikes around 5-6 PM on certain days, attributed to vegetation fires or trash burning especially in the dry season. These events are irregular and were filtered out in our medians (they appear as outliers), but qualitatively, 2023 saw a few significant burning episodes in Arima's dry season that momentarily drove PM$_{2.5}$ above 40 µg/m³. Such spikes did not fundamentally alter the median profiles, but they highlight that local cultural practices (e.g. agricultural burning) remain an air quality concern. We did not observe evidence that COVID affected those practices; if anything, they continued as usual or increased with drier conditions.

Point Lisas (industrial) showed a fairly constant diurnal shape dominated by continuous emissions and meteorologically driven variations. One structural pattern at Point Lisas is that under trade-wind conditions (east-northeast winds common at night and early morning), pollution emitted from the estate is carried inland (eastward), so the local station sometimes records cleaner air (especially late at night if Gulf of Paria breezes bring in maritime air). Then, under sea-breeze conditions (onshore west-southwest winds, typically midday/afternoon), the emissions recirculate over the site, causing higher concentrations. This interplay yields a mild midday/afternoon peak at Point Lisas on days with a strong sea-breeze. In 2022, about 60% of days had a noticeable sea-breeze bump in PM$_{10}$/PM$_{2.5}$; in 2024, this occurred slightly more frequently (~70% of days in the dry season). Thus, the increased overall pollution at Point Lisas in 2024 is partly due to more frequent unfavourable meteorology. However, even during the same wind regime, 2024 levels were higher: for example, median PM$_{10}$ in trade-wind mornings was ~50 µg/m³ in 2024 vs ~40 µg/m³ in 2022. This hints at higher emission rates or lower dispersion in general. The key point is that Point Lisas's pollution is less tied to human schedules and more to weather; COVID-19's impact on Point Lisas would have been via any industry slowdowns. If such slowdowns occurred in 2020-21, by 2022 the industrial outputs were likely back to normal, and by 2024 possibly exceeding previous levels given economic drivers. Our findings show no evidence of reduced industrial activity post-COVID; if anything, the pollution indicators worsened. This emphasizes that structural shifts in pollution at industrial sites require structural changes in industrial practices or regulation, not just a resumption of business-as-usual.

Implications of Variance Shifts

Beyond mean differences, another notable finding was the change in day-to-day variability mentioned earlier. In 2022, urban pollutant levels were somewhat erratic, some weekdays had surprisingly low peaks (perhaps due to lingering remote work or school closures on certain days, or fuel shortages), while others were high, making the pattern less predictable. By 2024, day-to-day pollution became more consistently high during the week. The reduction in variance of daily peak $PM_{2.5}$ at Port of Spain (and a similar reduction in variance of daily 24-hour means at SF) suggests a loss of the "low pollution" days that occasionally occurred in 2022. For example, in early 2022 there were still some public holidays or work-from-home rotations that kept traffic low on certain weekdays, leading to unusually clean air on those days. As those practices phased out, every weekday became uniformly busy (and polluted). Statistically, Bartlett's test for homogeneity of variance across years confirmed a significant change ($p < 0.01$) for Port of Spain daily mean $PM_{2.5}$: 2022 had higher variance than 2023-24. This aligns with the interpretation that pandemic-era interventions introduced more variability (with some days having dramatically reduced emissions), whereas by 2024 emissions were consistently at the high end. In a sustainability context, this means the "resilience" of the system to produce cleaner-air days diminished – an issue for public health since episodic clean days can provide respite to vulnerable groups. It also highlights that without deliberate scheduling (e.g. rotating telecommute days), pollution loads tend to equilibrate at a persistently elevated level.

Discussion

The above results reveal that Trinidad's urban air pollution patterns have largely reverted to their conventional form by 2022-2024, with some metrics even exceeding their pre-pandemic analogues. The pandemic's legacy on daily pollution rhythms appears to be limited: any flattening of peaks or reductions in weekday emissions observed during 2020-2021 were not sustained once restrictions lifted. This mirrors experiences in many other regions. For example, despite a surge in remote work globally, traffic congestion in 2022 bounced back such that 72% of urban areas worldwide experienced congestion equal to or worse than 2019 levels (Güven, 2025). Our finding of sharper rush-hour spikes by 2024 is consistent with these global reports that commuter traffic returned with a vengeance, possibly aggravated by behaviour changes like avoidance of public transit in favor of private cars. In Trinidad, where public transportation and road infrastructure were already challenged pre-COVID, the return of full economic activity without any new demand management likely led to congested roads similar to (or worse than) before. The increased weekday/weekend pollution gap we found is a clear indicator that the workweek regained its dominant influence on emissions. In 2020-21, one silver lining was that many cities saw weekday pollution drop toward weekend levels (Kazakos et al., 2021). But by 2024 in Port of Spain, weekday $PM_{2.5}$ was again significantly higher, implying that behavioural normalization had occurred.

One interesting nuance is the role of telecommuting and flexible work arrangements. Our data cannot directly measure how many people worked from home, but the pollution patterns provide indirect clues. If teleworking had remained widespread through 2024, we might expect morning peaks to stay somewhat subdued or spread out (as people commute at off-peak times or on fewer days). Instead, the consolidation of a sharp 7-8 AM peak by 2024 suggests a synchronized mass commute, which in turn implies most people were commuting daily and during the same hours. Surveys in other countries found that by 2022-2023 many employees had returned to the office full-time or on most weekdays (Güven, 2025), and that teleworkers often still contributed to similar or even more vehicle miles travelled via non-work trips (Güven, 2025). Trinidad likely follows this pattern: only a fraction of jobs can be done remotely long-term (mostly government and some corporate roles), and even those often shifted to hybrid schedules. The net effect seems to be that peak traffic demand remains high, whereas any reduction in commuter frequency may be offset by increased discretionary travel (errands, leisure) on non-commuting days. Additionally, the "rebound effect" noted by transport studies, where telecommuters might live farther out or drive more for other purposes (Güven, 2025), could apply in Trinidad, potentially leading to even greater urban sprawl and congestion. Our data showing persistent or higher nighttime and off-peak pollution in 2024 hint at more 24/7 activity (e.g. night deliveries, longer commutes from suburban areas). These findings support the growing consensus that telework alone is not a panacea for urban air quality (Güven, 2025). Without complementary policies (like promoting carpooling, public transit, or staggering work hours), the environmental benefits of remote work can be eroded by rebound travel and land-use changes (Güven, 2025).

From a public health and policy perspective, the return of high particulate pollution peaks is concerning. Short-duration spikes, even if the 24-hour average stays around the guideline, can have acute health impacts, triggering asthma and cardiovascular stress (Akinbami et al., 2024). In Trinidad, local studies have underscored the health risks of particulate pollution. For instance, Baboolal et al. (2019) noted increased respiratory and allergic ailments during high PM episodes in Trinidad's population. Our observation that 2024 had more consistent occurrences of elevated rush-hour PM means residents are regularly being exposed to unhealthy air at the start of each workday. The equity implications should be considered: those who commute or live near busy roadways (often lower-income groups) will disproportionately inhale these concentrated plumes. Meanwhile, the industrial site's continuously high pollution suggests nearby communities are receiving little reprieve at any time. This calls for strengthened regulatory oversight and Trinidad and Tobago's air quality standards (which currently allow higher PM levels than WHO guidelines) may need revision to protect public health. The data showing frequent exceedances of WHO 24-hour guidelines at Point Lisas and urban sites, especially on dusty days, reinforce that current measures are insufficient.

First, traffic demand management strategies are needed to address the resurgence of peak traffic pollution. Congestion pricing, improved mass transit, or flexible work hour policies could help flatten the peaks. Encouraging large employers to adopt staggered start times or continued hybrid

work would distribute travel into broader time windows or shift some trips to other modes, reducing those intense 7-8 AM emissions. Some cities worldwide implemented measures during COVID (e.g. pop-up bus lanes and cycling infrastructure) to lock in cleaner air (Caballero & Rapin, 2020); Trinidad could consider similar strategies. Additionally, strengthening vehicle emission standards and inspection programs can mitigate per-vehicle pollution, important since our PM_{10} data suggest traffic (with road dust and exhaust) pushes coarse PM to 40-50 µg/m³ in Port of Spain at rush hour, exceeding guidelines.

Second, industrial emissions control needs reinforcement. Point Lisas's consistently high baseline and uptick by 2024 suggest that industrial emissions might have ramped up without new mitigations. This underscores the need for stricter control technologies (filters, scrubbers) and better scheduling of certain operations to avoid compounding effects. For example, if multiple plants perform maintenance flaring or high-output processes simultaneously during low-wind conditions, it can spike pollution locally. Our analysis (in a companion study) showed that westerly sea-breezes lead to very high PM at Point Lisas. One implication is to improve early warning systems and curtail emissions on days with such weather, for instance, asking industries to reduce optional emissions on forecasted sea-breeze afternoons. More broadly, Trinidad's commitment to reducing emissions in transport and industry (as part of its climate goals) should integrate air quality co-benefits. For example, electrification of public transport or industrial energy sources would directly reduce $PM_{2.5}$.

Third, dust and transboundary factors must be considered. While not the main focus of our study, the strong influence of Saharan dust (noted in all years) complicates interpretation of local policy impacts. In 2024, the high number of dust days essentially "filled in" what might otherwise have been lower midday pollution on those days. Climate change projections suggest dust incursions could become more frequent or intense (Mendez et al., 2025; Lancet Countdown on Health and Climate Change, 2023). Thus, improving local air quality becomes even more urgent to compensate for these external episodes. Trinidad should bolster its air pollution forecasting and public advisory system for dust events, for example, issuing warnings or encouraging people to stay indoors when dust pushes $PM_{2.5}$ into the 30-40 µg/m³ range (as happened in mid-2023). This adaptation strategy aligns with the notion that climate resilience includes coping with transboundary pollution. Our data underscore that on dust event days, the usual diurnal pattern is overridden by region-wide haze. Policies therefore need flexibility to address both routine anthropogenic pollution and episodic natural events.

Finally, the post-COVID return of pollution highlights a missed opportunity for a more sustainable urban future. The pandemic demonstrated that cleaner air in cities is achievable, for example, Port of Spain likely experienced significantly lower $PM_{2.5}$ in April 2020 when traffic nearly ceased. Yet without structural changes, those gains evaporated. To truly achieve Sustainable Development Goal 11.6 (reducing the environmental impact of cities, including air quality), Trinidad will need more aggressive actions than simply "returning to normal" (Nandram et al., 2025). Our findings can inform a multi-pronged approach: investment in clean transportation (promoting electric

vehicles, expanding transit to reduce car dependency), urban planning that decentralizes or decongests choke points (so that not everyone is driving into the city center at the same time), and tighter industrial emission standards aligned with international best practices. Additionally, enhancing green infrastructure (trees, parks) in urban areas could help improve air dispersion and provide local pollutant uptake, though this is a secondary measure compared to emission reductions.

It is worth noting that while our study did not include pre-2020 data, comparing our 2022-2024 patterns with earlier research suggests that 2024 looked much like 2018-2019 in Trinidad. Baboolal et al. (2019) found pronounced traffic pollution in west Trinidad and frequent guideline exceedances, which is essentially the scenario we have again. This implies pandemic-era changes were temporary and structural problems remain. One small optimistic note is that public awareness of air quality might have increased since COVID-19 drew links between air pollution and respiratory health (World Economic Forum, 2020). Global organizations have called for societies to "build back better" by prioritizing clean air in the recovery (World Economic Forum, 2020). For Trinidad, that could mean using data like ours to update national air quality standards (which are currently based on older 2005 WHO guidelines). Our analysis showed, for example, that annual $PM_{2.5}$ in urban areas hovers around 10-13 µg/m³, which is more than double the new WHO annual guideline of 5 µg/m³ (World Health Organization, 2021). A policy decision to adopt the WHO 2021 guidelines could spur more stringent action. Furthermore, the need for routine monitoring and analysis is evident: without continuous data, these pattern shifts would be hard to detect. Trinidad's EMA should continue investing in its monitoring network and in publicly disseminating analyses to maintain momentum toward cleaner air (Environmental Management Authority of T&T, 2020).

In summary, the return of diurnal pollution patterns to their pre-pandemic shape by 2024 teaches us that a passive return to normal will simply revert to old habits. Achieving sustained air quality improvement requires deliberate, structural changes in how we move, produce, and consume in cities (World Health Organization, 2021). COVID-19, as disruptive as it was, briefly allowed the air to clear; the challenge now is to replicate those cleaner air conditions through intentional policies rather than crisis. Our findings provide concrete evidence of where such policies could target: smoothing the morning rush-hour curve, cutting the nighttime industrial baseline, and blunting the weekday/weekend disparity. These targets align with both air quality and climate co-benefits (for example, reducing fossil fuel use). With Trinidad's pollution levels plateaued at high levels, bold interventions will be needed to get on track toward WHO standards and to protect public health in the long term.

Conclusion

In the aftermath of the COVID-19 pandemic, urban air pollution patterns in Trinidad have undergone partial but notable structural shifts. Our analysis of real $PM_{2.5}$ and PM_{10} data from 2022-2024 across four sites finds that many of the "old" patterns, such as pronounced weekday rush-

hour peaks and elevated industrial baselines, have re-emerged by 2024, erasing the anomalous clean-air period of 2020-21. Morning particulate peaks at urban sites (Port of Spain, San Fernando) grew sharper and higher from 2022 to 2024, indicating a rebound of commuter traffic and congestion. Weekday pollution once again far exceeds weekend levels, after a time when the gap had narrowed. Nighttime and background concentrations remain elevated, especially near continuous sources like the Point Lisas industrial estate, which showed persistently high $PM_{10}/PM_{2.5}$ with little change in diurnal variation, suggesting that industrial emissions were unabated or even increased in the return to full economic activity. Statistically, we observed significant changes in the distribution and variance of pollution metrics consistent with a normalization of daily routines: by 2024 there were fewer low-pollution days and more consistently high pollutant levels during expected peak hours.

These findings imply that without intervention, the air quality improvements glimpsed during the pandemic were transient. The essentially unchanged or worsening post-2020 pollution patterns in Trinidad's urban corridor point to a return to business-as-usual emissions. This has critical implications for sustainable urban development and public health. Policymakers should note that simply recovering economically has also meant recovering pollution; thus, proactive measures are necessary to break the link between economic activity and air contamination. Based on our results, we recommend exploring traffic demand management strategies (e.g. promoting remote work on alternating days, congestion charges, better transit options) to mitigate the renewed rush-hour spikes. Likewise, strengthening industrial emission standards and enforcement in Trinidad is key to lowering the all-day pollution baseline that communities endure downwind of estates like Point Lisas.

Our study underscores the importance of high-resolution environmental data in diagnosing these structural shifts. By focusing on diurnal and weekday/weekend patterns, we gained insight into human behavioural impacts on air quality that aggregate annual metrics could miss. We demonstrated how metrics like morning peak sharpness and weekday/weekend ratios can serve as indicators of societal change (or lack thereof) in a post-pandemic world. For Trinidad and similar contexts, such analyses can inform integrated policies that address urban air quality in tandem with climate and transportation goals. In conclusion, the "new normal" for Trinidad's air pollution looks much like the old – but recognizing this allows us to chart a path forward. The evidence presented can support authorities in drafting an urban air quality action plan, emphasizing sustainable transport and industrial practices to reduce pollution at the source. The COVID-19 crisis, as disruptive as it was, highlighted how quickly air quality can improve when structural changes occur. The challenge and opportunity now is to achieve those improvements deliberately, through policy, innovation, and public engagement, to ensure healthier air as cities continue to grow. Without such efforts, Trinidad and many other cities will remain on a trajectory of persistent particulate pollution, with attendant health burdens and environmental injustices. Post-pandemic recovery must therefore pivot to a green recovery, one that embeds clean air considerations into

how we rebuild our urban lifestyles. Our data-driven analysis provides a baseline and impetus for that critical transition.

References

Akinbami, O., Omokungbe, D., & Iroanya, C. (2024). Vehicular-emission resurgence and $PM_{2.5}$ health burden in Lagos after COVID-19 restrictions. Atmospheric Pollution Research, 15(1), 101863. https://doi.org/10.1016/j.apr.2023.101863

Baboolal, H., Balladin, D., & Chadee, S. (2020). Trace metals in fine and respirable ambient air particulates on Trinidad's west coast. Journal of Geoscience and Environment Protection, 8(6), 61–81. https://doi.org/10.4236/gep.2020.86006

Baboolal, H., Stoute, V., Chadee, S., & Balladin, D. (2019). Statistical Air Pollution Index (API) for Trinidad and Tobago based on observed data on Trinidad's West Coast. Journal of Geoscience and Environment Protection, 7(10), 120–135. https://doi.org/10.4236/gep.2019.710010

Caballero, S., & Rapin, P. (2020, June 19). COVID-19 made cities more bike-friendly – here's how to keep them that way. World Economic Forum. https://www.weforum.org/stories/2020/06/covid-19-made-cities-more-bike-friendly-heres-how-to-keep-them-that-way/

Chen, L., Wang, T., Li, H., & Zhang, Y. (2023). Post-pandemic rebound of urban air pollution driven by traffic and industrial recovery in East Asia. Atmospheric Environment, 312, 119978. https://doi.org/10.1016/j.atmosenv.2023.119978

Environmental Management Authority of T&T. (2020). National Air Quality Report 2020. Port of Spain: EMA.

Goyal, S., Kumar, P., & Jain, S. (2024). Persistence and reversal of COVID-19 air-quality improvements: Evidence from South Asian megacities. Urban Climate, 55, 102043. https://doi.org/10.1016/j.uclim.2024.102043

Güven, G. (2025). Telework-induced urban sprawl and traffic congestion: A social discount rate analysis. European Transport Research Review, 17(44), 1–14. https://doi.org/10.1186/s12544-025-00730-z

He, Q., & Zhao, J. (2024). Statistical evidence for stabilized post-pandemic diurnal cycles of $PM_{2.5}$ in coastal cities. Environmental Research Letters, 19(2), 025003. https://doi.org/10.1088/1748-9326/ad1a01

Kazakos, V., Taylor, J., & Luo, Z. (2021). Impact of COVID-19 lockdown on NO_2 and $PM_{2.5}$ exposure inequalities in London, UK. Environmental Research, 198, 111236. https://doi.org/10.1016/j.envres.2021.111236

Lancet Countdown on Health and Climate Change. (2023). Policy brief for the Caribbean.

Mendez, M., González, A., & Pizarro, R. (2025). Climate variability and Saharan dust intrusions over the Caribbean: Multi-year assessment of PM trends. Atmospheric Research, 302, 107236. https://doi.org/10.1016/j.atmosres.2024.107236

Nandram, A., Ramkissoon, A., & Joseph, S. (2025). Integrating air-quality data and transport policy for sustainable urban mobility in Trinidad and Tobago. Caribbean Journal of Earth and Environmental Science, 7(1), 55–68.

Thambiran, T., Pillay, K., & Wright, C. (2023). Air quality management in African cities: Lessons from the COVID-19 lockdown. Environmental Challenges, 13, 100762. https://doi.org/10.1016/j.envc.2023.100762

Venter, Z. S., Aunan, K., Chowdhury, S., & Lelieveld, J. (2020). COVID-19 lockdowns cause global air pollution declines. Proceedings of the National Academy of Sciences, 117(32), 18984–18990. https://doi.org/10.1073/pnas.2006853117

World Economic Forum. (2020, May 19). How we can keep enjoying cleaner air post-COVID-19. Retrieved from https://www.weforum.org/agenda/2020/05/5-steps-businesses-can-take-to-protect-air-quality-post-covid-19/

World Health Organization (WHO). (2021). WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva: WHO. Retrieved from https://www.who.int/publications/i/item/9789240034228

Zhou, R., Li, Q., & Zhang, M. (2024). Evaluating weekday–weekend air-quality shifts in post-lockdown megacities using machine-learning decomposition. Science of the Total Environment, 905, 167220. https://doi.org/10.1016/j.scitotenv.2023.167220