ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.2306

Spatiotemporal Patterns and Lagged Effects in Urban Air Quality: A Comparative Analysis of Two Central American Cities

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Abstract* — Air pollution remains a critical public health and sustainability challenge, particularly in rapidly urbanizing regions with limited regulatory monitoring infrastructure. While most urban air quality assessments rely on mean concentration comparisons and exceedance thresholds, less attention has been given to short-term temporal persistence dynamics that influence exposure duration. This study introduces the concept of urban atmospheric persistence to evaluate short-term retention of PM2.5 concentrations in two Central American urban systems using hourly open-access sensor data. A comparative time-series framework was applied to analyze lag-based autocorrelation (1–6 hours) over a multi-week period, including combustion-intensive celebration days. Results reveal strong immediate dependence in both cities (r = 0.53 Lag 1), but distinct decay trajectories thereafter. The city of San Pedro Sula exhibits sustained multi-hour persistence, including secondary reinforcement at Lag 3 (0.53), whereas City of Tegucigalpa demonstrates faster monotonic decay, approaching near-zero correlation by Lag 6. These findings suggest that urban systems may differ not only in pollution magnitude but also in atmospheric retention structure. The study contributes empirical evidence from an underrepresented region and demonstrates the analytical value of combining open sensor networks with time-series methods. Limitations include the absence of meteorological covariate integration and API-based retrieval constraints inherent to open-access platforms, which restricted the analysis to approximately 1000 hourly observations per monitoring location. Despite these constraints, the results provide a replicable framework for evaluating temporal persistence as a complementary indicator for urban sustainability assessment.

***Keywords*— PM2.5; autocorrelation; urban atmospheric persistence; time-series analysis; Central America.**

I. Introduction

Air pollution remains one of the leading environmental risk factors globally, particularly in rapidly urbanizing regions [1]–[3]. Fine particulate matter (PM2.5) has been consistently associated with increased cardiovascular morbidity, respiratory disease, and premature mortality [4], [5]. The 2021 WHO Global Air Quality Guidelines lowered recommended PM2.5 thresholds in response to growing epidemiological evidence demonstrating adverse health impacts even at relatively low concentrations [1].

In Latin America, particulate pollution represents a persistent public health and development challenge. [6]–[9]. Institutional assessments emphasize that reductions in PM2.5 exposure can yield measurable gains in life expectancy and economic productivity [6], [7]. However, regional monitoring capacity remains heterogeneous, and analytical approaches frequently rely on mean concentration comparisons or exceedance counts [8]–[10].

Traditional air quality assessments emphasize annual means, regulatory thresholds, and compliance indicators. Yet urban exposure is not determined solely by peak magnitude but also by the duration and persistence of pollutant shocks. A transient spike that dissipates rapidly may represent a different risk profile compared to a moderate peak that remains embedded in the atmosphere for multiple hours.

Time-series analysis provides methodological tools for characterizing temporal dependence and short-term memory in environmental data [11]–[14]. Autocorrelation functions (ACF) quantify lagged relationships between pollutant concentrations at time t and previous observations at time $t - k$, enabling evaluation of how rapidly atmospheric systems dissipate emission shocks [11], [12], [15].

While PM2.5 forecasting literature frequently incorporates lagged predictors and related temporal dynamics [16]–[21], comparative persistence analyses remain limited in Central America. Most regional studies emphasize descriptive statistics or daily averages, potentially obscuring short-term atmospheric memory structures.

This study introduces the concept of urban atmospheric persistence as a diagnostic framework to evaluate short-term retention dynamics of PM2.5 in two Central American urban systems. Using hourly data and lag-based autocorrelation, the research examines whether pollutant shocks dissipate at similar rates or whether distinct persistence regimes emerge.

The contribution of this study is threefold:

1) It shifts analytical focus from static averages to dynamic temporal retention.
2) It provides comparative evidence from an underrepresented region.
3) It proposes urban atmospheric persistence as a replicable metric for sustainability-oriented air quality analysis.

By integrating time-series methods with urban environmental assessment, this research expands the analytical toolkit available for policy-relevant air quality evaluation in developing urban contexts.

II. LITERATURE REVIEW AND THEORETICAL BACKGROUND

A. PM2.5 as a Public Health and Sustainability Priority

Fine particulate matter (PM2.5) is widely recognized as one of the most consequential ambient air pollutants due to its ability to penetrate deep into the respiratory system and enter systemic circulation [1]–[4]. Global burden assessments consistently rank ambient PM2.5 exposure among the top environmental risk factors contributing to mortality and morbidity [3], [4].

The Air Quality Life Index estimates that sustained exposure to elevated PM2.5 levels reduces average life expectancy across multiple regions, including Latin America [6]. Economic analyses further demonstrate that particulate pollution imposes substantial health-related financial costs on developing economies [7].

From a sustainability and governance perspective, air pollution is increasingly framed as a systemic urban development constraint [7]–[9]. Regional assessments highlight persistent monitoring gaps, uneven institutional capacity, and enforcement heterogeneity across Latin American cities [8], [9].

B. Open Data Platforms and Low-Cost Sensing in Data-Limited Regions

The expansion of open data platforms has significantly improved environmental data accessibility. OpenAQ aggregates publicly available air quality measurements and enables reproducible API-based environmental analytics [22].

Parallel to open data expansion, low-cost sensor ecosystems have increased spatial coverage in data-limited regions. Although originally designed for community-level environmental monitoring, recent evaluations demonstrate that low-cost PM sensors can provide scientifically usable data when properly interpreted [23], [24]. Quality assurance frameworks emphasize transparency in processing and acknowledgment of uncertainty [24], [25]. These developments are particularly relevant in regions where traditional regulatory-grade monitoring networks remain sparse.

C. Temporal Dependence and Urban Atmospheric Persistence

Time-series analysis provides foundational tools for evaluating temporal dependence structures in environmental data [11]–[14]. Autocorrelation functions are widely used to diagnose short-term memory and persistence behavior in pollutant time series [11], [15].

Air quality forecasting literature consistently demonstrates that lagged PM2.5 values are strong predictors of short-term concentration dynamics [18]–[21]. This empirical dependence suggests that pollutant shocks may persist beyond the immediate emission hour.

Comparative urban studies further indicate that temporal persistence patterns may differ across cities due to variations in emission continuity, dispersion conditions, and urban morphology [16], [17].

Building on these principles, this study operationalizes urban atmospheric persistence as the measurable degree of short-term lag dependence in hourly PM2.5 concentrations.

III. METHODOLOGY

A. Study Design

This study adopts a quantitative comparative time-series design to evaluate short-term persistence patterns of PM2.5 concentrations in two major urban environments in Central America. Rather than focusing exclusively on mean concentration levels, the analysis emphasizes lag-based temporal dependence structures through Pearson autocorrelation estimation [11], [12].

B. Data Sources and Sensor Characteristics

Hourly PM2.5 data were obtained from publicly available monitoring stations accessed via the OpenAQ platform [22]. All selected monitoring stations correspond to the same sensor technology class, ensuring measurement consistency across locations.

Four monitoring stations were included: (1) Three stations in San Pedro Sula, (2) One station in Tegucigalpa. The study period spans from December 8 to February 12. All values were reported in µg/m³. Only PM2.5 observations were retained.

C. Data Processing

Data were processed using structured time-series preparation procedures. The following steps were implemented:

1) Parameter filtering (PM2.5 only)
2) Datetime standardization
3) Removal of incomplete records
4) Aggregation of San Pedro Sula stations into a unified hourly mean series
5) Retention of Tegucigalpa as single-station series

Hourly resolution was preserved to maintain sufficient temporal granularity for autocorrelation estimation. Daily averaging would obscure short-term shock propagation dynamics [11].

D. Lag Construction and Autocorrelation Estimation

Lagged variables were constructed for 1–6-hour intervals. For each lag k, PM2.5(t) was correlated with PM2.5(t − k). Pearson correlation coefficients were computed following standard time-series dependence methodology [11], [12].

IV. RESULTS

This section presents the empirical findings of the comparative time-series analysis between San Pedro Sula (SPS) and Tegucigalpa (TGU). Results are structured in four stages: (1) descriptive statistics, (2) event-based comparison, (3) hourly distribution patterns, and (4) lag-based autocorrelation analysis to evaluate short-term atmospheric persistence.

A. Descriptive Statistics

Table I summarizes hourly PM2.5 statistics for both cities. San Pedro Sula recorded a higher mean concentration (14.71 µg/m³) than Tegucigalpa (4.82 µg/m³), along with greater upper-range values (P90: 28.69 vs. 12.21 µg/m³). Maximum concentrations reached 131.76 µg/m³ in San Pedro Sula and 94.22 µg/m³ in Tegucigalpa, indicating more intense peak events in the former.

TABLE I
DESCRIPTIVE STATISTICS OF HOURLY PM2.5 (µG/M³)

Statistics	San Pedro Sula	Tegucigalpa
Mean	14.71	4.82
Standard Deviation	13.66	7.85
90^{th} percentile	28.69	12.21
Maximum	131.76	94.22

San Pedro Sula exhibited a substantially higher baseline concentration (mean = 14.71 µg/m³) compared to Tegucigalpa (mean = 4.82 µg/m³). Variability was also greater in San Pedro Sula, as reflected by a higher standard deviation (13.66 vs. 7.85 µg/m³), indicating more pronounced fluctuations in particulate levels.

The 90th percentile in San Pedro Sula (28.69 µg/m³) more than doubled that of Tegucigalpa (12.21 µg/m³), suggesting a higher frequency of elevated exposure episodes. Maximum observed concentrations reached 131.76 µg/m³ in San Pedro Sula and 94.22 µg/m³ in Tegucigalpa, confirming the presence of extreme short-term pollution spikes in both systems, though more severe in San Pedro Sula.

Overall, descriptive results indicate that San Pedro Sula experiences both higher average pollution levels and greater episodic intensity relative to Tegucigalpa.

B. Event-Based Comparison

To examine emission amplification effects during combustion-intensive periods, PM2.5 concentrations were compared between celebration days and regular days.

During celebration days, San Pedro Sula reached an average concentration of 18.24 µg/m³, compared to 3.36 µg/m³ in Tegucigalpa. On regular days, average concentrations were 14.54 µg/m³ in San Pedro Sula and 4.90 µg/m³ in Tegucigalpa.

These results indicate that San Pedro Sula experienced an approximate 25% increase in average concentration during combustion-related events relative to regular days. In contrast, Tegucigalpa recorded lower celebration-day averages than regular-day levels, suggesting differences in combustion intensity, regulatory context, or atmospheric dispersion conditions during the same period.

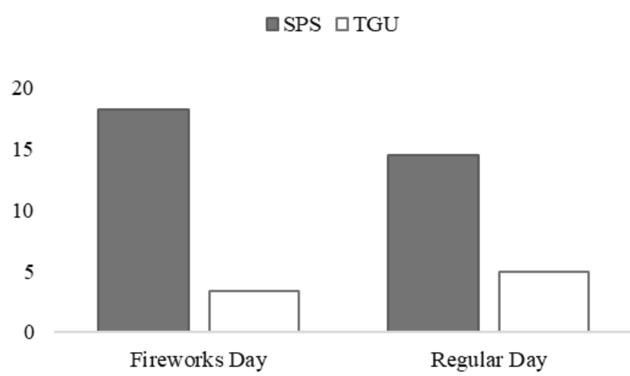

Fig. 1. Event-based comparison of average PM2.5 levels.

C. Hourly Distribution Patterns

Hourly concentration profiles were analyzed to assess diurnal emission structures and temporal variability.

San Pedro Sula demonstrates pronounced morning and evening peaks, consistent with commuter traffic cycles and sustained urban activity patterns. Concentrations increase during early morning hours, peak again in late afternoon, and decrease overnight.

Tegucigalpa exhibits lower amplitude variation and more moderate fluctuations across the 24-hour cycle. Although minor peaks are observable, the overall diurnal curve remains comparatively stable and less volatile relative to San Pedro Sula.

These differences suggest variation in emission intensity, traffic continuity, and potentially urban ventilation regimes. Fig. 2 illustrates the diurnal distribution of PM2.5 concentrations, revealing distinct emission and retention structures between the two cities.

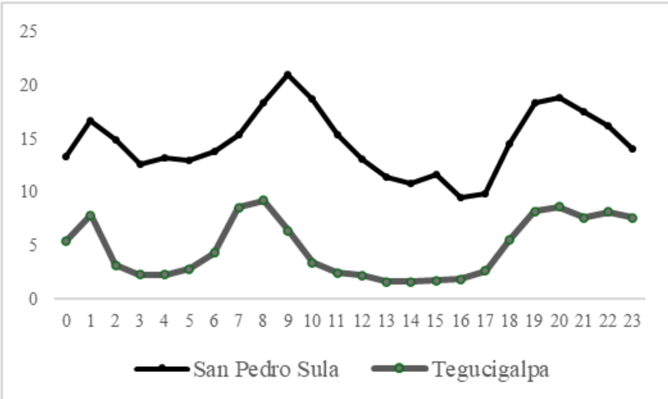

Fig. 2. Diurnal profile of mean hourly PM2.5 concentrations in San Pedro Sula and Tegucigalpa.

D. Autocorrelation and Lag Structure

To evaluate short-term atmospheric persistence, lag-based autocorrelation coefficients were computed for hourly lags ranging from 1 to 6 hours using Pearson correlation.

For Lag 3, which exhibited the most pronounced divergence, 1027 paired observations were available for San Pedro Sula and 993 paired observations for Tegucigalpa, ensuring statistical robustness of the correlation estimates.

TABLE II
LAG-BASED AUTOCORRELATION COEFFICIENTS WITH 95% CONFIDENCE INTERVALS

Lag (h)	SPS r	SPS 95% CI	TGU r	TGU 95% CI
1	0.53	[0.50, 0.56]	0.53	[0.50, 0.56]
2	0.42	[0.38, 0.46]	0.32	[0.28, 0.36]
3	0.53	[0.50, 0.56]	0.30	[0.26, 0.34]
4	0.28	[0.24, 0.32]	0.14	[0.10, 0.18]
5	0.21	[0.17, 0.25]	0.06	[0.02, 0.10]
6	0.28	[0.24, 0.32]	0.05	[0.01, 0.09]

SPS = San Pedro Sula; TGU = Tegucigalpa. CIs computed via Fisher's z-transformation ($n \geq 993$ for all lags).

Both cities exhibit strong immediate persistence at Lag 1 ($r = 0.53$), indicating that PM2.5 concentrations remain highly correlated one hour after initial measurement. However, divergence emerges beyond the first hour. San Pedro Sula maintains elevated correlation at Lag 3 ($r = 0.53$), revealing a secondary reinforcement pattern. In contrast, Tegucigalpa displays a monotonic decay trajectory, with correlation decreasing steadily from Lag 2 onward and approaching near-zero values by Lag 5 and Lag 6. At Lag 3, the non-overlapping 95% confidence intervals between cities (SPS: [0.50, 0.56]; TGU: [0.26, 0.34]) confirm that this divergence is statistically meaningful, representing a 76% relative difference in autocorrelation magnitude. The autocorrelation decay trajectories for both cities are illustrated in Fig. 3.

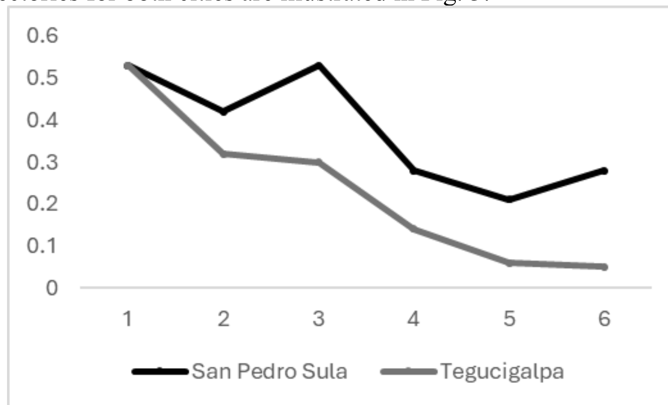

Fig. 3. Lag-based autocorrelation coefficients (1–6 hours) of hourly PM2.5 concentrations in San Pedro Sula and Tegucigalpa.

E. Robustness and Data Integrity Checks

To ensure the internal consistency and reliability of the lag-based persistence analysis, additional validation procedures were conducted.

First, duplicate timestamp records were evaluated across both cities. No duplicated hourly observations were detected within the analyzed period, ensuring temporal alignment and one-to-one pairing for lag construction.

Second, lagged correlations were not computed using built-in autocorrelation shortcuts but were manually implemented through explicit Pearson correlation formulations in DAX. For each lag k, the following procedure was applied:

1) Construction of a shifted hourly series PM_{t-k} for each city.
2) Computation of paired means.
3) Explicit calculation of covariance and standard deviation components.
4) Division of covariance by the product of standard deviations.

This manual formulation avoids black-box correlation outputs and guarantees transparency in the estimation process.

Third, the number of paired observations per lag was verified. For Lag 3—the lag exhibiting the strongest divergence—San Pedro Sula retained 1027 valid hourly pairs, and Tegucigalpa retained 993 valid pairs. These sample sizes exceed common minimum thresholds for stable Pearson correlation estimation in time-series applications [15], [16].

No anomalous structural breaks were observed in the time window analyzed. The persistence divergence pattern remained consistent across multiple lag levels, reinforcing the robustness of the identified atmospheric retention regimes.

V. DISCUSSION

A. Urban Atmospheric Persistence Regimes

The comparative analysis reveals that although both Tegucigalpa and San Pedro Sula exhibit strong immediate temporal dependence at Lag 1 ($r = 0.53$), their decay trajectories diverge substantially beyond the first hour.

San Pedro Sula demonstrates a non-monotonic decay pattern, including a secondary reinforcement at Lag 3 ($r = 0.53$), suggesting that pollutant concentrations remain statistically linked beyond immediate emission shocks. This pattern contrasts with Tegucigalpa, where autocorrelation declines steadily from Lag 1 (0.53) to Lag 6 (0.05), indicating faster dissipation and weaker short-term atmospheric memory.

From a time-series perspective, the persistence observed in San Pedro Sula is consistent with short-term autoregressive behavior frequently reported in PM2.5 studies [15], [16], [19]. However, the secondary reinforcement pattern at intermediate lags suggests overlapping emission cycles or delayed atmospheric stabilization processes, rather than simple exponential decay.

This finding supports the conceptual framing of urban atmospheric persistence as a measurable system property. While mean concentrations describe magnitude, autocorrelation decay profiles describe retention dynamics — a dimension directly relevant for cumulative exposure assessment.

B. Structural and Dispersion Mechanisms (Interpretative Analysis)

Although meteorological variables were not directly incorporated, the persistence profiles are consistent with differences in urban dispersion regimes.

Short-term PM2.5 persistence is commonly influenced by continuous emission intensity, urban morphology, atmospheric stability, ventilation corridors, and topographic constraints [18].

The sustained intermediate-lag correlation in San Pedro Sula suggests that emission shocks may overlap temporally before complete dissipation occurs. In contrast, the monotonic decay observed in Tegucigalpa indicates that concentration peaks are less likely to persist across multiple hourly windows.

It is important to emphasize that these interpretations remain inferential and are not causal claims. However, the divergence in decay structures indicates that atmospheric systems may differ in retention capacity even when short-term immediate dependence appears similar.

This reinforces the argument that evaluating cities solely through mean concentration comparisons may obscure critical structural differences in exposure duration.

C. Event Amplification and Persistence Interaction

Event-based comparisons further contextualize the lag structure results.

During combustion-intensive celebration days, San Pedro Sula exhibited a mean concentration of 18.24 µg/m³, compared to 3.36 µg/m³ in Tegucigalpa. On regular days, the difference remained substantial (14.54 µg/m³ vs. 4.90 µg/m³).

The higher baseline and amplified event response in San Pedro Sula, combined with its slower decay trajectory, suggest a compounding effect: elevated peaks coincide with extended persistence windows.

From an exposure perspective, this implies that not only are peak values higher, but the duration of elevated concentration states may also be longer. Such combined magnitude–duration interactions are relevant for health risk evaluation, as exposure intensity is influenced by both concentration and time [1]–[4].

D. Implications for Sustainability-Oriented Monitoring

Traditional air quality management frameworks prioritize: Annual means, Daily exceedance counts, Regulatory compliance thresholds.

However, the present findings indicate that temporal retention dynamics represent an additional diagnostic dimension.

Cities exhibiting slower decay profiles may require more aggressive real-time emission control during high-risk periods, structural mitigation strategies targeting continuous emission sources, ventilation-enhancing urban design interventions.

In contrast, cities with faster dissipation patterns may benefit more from targeted peak-reduction strategies rather than sustained suppression measures.

By operationalizing lag-based autocorrelation as a practical metric, this study proposes urban atmospheric persistence as a replicable tool for sustainability assessment in data-limited contexts. The method relies on high-frequency open data and does not require complex atmospheric modeling, making it accessible for municipalities with constrained technical resources.

E. Statistical Considerations and Robustness

Although the primary objective of this study was descriptive and comparative, several methodological considerations were addressed to ensure statistical robustness in the estimation of lag-based autocorrelation coefficients.

First, Pearson correlation was selected as the dependence metric due to its interpretability and widespread use in time-series analysis for evaluating short-term linear temporal dependence [15], [16]. Given the hourly resolution and the relatively large sample size for each city ($n > 900$ observations), correlation estimates are statistically stable and unlikely to be driven by random fluctuation.

Second, while full stationarity diagnostics (e.g., Augmented Dickey–Fuller tests) were not implemented, the analysis focuses on short-term lag structures (1–6 hours), where weak non-stationarity effects are less likely to distort dependence patterns compared to long-horizon modeling frameworks. The objective was not to construct predictive models, but to evaluate relative decay trajectories across urban systems under comparable temporal windows.

Third, 95% confidence intervals were computed for all autocorrelation coefficients using Fisher's z-transformation, enabling direct comparison of persistence levels across cities. The non-overlapping intervals at Lag 3 (SPS: [0.50, 0.56]; TGU: [0.26, 0.34]) confirm that the divergence in decay trajectories is statistically distinguishable and not attributable to sampling variability.

Fourth, autocorrelation coefficients were computed consistently using the same lag structure and identical methodological procedures across both cities. This ensures internal comparability and reduces methodological bias.

Importantly, the proposed framework of urban atmospheric persistence does not require complex autoregressive modeling to generate meaningful diagnostic insights. Instead, it offers a computationally accessible and reproducible metric for data-limited contexts, particularly in regions where extended regulatory datasets may not be available. In such settings, lag-based correlation analysis provides a transparent method to evaluate short-term atmospheric retention dynamics without overfitting or model overparameterization.

Finally, the interpretation of persistence patterns is intentionally conservative. Correlation values are treated as indicators of temporal dependence rather than causal mechanisms. The observed divergence in decay trajectories between cities is therefore interpreted as structural variation in atmospheric behavior, not as definitive attribution to specific meteorological or infrastructural factors.

This methodological positioning balances analytical rigor with contextual feasibility and supports the replicability of the proposed approach in other developing urban environments.

VI. CONCLUSIONS

This study analyzed hourly PM2.5 concentrations in San Pedro Sula and Tegucigalpa using lag-based autocorrelation to evaluate short-term urban atmospheric persistence. While both cities exhibited strong immediate temporal dependence ($r = 0.53$ Lag 1), their decay trajectories diverged significantly beyond the first hour.

San Pedro Sula demonstrated sustained multi-hour persistence, including a secondary reinforcement pattern at Lag 3 ($r = 0.53$), indicating that pollutant concentrations remain statistically linked beyond immediate emission shocks. In contrast, Tegucigalpa exhibited a monotonic decay pattern, with correlations approaching near-zero values by Lag 6.

These findings suggest that urban atmospheric systems differ not only in pollution magnitude but also in short-term retention dynamics. Mean concentrations capture exposure intensity, but lag-based decay profiles reveal exposure duration — a dimension directly relevant for cumulative health risk assessment.

By operationalizing urban atmospheric persistence as a measurable short-term dependence metric, this study expands the analytical toolkit available for sustainability-oriented air quality monitoring in data-limited contexts. The approach is computationally accessible, reproducible, and compatible with open-access sensor networks.

The results contribute empirical evidence from an underrepresented Central American region and demonstrate that temporal persistence analysis can complement traditional regulatory metrics to inform differentiated urban environmental strategies.

VII. LIMITATIONS AND FUTURE RESEARCH

This study has several limitations. First, meteorological covariates such as wind speed, atmospheric stability, and inversion dynamics were not incorporated into the modeling framework. As a result, interpretations regarding dispersion mechanisms remain inferential rather than causal.

Second, the dataset was constrained by public API retrieval limits, allowing extraction of approximately 1000 hourly observations per monitoring location. While sufficient for short-term lag estimation, this constraint limits the evaluation of seasonal or long-term persistence regimes.

Third, San Pedro Sula was represented by three aggregated stations, whereas Tegucigalpa was represented by a single monitoring point. Although sensor technology consistency was maintained, expanded spatial coverage would strengthen robustness and allow intra-urban heterogeneity analysis.

Future research may integrate meteorological modeling frameworks [11], autoregressive structures, and spectral analysis techniques to further characterize persistence dynamics. Expanding the comparative framework to additional Central American and Latin American urban centers would allow evaluation of whether identified persistence regimes represent structural regional patterns or city-specific atmospheric behavior.

Additionally, incorporating extended multi-season datasets would enable assessment of whether short-term urban atmospheric persistence varies across climatic regimes and emission cycles.

ACKNOWLEDGMENT

Generative AI tools were used exclusively for language editing and structural refinement. The authors retain full responsibility for the integrity of the data, methodology, and conclusions presented.

REFERENCES

[1] World Health Organization, WHO Global Air Quality Guidelines: PM2.5, PM10, Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide, Geneva, Switzerland, 2021.

[2] World Health Organization, “Ambient (outdoor) air pollution,” WHO Fact Sheet, 2023. [Online]. Available: https://www.who.int

[3] Health Effects Institute, State of Global Air 2023, Boston, MA, USA, 2023.

[4] Institute for Health Metrics and Evaluation (IHME), Global Burden of Disease Results Tool: Ambient PM2.5 Exposure Estimates, Seattle, WA, USA, 2023.

[5] S. Liu et al., “Global burden of cardiovascular diseases attributable to PM2.5 exposure,” The Lancet Regional Health, vol. 30, 2025.

[6] Air Quality Life Index (AQLI), University of Chicago EPIC, Air Quality Life Index: Latin America Fact Sheet, Chicago, IL, USA, 2024.

[7] World Bank, The Global Health Cost of Ambient PM2.5 Air Pollution, Washington, DC, USA, 2020.

[8] World Bank, World Development Indicators: PM2.5 Exposure Data, Washington, DC, USA, 2023.

[9] H. Riojas-Rodríguez et al., “Air pollution management and control in Latin America and the Caribbean: Implications for climate change,” Revista Panamericana de Salud Pública, vol. 40, no. 3, pp. 150–159, 2016.

[10] World Health Organization, WHO Ambient Air Quality Database (Update 2022), Geneva, Switzerland, 2022.

[11] G. E. P. Box, G. M. Jenkins, G. C. Reinsel, and G. M. Ljung, Time Series Analysis: Forecasting and Control, 5th ed., Hoboken, NJ, USA: Wiley, 2015.

[12] R. J. Hyndman and G. Athanasopoulos, Forecasting: Principles and Practice, 3rd ed., Melbourne, Australia: OTexts, 2021.

[13] J. D. Hamilton, Time Series Analysis, Princeton, NJ, USA: Princeton University Press, 1994.

[14] P. J. Brockwell and R. A. Davis, Introduction to Time Series and Forecasting, 3rd ed., New York, NY, USA: Springer, 2016.

[15] C. Chatfield, The Analysis of Time Series: An Introduction, 6th ed., Boca Raton, FL, USA: CRC Press, 2003.

[16] G. Shumway and D. Stoffer, Time Series Analysis and Its Applications, 4th ed., New York, NY, USA: Springer, 2017.

[17] L. Bermejo et al., “Time trends and persistence of PM2.5 in megacities,” Environmental Science and Pollution Research, vol. 30, pp. 11234–11248, 2023.

[18] G. A. Salini et al., “A study of the dynamic behaviour of fine particulate matter time series,” Aerosol and Air Quality Research, vol. 15, pp. 123–135, 2015.

[19] T. Liu et al., “Time series forecasting of air quality based on regional numerical modeling output,” Journal of Geophysical Research: Atmospheres, vol. 123, pp. 485–499, 2018.

[20] N. Zaini et al., “PM2.5 forecasting for an urban area based on deep learning,” Scientific Reports, vol. 12, 2022.

[21] Y. Chen et al., “Improved prediction of hourly PM2.5 concentrations using deep learning models,” Science of the Total Environment, vol. 912, 2024.

[22] OpenAQ, “OpenAQ API Documentation (v3),” OpenAQ, 2024. [Online]. Available: https://docs.openaq.org

[23] AirGradient, AirGradient Outdoor Monitor Technical Documentation, 2024. [Online]. Available: https://www.airgradient.com

[24] J. Barkjohn et al., “Air quality sensor experts convene: Current quality assurance considerations for credible data,” ACS ES&T Air, vol. 4, no. 3, 2024.

[25] U.S. Environmental Protection Agency, Air Sensor Guidebook, EPA, Washington, DC, USA, 2023.