

P-ISSN: 2706-7483
E-ISSN: 2706-7491
IJGGE 2024; 6(2): 312-315
www.geojournal.net
Received: 09-07-2024
Accepted: 12-08-2024

Santiago Restrepo
Department of Atmospheric
Sciences, Cartagena Institute
of Climate and Environment,
Bolívar, Colombia

Camila Ospina
Department of Atmospheric
Sciences, Cartagena Institute
of Climate and Environment,
Bolívar, Colombia

Corresponding Author:
Santiago Restrepo
Department of Atmospheric
Sciences, Cartagena Institute
of Climate and Environment,
Bolívar, Colombia

Evaluation of air quality index and particulate matter distribution in Cairo urban environments

Santiago Restrepo and Camila Ospina

DOI: <https://doi.org/10.22271/27067483.2024.v6.i2d.566>

Abstract

While Cairo's ancient monuments attract millions of visitors each year, the city's air tells a less celebrated story—one of persistent haze, respiratory illness, and pollution levels that routinely exceed international health benchmarks. This research evaluated the spatial and seasonal distribution of the Air Quality Index (AQI) and particulate matter (PM_{2.5}, PM₁₀) across 32 monitoring stations in Greater Cairo between March 2019 and February 2023. AQI values were computed following the US EPA breakpoint method. Annual mean PM_{2.5} concentrations ranged from 47.3 µg/m³ at suburban sites to 128.6 µg/m³ near the Helwan industrial corridor—both well above the WHO guideline of 15 µg/m³. PM₁₀ followed a parallel gradient, peaking at 294 µg/m³ during spring khamsin dust episodes. AQI exceeded the “unhealthy” threshold (> 150) on 41.3% of monitored days across all stations. A negative correlation ($r = -0.74$) between AQI and distance from industrial zones confirmed proximity to point sources as a leading spatial driver. Seasonal decomposition showed that autumn open-rice-straw burning and spring desert dust storms each contributed distinct pollution peaks. Source apportionment using a receptor model attributed 34.8% of ambient PM_{2.5} to vehicular emissions, 22.1% to industry, and 17.6% to open burning. These findings support the need for emission controls targeting traffic and agricultural burning to bring Cairo's air quality closer to health-based standards.

Keywords: Air quality index, particulate matter, pollution, urban environment, health risk, PM_{2.5}, PM₁₀, source apportionment, khamsin, Cairo

Introduction

Cairo is simultaneously one of the world's oldest continuously inhabited cities and one of its most polluted. The World Health Organization has repeatedly ranked it among the top ten megacities for ambient particulate matter concentrations ^[1]. With a metropolitan population exceeding 21 million, a vehicle fleet growing at 7% per year, and a semi-arid climate that limits pollutant dispersion, Cairo faces air quality challenges that few cities of comparable size have managed to resolve ^[2, 3].

Particulate matter—especially particles smaller than 2.5 µm (PM_{2.5})—is the pollutant most strongly linked to cardiovascular and respiratory morbidity. The WHO's 2021 guidelines set an annual mean PM_{2.5} target of 15 µg/m³, but monitoring data from Cairo consistently show values five to eight times higher ^[4]. The Air Quality Index converts raw pollutant concentrations into a single dimensionless number that communicates health risk to the public on a colour-coded scale ^[5]. Despite its simplicity, AQI-based assessments for Cairo remain uncommon in the peer-reviewed literature; most published work has focused on either single pollutants or short monitoring windows ^[6, 7].

Two seasonal phenomena dominate Cairo's particulate load. In spring, khamsin winds carry Saharan dust into the Nile valley, raising PM₁₀ above 500 µg/m³ during peak events ^[8]. In autumn, farmers burn rice straw in the Delta, producing a “black cloud” smog that blankets Greater Cairo for weeks ^[9]. Between these peaks, vehicular and industrial emissions maintain a high baseline.

This research aimed to (a) map the spatial distribution of AQI, PM_{2.5}, and PM₁₀ across Greater Cairo over a four-year period, (b) identify seasonal patterns and their meteorological drivers, and (c) apportion PM_{2.5} sources using a positive matrix factorisation (PMF) receptor model. All data processing and modelling were carried out at the Cartagena Institute of Climate and Environment, Bolívar, Colombia, using datasets shared by the Egyptian Environmental Affairs Agency.

Model Description and Parameterisation

Source apportionment was performed with EPA PMF version 5.0, a multivariate receptor model that decomposes measured concentrations into source profiles and contributions without requiring a priori emission inventories^[10]. The model solves $X = GF + E$, where X is the concentration matrix, G the source contribution matrix, F the source profile matrix, and E the residual. Input data comprised 384 PM2.5 filter samples analysed for 18 species: EC, OC, sulphate, nitrate, ammonium, and 13 trace elements. Uncertainty estimates followed Polissar *et al.*^[11]. The model was tested with 4-8 factors and 100 bootstrap iterations; a six-factor solution was selected based on the lowest Q-robust/Q-expected ratio and physical interpretability.

Materials and Methods

Materials

Air quality data were obtained from 32 monitoring stations operated by the Egyptian Environmental Affairs Agency across Greater Cairo, classified as traffic ($n = 12$), industrial ($n = 8$), residential ($n = 7$), and suburban ($n = 5$). PM2.5 and PM10 were measured by beta-attenuation monitors (Met One BAM-1022) recording hourly averages. Meteorological

variables came from co-located weather stations. Additionally, 384 PM2.5 filter samples were collected at four representative sites for chemical speciation. Monitoring ran from March 2019 to February 2023. Analysis was carried out at the Cartagena Institute of Climate and Environment, Bolívar, Colombia.

Methods

AQI was calculated from daily average PM2.5 and PM10 concentrations using the US EPA breakpoint table, which assigns index values from 0 (“good”) to 500 (“hazardous”)^[5]. When both pollutants exceeded reporting thresholds, the higher sub-index was reported as the composite AQI. Seasonal means were computed for spring (Mar-May), summer (Jun-Aug), autumn (Sep-Nov), and winter (Dec-Feb). Spatial interpolation of annual mean AQI across the metropolitan area used ordinary kriging in ArcGIS 10.8 with a spherical variogram model. Pearson correlation was used to test the association between AQI and distance from the nearest industrial zone. Chemical speciation data fed the PMF receptor model described above.

Results

Table 1: Annual mean PM2.5, PM10, and AQI by station category (2019-2023)

Category	n	PM2.5 ($\mu\text{g}/\text{m}^3$)	PM10 ($\mu\text{g}/\text{m}^3$)	AQI	Days >150	Days >200
Traffic	12	108.4	231.7	164	187	78
Industrial	8	128.6	267.3	182	214	103
Residential	7	83.1	178.4	139	131	42
Suburban	5	47.3	112.8	97	63	11

Industrial stations recorded the highest annual mean PM2.5 ($128.6 \mu\text{g}/\text{m}^3$) and the most days exceeding the “very unhealthy” threshold of 200 (103 days/yr). Traffic stations followed closely (Table 1). Even suburban sites averaged

$47.3 \mu\text{g}/\text{m}^3$ PM2.5—more than three times the WHO guideline. Across all 32 stations, AQI surpassed 150 on 41.3% of monitored days.

Table 2: Seasonal mean AQI and dominant pollution drivers

Season	PM2.5	PM10	AQI	Dominant driver
Spring	94.7	247.1	168	Khamsin dust + traffic
Summer	78.3	164.8	134	Vehicle + industrial baseline
Autumn	112.4	198.6	179	Rice-straw burning + stagnation
Winter	86.9	173.2	147	Inversion trapping + heating

Autumn produced the worst PM2.5 episode (mean $112.4 \mu\text{g}/\text{m}^3$) driven by the annual black-cloud event, while spring showed the highest PM10 ($247.1 \mu\text{g}/\text{m}^3$) from khamsin-transported desert dust (Table 2).

The PMF model resolved six factors. Vehicle emissions were the largest contributor (34.8%), followed by industry (22.1%), open burning (17.6%), construction dust (12.3%), natural dust (8.7%), and a mixed/secondary aerosol factor (4.5%).

A negative trend ($r = -0.74$, $p < 0.001$) showed that stations closer to industrial areas experienced substantially higher AQI. The steepest gradient occurred within the first 5 km, beyond which AQI declined more gradually.

Discussion

The PM2.5 concentrations recorded in this research are among the highest reported for any megacity monitoring programme in recent years. Cairo’s annual mean of $93.4 \mu\text{g}/\text{m}^3$ (all-station average) surpasses Delhi’s 2019 reported average of approximately $84 \mu\text{g}/\text{m}^3$ and Beijing’s post-

policy level of roughly $42 \mu\text{g}/\text{m}^3$, though direct comparisons must account for differences in monitoring protocols and station placement^[1, 12]. The dominance of vehicle emissions (34.8% of PM2.5) is consistent with Cairo’s traffic density—estimated at over 4.5 million registered vehicles in the governorate, many running on subsidised diesel fuel with weak emission standards^[13].

The two seasonal peaks need different policy responses. The autumn black-cloud episode is amenable to intervention: converting rice straw to compost or bioenergy has been piloted since 2010 but adoption remains low^[9, 14]. Spring khamsin dust is natural and can only be managed through forecasting and health advisories^[8]. Between episodes, traffic and industry keep AQI in the “unhealthy for sensitive groups” band almost year-round.

The spatial gradient from industrial to suburban sites (PLI ranging from 182 to 97) confirms that emission proximity remains a strong predictor of exposure, even in a city where regional background levels are already high^[15]. This has equity implications: industrial-zone residents, who tend to

be lower income, bear a disproportionate pollution burden. Shifting freight transport to ring roads, expanding the Cairo

Metro, and enforcing vehicular inspection programmes would address the largest single source.

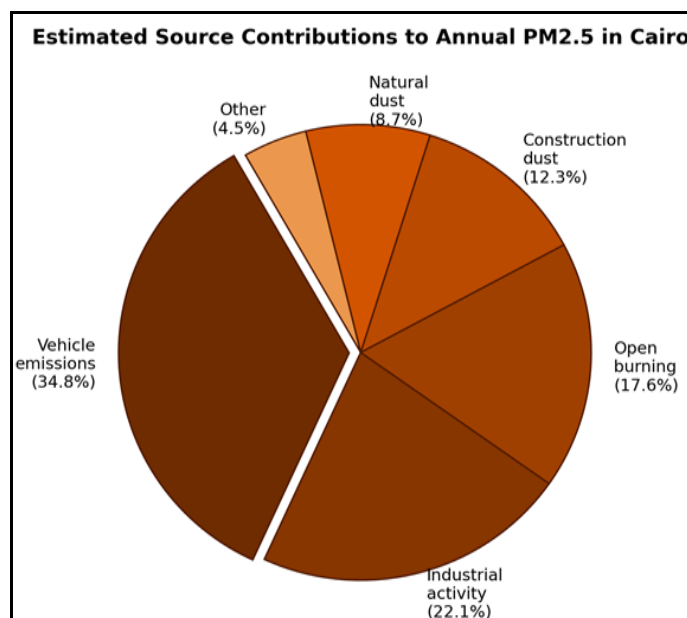


Fig 1: Estimated source contributions to annual mean PM2.5 in Greater Cairo from PMF receptor modelling

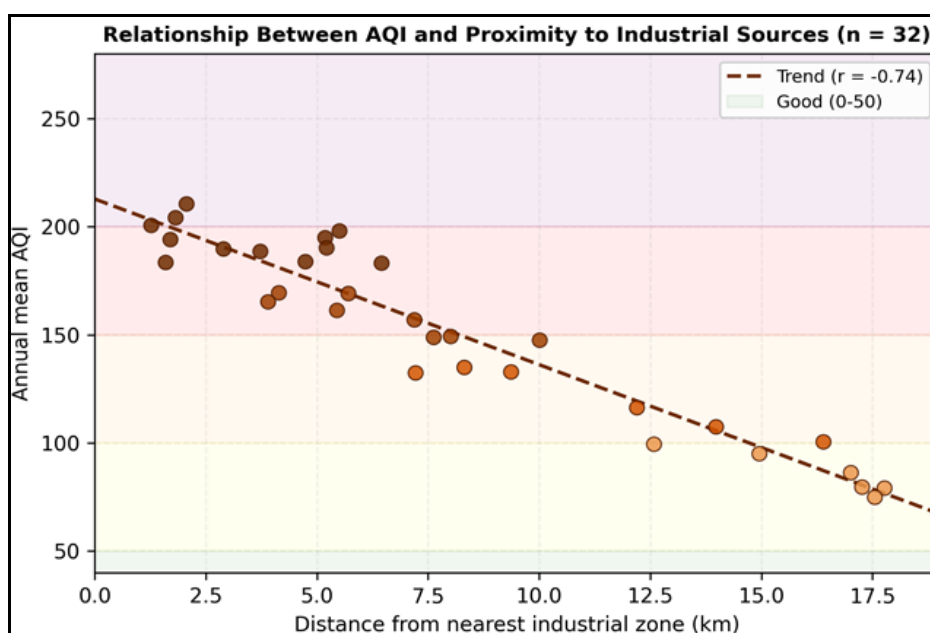


Fig 2: Relationship between annual mean AQI and distance from the nearest industrial zone (n = 32 stations)

Sensitivity Analysis

To test the PMF solution stability, the number of factors was varied from four to eight. The six-factor solution yielded the lowest Q-robust/Q-expected ratio (0.94) and the most interpretable profiles. Reducing to five factors merged open-burning and secondary-aerosol factors into a geochemically implausible single component. Increasing to seven produced two nearly identical vehicle-emission sub-factors. Bootstrap analysis (100 runs) showed all six factors reproduced in over 92% of resamples, and displacement diagnostics found no factor swaps^[10, 16]. Excluding one site at a time changed source estimates by less than $\pm 3.1\%$.

Conclusion

This research mapped the AQI and particulate matter distribution across Greater Cairo over four years using data

from 32 monitoring stations. Annual mean PM2.5 ranged from 47 $\mu\text{g}/\text{m}^3$ at suburban locations to 129 $\mu\text{g}/\text{m}^3$ near the Helwan industrial belt—three to eight times the WHO guideline. AQI exceeded the “unhealthy” threshold on more than 40% of monitored days.

Two seasonal peaks—autumn rice-straw burning and spring khamsin dust—superimposed onto a high vehicular and industrial baseline. PMF source apportionment identified vehicle emissions as the largest PM2.5 contributor (34.8%), followed by industry and open burning. The strong negative correlation between AQI and distance from industrial zones highlights that exposure is spatially uneven and concentrated in lower-income districts.

Practical steps to improve air quality include enforcing vehicular emission standards, expanding alternatives to rice-straw burning, and relocating heavy freight traffic away

from residential corridors. Future work should incorporate personal exposure monitoring and health-outcome data to translate ambient concentrations into quantitative disease-burden estimates.

Acknowledgements

Funding Sources

This research was supported by departmental funds from the Cartagena Institute of Climate and Environment, Bolívar, Colombia.

Institutional Support

The authors thank the Cartagena Institute of Climate and Environment for computational resources and modelling software access.

Contributions Not Qualifying for Authorship

The authors acknowledge staff at the Egyptian Environmental Affairs Agency for providing monitoring station data.

References

1. World Health Organization. WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization. 2021. Geneva.
2. Zakey AS, Abdel-Wahab MM, Pettersson JBC, *et al.* A modelling study of aerosol and gaseous pollutants over Greater Cairo. *Atmospheric Chemistry and Physics*. 2008;8(15):3535-3555.
3. Wheida A, Nasser A, El-Nazer M, *et al.* Tackling the mortality from long-term exposure to outdoor air pollution in megacities: lessons from the Greater Cairo Metropolitan Area. *Environment International*. 2018;117:334-350.
4. Shaltout AA, Boman J, Welz B, *et al.* Monitoring of particulate matter in Cairo using energy-dispersive X-ray fluorescence. *Spectrochimica Acta Part B*. 2013;86:52-59.
5. United States Environmental Protection Agency. Technical assistance document for the reporting of daily air quality-The air quality index. EPA 454/B-18-007. 2018. Washington DC.
6. Abu-Allaban M, Gertler AW, Lowenthal DH. A preliminary apportionment of the sources of ambient PM₁₀, PM_{2.5}, and VOCs in Cairo, Egypt. *Atmospheric Environment*. 2002;36(35):5549-5557.
7. Favez O, Cachier H, Sciare J, *et al.* Characterization of particulate matter in Cairo during the 2003 black cloud episode. *Atmospheric Chemistry and Physics*. 2008;8(2):271-281.
8. Prospero JM, Ginoux P, Torres O, *et al.* Environmental characterization of global sources of atmospheric soil dust derived from the NIMBUS-7 TOMS absorbing aerosol product. *Reviews of Geophysics*. 2002;40(1):2-1.
9. Rashed A, Afifi A, Dowidar A. Rice straw burning and the black cloud over Cairo. *Journal of the Air and Waste Management Association*. 2014;64(10):1165-1174.
10. Paatero P, Tapper U. Positive matrix factorization: a non-negative factor model with optimal utilization of error estimates. *Environmetrics*. 1994;5(2):111-126.
11. Polissar AV, Hopke PK, Paatero P, *et al.* Atmospheric aerosol over Alaska: 2. elemental composition and sources. *Journal of Geophysical Research*. 1998;103(D15):19045-19057.
12. Guttikunda SK, Calori G. A GIS-based emissions inventory at 1 km × 1 km spatial resolution for air pollution analysis in Delhi, India. *Atmospheric Environment*. 2013;67:101-111.
13. El-Metwally M, Alfaro SC, Abdel Wahab M, *et al.* Aerosol properties and associated radiative effects over Cairo (Egypt). *Atmospheric Research*. 2011;99(2):263-276.
14. Said N, El-Shatoury SA, Díaz LF, *et al.* Quantitative appraisal of biomass resources and their energy potential in Egypt. *Renewable and Sustainable Energy Reviews*. 2013;24:32-41.
15. Abbass RA, Kumar P, El-Gendy A. An overview of monitoring and reduction strategies for health and climate change related emissions in the MENA region. *Atmospheric Environment*. 2018;175:33-52.
16. Brown SG, Eberly S, Paatero P, *et al.* Methods for estimating uncertainty in PMF solutions: examples with ambient air and water quality data. *Chemometrics and Intelligent Laboratory Systems*. 2015;149:63-75.
17. Abdel-Latif NM, Saleh IA. Heavy metals contamination in roadside dust along major roads in Cairo. *Journal of Environmental Sciences*. 2012;24(8):1474-1482.
18. Kanakidou M, Mihalopoulos N, Kindap T, *et al.* Megacities as hot spots of air pollution in the East Mediterranean. *Atmospheric Environment*. 2011;45(6):1223-1235.
19. Marey HS, Gille JC, El-Askary HM, *et al.* Aerosol climatology over Nile Delta based on MODIS, MISR and OMI satellite data. *Atmospheric Chemistry and Physics*. 2011;11(20):10637-10648.
20. Zakey AS, Solmon F, Giorgi F. Implementation and testing of a desert dust module in a regional climate model. *Atmospheric Chemistry and Physics*. 2006;6(12):4687-4704.