

Spatiotemporal Distribution of Ambient PM_{2.5} in Iran Using ACAG Satellite-Derived Data (2019–2023): A Ground Based Validation in Mashhad

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Abstract

Background: Fine particulate matter (PM_{2.5}) is a major environmental health concern, but its spatial and temporal distribution across Iran remains incompletely characterized because ground monitoring networks have uneven coverage. This study assessed nationwide annual mean PM_{2.5} variations across 31 Iranian provinces during 2019–2023 using a standardized satellite-derived dataset. **Methods:** Annual mean PM_{2.5} data were obtained from the Atmospheric Composition Analysis Group satellite product. Provincial means were estimated using zonal statistics in ArcGIS. Population data from the Statistical Center of Iran were used to calculate population-weighted national annual means, yielding 155 province-year observations. Spatial distributions and changes between 2019 and 2023 were evaluated using GIS. Temporal differences were assessed with the Friedman test, followed by Wilcoxon signed-rank tests with Bonferroni adjustment. Local validation used Mashhad ground measurements (2019–2022) and Pearson correlation, RMSE, and mean bias. **Results:** Substantial spatial and temporal heterogeneity was observed. The population-weighted national mean PM_{2.5} was 31.78 µg/m³ in 2019, decreased to 28.17 µg/m³ in 2020, and increased to 31.76, 32.54, and 33.43 µg/m³ in 2021–2023. The national mean rose by 5.2% between 2019 and 2023. Significant temporal differences were found (Friedman $\chi^2 = 65.342$, $df = 4$, $P < 0.001$). Bushehr had the highest five-year mean (52.45 ± 6.40 µg/m³), while Ardabil had the lowest (20.11 ± 0.77 µg/m³). The interprovincial difference increased from 27.26 to 40.84 µg/m³. PM_{2.5} increased in 21 of 31 provinces; Bushehr showed the largest absolute increase (+13.69 µg/m³), and Golestan the greatest relative increase (+43.43%). Mashhad validation showed moderate correlation ($R = 0.645$, RMSE = 8.39 µg/m³, mean bias = +8.10 µg/m³), indicating satellite overestimation but reliable temporal and spatial agreement. **Conclusion:** PM_{2.5} in Iran showed significant temporal variation and marked geographical heterogeneity during 2019–2023, with a decline in 2020 followed by increases through 2023. National averages may obscure subnational disparities, supporting geographically targeted monitoring and control. Satellite estimates were useful for relative comparisons but require bias correction and stronger ground networks. This framework provides a national baseline for future environmental and epidemiological research.

Keywords: PM_{2.5}; air pollution; satellite derived data; spatial analysis; temporal trends; Iran; environmental health

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Introduction

Air pollution is a major environmental challenge threatening public health, ecosystem sustainability, and socioeconomic development. Among air pollutants, fine particulate matter with an aerodynamic diameter of ≤ 2.5 μm (PM_{2.5}) is of particular concern because of its ability to penetrate deeply into the respiratory system, cross the alveolar capillary barrier, and enter the systemic circulation. Extensive epidemiological and toxicological evidence has linked both short and long term PM_{2.5} exposure to cardiovascular and respiratory diseases, lung cancer, cerebrovascular disease, metabolic dysfunction, adverse pregnancy outcomes, and premature mortality. Accordingly, ambient PM_{2.5} is recognized as one of the leading environmental risk factors contributing to the global burden of disease and avoidable mortality [1, 2]. Accurate characterization of its spatial distribution and temporal variability is therefore essential for exposure assessment, epidemiological research, burden of disease estimation, and evidence based air quality management [3].

Reliable assessment of PM_{2.5} exposure requires adequate spatial coverage and temporal consistency. However, conventional ground-based monitoring networks are often sparse and unevenly distributed, particularly in rural, suburban, mountainous, and resource limited regions, limiting their ability to capture spatial heterogeneity and support representative nationwide assessments [4, 5]. Satellite remote sensing has therefore become an important complementary approach, enabling large-scale and spatially continuous estimation of PM_{2.5} by integrating aerosol optical depth (AOD), ground based measurements, meteorological variables, chemical transport models, and geospatial information [4]. Among available global products, PM_{2.5} datasets developed by the Atmospheric Composition Analysis Group (ACAG) integrate satellite observations, atmospheric chemical transport modeling, and calibrated ground measurements to provide globally consistent estimates with near global coverage. These datasets have become valuable resources for long term exposure assessment, environmental epidemiology, burden of disease analyses, and national scale air quality research, particularly where monitoring infrastructure is limited [6, 7]. Although uncertainties related to atmospheric conditions, aerosol composition, meteorology, and regional emission characteristics remain, continued improvements in satellite retrieval algorithms, chemical transport models, and calibration procedures have enhanced the reliability of these products for large scale environmental and epidemiological investigations [4, 7].

Iran faces substantial air pollution challenges associated with rapid urbanization, industrial development, high energy demand, fossil fuel use, transportation emissions, and recurrent dust events. In a nationwide assessment covering 429 counties and 31 provinces, the annual population weighted PM_{2.5} concentration in 2018 was estimated at 30.1 $\mu\text{g}/\text{m}^3$ using ground monitored data and 38.6 $\mu\text{g}/\text{m}^3$ using satellite based estimates; satellite derived

exposure was associated with approximately 58,873 premature deaths and an economic loss of about US\$12.8 billion [8]. City level evidence has similarly demonstrated a substantial and persistent PM_{2.5} burden. Nevertheless, existing Iranian evidence remains geographically and temporally heterogeneous, as many studies have focused on specific cities or industrial areas and have differed in study period, duration, measurement approach, spatial coverage, and analytical methodology. This heterogeneity limits direct comparisons across regions and time and prevents a consistent characterization of the nationwide spatial distribution and temporal evolution of PM_{2.5} [9].

Recent advances in globally harmonized satellite derived PM_{2.5} datasets provide an opportunity to overcome these limitations. The ACAG Version 6 product offers annual PM_{2.5} estimates using a globally consistent methodology and sufficiently high spatial resolution for national and subnational assessments. Its standardized framework enables direct comparison across geographical regions and time periods and supports the identification of pollution hotspots, regional disparities, and temporal trends [4]. However, although ACAG derived products have been widely used in global burden of disease assessments and international environmental studies, their potential for comprehensive nationwide characterization of recent PM_{2.5} patterns across Iran has not yet been fully explored [10]. Existing Iranian studies have primarily relied on ground based monitoring, city specific analyses, or regional modeling, and nationally consistent information on recent spatiotemporal variation across all provinces remains limited [11, 7].

Therefore, the present study aimed to comprehensively characterize the spatiotemporal distribution of ambient PM_{2.5} across Iran using the ACAG satellite derived annual PM_{2.5} dataset for 2019–2023. Provincial mean concentrations and interannual variations were evaluated, spatial disparities among provinces were quantified, and nationwide PM_{2.5} patterns were visualized using GIS based mapping. By providing a harmonized assessment of recent PM_{2.5} concentrations across all provinces, this study provides a consistent evidence base for environmental surveillance, exposure assessment, future epidemiological research, and the development of both national and geographically targeted air quality management strategies.

Materials and Methods

Study area

Iran is located in southwestern Asia between 25°–40° N and 44°–64° E and covers approximately 1.65 million km². The country exhibits substantial geographical and climatic diversity, including humid northern coastal regions, extensive arid and semi-arid interiors, and mountainous areas dominated by the Alborz and Zagros ranges. These geographical characteristics influence atmospheric circulation, pollutant dispersion, and precipitation patterns, contributing to considerable spatial variability in ambient PM_{2.5} concentrations.

Iran is affected by both anthropogenic emission sources including transportation, industry, fossil-fuel combustion,

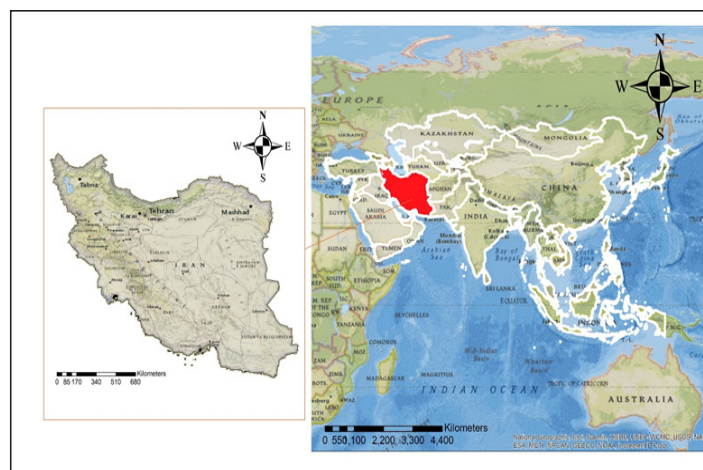


Figure 1. Location of Iran in Asia and the Middle East and the Spatial Distribution of the 31 Provinces Included in the Study

and urbanization and natural sources such as recurrent dust storms and transboundary mineral dust transport, particularly in western, southwestern, and southeastern regions. The entire territory of Iran was considered the study domain, and analyses were conducted for all 31 provinces to enable consistent nationwide comparison during 2019–2023 (Figure 1) [12].

Satellite derived PM_{2.5} data

Annual ambient PM_{2.5} concentration data were obtained from the Atmospheric Composition Analysis Group (ACAG) global surface PM_{2.5} dataset. The ACAG product was selected because it provides spatially continuous estimates of annual mean surface PM_{2.5} concentrations across regions where ground based monitoring networks are spatially heterogeneous or unavailable. The dataset integrates satellite based aerosol observations with atmospheric chemical transport modeling and ground based observations to generate globally consistent estimates of surface PM_{2.5} concentrations. This integrated framework enables the estimation of PM_{2.5} concentrations over both monitored and unmonitored areas and provides a consistent basis for spatial and temporal comparisons across large geographical domains. For the present analysis, the annual mean PM_{2.5} product from the ACAG Version 6 dataset was used [7, 13]. Five consecutive annual datasets corresponding to 2019, 2020, 2021, 2022, and 2023 were downloaded and processed independently. The spatial resolution of the raster data was approximately $0.01^\circ \times 0.01^\circ$, referenced to the WGS 1984 geographic coordinate system. The use of annual mean data was intended to minimize the influence of short term temporal fluctuations and provide a consistent measure of long term ambient PM_{2.5} exposure for each geographical unit. All annual datasets were processed using the same spatial reference, spatial resolution, and analytical procedures to ensure comparability across years.

Data preprocessing and spatial standardization

The downloaded annual PM_{2.5} raster datasets were imported into ArcGIS for spatial preprocessing and analysis. Before extraction of provincial level estimates,

the coordinate reference system, spatial extent, raster resolution, and data structure of all five annual datasets were examined to ensure consistency. The annual PM_{2.5} rasters were clipped to the geographical boundary of Iran using the national administrative boundary layer. A polygon shapefile representing the 31 provinces of Iran was subsequently used as the spatial unit for aggregation. Quality control was performed before statistical analysis. Raster cells containing missing or invalid values were excluded from calculations. The same provincial boundaries and processing procedure were applied to all five years to prevent methodological differences from introducing artificial spatial or temporal variability.

Provincial-level PM_{2.5} estimation and population-weighted national exposure

To characterize the spatial distribution of ambient PM_{2.5} across Iran, annual mean PM_{2.5} concentrations were estimated separately for each of the 31 provinces for each year from 2019 to 2023. The annual ACAG PM_{2.5} raster datasets were spatially overlaid with Iran's administrative boundary layer, and provincial-level concentrations were derived using the Zonal Statistics tool in ArcGIS. Each province was defined as an individual spatial zone, and the corresponding annual PM_{2.5} raster served as the input value dataset. For each province and study year, the arithmetic mean of all valid raster cell values within the provincial boundary was calculated to represent the annual mean ambient PM_{2.5} concentration. The same provincial boundaries, raster-processing workflow, and analytical procedures were consistently applied across all five study years to ensure temporal comparability. This procedure generated a structured dataset comprising 155 province-year observations (31 provinces $\times$ 5 years), with PM_{2.5} concentrations expressed in $\mu\text{g}/\text{m}^3$. These provincial estimates were subsequently used to quantify spatial variability among provinces, assess temporal changes, calculate absolute and relative changes in PM_{2.5} concentrations between 2019 and 2023, and produce the spatial distribution and temporal change maps presented in the subsequent analyses. To obtain a population-

representative estimate of national PM_{2.5} exposure, annual provincial population estimates for 2019–2023 were obtained from the Statistical Center of Iran (SCI). These estimates were based on the 2016 Population and Housing Census as the reference baseline and were projected using the standard cohort-component method, with annual values for the intercensal period derived through linear interpolation between the 2016 census counts and the SCI's official 2026 provincial population projections [14]. No provincial boundary changes occurred during 2019–2023 that would affect comparability across years.

The annual population estimates were matched with the corresponding provincial PM_{2.5} concentrations, and the population-weighted national mean PM_{2.5} concentration for each year was calculated as:

$$PM_{2.5}^{weighted} = (\sum (C_i \times P_i)) / (\sum P_i)$$

where C_i represents the annual mean PM_{2.5} concentration in province i and P_i represents the corresponding provincial population.

This approach ensured that more populous provinces contributed proportionally more to the national exposure estimate, while the unweighted provincial means were retained for describing spatial heterogeneity and repeated-measures statistical analyses. The ACAG Version 6 product has been extensively validated against ground-based measurements in multiple global and regional studies [7]. In the present study, a local validation was performed using ground-based measurements from Mashhad (Section 2.8). However, the spatial heterogeneity and temporal incompleteness of Iran's ground-monitoring network preclude consistent province-year paired validation across all 31 provinces. Therefore, ACAG estimates were considered the best available spatially continuous exposure dataset for this nationwide assessment and were interpreted as satellite-derived ambient PM_{2.5} concentrations. The uncertainties inherent to the underlying data-fusion methodology are acknowledged and discussed in the Limitations section.

Assessment of temporal variation

Temporal variation in PM_{2.5} concentrations was assessed at both the national and provincial levels. For each year, the mean PM_{2.5} concentration across the 31 provinces was calculated to characterize the overall temporal pattern of ambient PM_{2.5} across Iran. These annual national estimates were subsequently used to generate a temporal trend plot covering the period 2019–2023. At the provincial level, changes between the beginning and end of the study period were quantified as:

$$\Delta PM_{2.5} = PM_{2.5,2023} - PM_{2.5,2019}$$

A positive $\Delta PM_{2.5}$ value indicated an increase in the annual mean PM_{2.5} concentration between 2019 and 2023, whereas a negative value indicated a decrease. The magnitude of relative change was additionally calculated as:

$$\%Change = (PM_{2.5,2023} - PM_{2.5,2019}) / PM_{2.5,2019} \times 100$$

This approach enabled identification of provinces experiencing the greatest increases or decreases in annual PM_{2.5} concentrations during the study period.

Spatial analysis and mapping

Geospatial analyses were performed using ArcGIS to characterize the spatial distribution of PM_{2.5} across Iran. Separate provincial level choropleth maps were generated for each year from 2019 to 2023. To facilitate meaningful visual comparison between years, the same classification framework and concentration scale were applied to all annual maps whenever technically feasible. This approach allowed areas with persistently high or low PM_{2.5} concentrations to be readily identified and enabled visual assessment of changes in the geographical distribution of pollution over time. In addition, a difference map was generated based on the change in annual mean PM_{2.5} concentration between 2019 and 2023. Provinces were categorized according to whether they experienced an increase or decrease in PM_{2.5} concentrations during the study period.

Statistical analysis

Descriptive statistics, including the mean, standard deviation, minimum, maximum, and range, were computed to summarize the distribution of provincial PM_{2.5} concentrations for each study year. Given the repeated measures structure of the dataset (the same 31 provinces measured across five consecutive years), temporal changes were evaluated using non parametric methods.

The Shapiro–Wilk test was applied as a preliminary check for normality of the annual provincial PM_{2.5} distributions. Deviations from normality were observed across multiple years ($P < 0.05$). Consequently, the Friedman test was selected as a conservative non parametric alternative to repeated measures ANOVA to assess overall temporal differences across the five study years, as this approach does not rely on the assumption of multivariate normality, which is particularly appropriate given the moderate sample size ($n = 31$ provinces).

The Friedman test revealed a statistically significant overall difference in provincial PM_{2.5} concentrations across the five years ($\chi^2(4) = 65.342$, $N = 31$, $P < 0.001$). To identify specific interannual differences, post hoc pairwise comparisons were performed using the Wilcoxon signed rank test. To control the family wise error rate arising from multiple comparisons, a Bonferroni correction was applied. Given that ten pairwise comparisons were conducted, the significance threshold was adjusted to $\alpha = 0.005$ ($0.05 / 10$).

All statistical analyses were performed using IBM SPSS Statistics, version 27.0 (IBM Corp., Armonk, NY, USA). A two sided significance level was considered, with the adjusted threshold of $P < 0.005$ applied for pairwise comparisons to ensure the robustness of the inferential conclusions.

Table 1. Population Weighted National Mean PM_{2.5} Concentrations in Iran, 2019–2023

Year	Unweighted provincial mean (µg/m ³)	Population weighted national mean (µg/m ³)	Total population (thousand)
2019	31.38	31.78	82,711
2020	28.08	28.17	83,410
2021	31.58	31.76	84,053
2022	32.51	32.54	84,700
2023	33.37	33.43	85,327

Note: PM_{2.5} concentrations are expressed in µg/m³. Population weighted national means were calculated by weighting annual provincial PM_{2.5} concentrations by the corresponding provincial population estimates.

Local validation using ground-based monitoring data from Mashhad

To assess the reliability of the ACAG satellite-derived PM_{2.5} estimates in an Iranian urban context, we conducted a local consistency check using ground-based measurements from Mashhad, the second-most populous city in Iran. Daily PM_{2.5} concentrations were obtained from the regulatory monitoring network of Mashhad, which comprises 26 stations distributed across the city. For each year, we first excluded stations with less than 70% data coverage to ensure representativeness and removed unrealistic outliers (values > 500 µg/m³). The annual mean PM_{2.5} concentration for Mashhad was then calculated as the arithmetic mean of daily means across all eligible stations. This procedure yielded annual means for the years 2019–2022 (17.33, 18.84, 20.46, and 24.92 µg/m³, respectively). The year 2023 was excluded from the validation because only 8 stations met the data coverage criterion, leading to a biased representation of the city-wide average.

The annual ground-based means were then compared with the corresponding ACAG satellite-derived estimates for the same years, extracted for the geographic area of Mashhad. We calculated the Pearson correlation coefficient (R) and the coefficient of determination (R²) to assess linear agreement, the Root Mean Square Error (RMSE) to quantify absolute error, and the mean bias (satellite minus ground) to identify systematic over- or underestimation. All statistical analyses were performed using IBM SPSS Statistics, version 27.0 (IBM Corp.,

Armonk, NY, USA). This validation was intended as a local indicator of the general consistency of the ACAG product in Iran, rather than a comprehensive nationwide validation, given the spatial heterogeneity of monitoring networks across the country.

Results

Spatial distribution of annual mean PM_{2.5} across Iran

A total of 155 province-year observations representing annual mean PM_{2.5} concentrations across Iran's 31 provinces were analyzed for the period 2019–2023. Substantial geographical heterogeneity was observed throughout the study period, with consistently higher concentrations in several southern, southwestern, southeastern, and central provinces, including Bushehr, Khuzestan, Sistan and Baluchestan, Kerman, and Kohgiluyeh and Boyer-Ahmad, whereas comparatively lower concentrations were generally observed in northern and northwestern provinces, particularly Ardabil, Gilan, and North Khorasan (Figure 2).

Provincial PM_{2.5} concentrations ranged from 20.86–48.12 µg/m³ in 2019, 19.88–46.56 µg/m³ in 2020, 19.72–48.88 µg/m³ in 2021, 19.12–56.91 µg/m³ in 2022, and 20.96–61.80 µg/m³ in 2023. Bushehr consistently recorded the highest annual concentrations, whereas Ardabil remained the least polluted province throughout the study period. The mean concentration across the 31 provinces declined from 31.38 µg/m³ in 2019 to 28.14

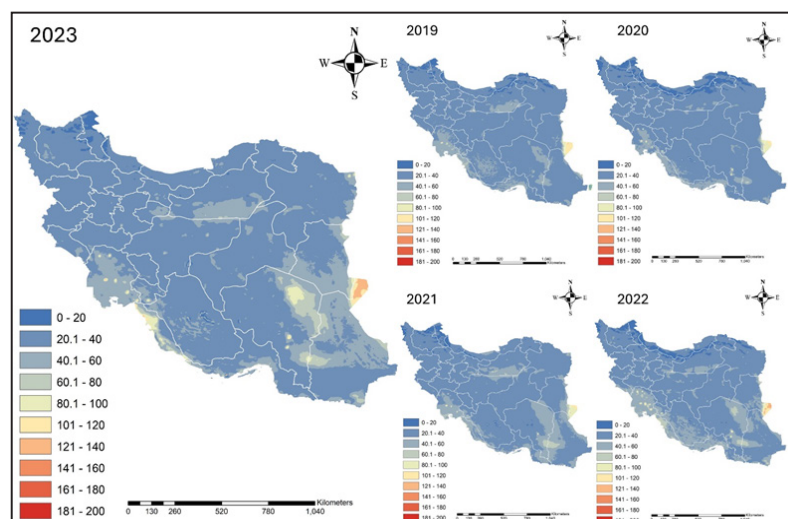


Figure 2. Spatial Distribution of Annual Mean PM_{2.5} Concentrations Across the 31 Provinces of Iran During 2019–2023.

Table 2. Annual Mean PM_{2.5} Concentrations (µg/m³) Across the 31 Provinces of Iran During 2019–2023

Province	2019	2020	2021	2022	2023	Five year mean
East Azerbaijan	26.27	23.02	25.09	28.36	27.68	26.08
West Azerbaijan	23.86	22.5	23.25	25.44	25.93	24.2
Ardabil	20.86	19.88	19.72	19.12	20.96	20.11
Isfahan	33.3	27.8	31.97	33.24	33.59	31.98
Alborz	29.08	25.01	26.93	25.81	28.92	27.15
Ilam	33.49	31.06	34.1	39.45	35.49	34.72
Bushehr	48.12	46.56	48.88	56.91	61.8	52.45
Tehran	32.29	27.12	30.58	28.99	31.74	30.14
Chaharmahal and Bakhtiari	32.64	26.22	27.78	30.83	32.45	29.98
South Khorasan	31.96	28.68	34.16	34.15	37.39	33.27
Razavi Khorasan	28.16	27.15	32.14	31.37	34.06	30.58
North Khorasan	21.84	19.89	25.76	22.98	26.6	23.42
Khuzestan	44.22	40.74	44.16	52.42	44.37	45.18
Zanjan	25.95	23	23.52	25	25.34	24.56
Semnan	33.51	28.4	37.33	30.94	35.88	33.21
Sistan and Baluchestan	40.15	36.27	43.81	44.03	46.59	42.17
Fars	37.59	32.75	33.14	38.29	35.73	35.5
Qazvin	26.86	23.59	25.75	25.76	26.55	25.7
Qom	35.04	32.56	35.52	36.54	36.51	35.23
Kurdistan	28.06	24.92	27.5	28.33	27.89	27.34
Kerman	35.67	30.79	37.16	39.06	43.27	37.19
Kermanshah	30.46	28.96	31.83	32.68	30.65	30.92
Kohgiluyeh and Boyer Ahmad	37.96	33.97	36.11	39.34	39.43	37.36
Golestan	21.78	20.4	29.79	25.08	31.24	25.66
Gilan	23.07	20.13	23.16	19.62	23.91	21.98
Lorestan	32.58	28.25	31.82	33.54	31.96	31.63
Mazandaran	25.33	20.4	28.91	21.6	26.74	24.6
Markazi	31.92	27.04	28.8	31.37	30.51	29.93
Hormozgan	39.66	38.88	39.7	43.19	37.66	39.81
Hamadan	29.86	28.11	29.09	31.83	29.95	29.77
Mean across 31 provinces	31.38	28.14	31.58	32.51	33.36	31.39

µg/m³ in 2020 before increasing to 33.36 µg/m³ in 2023, indicating a temporary decline followed by a subsequent increase in nationwide pollution levels.

Temporal variation in PM_{2.5} concentrations

The population-weighted national mean PM_{2.5} concentration exhibited a pronounced non-linear temporal pattern (Table 1). National exposure declined from 31.78 µg/m³ in 2019 to 28.17 µg/m³ in 2020 before increasing to 31.76, 32.54, and 33.43 µg/m³ in 2021, 2022, and 2023, respectively. Overall, the population-weighted national mean increased by 1.65 µg/m³, corresponding to a 5.2% increase between 2019 and 2023.

The population-weighted estimates closely paralleled the corresponding unweighted provincial means, indicating that population weighting did not substantially alter the overall temporal pattern but provided a more representative estimate of national population exposure.

Provincial differences in PM_{2.5} concentrations

Marked differences were observed among provinces throughout the study period (Table 2). Across the five-year period, Bushehr had the highest average PM_{2.5} concentration (52.45 ± 6.40 µg/m³), whereas Ardabil had the lowest (20.11 ± 0.77 µg/m³). The provincial ranking remained broadly stable over time, with Bushehr, Khuzestan, and Sistan and Baluchestan consistently appearing among the most polluted provinces. An important finding was the widening gap between provinces. The difference between the highest and lowest annual provincial concentrations increased from 27.26 µg/m³ in 2019 to 40.84 µg/m³ in 2023, indicating increasing spatial inequality in PM_{2.5} exposure.

Changes in PM_{2.5} concentrations between 2019 and 2023

PM_{2.5} concentrations changed substantially across provinces during the study period (Figure 3). Between 2019 and 2023, concentrations increased in 21 provinces and decreased in 10 provinces, with absolute changes

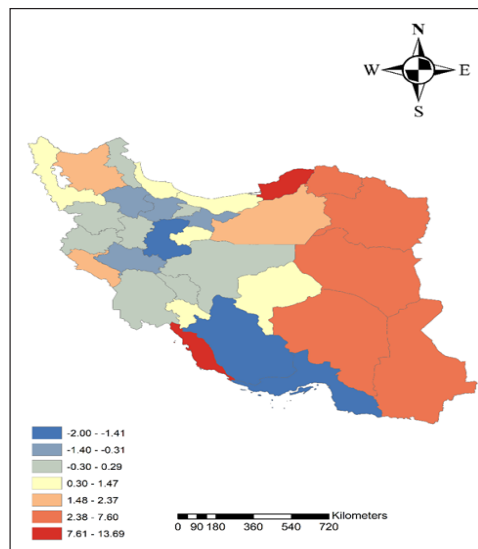


Figure 3. Spatial distribution of absolute changes in annual mean PM_{2.5} concentrations ($\Delta\text{PM}_{2.5} = \text{PM}_{2.5,2023} - \text{PM}_{2.5,2019}$) across the 31 provinces of Iran between 2019 and 2023.

ranging from -2.00 to $+13.69 \mu\text{g}/\text{m}^3$.

The largest absolute increase occurred in Bushehr, where concentrations increased by $13.69 \mu\text{g}/\text{m}^3$ (28.45%), while Hormozgan exhibited the greatest absolute reduction ($-2.00 \mu\text{g}/\text{m}^3$, -5.04%). The largest increases were concentrated in Bushehr, Golestan, Kerman, Sistan and Baluchestan, Razavi Khorasan, and South Khorasan, whereas relatively modest declines were observed in Hormozgan, Fars, Markazi, Lorestan, and Zanjan.

Relative percentage change

The relative percentage change in provincial PM_{2.5} concentrations ranged from -5.04% to $+43.43\%$ during 2019–2023 (Figure 4). The greatest relative increase was observed in Golestan (43.43%), followed by Bushehr (28.45%) and North Khorasan (21.80%), whereas Hormozgan experienced the largest relative decrease (-5.04%).

Overall, 67.7% of provinces (21 of 31) experienced increasing PM_{2.5} concentrations, while 32.3% (10 of 31) showed declining concentrations, demonstrating considerable regional variation in temporal trends.

Statistical analysis of temporal changes

The Friedman test demonstrated a significant overall difference in provincial PM_{2.5} concentrations across the five study years ($\chi^2 = 65.342$, $\text{df} = 4$, $P < 0.001$), confirming that annual concentrations varied significantly over time (Table 3).

Post hoc Wilcoxon signed-rank tests with Bonferroni correction identified significant differences between 2019 and 2020, 2020 and 2021, 2020 and 2022, 2020 and 2023, and 2021 and 2023 (all $P < 0.001$). No significant differences were observed between 2019 and 2021, 2019 and 2022, 2019 and 2023, 2021 and 2022, or 2022 and 2023 after adjustment for multiple comparisons.

Local validation against ground-based measurements in Mashhad

To evaluate the consistency of the ACAG satellite-derived PM_{2.5} estimates with ground observations in an Iranian urban setting, annual mean concentrations from the Mashhad monitoring network were compared with corresponding satellite estimates for the period 2019–2022. The annual ground-based means were 17.33, 18.84, 20.46, and $24.92 \mu\text{g}/\text{m}^3$, respectively, while the satellite-derived means for the same years were 27.60, 25.65, 30.60, and $30.12 \mu\text{g}/\text{m}^3$. The comparison showed a moderate positive correlation ($R = 0.645$, $R^2 = 0.416$), with a root mean square error (RMSE) of $8.39 \mu\text{g}/\text{m}^3$ and a mean bias of $+8.10 \mu\text{g}/\text{m}^3$ (satellite minus ground), indicating a systematic overestimation by the satellite product. The absolute difference ranged from $5.20 \mu\text{g}/\text{m}^3$ in 2022 to $10.27 \mu\text{g}/\text{m}^3$ in 2019. Table 4 summarizes the annual comparison.

In 2023, the ground-based mean in Mashhad was $52.86 \mu\text{g}/\text{m}^3$, whereas the satellite estimate was $34.99 \mu\text{g}/\text{m}^3$ (difference = $-17.87 \mu\text{g}/\text{m}^3$). However, this year was excluded from the formal validation statistics because

Table 3. Results of the friedman test and Post hoc pairwise comparisons of annual mean PM_{2.5} concentrations across the 31 provinces of Iran during 2019–2023.

Statistical analysis	Comparison	Test statistic (Z)	P value	Significant after Bonferroni correction
Friedman test	Overall comparison across 2019–2023	$\chi^2 = 65.342$, $\text{df} = 4$	<0.001	Yes
Wilcoxon signed rank test	2020 vs. 2019	-4.86	<0.001	Yes
	2021 vs. 2019	-0.196	0.845	No
	2022 vs. 2019	-1.676	0.094	No
	2023 vs. 2019	-2.607	0.009	No
	2021 vs. 2020	-4.84	<0.001	Yes
	2022 vs. 2020	-4.801	<0.001	Yes
	2023 vs. 2020	-4.821	<0.001	Yes
	2022 vs. 2021	-1.754	0.079	No
	2023 vs. 2021	-3.577	<0.001	Yes
	2023 vs. 2022	-1.695	0.09	No

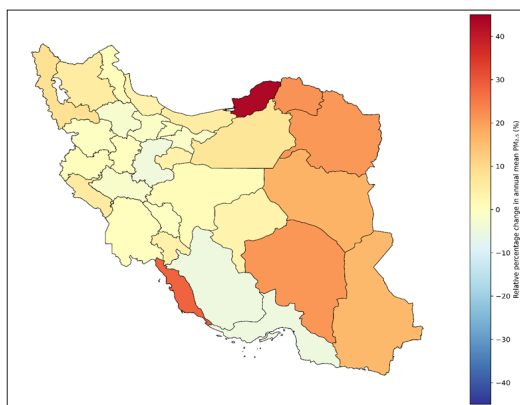


Figure 4. Heatmap of the relative percentage change in annual mean PM_{2.5} concentrations across Iran (2019–2023). Positive values (warmer colors) indicate an increase, while negative values (cooler colors) indicate a decrease relative to 2019.

only 8 out of 26 monitoring stations met the data coverage criterion ($\geq 70\%$ data completeness). The remaining stations were predominantly located in high-traffic or industrial areas, likely biasing the city-wide ground average upward. The satellite estimate, which provides spatially continuous coverage, may therefore offer a more representative city-wide average for 2023. Consequently, the 2023 data were treated as a data-quality caveat rather than part of the validation analysis.

Discussion

The present nationwide analysis provides a standardized assessment of satellite-derived PM_{2.5} concentrations across all 31 provinces of Iran during 2019–2023 and demonstrates three principal findings: (i) significant temporal variation characterized by a marked decline in 2020 followed by increasing concentrations through 2023, (ii) persistent population-weighted exposure substantially exceeding the WHO annual guideline throughout the study period, and (iii) pronounced and widening geographical disparities among provinces. These findings indicate that national averages alone are insufficient to characterize PM_{2.5} exposure patterns across Iran and highlight the importance of geographically resolved assessments for environmental health research and policy.

The population-weighted national mean PM_{2.5} concentration declined from 31.78 $\mu\text{g}/\text{m}^3$ in 2019 to 28.17 $\mu\text{g}/\text{m}^3$ in 2020 before increasing to 33.43 $\mu\text{g}/\text{m}^3$ in 2023, representing an overall increase of 5.2% during

the study period. These values are broadly consistent with previous nationwide estimates reported by Faridi et al., who estimated population-weighted annual PM_{2.5} concentrations of 30.1 $\mu\text{g}/\text{m}^3$ using ground monitoring data and 38.6 $\mu\text{g}/\text{m}^3$ using satellite-derived estimates for 2018 [8]. Although methodological differences including study period, spatial resolution, and exposure estimation approach limit direct numerical comparison, the comparable magnitude reinforces evidence that population exposure to PM_{2.5} has remained persistently high in Iran.

The temporal pattern observed in the present study should be interpreted within the broader context of previous Iranian research. Long-term analyses by Yousefi et al. demonstrated substantial historical variability in aerosol concentrations influenced by land-use change, environmental conditions, and air pollution control measures [15]. Unlike that multi-decadal assessment, the present study captures short-term year-to-year dynamics during 2019–2023, revealing a pronounced decline in 2020 followed by progressive increases thereafter. Rather than representing conflicting evidence, these findings illustrate how short-term fluctuations may differ from long-term national trends.

The temporary reduction observed in 2020 coincided with COVID-19 restrictions that substantially reduced transportation and economic activity. Although the present study was not designed to identify causal mechanisms, reduced anthropogenic emissions during lockdown represent a plausible explanation for the observed decline. Nevertheless, this interpretation should remain cautious because meteorological variability, regional aerosol transport, and natural dust processes were not explicitly incorporated into the analysis. Consequently, the post-2020 increase should be interpreted as reflecting multiple interacting factors rather than a single causal process.

Comparison with city-level studies further illustrates the importance of geographical scale. Declining PM_{2.5} trends reported for Tehran [16] and Khorramabad [17] differ from the nationwide post-2020 increase identified here, suggesting that local emission controls and meteorological conditions may influence individual cities differently from broader national exposure patterns. At the same time, previous studies consistently demonstrate that PM_{2.5} concentrations across Iranian cities remain well above WHO recommendations, including Tehran and Mashhad [9, 18], supporting the conclusion that temporary improvements have not translated into health-protective air quality levels.

Table 4. Comparison of annual mean PM_{2.5} concentrations between ground-based measurements in Mashhad and ACAG satellite estimates (2019–2022).

Year	Ground	Satellite	Difference (Satellite – Ground)	Relative difference (%)
2019	17.33	27.6	10.27	59.3
2020	18.84	25.65	6.81	36.1
2021	20.46	30.6	10.14	49.6
2022	24.92	30.12	5.2	20.9
Mean	20.39	28.49	8.1	39.7

*Relative difference = (satellite – ground) / ground $\times$ 100. Positive values indicate satellite overestimation.

From a public health perspective, the observed exposure levels remain particularly concerning. Even the lowest population-weighted national mean recorded in 2020 exceeded the WHO annual guideline of 5 $\mu\text{g}/\text{m}^3$ by more than fivefold, while the highest estimate in 2023 exceeded it by approximately 6.7 times. Previous Iranian studies have linked comparable exposure levels with substantial mortality and economic burdens [8, 9], indicating that the elevated concentrations observed in the present study are likely to have important public health implications despite the ecological design of the analysis.

One of the most important findings is the pronounced spatial heterogeneity across provinces. Provincial five-year mean concentrations ranged from $20.11 \pm 0.77 \mu\text{g}/\text{m}^3$ in Ardabil to $52.45 \pm 6.40 \mu\text{g}/\text{m}^3$ in Bushehr, representing more than a twofold difference between the least and most polluted provinces. Furthermore, the gap between the highest and lowest annual provincial concentrations widened from $27.26 \mu\text{g}/\text{m}^3$ in 2019 to $40.84 \mu\text{g}/\text{m}^3$ in 2023, indicating increasing geographical inequality in PM_{2.5} exposure.

The elevated concentrations observed in southern and southwestern provinces appear consistent with previous evidence highlighting the importance of regional dust transport and land-surface processes. Studies conducted in Khuzestan have demonstrated that transboundary dust originating from Iraq and surrounding desert regions contributes substantially to particulate pollution through regional atmospheric transport pathways [19, 20]. Similarly, Yousefi et al. identified land-use change as an important determinant of aerosol variability in dust-dominated regions [15]. Although these studies cannot directly explain the conditions in every province, they provide a plausible regional context for interpreting the elevated concentrations observed in Bushehr, Khuzestan, and neighboring provinces.

Conversely, Ardabil consistently exhibited the lowest PM_{2.5} concentrations throughout the study period. While its mountainous terrain, higher altitude, and relatively humid climatic conditions may contribute to improved atmospheric dispersion, the available evidence is insufficient to attribute this pattern to any single environmental factor. Future studies integrating meteorological variables, topography, land-use characteristics, and emission inventories will be necessary to identify the mechanisms underlying provincial differences.

The use of satellite-derived PM_{2.5} estimates represents an important methodological consideration. Previous studies have shown that differences between satellite products, ground monitoring networks, and atmospheric chemistry models arise from variations in spatial resolution, input data, and fusion algorithms [8, 21]. Likewise, Shen et al. demonstrated that incorporating geophysical information substantially improves satellite-based PM_{2.5} estimation in regions with sparse monitoring coverage [13]. Given the uneven distribution of Iran's regulatory monitoring stations, ACAG provides an important complementary exposure dataset for nationwide spatial assessment. Nevertheless, satellite-derived concentrations

should be interpreted as spatial exposure estimates rather than direct replacements for ground observations.

The widening interprovincial disparities identified in this study also have important policy implications. Uniform national interventions may produce unequal benefits where dominant pollution mechanisms differ among provinces. Urban and industrial regions may benefit primarily from transportation and combustion emission controls, whereas dust-prone provinces may additionally require ecosystem restoration, land degradation management, wetland conservation, and regional environmental cooperation [15, 20, 22]. Evidence from Khuzestan demonstrates that local emission reductions alone may be insufficient where transboundary dust contributes substantially to ambient particulate concentrations [20].

The observed geographical heterogeneity is equally relevant for epidemiological research. Reliance on a single national exposure estimate may obscure substantial differences in provincial exposure, potentially introducing exposure misclassification in health impact assessments. Previous studies from Mashhad, Tehran, and Tabriz have demonstrated associations between PM_{2.5} exposure and mortality or cardiovascular outcomes [9, 18, 23], suggesting that the spatial inequalities identified here may translate into important differences in population health risks, although province-specific causal relationships cannot be established within the present ecological framework.

First, although a local validation in Mashhad was performed (Section 3.7), a nationwide province-year matched validation was not possible because consistent monitoring coverage across all provinces was unavailable. Second, annual mean concentrations do not capture short-term pollution peaks associated with severe dust events. Third, explanatory variables such as meteorology, land use, emission inventories, and population density were not incorporated into causal analyses. Finally, the present study did not directly estimate attributable mortality or economic costs. These limitations do not diminish the value of the nationwide spatial assessment but indicate important priorities for future research integrating satellite-derived exposure estimates with environmental predictors and health outcomes.

Overall, this study demonstrates that PM_{2.5} pollution in Iran remains a substantial and geographically heterogeneous environmental health challenge. The combination of persistent exposure above WHO recommendations, widening interprovincial disparities, and increasing post-2020 concentrations underscores the need for geographically targeted monitoring and mitigation strategies. Integrating standardized satellite-derived exposure estimates with ground monitoring and environmental predictors may provide a stronger evidence base for future risk assessment and air quality management. The local validation against ground-based measurements in Mashhad revealed a moderate correlation ($R = 0.645$, $R^2 = 0.416$) between the ACAG satellite-derived PM_{2.5} estimates and ground observations for 2019–2022, with a systematic overestimation by the satellite product (mean bias = $+8.10 \mu\text{g}/\text{m}^3$). This level

of agreement is consistent with previous global and regional assessments, which have reported that satellite-derived PM_{2.5} products tend to overestimate ground concentrations in areas with complex aerosol composition, dust influence, or limited ground monitoring coverage [4, 7]. The overestimation observed here may be attributed to several factors. First, the spatial mismatch between point-based ground measurements and area-averaged satellite estimates can lead to discrepancies, particularly in urban environments with heterogeneous emission sources [5]. Second, the presence of mineral dust in the region, especially during dust events, can affect aerosol optical depth (AOD) retrievals and subsequent PM_{2.5} estimations, as dust particles have different optical properties compared to anthropogenic aerosols [7]. Third, the data-fusion algorithms used in ACAG, while globally consistent, may not fully capture local-scale emission patterns and meteorological conditions specific to Iranian cities [13].

The systematic overestimation found in this study is further supported by previous nationwide estimates in Iran. Faridi et al. [8] reported that the population-weighted annual PM_{2.5} concentration in 2018 was 30.1 µg/m³ using ground monitoring data but 38.6 µg/m³ using satellite-based estimates, indicating a similar overestimation of approximately 8.5 µg/m³. This consistency across independent studies suggests that the bias is not an artifact of our analysis but rather a characteristic of satellite-derived products in the Iranian context. Nevertheless, The moderate correlation observed in Mashhad indicates that the satellite product reliably captures the temporal and spatial patterns of PM_{2.5}, even if absolute concentrations are systematically higher. Therefore, relative comparisons across provinces and years such as the widening disparities and increasing trends identified in this study remain valid and robust.

The substantial discrepancy observed in 2023 (ground: 52.86 µg/m³; satellite: 34.99 µg/m³) deserves particular attention. In that year, only 8 out of 26 monitoring stations in Mashhad met the data coverage criterion (≥70% data completeness), and these stations were predominantly located in high-traffic or industrial areas. This spatial bias likely inflated the city-wide ground average, making it unrepresentative of true population exposure. The satellite estimate, which provides spatially continuous coverage, may therefore offer a more reliable estimate for that year. This finding underscores a critical limitation of ground-based monitoring networks in Iran: when station coverage declines, the remaining stations may disproportionately represent pollution hotspots, leading to biased exposure estimates [5, 7]. It also highlights the importance of integrating satellite data with ground observations to ensure accurate exposure assessment, especially in regions where monitoring infrastructure is uneven or deteriorating. Previous studies have similarly emphasized that satellite-derived products can complement sparse ground networks and provide more representative exposure estimates at the national and subnational levels [10, 13].

From a methodological perspective, the validation results support the use of the ACAG product for the

spatial and temporal analyses presented in this study. The moderate correlation and systematic bias are within the range reported in other global validation studies [4, 7], and the bias is consistent across years, which means that relative comparisons between provinces remain meaningful. However, the absolute concentration estimates should be interpreted with caution, and future studies should consider applying bias-correction techniques. For instance, incorporating geophysical a priori information, such as land use, elevation, and meteorological variables, has been shown to improve satellite-based PM_{2.5} estimation in regions with sparse monitoring coverage [13]. Additionally, machine learning approaches that integrate satellite data with ground measurements have demonstrated potential for improving accuracy in Iranian cities such as Tehran [10]. Such refinements could further enhance the reliability of exposure estimates for epidemiological and policy applications.

In summary, the local validation in Mashhad provides indicative support that the ACAG satellite product is a valuable tool for assessing spatial and temporal patterns of PM_{2.5} in Iran, despite a systematic overestimation. The findings reinforce the importance of maintaining and expanding ground monitoring networks to validate and calibrate satellite data, particularly in countries with diverse climatic and emission sources. The widening provincial disparities identified in this study, which are corroborated by both satellite and ground data, underscore the need for geographically targeted air quality management strategies. Future research should integrate satellite-derived exposure estimates with ground-based measurements, meteorological variables, and emission inventories to further refine exposure assessment and support evidence-based policymaking in Iran.

Strengths and limitations

This study has several important strengths. First, it provides a nationwide and spatially comprehensive assessment of annual mean PM_{2.5} concentrations across all 31 provinces of Iran over a five-year period, generating a standardized dataset of 155 province-year observations. Second, the use of a consistent satellite-derived PM_{2.5} product across the entire study period enabled direct comparison among provinces and years while reducing methodological inconsistencies associated with combining measurements from different monitoring networks, instruments, and sampling protocols. Third, the spatially continuous nature of the dataset allowed the characterization of PM_{2.5} patterns in provinces with limited or unavailable ground-based monitoring information. Fourth, a local validation against ground-based measurements from Mashhad was conducted, which provided indicative evidence of the general consistency of the ACAG product for relative comparisons across provinces and years. Fifth, the calculation of population-weighted national means provided a more representative measure of national population exposure compared with an unweighted provincial average. Finally, the repeated-measures analytical framework enabled formal statistical

evaluation of temporal changes rather than relying solely on descriptive comparisons.

Several limitations should also be considered when interpreting the findings. Satellite-derived PM_{2.5} estimates represent model-based exposure surfaces and may differ from concentrations measured directly at ground-level monitoring stations, particularly in areas with complex terrain, unusual aerosol composition, or sparse observational data. Although a local validation was performed using ground-based measurements from Mashhad, this validation was limited to a single city and covered only four years (2019–2022, $n = 4$), which restricts the statistical robustness of the correlation analysis and precludes generalization to all provinces. Furthermore, a nationwide province-year matched validation was not possible because consistent monitoring coverage across all provinces was unavailable. Consequently, the reported provincial estimates should be interpreted as satellite-based spatial estimates rather than direct replacements for regulatory ground measurements. In addition, aggregation of raster estimates to the provincial level may obscure important intra-provincial variability, especially within large provinces containing urban, industrial, rural, and desert areas with substantially different pollution characteristics. The population-weighted national estimates provide a more population-representative measure of national PM_{2.5} exposure than an unweighted average across provinces. Nevertheless, these estimates remain subject to the limitations of the underlying satellite-derived exposure product and the use of provincial population totals rather than finer-scale population distributions. In addition, population weighting at the provincial level may not fully capture within-province differences in population density and exposure. Furthermore, this study did not explicitly account for potential spatial dependence among provinces (e.g., through spatial autocorrelation), as the primary objective was descriptive mapping and temporal trend analysis rather than spatial regression or causal modeling. Moreover, this study was descriptive and ecological in nature and did not quantify the contribution of specific emission sources, meteorological factors, long-range dust transport, or other determinants of PM_{2.5} variability. Consequently, potential explanations for the observed temporal and spatial patterns should be interpreted cautiously, and causal inferences particularly regarding health outcomes are not warranted. The uncertainty estimates associated with the ACAG annual PM_{2.5} products (e.g., ensemble standard deviations) were not consistently available for all province-year combinations; therefore, confidence intervals for individual provincial estimates were not reported. Additionally, the present study did not directly incorporate meteorological parameters, emission inventories, population density, land use/land cover characteristics, topography, or dust source indicators into the statistical analysis. This limitation is important because previous studies have demonstrated that PM_{2.5} variability in Iran is affected by multiple interacting factors, including land use change, regional dust transport, climatic variability, and anthropogenic

emissions [15, 20, 22]. Future studies should therefore integrate satellite-derived PM_{2.5} with these explanatory variables to determine the mechanisms underlying the observed provincial differences. Furthermore, the present analysis focused on annual PM_{2.5} concentrations and therefore does not characterize short-term exposure peaks. This is particularly relevant for dust-prone provinces, where extreme dust events can produce concentrations substantially higher than annual averages [19, 22]. Future research should combine annual exposure estimates with daily or hourly data to distinguish chronic exposure patterns from acute pollution episodes. Finally, the present study did not estimate attributable mortality, morbidity, or economic costs. Nevertheless, previous national and city-level studies have demonstrated substantial health and economic consequences associated with PM_{2.5} exposure in Iran [8, 9, 18]. The nationwide exposure estimates generated here could therefore serve as an important input for subsequent province-specific health impact assessments. Combining these spatially resolved exposure estimates with population, baseline mortality, disease-specific relative risks, and socioeconomic data could provide a more comprehensive assessment of the health and economic consequences of PM_{2.5} across Iran.

In conclusion, this nationwide assessment demonstrated marked spatial and temporal heterogeneity in ambient PM_{2.5} concentrations across Iran, with substantial differences among provinces and changing pollution patterns over the study period. The findings show that population-weighted national estimates provide a more representative picture of overall population exposure, whereas province-level analyses are essential for identifying geographical inequalities that may be obscured by national averages. From a public health perspective, the persistence of elevated PM_{2.5} exposure across many provinces highlights the need for continued attention to air quality as a major environmental health priority. The pronounced regional differences observed in this study suggest that populations are unlikely to experience the same level of exposure or health risk across the country, underscoring the importance of geographically informed public health planning. For policymakers, these findings support the development of region-specific air quality management strategies rather than relying solely on uniform national interventions. The nationwide spatial assessment presented here can help prioritize monitoring, identify high-exposure areas, and guide more efficient allocation of resources for pollution control and environmental health interventions. Future research should integrate satellite-derived PM_{2.5} estimates with ground-based monitoring, meteorological variables, land-use characteristics, emission sources, and health outcome data to better understand the drivers of regional disparities and strengthen evidence for targeted air quality policies and epidemiological assessments.

Declarations

Ethics approval and consent to participate

The study protocol was approved by the Research

Council of Shahid Beheshti University of Medical Sciences as part of the CAREX-Iran research initiative (Grant No. 43021417). Formal ethics committee approval and informed consent were not required because the study exclusively used publicly available, aggregated satellite-derived environmental data and did not involve human participants, animals, or identifiable personal information.

Consent for publication

Not applicable.

Availability of data and materials

The annual PM_{2.5} data used in this study were obtained from the Atmospheric Composition Analysis Group (ACAG) Version 6 global surface PM_{2.5} dataset. The processed provincial-level dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

HR conceptualized the study, developed the methodology, curated the data, performed the formal analysis, prepared the figures, and wrote the original manuscript draft. MM contributed to the methodology, supervised the study, and critically revised the manuscript. MS contributed to the methodology and manuscript revision. FS contributed to data interpretation and manuscript revision. SY contributed to scientific review and manuscript revision. HSN contributed to data interpretation and manuscript revision. MV contributed to manuscript revision. AMJ supervised the study, provided conceptual guidance, and critically revised the manuscript. All authors reviewed and approved the final manuscript.

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