Comparative assessment of PM2.5 pollution in Uzbekistan and international air quality standards

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Abstract. This study evaluates fine particulate matter (PM2.5) pollution in Uzbekistan's major urban centers, with a particular focus on Tashkent. Real-time monitoring data from the U.S. Embassy air quality station (2020–2025) and national environmental statistics were analyzed to determine compliance with international guidelines. The results indicate that annual average PM2.5 concentrations substantially exceed the World Health Organization (WHO) limit of 5 µg/m³, reaching 52.3 µg/m³ in Tashkent during 2024, and similarly elevated values in Olmaliq (44.0 µg/m³) and Navoiy (38.5 µg/m³). Seasonal variation shows critical wintertime peaks associated with domestic heating, traffic emissions, and weak atmospheric circulation. A comparative assessment reveals that Uzbekistan's national standards (35–50 µg/m³) remain far more lenient than WHO, U.S. EPA, and EU regulations. This work is the first systematic analysis contextualizing Uzbekistan's PM2.5 data against global benchmarks. The findings underscore the urgent need for aligning national regulations with international standards, expanding real-time monitoring networks, and implementing targeted policy measures to protect public health.

Keywords: PM2.5, air pollution, air quality standards, WHO guidelines, public health; seasonal variation, Uzbekistan.

1. Introduction

Air pollution has emerged as one of the leading global environmental and health concerns of the twenty-first century. Among the numerous pollutants, fine particulate matter PM2.5 and PM10 poses the greatest risk because of its ability to penetrate deep into the respiratory system and even enter the bloodstream, triggering cardiovascular diseases, respiratory illnesses, and premature mortality (Brook et al., 2010; Pope & Dockery, 2006). Long-term epidemiological studies across North America and Europe have established strong evidence linking chronic exposure to PM2.5 with asthma, chronic obstructive pulmonary disease (COPD), ischemic heart disease, and reduced life expectancy (Brook et al., 2010; Pope & Dockery, 2006; Burnet et al., 2014; Cohen et al., 2017). The Global Burden of Disease (GBD) analysis confirms that ambient particulate pollution contributes to millions of premature deaths annually, ranking it among the top risk factors worldwide (Lelieveld et al., 2015; Cohen et al., 2017).

In response to this threat, international organizations have set progressively stricter air quality standards. The World Health Organization (WHO) in its 2021 guidelines recommends an annual average PM2.5 limit of 5 µg/m³ and a 24-hour average of 15 µg/m³ (WHO, 2021). The

United States Environmental Protection Agency (EPA) sets comparatively higher thresholds: 12 µg/m³ annually and 35 µg/m³ for the daily average (US EPA, 2020). The European Union regulates PM2.5 at an annual limit of 25 µg/m³ and PM10 at a daily limit of 50 µg/m³ (EEA, 2019). These benchmarks are anchored in epidemiological evidence and serve as the foundation for environmental policies aimed at protecting public health.

In contrast, Uzbekistan maintains more lenient regulations. The national standard O‘zDSt 3286:2018 permits PM2.5 concentrations of 35–50 µg/m³ and PM10 up to 150 µg/m³ (O‘zDSt, 2018), while older GOST norms allow similar or even higher levels (GOST, 1986). Recent monitoring reports from the State Committee for Ecology highlight that annual PM2.5 concentrations in cities such as Tashkent, Olmaliq, Chirchiq, and Navoi frequently range from 30 to 45 µg/m³, with winter months showing particularly severe exceedances (State Committee for Ecology and Environmental Protection of the Republic of Uzbekistan, 2022). Other regional and global studies emphasize similar seasonal patterns driven by coal-based heating, industrial emissions, weak atmospheric circulation, and dense traffic (Cheng et al., 2018).

Contemporary literature underscores the urgency of aligning national standards in developing regions with WHO benchmarks. Anenberg et al. (2022) argue that adopting stricter standards could prevent millions of premature deaths globally, while Yang et al. (2023) demonstrate that the integration of local emission inventories with real-time monitoring systems provides more effective policy guidance. Advances in monitoring technologies, such as low-cost optical laser sensors, machine-learning-driven forecasting, and satellite-based PM2.5 mapping, offer powerful tools for evidence-based governance (Shen et al., 2021; Zhang et al., 2024). Despite these advances, Uzbekistan’s integration of such technologies into national air quality management remains limited, creating a gap between scientific evidence and environmental policy.

Taken together, the situation in Uzbekistan reflects a dual challenge: persistently high particulate concentrations in major industrial cities and relatively lax national standards compared with WHO, EPA, and EU norms. This research addresses that gap by systematically assessing PM2.5 concentrations in urban Uzbekistan, benchmarking them against international standards, and critically analyzing the adequacy of national regulations. The novelty of this work lies in its multi-year use of real-time data contextualized with global benchmarks, and its aim is to generate scientific evidence for regulatory harmonization and improved environmental health protection.

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2. Materials and methods

This study assessed air quality in Uzbekistan with a focus on Tashkent, the country's largest and most industrialized city. The primary data source was the U.S. Embassy Air Quality Monitoring Station in Tashkent (41.31°N, 69.28°E), which has operated continuously since 2018 using a laser-based optical particle counter approved by the U.S. Department of State. The monitor collects hourly PM2.5 samples (53 minutes collection, 7 minutes analysis) and transmits data in real time to the AirNow (U.S., EPA) platform. Supplementary information was cross-checked with AQICN and IQAir online databases, covering other major industrial cities such as Olmaliq and Navoi.

The study primarily focused on PM2.5 concentrations, while PM10 and selected gaseous pollutants (NO_2, SO_2, CO, O_3) were considered when available. Data from January 2020 to March 2025 were aggregated into daily, monthly, seasonal, and annual averages. These values were compared against WHO (2021), U.S. EPA (2020), and EEA (2019) standards.

For data processing, erroneous or missing values were excluded. Statistical analysis included descriptive indicators (mean, median, standard deviation), seasonal variability, and comparisons with international thresholds. Visualization techniques (heatmaps, time-series plots) were applied to highlight temporal trends.

The analysis is constrained by reliance on a single monitoring site in Tashkent, with limited availability of PM10 and traffic/energy-consumption data, which reduces the capacity to identify emission sources comprehensively. Nonetheless, this dataset provides the first multi-year, high-resolution evaluation of PM2.5 in Uzbekistan benchmarked against global standards.

3. Results

The analysis of multi-year observations (2020–2025) from the U.S. Embassy air monitoring station in Tashkent demonstrates that PM2.5 concentrations consistently exceed WHO guideline values. Annual averages in Tashkent reached 52.3 µg/m³ in 2024, more than ten times higher than the WHO annual threshold of 5 µg/m³, while comparable exceedances were recorded in Olmaliq (44.0 µg/m³) and Navoi (38.5 µg/m³).

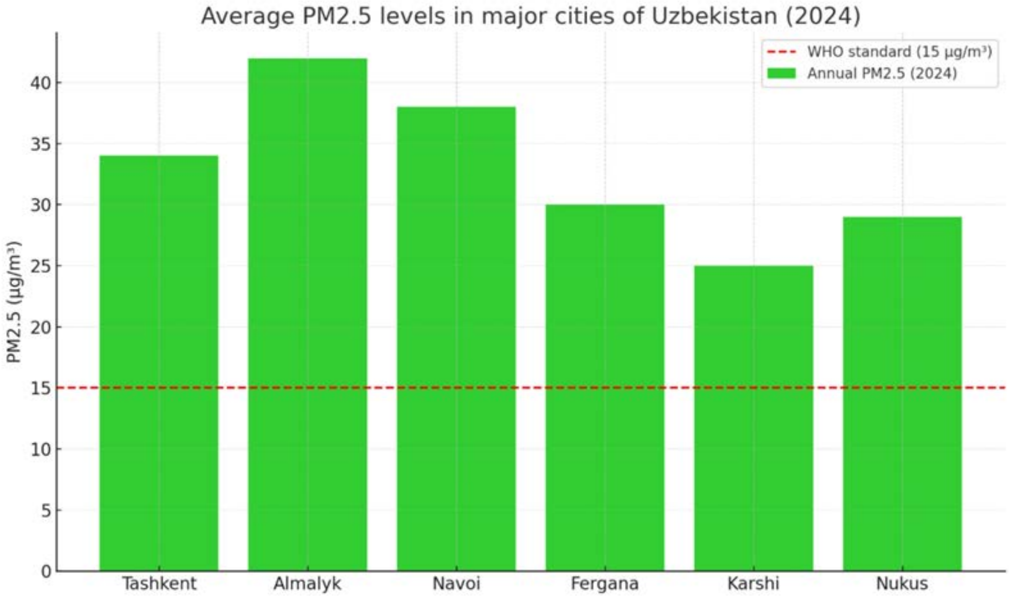

Figure 1. Average PM2.5 levels in major cities of Uzbekistan in 2024

These concentrations fall within exposure ranges that epidemiological studies associate with elevated risks of cardiovascular and respiratory morbidity, indicating that the observed levels carry significant implications for urban public health in Uzbekistan.

Daily averages frequently surpassed 100 µg/m³ during winter months, especially in January, February, November, and December. This is reflected in the daily Air Quality Index (AQI) heatmap, where many days fall into "unhealthy" (AQI >150) or "very hazardous" (AQI >200) categories. By contrast, summer months generally exhibited cleaner air, with average PM2.5 values within or below the WHO 24-hour limit of 15 µg/m³, largely due to stronger atmospheric circulation and reduced heating emissions. The pronounced winter peaks are consistent with increased domestic heating demand, lower atmospheric mixing heights, and frequent temperature inversions, all of which are known to enhance particulate accumulation in continental-climate cities

Comparative evaluation of international and national standards shows that Uzbekistan's permissible values for PM2.5 (35–50 µg/m³ for 24-h average) and PM10 (100–150 µg/m³) are two to three times higher than WHO and EPA recommendations, leaving substantial gaps in public health protection. For example, while WHO stipulates 15 µg/m³ for 24-hour PM2.5, national norms still allow up to 50 µg/m³.

Table 1. Comparative international and national standards for PM2.5 and PM10

Organization / Standard	PM2.5 24-hour Limit (µg/m³)	PM10 24-hour Limit (µg/m³)	Notes

WHO (2021)	15 µg/m³	45 µg/m³	Strictest guideline
USA – EPA	35 µg/m³	150 µg/m³	Official federal standard
European Union EEA (2019)	25 µg/m³	50 µg/m³	Based on EN 12341 standard
Uzbekistan – O‘zDSt (national standard)	35–50 µg/m³	100–150 µg/m³	Varying values, depending on specific regions
GOST 17.2.3.01–86	50 µg/m³	150 µg/m³	Based on legacy Soviet-era norms

This discrepancy explains why average annual concentrations of 30–45 µg/m³ in Uzbek cities (State Committee for Ecology and Environmental Protection of the Republic of Uzbekistan, 2022; AQICN.org, 2024) are officially considered "permissible," despite being clearly hazardous internationally.

This regulatory discrepancy means that pollution levels considered 'permissible' under national norms would still be classified as harmful or hazardous under WHO and EPA frameworks, highlighting a substantial misalignment in health protection thresholds.

Seasonal analysis further confirms pronounced winter peaks, with PM2.5 levels frequently exceeding 80–100 µg/m³. In February and December 2023, exceptionally high daily averages above 120 µg/m³ were recorded, corresponding to AQI values >200 ("very hazardous"). During April–August 2024, air quality improved, with daily averages dropping to 8–15 µg/m³, yet WHO guidelines were still exceeded for at least three to four months of the year.

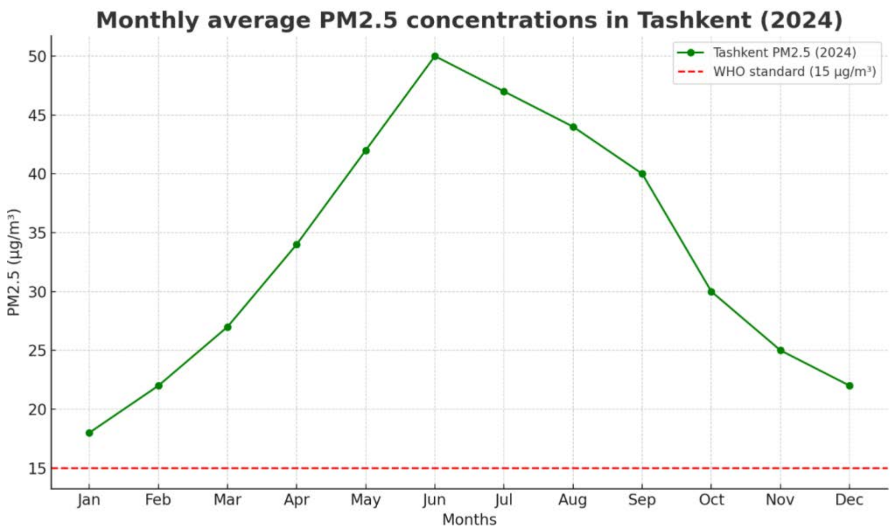

Figure 2. Monthly average PM2.5 concentrations in Tashkent during 2024

Long-term daily AQI visualization highlights these cycles, with winter months consistently in "unhealthy" or worse categories, while spring and summer show temporary improvement.

Figure 3. High-precision PM2.5 monitoring station at the U.S. Embassy in Tashkent

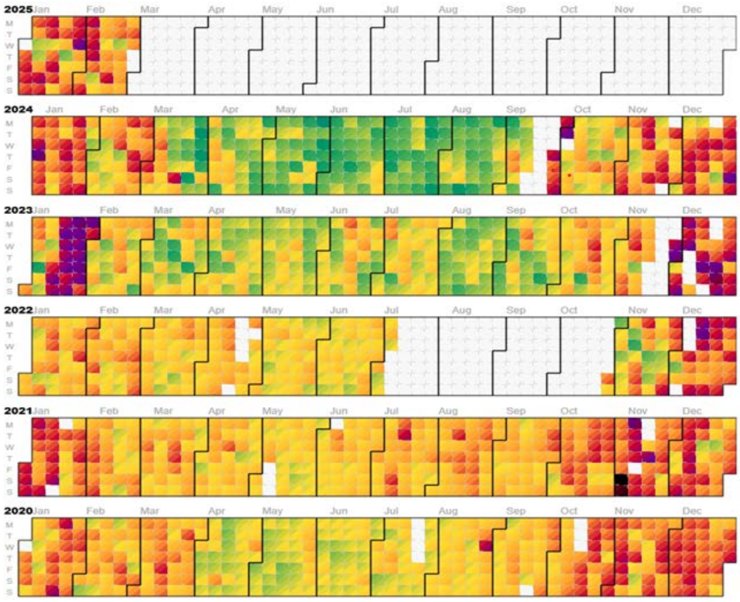

Figure 4. Daily Air Quality Index (AQI) in Tashkent from 2020 to 2025
(source: Querol et al., 2022)

Short-term extreme episodes were also observed. On 23 March 2025, at 22:00 local time, Tashkent registered a PM2.5 concentration of 68 µg/m³, equivalent to an AQI of 160 (“unhealthy”), while PM10 levels reached 212.7 µg/m³, exceeding WHO’s daily guideline (45 µg/m³) nearly fivefold. Other pollutants measured at the same time included NO_2 (60 µg/m³), CO (666 µg/m³), and SO_2 (32.5 µg/m³), suggesting combined emissions from traffic and industry.

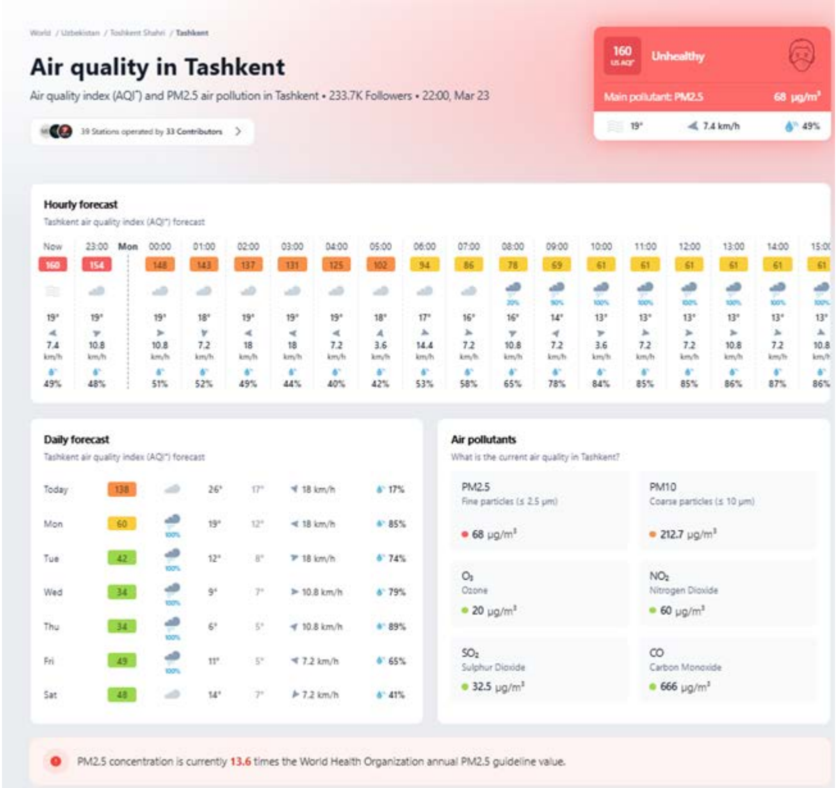

Figure 5. Air quality in Tashkent on March 23, 2025, at 22:00 local time

Statistical analysis further supports these findings. Pearson correlation analysis showed a significant negative relationship between PM2.5 and temperature ($r = –0.62$, $p < 0.01$), indicating higher particle accumulation in colder conditions. A moderate positive correlation with relative humidity ($r = 0.41$, $p < 0.05$) suggests that moist air may enhance particle suspension. No significant correlation with wind speed was observed ($r = –0.19$, $p > 0.05$).

Trend analysis of annual averages from 2020 to 2025 showed no statistically significant decline ($R^2 = 0.12$, $p > 0.05$), indicating that year-to-year variability is driven largely by seasonal factors rather than structural improvements in air quality.

Due to limited availability of PM10 datasets, only episodic values could be reported. For example, the concentration of 212.7 µg/m³ on March 23, 2025, illustrates extreme exceedances, but insufficient data prevented robust trend or seasonal analysis for PM10.

Collectively, Figures 1–5 and Table 1 provide robust evidence that particulate matter pollution in Uzbekistan remains chronically high, subject to strong seasonal variation, and substantially above internationally recognized safe levels.

4. Discussion

This study demonstrates that fine particulate matter pollution ($PM_{2.5}$) in Uzbekistan's major urban centers remains chronically elevated and far above internationally accepted air quality thresholds. Annual mean concentrations exceeding 50 µg/m³ in Tashkent and above 40 µg/m³ in

Olmaliq and Navoi place Uzbekistan among the most polluted regions of Central Asia. Such levels align with global evidence showing that sustained exposure to $PM_{2.5}$ substantially increases the burden of cardiovascular, respiratory, and metabolic diseases (Lelieveld et al., 2015; Burnett et al., 2014; Cohen et al., 2017; Burnett et al., 2018; GBD, 2023). The concentrations recorded in Tashkent are comparable to those observed in severely polluted Asian megacities (Wang et al., 2014), indicating that air quality in Uzbekistan has reached a level of concern that warrants urgent scientific and policy attention.

The strong seasonal contrast in $PM_{2.5}$ levels highlights the dominant influence of wintertime emission sources and meteorological stagnation. Peaks above 80–120 $\mu g/m^3$ correspond closely with periods of intensified domestic heating, increased combustion of low-quality fuels, reduced boundary-layer height, and frequent temperature inversions mechanisms widely documented in cold-climate regions (Zhang et al., 2019; Kholmatov et al., 2021; Lu et al., 2021). The negative correlation between $PM_{2.5}$ and temperature ($r = -0.62$) observed in this study reinforces the sensitivity of Uzbekistan's urban atmosphere to seasonal heating patterns and stagnant meteorological conditions. Episodic spikes of PM_{10} further demonstrate the influence of coarse particulates related to industrial activity, road dust, and construction, consistent with findings across Central Asia and China (Hong et al., 2020).

Comparison with international $PM_{2.5}$ regulations reveals a substantial misalignment between Uzbekistan's permissible limits and those of WHO, the U.S. EPA, and the European Union. While WHO recommends an annual mean of 5 $\mu g/m^3$ and a daily limit of 15 $\mu g/m^3$, Uzbekistan's national standards allow 35–50 $\mu g/m^3$ for $PM_{2.5}$, levels that international health frameworks classify as "harmful" or "hazardous" (WHO, 2021; US EPA, 2020). This regulatory gap partly explains the chronic exposure experienced by the urban population. Similar gaps in low- and middle-income countries have been associated with high rates of air pollution–related mortality (Vohra et al., 2021; Zhao et al., 2018).

In contrast to Uzbekistan's stagnating $PM_{2.5}$ trends, sustained reductions in Europe, North America, and East Asia were achieved through integrated monitoring systems, aggressive emission controls, clean household energy transitions, and low-emission transport strategies (Querol et al., 2022; Zhang et al., 2019; UNEP, 2022). China's 2013–2017 clean air reforms, for example, successfully reduced $PM_{2.5}$ by up to 40% in major cities through coordinated multi-sector interventions. The lack of comparable policy actions in Uzbekistan combined with limited monitoring capacity outside the capital helps explain the persistence of hazardous particulate concentrations and the absence of a long-term declining trend from 2020 to 2025.

From an ecological perspective, prolonged deposition of fine particulate matter may disrupt soil microbiota, reduce photosynthetic performance, and accelerate tree decline in polluted regions.

Evidence suggests that $PM_{2.5}$ can alter leaf-surface chemistry, reduce stomatal conductance, and weaken urban vegetation resilience, raising concerns regarding Uzbekistan's semi-arid environment where ecosystems are already stressed by heat and water scarcity (Li et al., 2020). This represents an important research gap that warrants interdisciplinary assessment.

Overall, the findings underscore the urgent need for Uzbekistan to harmonize its national standards with WHO guidelines, expand its monitoring network, modernize heating and industrial technologies, and implement early-warning systems. Without coordinated structural reforms, $PM_{2.5}$ pollution will remain one of the most pressing threats to public health, ecological stability, and long-term urban sustainability in Uzbekistan.

4.1. Policy and technical implications

The results of this study underscore an urgent need for Uzbekistan to modernize its air quality management framework through coordinated regulatory, technological, and institutional reforms. Current national $PM_{2.5}$ standards set at 35–50 µg/m³ for the 24-hour limit remain two to three times more lenient than WHO guidelines, resulting in a regulatory environment that fails to protect public health. Harmonizing national thresholds with WHO recommendations is a necessary first step toward reducing long-term exposure risks.

A stronger and more spatially comprehensive monitoring network is essential. At present, real-time data are available almost exclusively for Tashkent, limiting the country's ability to assess regional disparities and identify pollution hotspots. Expanding continuous monitoring to industrial centers such as Olmaliq, Chirchiq, Fergana, Bukhara, and Navoi would provide a more representative environmental assessment. Integrating low-cost optical sensors with satellite-derived $PM_{2.5}$ estimates and GIS-based risk mapping could substantially improve spatial resolution and enable early-warning tools for vulnerable populations.

From a sectoral perspective, targeted emission controls are critical. Tightening industrial emission standards, introducing best available technologies (BAT) in metallurgy and chemical manufacturing, and enforcing real-time stack monitoring could reduce point-source pollution. In the household sector, transitioning from coal and low-quality solid fuels to cleaner alternatives such as natural gas, electricity, or certified pellets would mitigate winter peaks, which account for the most hazardous episodes. Transport reforms, including stricter vehicle inspection standards, accelerated turnover of old diesel fleets, improved public transit, and incentives for electric mobility, represent additional high-impact measures.

Fiscal and economic policies may also serve as effective regulatory tools. Differential taxation on high-emission fuels, subsidies for energy-efficient household heating systems, and pollution fees for the largest industrial emitters are widely used internationally and supported by scientific evidence (Anenberg et al., 2022; Querol et al., 2022). Implementing such instruments in Uzbekistan would not only lower emissions but also provide financial resources to maintain monitoring infrastructure and support clean energy programs.

Collectively, these policy and technical interventions form a scientifically grounded and internationally validated framework that could enable Uzbekistan to achieve measurable reductions in $PM_{2.5}$ concentrations and improve public health outcomes.

4.2. Limitations

Despite providing valuable multi-year evidence on particulate pollution in Uzbekistan, this study has several limitations. First, the analysis relies heavily on measurements from a single urban monitoring station located at the U.S. Embassy in Tashkent. While the high resolution and reliability of these data make them valuable, they may not fully capture intra-urban variability, microenvironmental influences, or pollution trends in other regions of the country. The absence of comparable long-term datasets for cities such as Olmaliq, Navoi, Andijan, and Bukhara restricts the spatial generalizability of the study.

Second, PM_{10} and gaseous pollutant concentrations (SO_2, NO_2, CO, O_3) were only intermittently available. This limits the ability to conduct detailed source apportionment and obstructs the identification of multi-pollutant interactions that often exacerbate air quality episodes. Without continuous data for multiple pollutants, more advanced statistical and chemical transport modeling such as multi-linear regression, machine-learning prediction models, or WRF-Chem simulations could not be performed.

Third, the absence of contextual datasets such as household fuel consumption, industrial emission inventories, traffic-flow statistics, meteorological boundary-layer measurements, and socioeconomic indicators limited the depth of causal analysis. As a result, while the study identifies strong seasonal patterns and meteorological correlations, it cannot quantitatively attribute $PM_{2.5}$ peaks to specific emission sources.

Finally, although the monitoring technology used by the U.S. Embassy station is internationally recognized and calibrated, uncertainties inherent in optical measurements particularly under high humidity or mixed aerosol conditions may influence reported concentration values. Nevertheless, despite these constraints, the dataset provides the most robust and reliable empirical evidence currently available in Uzbekistan and offers a critical foundation for future research, regulatory harmonization, and environmental policy development.

5. Conclusion

This study provides the most comprehensive multi-year assessment to date of fine particulate matter ($PM_{2.5}$) concentrations in Uzbekistan, revealing that air pollution levels in major urban and industrial centers consistently and substantially exceed WHO, EPA, and EU guidelines. Annual averages above 40–50 $\mu g/m^3$, combined with severe winter peaks driven by domestic heating, industrial emissions, and meteorological stagnation, indicate that urban populations are chronically exposed to concentrations associated with elevated cardiovascular, respiratory, and all-cause mortality risks. These findings position Uzbekistan among the most polluted regions of Central Asia and underscore the growing public health burden posed by particulate pollution.

The results highlight a critical regulatory gap: current national standards allow pollutant concentrations two to three times higher than international health-protective limits. Bridging this gap will require not only revising national air quality thresholds but also modernizing emission controls across the household, transport, and industrial sectors. Evidence from other regions demonstrates that integrated monitoring networks, clean-energy transitions, stricter vehicle and industrial emission standards, and robust enforcement mechanisms can produce rapid and sustained improvements in air quality. Uzbekistan now faces a similar opportunity to implement targeted, evidence-based policies capable of reducing $PM_{2.5}$ exposure and improving population well-being.

Beyond public health, the study also raises concerns regarding ecological stability. Chronic particulate deposition may accelerate tree decline, impair photosynthetic activity, alter soil microbiomes, and reduce the resilience of semi-arid ecosystems already stressed by water scarcity and rising temperatures. This dimension of air pollution remains insufficiently studied in Uzbekistan and warrants deeper interdisciplinary investigation.

Looking ahead, future research should prioritize expanding continuous monitoring beyond Tashkent, developing detailed emission inventories for household, industrial, and transport sectors, and integrating satellite observations with ground-based measurements. Advanced modeling tools such as machine-learning predictors, chemical transport models, and high-resolution dispersion simulations would also enhance our understanding of pollution sources and seasonal dynamics. Strengthening collaboration between environmental agencies, public health institutions, and academic research groups will be essential for building a more accurate and actionable air quality management framework.

In conclusion, unless decisive structural interventions are implemented, particulate pollution will remain one of the most pressing threats to environmental safety, public health, and long-term urban sustainability in Uzbekistan. This study provides a robust evidence base to guide policy reform and lays the groundwork for future scientific efforts aimed at improving air quality and protecting human and ecosystem health.

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