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Urban $PM_{2.5}$ pollution in Kazakhstan: health burden and economic costs

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Ambient particulate matter ($PM_{2.5}$) exposure constitutes the leading global risk factor for non-communicable diseases. This study assesses the healthcare and economic burdens of air pollution in Kazakhstan's two major urban cities, Almaty and Astana. During 2022–2024, $PM_{2.5}$-attributable excess mortality reached 2108 ± 144 deaths in Almaty and 676 ± 41 deaths in Astana annually. The results of this research suggest that compliance with the World Health Organization (WHO) air quality guideline for annual average $PM_{2.5}$ concentrations (5 μg m^{-3}) can potentially prevent 1196–1698 and 446–497 deaths in Almaty and Astana, respectively. Economic losses from $PM_{2.5}$-related mortality were estimated at USD 2.8–4.6 billion for Almaty and USD 0.9–1.5 billion for Astana per year throughout the study period. Achieving the WHO-recommended annual $PM_{2.5}$ limit of 5 μg m^{-3} by 2022 might yield annual economic benefits of USD 2941–3685 million in Almaty and USD 863–1043 million in Astana. These findings highlight the urgency of comprehensive, coordinated air quality management strategies, with a particular emphasis on fossil fuel phase-out initiatives.

Environmental significance

Ambient particulate matter ($PM_{2.5}$) is a leading global health threat, but its impact in Central Asia remains understudied. Air pollution in Kazakhstan poses a crucial environmental and public health challenge, with significant economic consequences. This study provides the first city-level estimate of both health and economic losses from $PM_{2.5}$ in Kazakhstan's two major urban cities, Almaty and Astana, based on recent and reliable data. Exposure to $PM_{2.5}$ causes over 2700 premature deaths annually and economic losses exceeding USD 3.7 billion. Achieving the WHO air quality guidelines (5 μg m^{-3}) could prevent 1642–2195 premature deaths and save USD 3.8–4.7 billion in economic costs, representing up to 8.9% of regional GDP. These findings provide critical evidence that the government is not effectively implementing state-of-the-art air quality management strategies, emphasizing the urgent need for fossil fuel phase-out initiatives to reduce public health risks and economic vulnerabilities in rapidly urbanizing areas worldwide. Particular attention is paid to the importance of establishing a credible air quality network and advocating for its role in decision-making.

1 Introduction

Ambient air pollution is a leading contributor to preventable premature mortality worldwide, accounting for an estimated 8.3 million deaths in 2019,[1] and this number was expected to rise to about 10 million by 2022.[2] The estimated economic burden from increased mortality and morbidity from ambient air pollution exposure exceeded 4.8% of the global gross domestic product.[3] In 2010, air pollution-related economic losses, including mortality and morbidity costs, were valued at approximately USD 1.7 trillion in the Organization for Economic Cooperation and Development (OECD) countries, USD 1.4 trillion in China, and USD 0.5 trillion in India.[4]

Fine particulate matter ($PM_{2.5}$) is among the most extensively studied air pollutants and has a pronounced impact on public health. Even short-term exposure to $PM_{2.5}$ has been linked to significant adverse health outcomes. Yu *et al.* have estimated that, between 2000 and 2019, approximately one million annual premature deaths were attributable to short-term $PM_{2.5}$ exposure,[5] representing 2.08% of total global mortality, or 17 premature deaths per 100 000 people. $PM_{2.5}$ serves as a major environmental risk factor for cardiovascular and respiratory diseases,[6] contributing to reduced lung function, elevated chronic obstructive pulmonary disease (COPD) prevalence,[7,8] increased burden of lower respiratory infections (LRI),[9] and a rising number of lung cancer cases.[10]

Although quantifying air pollution-related fatalities and health conditions remains challenging, epidemiological cohort

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studies establish a robust framework for obtaining reliable estimates. Several modeling approaches have been developed to assess the relationship between $PM_{2.5}$ exposure and associated health risks. The Institute for Health Metrics and Evaluation (IHME), a research institute at the University of Washington, regularly conducts periodic assessments through its Global Burden of Disease (GBD) studies, quantifying the health impacts of various risk factors, including estimates of mortality attributable to ambient air pollution. The GBD study employs the Integrated Exposure Response (IER) model, synthesizing findings from around 100 studies.[11] An alternative is the Global Exposure Mortality Model (GEMM), which offers a comprehensive framework for assessing the health impacts of air pollution by focusing on all-natural cause mortality. Unlike the IER model, which incorporates data from multiple pollution sources and risk factors, the GEMM directly links $PM_{2.5}$ concentrations and mortality using cohort data from diverse geographic regions.[12] When combined with calculations of associated health costs, including both mortality and morbidity, these models allow for the quantification of the economic burden of air pollution. Estimation of these costs requires determining an individual's willingness to pay for a marginal reduction in mortality risk, and this valuation is applied to calculate mortality costs using the Value of Statistical Life (VSL) approach.[13,14]

Several examples demonstrate the effectiveness of an integrative approach to assessing and mitigating air pollution impacts. A groundbreaking study by Burnett *et al.*[12] utilizing GEMM estimated that ambient fine particulate air pollution contributed to 8.9 million people's global mortality, 120% higher than previous estimates. This positions air pollution as comparable to other major mortality risk factors, such as poor diet (10.3 million deaths) and cigarette smoking (6.3 million deaths). Subsequent research by Weichenthal *et al.*[15] suggests these global $PM_{2.5}$-related mortality numbers could be conservative, potentially overlooking an additional 1.5 million deaths. In India, Nair *et al.*[16] estimated 80 447 premature deaths from $PM_{2.5}$ exposure in 2017, corresponding to an economic loss of USD 90 185.6 million calculated *via* the VSL approach. Policy enforcement also plays a critical role. Peng *et al.*[17] emphasized that inadequate enforcement of air pollution control measures could result in 14 200 to 59 000 additional $PM_{2.5}$-linked deaths by 2040, compared to a scenario of stricter enforcement that could limit excess deaths to between 5900 and 8700 by 2040. The recent study by Shao *et al.*[18] utilized the GEMM to highlight the effectiveness of Chinese Air Pollution Control Strategies, achieving a 68.2% reduction in $PM_{2.5}$ concentration in the Beijing–Tianjin–Hebei region and an estimated decrease of 45 833 deaths over the period from 2013 to 2022. The GEMM has further been applied to estimate disease-specific excess mortality and loss of life expectancy (LLE) using global datasets from 2015. For instance, Lelieveld *et al.*[19] reported that $PM_{2.5}$ exposure contributed to a global LLE of 2.9 years (2.3–3.5 years). Their findings suggest that eliminating fossil fuel emissions could increase global mean life expectancy by 1.1 years (0.9–1.2 years), while removing all potentially controllable anthropogenic emissions could raise it by 1.7 years (1.4–2.0 years).

Integrative modeling tools are also valuable for assessing the health burden of air pollution in remote areas. Xu *et al.*[20] used the GEMM to show that, despite declining $PM_{2.5}$ levels in major metropolitan areas, the Yangtze River Delta region experienced 239 000 premature deaths in 2019, with significant disparities between cities of differing economic status and sizes. The GEMM has proven instrumental in evaluating the effectiveness of the clean air policy. Pac *et al.*[21] analyzed air quality interventions in Kraków, Poland, where restrictions on coal and solid fuels yielded significant public health benefits. Compared to 2019 $PM_{2.5}$ levels, these interventions were associated with a 35.7% reduction in childhood asthma cases, a 16.8% decrease in preterm births, and a 12.3% decline in low-birth-weight incidents.

Moreover, the Paris Agreement's goal of limiting global temperature rise to 1.5 °C may yield significant health benefits related to premature mortality and morbidity. Markandya *et al.*[22] demonstrated that the health co-benefits can outweigh mitigation costs by a ratio of 1.4 to 2.45, indicating economic feasibility in certain scenarios and countries when health outcomes are considered. In the United States, Mailloux *et al.*[23] estimated that implementing a clean energy policy to eliminate energy-related emissions could prevent 53 200 premature deaths annually, resulting in USD 608 billion (range: USD 537–678 billion) in benefits from avoided $PM_{2.5}$-related illness and mortality. Similarly, Tang *et al.*[24] projected that China's clean air policies could prevent 95 000 premature deaths by 2030, assuming over 80% of the population resides in areas with $PM_{2.5}$ levels below the current annual air quality standard (35 μg m^{-3}). Additionally, achieving this scenario could avert 118 000 and 614 000 $PM_{2.5}$-related deaths by 2030 and 2050, respectively, while generating net economic benefits of USD 393–3017 billion by meeting the country's nationally determined contributions under the Paris Agreement.

Research addressing the health and economic threats of ambient air pollution in low- and middle-income countries remains notably scarce.[25] As Mannucci and Franchini[26] highlighted, these countries have undergone rapid urbanization and industrialization development over a relatively short period, resulting in the highest air pollution-related burdens in recent years. Such investigations are particularly crucial for cities in countries such as Kazakhstan, where limited data availability complicates cost–benefit analyses of implemented environmental policies.[27] Comparable to developed countries with extensive networks of automated monitoring stations, researchers in Kazakhstan must establish source–receptor relationships through independent measurements, requiring an abundant consideration of sampling sites, timing, and analytical methods to ensure data reliability. Such investigations are fundamental for risk assessment, aiding in developing evidence-based policies and implementing sustainable and effective solutions. By addressing these gaps, studies from Kazakhstan and similar countries can enhance the global understanding of air pollution's health and economic impacts, equipping public health professionals with accurate information to monitor population exposure and guide policy decisions.[28]

Kazakhstan consistently ranks among the most polluted countries, with annual average $PM_{2.5}$ concentrations ranging from 15 μg m^{-3} to 31.1 μg m^{-3} over the last five years, exceeding WHO's limits (5 μg m^{-3}) by 3–6.2 times.[29] Despite severe pollution in Kazakhstan, with a 1.14 to 15.6-fold exceedance of $PM_{2.5}$ levels compared to WHO's standard in 17 of the 22 cities studied, research studies remain scarce.[30,31] Major cities, Almaty and Astana, show consistently high pollutant levels. In Almaty, studies have reported increased concentrations of benzene, toluene, ethylbenzene, and xylene,[32] CO_2, and suspended solids above local standards, which are already less stringent than WHO recommendations.[33] Additionally, Kerimray *et al.*[34] found PM_{10}, NO_2, SO_2, and total suspended particles surpassed standards set by the WHO, the European Union (EU), and Kazakhstan's local regulations. Installing $PM_{2.5}$ monitoring networks offers insights into particulate matter pollution, with studies reporting high $PM_{2.5}$ levels exceeding the WHO annual limit.[35–37]

The health impacts and economic costs of air pollution in Kazakhstan are largely unstudied and rarely incorporated into policy-making discussions. An exception is a study conducted by Kerimray *et al.*, which employed GEMM to estimate city-level health effects in Kazakhstan, linking an average of 8134 deaths across 21 cities to elevated $PM_{2.5}$ concentrations (average over 2015–2017), including 1831 deaths in Almaty and 939 in Astana.[30] According to Li *et al.*, short-term $PM_{2.5}$ exposure in 2022 caused 456 and 72 annual premature deaths in Almaty and Astana, respectively.[38] Agibayeva *et al.* estimated Disability-Adjusted Life Years (DALY) associated with $PM_{2.5}$ inhalation exposure equal to 2160 to 7531 years for Astana's population in 2019.[39]

This paper assesses the health and economic burden of air pollution in Kazakhstan's two largest cities, Almaty and Astana, in 2022–2024, with the following objectives: (i) to quantify the premature mortality linked to elevated levels of $PM_{2.5}$ in ambient air; (ii) analyze the potential benefits of reducing air pollution; and (iii) examine the challenges regarding data availability, reliability, and the scarcity of public health economic research in Kazakhstan.

2 Methods

2.1 Study area

Kazakhstan, the northernmost country in Central Asia, ranks as the ninth-largest nation globally by land area, with a dispersed population. The major cities in Kazakhstan, Almaty and Astana, with populations of 2.23 million and 1.43 million, respectively,[40] experience substantial air pollution challenges (Fig. 1). Both cities share similar pollution sources, including coal-fired central heat and power plants (CHPPs), outdated vehicle fleets, residential coal and biomass combustion, airborne dust, and additional contributing factors.[41]

Almaty's energy and heating needs are met by three CHPPs. While CHPP-1 operates on natural gas, CHPP-2 and CHPP-3 primarily use low-quality coal (ash content 42–44%) as their fuel source.[42] Ogbuabia *et al.* demonstrated that CHPPs in Almaty may contribute up to 39% of total $PM_{2.5}$ concentrations in the city and highlighted the need for denser ground-level monitoring stations.[43] The city's transport fleet consists of 667 600 vehicles, with 60% older than ten years and over half exceeding 20 years.[44] Despite a reported gasification effort, the residential sector in Almaty and its surrounding region still depends on coal, biomass, and waste for heating, cooking, and sauna.[36,37,45]

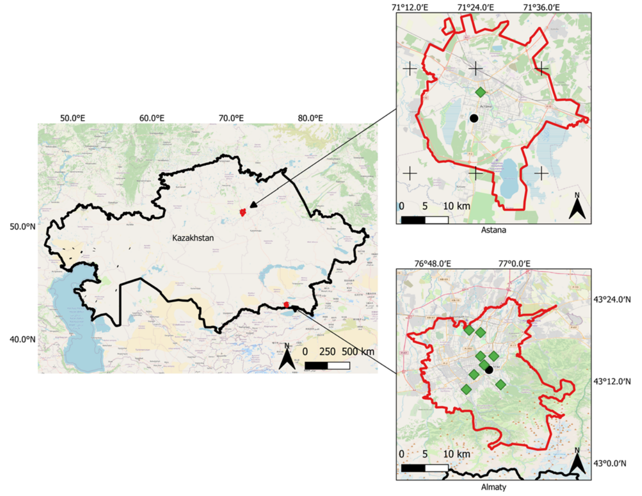

Fig. 1 Geographical location of Almaty and Astana, Kazakhstan. Green diamonds indicate AirKaz $PM_{2.5}$ sensors, black circles indicate AirNow monitoring stations.

Similarly, Astana's two CHPPs generate electricity and provide 67% of centralized heating, announcing their transition to natural gas for heat generation, which began with the 2022 heating season.[46,47] 20% of the city's 424 700 registered vehicles are older than 20 years.[44] Both cities attract significant migration from surrounding regions as economic hubs, amplifying economic activity and contributing to air pollution in urban and nearby areas. Despite comparable pollution sources, the geographical differences between Almaty and Astana significantly influence air pollution patterns and severity in each city. Almaty's air quality is compromised by several factors that restrict pollutant dispersion. The Ile Alatau Mountain range bordering the city's southern edge impedes horizontal air movement. Furthermore, Almaty frequently experiences thermal inversions and calm wind conditions, exacerbating pollutant accumulation. These phenomena are more prevalent during the colder months when the planetary boundary layer is at its lowest.[48] Consequently, average winter $PM_{2.5}$ concentration in Almaty reached 76 μg m^{-3}, compared sharply with summer levels of 10.3 μg m^{-3}.[36] Conversely, Astana is located on flat plains and benefits from an annual average wind speed that is 3.6 times higher than Almaty's, providing favorable conditions for pollutant dispersal.[37]

2.2 Estimation of mortality rate

2.2.1 Concentration-response function. This study employs the GEMM, an ensemble model based on epidemiological cohort studies that estimates the mortality risk associated with ambient $PM_{2.5}$ exposure.[30,49,50] The GEMM incorporates non-linear exposure–mortality relationships, both within individual cohorts and across combined datasets.[12] Most cohorts in GEMM studies were exposed to $PM_{2.5}$ below 30 μg m^{-3}, except for one high-exposure cohort of males in China, exposed up to 84 μg m^{-3}, considerably extending the model's applicability to higher pollution ranges.

In this study, both sets of coefficients were applied: one for cohorts with exposure to concentrations ≤30 μg m^{-3} and another model coefficients that included high-exposure cohort.

The GEMM model is defined by the hazard-ratio function (eqn (1)):

$$\mathrm{GEMM}(z) = \exp\left(\frac{\theta \ln\left(\frac{z}{\alpha}+1\right)}{1+\exp\left(-\frac{z-\mu}{\nu}\right)}\right) \tag{1}$$

where θ, μ, ν, and α are shape parameters of the mortality–concentration relationship in the GEMM(z) function as estimated by Burnett *et al.*,[12] and z represents the annual average $PM_{2.5}$ concentration, expressed as the difference between observed and baseline levels ($z_0 = 2.4$ μg m^{-3}), floor-capped at zero (eqn (2)).[12]

$$z = \max\left(0, \mathrm{PM}_{2.5} - 2.4\ \mu\mathrm{g\ m}^{-3}\right) \tag{2}$$

Mortality is subsequently estimated using eqn (3):

$$\Delta Y = Y_0 P\left(1 - \frac{\mathrm{GEMM}(z_0)}{\mathrm{GEMM}(z)}\right) \tag{3}$$

where ΔY is the number of deaths attributed to elevated $PM_{2.5}$ concentration, Y_0 is the baseline mortality rate by cause for a specific age group, GEMM(z) is the hazard ratio function estimated at different $PM_{2.5}$ concentrations, z_0 is the baseline $PM_{2.5}$ concentration, and P is the population of a specific age group. Mortality from specific causes was estimated for five disease categories from total mortality using ratios reported by Burnett *et al.*, due to the lack of cause-specific mortality data in Kazakhstan: lung cancer (LC), stroke, chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), and lower respiratory infections (LRI).[12] The mortality estimates were derived using the GEMM, with two input parameter sets considered: one excluding and another including the high-exposure cohort. Results were presented as the mean of the results from these two models. Uncertainty quantification employed the GEMM framework, with mean uncertainties computed as the root sum of squares. Results are presented in two categories: (1) mortality attributed to five specific causes and (2) mortality from non-communicable diseases combined with lower respiratory infections (NCD + LRI). All estimates compare observed mortality rates to a hypothetical scenario with zero mortality rate attributable to $PM_{2.5}$ at concentration 2.4 μg m^{-3}. All calculations were performed in Python 3.12 using numpy 2.2.6, with the GEMM model implemented in custom modules.

2.2.2 Data acquisition: pollution levels, exposed population, and baseline mortality data. Air quality monitoring with continuous, accurate pollutants data in Kazakhstan presents significant challenges, with multiple independent networks operating in Astana (three) and Almaty (four), each with reliability issues and data gaps. This study compares $PM_{2.5}$ concentration data from two independent monitoring sources in Almaty and Astana. The first source comprised a community-installed network of low-cost Pms5003 $PM_{2.5}$ sensors (Plantower, China) operated by AirKaz.org (https://airkaz.org/). Analysis included data from ten sensors in Almaty and two in Astana, demonstrating consistent data acquisition throughout 2022. Sensors with more than 20% missing data were excluded due to reliability concerns. Data for 2023–2024 were unavailable from this network consequently, therefore AirKaz results were not incorporated into mortality estimations for those years. The second source (AirNow) consisted of Beta Attenuation Mass Monitor (BAM 1020, Met One Instruments, U.S.) stations, operated by the US Embassy in Kazakhstan in both cities, which provided highly reliable measurements. However, the limitation of only one station per city prevents a comprehensive spatial representation of pollution levels, as air quality varies geographically within each urban area. Despite this constraint, these stations provided valuable data for comparison with other monitoring networks and for evaluating the sensitivity of mortality estimates to exposure variations. Additional details on data processing and quality control measures are provided in the SI (Text S1).

Additionally, summer $PM_{2.5}$ records (from May 1st to August 25th) for Almaty in 2022 were unavailable in the AirNow dataset due to technical issues. These data were retained because the AirNow's BAM instrument used at the site is the only reference-grade station available in Almaty. An alternative low-cost Airkaz sensor network, while providing continuous coverage, shows higher uncertainty and requires extensive calibration. Given the limited availability of regulatory-grade data in Kazakhstan, using the AirNow dataset ensured higher accuracy and comparability of concentrations despite partial temporal gaps.

Demographic data, including age structure and baseline mortality rates for Almaty and Astana, were obtained from the Kazakhstan demographic yearbooks, published annually by the Bureau of National Statistics.[40] These publications provide detailed population distribution and mortality rates stratified by 5-year age groups for each city (Fig. S1 and Table S1). Outliers and data from monitoring stations displaying anomalous distributions were excluded from the analysis, which are summarized in Table 2.

2.3 Estimation of economic costs

Elevated air pollution levels impose substantial economic burdens through adverse health outcomes, reduced productivity, and environmental degradation. This study quantifies the health-related economic costs attributed to increased $PM_{2.5}$ concentrations using the VSL approach, a widely adopted method that comprehensively assesses air pollution-related mortality risks in economic terms. The VSL represents the societal valuation of mortality risk reduction and can be estimated through multiple methodologies for a specific region or country, including market and non-market valuation techniques (Ashenfelter, 2006). Primary studies determining VSL are preferable but often resource-intensive and require substantial expertise. Alternatively, generalized approaches allow for VSL estimation by adjusting results from studies conducted in other countries.

Three distinct VSL estimates for Kazakhstan were derived from different studies. Wijnen (2021) estimated Kazakhstan's VSL of USD 733,711 (USD 0.55 million adjusted in 2022, Table 1) using a stated preference survey focused on the costs of fatal road crashes with 2012 data.[51] Viscusi and Masterman, proposed a methodology for countries lacking primary studies, calculating a VSL of USD 1.96 million for Kazakhstan in 2015 (USD 2.51 million for 2022).[52] Sweis (2022) incorporated an approach that accounts for the value of leisure time in VSL calculations, estimating the VSL at USD 0.9 million in 2019 (USD 1.05 million adjusted in 2022).[53] Together, these estimates provide a range of VSL values for Kazakhstan across different methodological frameworks and time periods.

Given the variability in the VSL estimates and the absence of a consensus on the most appropriate value for Kazakhstan, this study employed World Bank-recommended adjusted methodology to scale OECD-countries VSL values to Kazakhstan's economic context (eqn (4)).[3] Compared to three estimates of VSL for Kazakhstan, the OECD's meta-analysis used in the World Bank methodology is based on stated-preference studies. These studies estimated the value of a statistical life based on the willingness to pay (WTP) for a reduction in mortality risk.[3]

$$\mathrm{VSL}_{\mathrm{Kaz,Year}} = \mathrm{VSL}_{\mathrm{OECD}}\left(\frac{\mathrm{GDP}_{\mathrm{Kaz,Year}}}{\mathrm{GDP}_{\mathrm{OECD}}}\right)^{\varepsilon} \tag{4}$$

where $\mathrm{VSL}_{\mathrm{Kaz,Year}}$ is the VSL for Kazakhstan in a specific year, $\mathrm{VSL}_{\mathrm{OECD}}$ is the VSL for a sample of OECD countries, $\mathrm{GDP}_{\mathrm{Kaz,Year}}$ is the GDP per capita of Kazakhstan for a given year, deflated to 2011, in Purchasing Power Parity (PPP) prices, $\mathrm{GDP}_{\mathrm{OECD}}$ is the GDP per capita of a sample of OECD countries in the base year, and ε is the elasticity of VSL with respect to GDP, set at 1.2 as recommended for middle- and low-income countries.[3]

VSL values in 2011 PPP prices were converted to nominal values and inflation-adjusted to constant 2022 USD using the US Consumer Price Index. The adjusted VSL for Kazakhstan was estimated at constant 2022 USD 1.98 million in 2022, 1.96 million in 2023, and 2.09 million in 2024, based on OECD reference VSL (Table 1). All values used in economic cost calculations are presented in constant 2022 USD to support comparability. Other economic parameters, such as GDP per capita and inflation rates, were sourced from the World Bank database and presented in the SI (Text S2).

Table 1 VSL estimates for Kazakhstan from different studies

	VSL estimations, in 2022 USD million	
Study	Previous (year)	Adjusted, 2022
Wijnen (2021)	0.73 (2012)	0.55
Viscusi and Masterman (2017)	1.96 (2015)	2.51
Sweis (2022)	0.9 (2019)	1.05
Adjusted OECD VSL[a]	—	1.99

[a] Kazakhstan is not a member of the OECD.

3 Results and discussion

3.1 Annual spatial and temporal variation of $PM_{2.5}$ concentrations in Almaty and Astana

The annual mean concentrations of $PM_{2.5}$ for 2022 demonstrated consistent agreement between the monitoring networks despite differences in the number of stations and the spatial coverage. In Almaty, $PM_{2.5}$ concentrations averaged 36.3 μg m^{-3} (AirNow; excluding summer data) and 37.1 μg m^{-3} (AirKaz), while Astana recorded 22.2 μg m^{-3} (AirNow) and 23.0 μg m^{-3} (AirKaz) (Table 2). The consistency between data sources validates the reliability of both monitoring networks for trend analysis.

Subsequent years revealed distinct temporal trends in $PM_{2.5}$ concentrations primarily based on AirNow data. Almaty exhibited a decline from 36.3 μg m^{-3} (2022) to 28.7 μg m^{-3} (2023) and 24.3 μg m^{-3} (2024), resulting in a 33% reduction over the monitoring period. This improvement may be partially attributed to the incomplete $PM_{2.5}$ dataset for 2022 (AirNow), which lacked summer measurements characterized by lower concentrations of $PM_{2.5}$ due to reduced heating activities and enhanced atmospheric dispersion. Astana displayed a similar initial but less pronounced trend, with $PM_{2.5}$ concentrations decreasing from 22.2 μg m^{-3} (2022) to 17.9 μg m^{-3} (2023), followed by a slight increase to 18.6 μg m^{-3} (2024), maintaining a 16% reduction from 2022 baseline levels. Without source-resolved emission inventories and meteorological data analysis, attributing these trends to specific interventions or external factors remains challenging. Further investigations are necessary to elucidate the drivers behind these observed changes in $PM_{2.5}$ concentrations for both cities.

Despite these positive trends, the annual average concentrations of $PM_{2.5}$ in both urban centers persistently exceeded the WHO air quality guideline (5 μg m^{-3}) by substantial margins throughout the study period. In 2024, Almaty's $PM_{2.5}$ average concentrations (AirNow) remained 4.9 times higher than the recommended levels, while Astana exceeded WHO limits by a factor of 3.7. The magnitude of the exceedance was highest in 2022, with Almaty and Astana recording $PM_{2.5}$ concentrations 7.3 and 4.5 times above WHO recommendations, respectively.

Considerable temporal variability characterized $PM_{2.5}$ levels in both cities, evidenced by large standard deviations and extreme peak-to-baseline ratios (Table 2). The hourly maximum concentrations in 2022 varied between data sources: AirKaz showed a maximum value of 656.1 μg m^{-3} in Almaty, considerably higher than AirNow's 318.9 μg m^{-3}, possibly reflecting differences in network density and spatial representation. Conversely, AirNow recorded a higher maximum concentration in Astana (591.0 μg m^{-3}) than AirKaz (419.6 μg m^{-3}). This pattern of acute pollution episodes persisted in subsequent years (2023 and 2024), with AirNow data reporting maximum $PM_{2.5}$ levels of 227.2 μg m^{-3} (Almaty) and 276.3 μgm^{-3} (Astana), indicating the continued occurrence of severe air quality

Table 2 $PM_{2.5}$ hourly concentrations (μg m^{-3}) in Almaty and Astana from Airnow and AirKaz data sources

Year	City	Data source	Number of measurements	Average	SD	Min	Max
2022	Almaty	Airnow[a]	5726	36.3	36.3	0.3	318.9
		AirKaz	78 371	37.1	44.2	0.02	656.1
	Astana	Airnow	8127	22.2	38.7	0.1	591.0
		AirKaz	15 630	23.0	28.3	0.02	419.6
2023	Almaty	Airnow	8645	28.7	38.5	0.1	286.9
	Astana		7629	22.4	29.2	0.2	365.5
2024	Almaty		8417	24.3	27.9	0.1	227.2
	Astana		8410	18.6	20.8	0.3	276.3

[a] Data from summer months are absent. SD – standard deviation.

deterioration events despite overall improvements in annual averages.

3.2 Mortality due to $PM_{2.5}$ exposure

The total excess mortality attributable to ambient $PM_{2.5}$ exposure was substantial for the study period (Fig. 2). For Almaty, 2022 mortality estimates ranged from approximately 2081 ± 144 (AirNow) to 2108 ± 142 (AirKaz) deaths, while Astana resulted in 654 (AirNow) to 676 (AirKaz) deaths (Table 3). Temporal analysis revealed divergent trends between cities. Subsequent years showed moderate fluctuations in mortality estimates. Almaty exhibited a consistent declining trend from 2022 to 2024, with AirNow-based estimates decreasing from 2081 ± 142 to 1605 ± 105 deaths, representing approximately a 23% reduction. Conversely, Astana demonstrated less consistent patterns, with estimates fluctuating from 654 ± 40 (2022) to 580 ± 35 (2023) and subsequently increasing to 644 ± 39 (2024), reflecting temporal variability in exposure–mortality relationships that correspond to the changes in annual $PM_{2.5}$ concentrations. Comparing these mortality estimates to other causes of death in both cities highlights the significant public health burden posed by $PM_{2.5}$ exposure. For example, in Almaty, $PM_{2.5}$-attributable deaths for 2022 (2081–2108) exceeded deaths from road traffic accidents (120) and HIV/AIDS (24) by substantial margins.[54] Similarly, in Astana for the same year, estimated $PM_{2.5}$-related deaths (654–676) surpassed fatalities from both road traffic accidents (97) and HIV/AIDS (11).[54]

The estimated premature deaths based on observed annual $PM_{2.5}$ levels (AirKaz and AirNow data) in both cities and projections for scenarios meeting WHO interim targets (25 μg m^{-3}, 15 μg m^{-3}, 10 μg m^{-3}) and the final guideline (5 μg m^{-3}) (Table 3) consistently highlight the significant public health burden and the potential benefits of air quality improvement across 2022 to 2024.

As expected, achieving the WHO-recommended annual $PM_{2.5}$ concentration of 5 μg m^{-3} would provide maximum public health benefits. In 2022, this target could have potentially prevented 1671–1698 deaths in Almaty and 475–497 in Astana. For 2023, this number is estimated at 1355 deaths in Almaty and 397 in Astana. Similarly, 2024 projections indicate 1196 preventable deaths in Almaty and 446 in Astana at this concentration level. Detailed results on the potential number of avoidable deaths are given in Table S3.

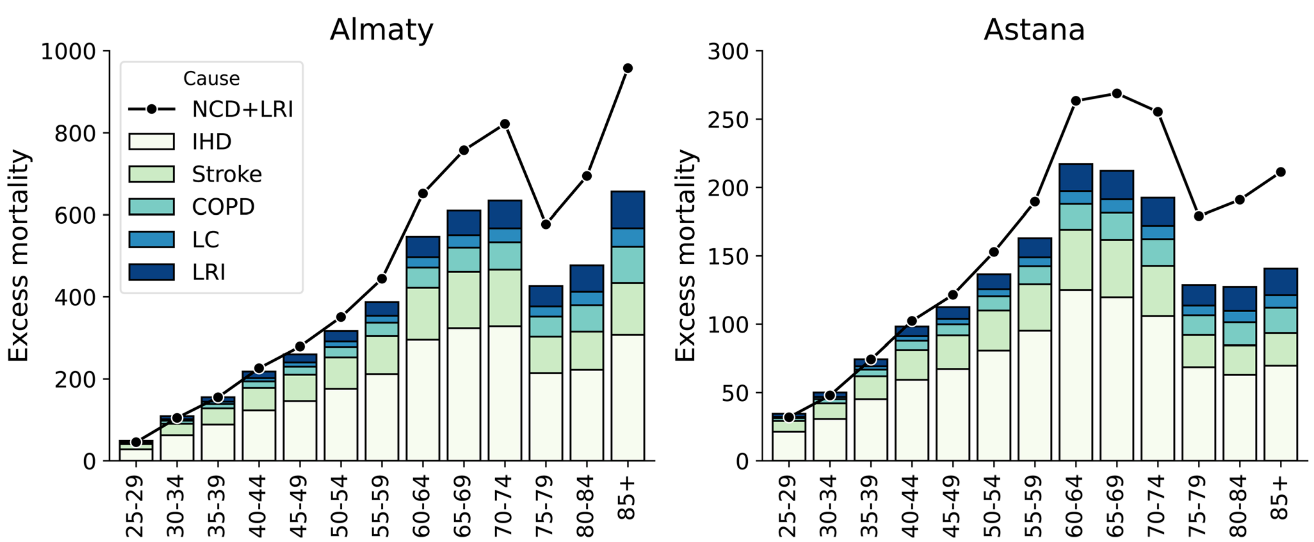

Fig. 2 The total premature deaths attributable to $PM_{2.5}$ exposure during 2022–2024 (summed for 3 years) in Almaty (left) and Astana (right). Average of two models (with and without high-exposure cohort) are shown. Please note different y-axis scales.

Table 3 Annual premature deaths attributable to $PM_{2.5}$ exposure in Almaty and Astana (2022–2024) under different $PM_{2.5}$ concentration scenarios. Average of two models (with and without high-exposure cohort) are shown[a]

				$PM_{2.5}$ concentration interim targets ($\mu g\ m^{-3}$)			
Year	City	AirKaz	AirNow	25	15	10	5
2022	Almaty	2108 ± 144	2081 ± 142	1637 ± 107	1146 ± 71	837 ± 51	410 ± 25
	Astana	676 ± 41	654 ± 40	714 ± 44	501 ± 29	366 ± 21	179 ± 10
2023	Almaty	NA*	1757 ± 115	1603 ± 104	1122 ± 69	820 ± 49	402 ± 24
	Astana		580 ± 35	728 ± 45	511 ± 30	373 ± 21	183 ± 10
2024	Almaty	NA*	1605 ± 105	1633 ± 107	1143 ± 71	835 ± 51	409 ± 25
	Astana		644 ± 39	787 ± 49	552 ± 33	403 ± 23	198 ± 11

[a] NA* AirKaz data for 2023 and 2024 were not available.

Progressive achievement of the WHO interim targets offers a phased approach to health improvement. In 2022, Almaty's $PM_{2.5}$ levels exceeded the first interim target (25 $\mu g\ m^{-3}$), reaching this threshold may have prevented approximately 444 deaths (AirNow). Astana, with concentrations of 22.2 $\mu g\ m^{-3}$ (AirNow) (Table 2), was potentially able to avert about 153 deaths by meeting the 15 $\mu g\ m^{-3}$ target. By 2023, Almaty remained above 25 $\mu g\ m^{-3}$, with potential prevention of 154 deaths upon target achievement. Astana approached the 15 $\mu g\ m^{-3}$ target, where compliance would be expected to save an estimated 69 lives.

Notably, 2024 marked significant air quality improvement for Almaty, with average $PM_{2.5}$ concentration falling below the WHO interim target of 25 $\mu g\ m^{-3}$. The focus shifted to a stricter interim target of 15 $\mu g\ m^{-3}$. Our results indicate that achieving this target may correspond to preventing approximately 459 deaths in Almaty. Reaching the same target in Astana could potentially avert 92 deaths. These findings consistently demonstrate the substantial public health advantages through progressive air quality improvements toward WHO-recommended levels.

A significant discrepancy is observed compared to the outcomes reported by Li *et al.*,[38] who estimated 456 and 72 deaths attributable to short-term ambient $PM_{2.5}$ exposure for Almaty and Astana, respectively, in 2022. In contrast, this study estimates 2081 ± 142 and 654 ± 40 deaths for the same year. This variation arises from methodological approaches and differing research objectives, as acute health impacts from short-term exposure account for smaller share of $PM_{2.5}$-related mortality, compared to cumulative health effects associated with chronic exposure, which are the focus of this study.

Comparison with the findings of Kerimray and others[30] reveals contrasting trends in premature mortality attributable to air pollution in Almaty and Astana. Almaty recorded increased annual average premature deaths from 1831 (2015–2017) to 2108 ± 144 (2022–2024, this study), while Astana declined from 939 to 676 ± 41 over the same periods. These divergent trends may reflect differential local policies, infrastructure development, and environmental and socio-economic factors. It is important to note that the previous study relied on annual $PM_{2.5}$ concentrations derived from the National Air Quality Monitoring Network (NAQMN),[30] operated by RSE Kazhydromet, which has documented inconsistencies and has been critiqued regarding data reliability.[55] Despite these concerns, NAQMN data remain widely used in policy decisions and research.[35,39,56] Therefore, the observed difference in premature mortality estimates between this study and study by Kerimray *et al.* may be attributable to the use of different data sources, as well as the different time periods. Further research is required to identify and quantify the underlying drivers of these trends.

3.3 Economic impact of ambient $PM_{2.5}$ pollution in Almaty and Astana

The total economic burden from mortality in Almaty and Astana for the period of 2022–2024 is substantial. In Almaty, the estimated economic burden from mortality ranged USD 3.4–4.6 billion in 2022, USD 2.9–3.8 billion in 2023, and USD 2.8–3.8 billion in 2024. For Astana, the economic burden was estimated to be USD 1.1–1.5 billion in 2022, USD 0.9–1.3 billion in 2023, and USD 1.1–1.5 billion in 2024. The potential economic benefits from premature mortality costs through $PM_{2.5}$ pollution reduction are considerable (Fig. 3 and Table S4). For Almaty during 2022–2024, the overall potential avoided costs from mitigating elevated $PM_{2.5}$ levels (*i.e.*, by meeting various WHO targets) demonstrated substantial variability: USD 743–3685 million in 2022, USD 264–2870 million in 2023, and USD 900–2699 million in 2024. Notably, 2024 calculations begin from the 15 $\mu g\ m^{-3}$ target since Almaty's annual $PM_{2.5}$ concentration fell below the 25 $\mu g\ m^{-3}$ interim target threshold (Table 1). Astana exhibited similar patterns with potential savings of USD 289–1043 million (2022), USD 130–825 million (2023), and USD 184–991 million.

Attaining the WHO's stringent annual $PM_{2.5}$ 5 $\mu g\ m^{-3}$ guideline would yield the most substantial economic benefits. In 2022, compliance could have resulted in potential savings of USD 2941–3685 million in Almaty and USD 863–1043 million in Astana, representing 7.1–8.9% and 3.7–4.5% of their respective gross regional products (GRP) for 2022. Subsequent years showed sustained economic benefits: USD 2395–2870 million (Almaty), and USD 709–825 million (Astana) in 2023, and USD 2264–2699 million (Almaty), and USD 852–991 million (Astana) in 2024.

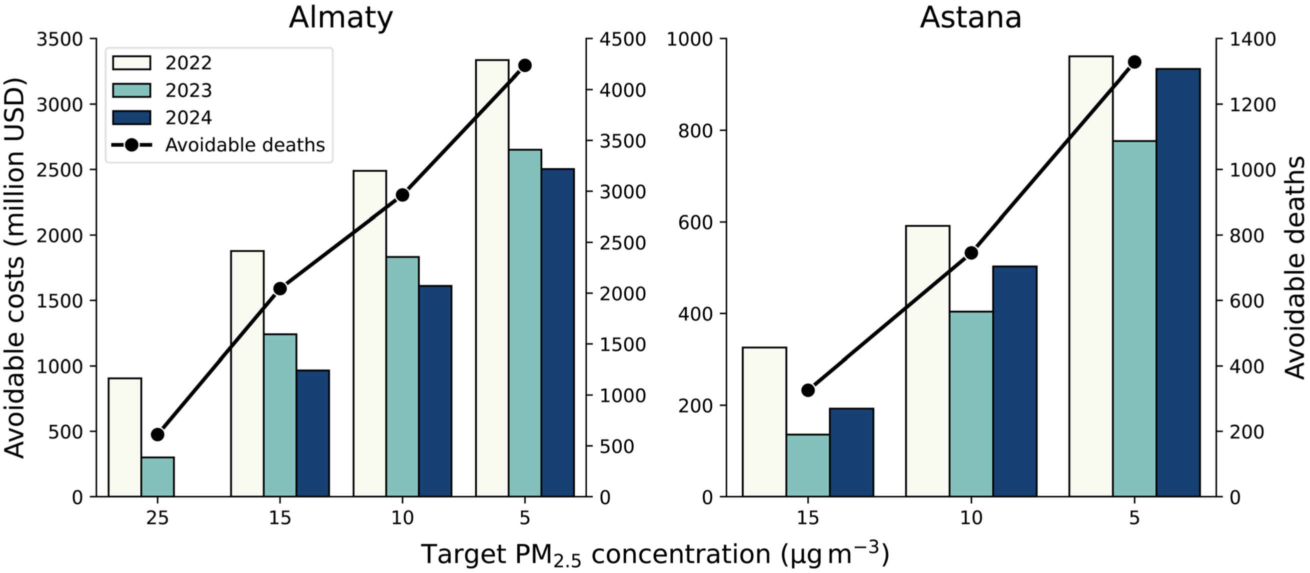

Fig. 3 Potential economic benefits and avoidable deaths from various counterfactual scenarios of reaching interim WHO $PM_{2.5}$ targets in 2022–2024 for Almaty (left) and Astana (right). Please note different *y*-axis scales.

3.4 Health burden assessment, pollution sources, and mitigation challenges

A comprehensive assessment of mortality and morbidity rates, as well as associated health risks, serves a critical governmental function, including healthcare burden estimation, targeted public health intervention development, effective risk communication with policymakers and the public, and tracking sustainable development goals. Furthermore, the economic valuation of air pollution impacts equips policymakers with essential information for prioritizing environmental health issues and implementing evidence-based mitigation strategies.[57]

According to the,[3] approximately 11 557 people die prematurely yearly in Kazakhstan due to poor air quality. The current study's findings for Almaty and Astana represent a significant proportion of this national burden, highlighting urban centers' severe air quality challenges. Additionally, the economic consequences are substantial: the World Bank reports $PM_{2.5}$ pollution costs Kazakhstan over USD 12 billion annually, or 5.3% of GDP,[58] while our analysis refine the economic cost of USD 286–8067 million to the combined impact in Almaty and Astana in 2022.

The extreme air quality challenges in Kazakhstan stem from multiple factors. Assanov *et al.* classified eight out of fourteen cities in Kazakhstan as having "high" atmospheric air pollution in 2019, according to the Air Pollution Index.[31] Major contributors include increased emission limits observed at the country's 21 CHPPs and 9 metallurgical enterprises. The issue is compounded by limited apportionment studies, hampering a comprehensive understanding of the various pollution sources and their relative contributions. Additionally, studies reported negligible changes in air quality during the COVID-19 lockdown, suggesting that traffic emissions may be less significant than officially reported.[56,59,60] This conclusion is further supported by the weak correlation between pollution levels and population densities, indicating the prominent role of non-traffic-related sources, such as industrial emissions and residential heating.

A substantial factor worsening air pollution in Kazakhstan is its heavy reliance on coal for CHPP plants and residential heating. Tursumbayeva *et al.* emphasized that coal, due to its affordability and availability, remains the primary energy source in these sectors.[37] Furthermore, the low quality of coal used in Kazakhstan, particularly in CHPP and private households, with an ash content of approximately 42%, exacerbates emissions. Moreover, CHPP accounts for 88.2% of Kazakhstan's total electricity generation. This dependence primarily results from the country's substantial proven coal reserves (34 billion tons, accounting for 2.4% of global reserves) and low cost.[42]

3.5 Policy landscape and future directions

Recognizing the severe impact of air pollution, the government of Kazakhstan has committed to reform. The 2013 "green economy" plan outlined key directives, including modernizing and consistently implementing advanced emission abatement technologies, transitioning gradually from coal to gas, and enforcing stricter air quality standards.[61] Kazakhstan has also pledged to reduce greenhouse gas emissions by 25% relative to 1990 levels by 2030, and to achieve net-zero emissions by 2060 in pursuit of carbon neutrality.[62] These initiatives also align with Sustainable Development Goals (SDGs): (SDG 12, which calls for significantly reducing the release of harmful chemicals and wastes into the air to minimize their adverse impacts on human health and the environment); SDG 11, which seeks to minimize the per capita environmental impact of cities and SDG 3, which aims to substantially reduce the number of deaths and illnesses caused by air pollution. However, despite these ambitious goals, the absence of a clear, actionable roadmap and well-defined strategies remains concerning. The only major planned measure is the modernization of the CHPP in Almaty, projected to cost approximately USD 703.6 million (at the exchange rate of 1 USD = 460.48 KZT).[63] This modernization is expected to achieve an 80% reduction in emissions. Our findings indicate that this substantial decrease in pollution could yield economic savings ranging from USD 1066 million to USD 6300 million due to reduced health and economic burdens associated with air pollution. These projected savings significantly exceed the total modernization costs, emphasizing the economic viability and potential return on investment of implementing advanced emission control measures.

Previous research suggests that ambitious global air quality policies could reduce exposure to anthropogenic $PM_{2.5}$ by approximately 75% by 2040, relative to 2015 levels, bringing concentrations well below WHO guidelines.[64,65] Globally, an estimated 1.05 million preventable deaths in 2017 were linked to fossil fuel combustion, which accounted for 27.3% of the total $PM_{2.5}$ burden.[66] These findings highlight the urgency for robust and coordinated actions to mitigate air pollution. Fragmented and inconsistent policies, as noted in earlier studies, can inhibit the development of comprehensive strategies,[67] emphasizing the need for data-driven interventions that account for both health and economic considerations.[68] Coal combustion emerges as the dominant contributor, responsible for over half of the emissions linked to fossil fuel-related mortality. Globally, fossil fuel emissions are estimated to cause 5.13 million deaths annually. The potential for the largest reductions in mortality from phasing out fossil fuels lies in high-income countries, where 85% of mortality attributable to fossil fuel use could be prevented due to their heavy reliance on fossil energy.[1]

3.6 Study limitations and future research directions

This study faced two primary limitations. First, while the GEMM model effectively characterizes associations between $PM_{2.5}$ exposure and non-accidental mortality across the concentration range for each cohort,[69] it fails to incorporate the varying emission characteristics at different $PM_{2.5}$ levels. This highlights the necessity for reassessment of contributions of fossil fuel combustion and other pollution sources, particularly under conditions of low and high $PM_{2.5}$ concentration scenarios.[66] Second, the absence of district-level statistical and air quality data within Almaty and Astana represents a significant constraint. Intra-urban air quality variability creates disparate exposure levels, leading to potential discrepancies in mortality and economic damage assessments at the subcity scale. This limitation emphasizes the need for localized air quality monitoring networks and comprehensive epidemiological investigations to enhance understanding of spatial health and economic impact variability within urban environments.

Future research should prioritize the development of spatially resolved exposure assessments and source-specific health impact models to improve precision in urban air quality management and policy formulation. Development of comprehensive datasets that integrate high-resolution air quality monitoring with detailed demographic and health outcome information is essential for accurately assessing the health and economic impacts of air pollution. Additionally, conducting localized epidemiological studies will help establish robust exposure–response relationships tailored to Kazakhstan's unique context.

4 Conclusions

The study reveals substantial health and economic burdens associated with $PM_{2.5}$ exposure in Kazakhstan's largest cities, Almaty and Astana. During 2022–2024, annual excess mortality attributable to ambient $PM_{2.5}$ pollution reached 2108 ± 144 in Almaty and 676 ± 41 in Astana. Model estimates indicate that adherence to WHO-recommended limits may prevent 1196–1698 and 446–497 deaths in Almaty and Astana, respectively. Moreover, even achieving the nearest interim target could have potentially averted 154–462 deaths in Almaty and 69–153 in Astana.

Economic losses from $PM_{2.5}$-related premature mortality were estimated at USD 2.8–4.6 billion for Almaty and USD 0.9–1.5 billion for Astana in 2022–2024. Implementation of the WHO annual limit by 2022 would correspond to generated economic savings of USD 2941–3685 million in Almaty and USD 863–1043 million in Astana, representing 7.1–8.9% and 3.7–4.5% of their gross regional products during the study period.

The observed $PM_{2.5}$ concentrations in both cities present alarming public health concerns, with levels consistently exceeding recommended thresholds and associated severe health implications. Economic repercussions extend beyond direct healthcare expenditures to encompass broader societal impacts, including lost labor productivity.

This analysis provide compelling evidence for the immediate implementation of stringent air quality improvement measures in Kazakhstan's major urban centers.

Author contributions

Aset Muratuly: conceptualization, formal analysis, methodology, software, validation, visualization, writing – original draft; Ravkat Mukhtarov: conceptualization, methodology, software, validation, investigation, writing – original draft; Ivan Radelyuk: conceptualization, validation, visualization, writing – original draft; Ferhat Karaca: validation, writing – review & editing, project administration, funding acquisition; Nassiba Baimatova: conceptualization, methodology, resources, data curation, writing – review & editing, supervision, project administration, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5va00194c.

The code for GEMM model is available at https://doi.org/10.5281/zenodo.15739362.

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