Thorac Res Pract. 2025;26(4):197-207
DOI: 10.4274/ThoracResPract.2025.2024-2-4

Original Article

Premature Deaths and Socio-economic Status: The Role of Fine Particulate Matter in Türkiye (2019)

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Cite this article as: Aykaç N, Çakmakcı Karakaya S, Erçelik Koncak M, et al. Premature deaths and socio-economic status: the role of fine particulate matter in Türkiye (2019). *Thorac Res Pract.* 2025;26(4):197-207

Abstract

OBJECTIVE: Air pollution, particularly particulate matter (PM), is a leading environmental risk factor contributing to global morbidity and premature mortality. The World Health Organization's (WHO) AirQ+© software is a vital tool for assessing the health impacts of air pollution. Our study used this software to estimate premature deaths attributable to long-term particulate matter ($PM_{2.5}$) exposure in Türkiye in 2019 and explored its relationship with each province's socio-economic status.

MATERIAL AND METHODS: We conducted an ecological study using annual average $PM_{2.5}$ levels from air quality stations. Due to limited $PM_{2.5}$ measurements (only 16% of stations), we derived $PM_{2.5}$ values from PM_{10} data using WHO's conversion coefficient for Türkiye.

Received: 10.08.2024 ***Revision Requested:*** 27.12.2024 ***Last Revision Received:*** 19.02.2025
Accepted: 26.05.2025 ***Epub:*** 10.06.2025 ***Publication Date:*** 26.06.2025

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Abstract

RESULTS: We identified the provinces with the highest $PM_{2.5}$ concentrations and associated mortality: Iğdır, Şırnak, Çorum, Düzce, and Kahramanmaraş had the highest concentrations, while Erzurum, Çorum, Iğdır, Sinop, and Kütahya had the highest mortality rates per 100,000 population. No significant correlation was found between premature deaths and the socio-economic development index of each province. Our study estimated 37,768 premature deaths attributed to long-term $PM_{2.5}$ exposure in adequately monitored provinces.

CONCLUSION: In 2019, Türkiye faced persistent air pollution, with $PM_{2.5}$ levels exceeding WHO's 2021 limits across all provinces and stations. Türkiye lacks specific $PM_{2.5}$ limits legislation. Our findings provide a fresh insight into the literature, highlighting policy reform needs. However, data deficiencies hindered analysis in some provinces, affecting nearly 20% of the population aged 30 and above and 31% of the total surface area. Therefore, the actual burden of air pollution-related deaths may be higher than our estimates, underscoring the need to address these challenges urgently.

KEYWORDS: Air pollution, particulate matter, software tool, premature death, socio-economic status

INTRODUCTION

Air pollution is a major public health issue globally, with 99% of the world's population breathing air exceeding World Health Organization (WHO) pollutant limits.[1] Key pollutants include particulate matter (PM_{10}, $PM_{2.5}$), nitrogen oxides (NO_2, NO_x), ozone (O_3), volatile organic compounds, carbon monoxide (CO), and sulfur dioxide (SO_2). PM is composed of solid/liquid particles, including dust, dirt, soot, smoke, and airborne liquid droplets.[2] These pollutants, which are among the main air pollutants in Türkiye, consist of carbon, heavy metals, inorganic ions, and polycyclic aromatic hydrocarbons. Wood stoves and forest fires are examples of primary PM sources, while power plants and coal burning are examples of secondary PM sources, which are generated in the atmosphere through intricate chemical reactions involving compounds like SO_2 and NO. Factories, cars, trucks, and construction sites can be primary or secondary sources of pollution.[2]

Particles ranging from 2.5 to 10 μm in diameter are categorized as PM_{10}, also known as coarse particles, while those with a diameter of ≤2.5 μm are labeled as $PM_{2.5}$, referred to as fine particles.[3] Air pollution affects human health in a variety of ways, with particularly prominent health issues in the respiratory, cardiovascular, and cerebrovascular systems. It has been proven that the pathogenic effect of $PM_{2.5}$ is greater on various body systems through the systemic circulation.[4,5] Epidemiological studies indicate that $PM_{2.5}$ poses a greater risk factor compared to PM_{10} concerning premature mortality and long-term health impacts.[6] WHO reports that air pollution causes about 7 million premature deaths annually.[1] Studies, such as those by Badyda et al.[7] in Poland, link $PM_{2.5}$ exposure to increased mortality rates from lung cancer and cardiopulmonary diseases.

Main Points

- In 2019, Türkiye faced persistent air pollution issues, with particulate matter ($PM_{2.5}$) levels exceeding World Health Organization-recommended limits across all provinces and stations.
- Still, Türkiye lacks specific legislation on $PM_{2.5}$ limits.
- The study estimated 37,768 premature deaths attributed to long-term $PM_{2.5}$ exposure in adequately monitored provinces.
- The actual burden of air pollution-related deaths may be higher than the estimates, underscoring the urgent need to address these challenges.

According to the United States Environmental Protection Agency (EPA), vulnerable groups include children, pregnant women, elderly individuals, and those with pre-existing heart and lung conditions.[8] Socio-economic status (SES) also influences susceptibility to air pollution. Air pollution is associated with low education and low income.[9,10] $PM_{2.5}$ exposure is assessed with a comprehensive socio-economic indicator [Socio-economic Development Ranking Research (SEGE)] that is not limited to education and income. Segments of society with low socio-economic levels live in air-polluted regions and industrial peripheries. The relationship between $PM_{2.5}$ exposure and SES remains complex and context dependent. While some studies indicate that higher SES regions may experience increased $PM_{2.5}$-related mortality due to greater industrial activity, energy consumption, and urbanization, others suggest a protective effect driven by improved healthcare infrastructure, environmental regulations, and economic investments in pollution control.[11] The variability in findings highlights the importance of considering spatial and socio-economic heterogeneity when analyzing air pollution's health impacts. Studies that rely on broader geographic units, such as province- or city-level data, may overlook localized inequalities, limiting the accuracy of assessments. Therefore, understanding the interaction between $PM_{2.5}$ exposure and SES at a finer spatial resolution is crucial for developing targeted policies that address environmental justice and public health disparities. An investigation conducted under the Air Pollution and Health: A European Approach 2 project examined the short-term effects of ambient particles on mortality across 29 European cities, highlighting modifications in effects. It revealed that a 10 μg/m³ increase in PM_{10} or black smoke concentrations in short-term exposures resulted in a 0.6% rise in mortality (95% confidence interval=0.4-0.8%), with slightly higher impacts among the elderly. Additionally, the study demonstrated that variations in effect parameters among cities indicate genuine effect modifications, attributed to distinct city characteristics.[12] The countries that suffer the highest exposure to air pollution are low- and middle-income countries.[1] It is understood that both outdoor air pollution and SES have negative effects on respiratory outcomes.[13,14] While the direct impact of $PM_{2.5}$ on mortality has received extensive attention in research, its function as a modifier in relation to the SES-mortality relationship has been infrequently assessed.[15] A recent study indicates that neglecting SES factors might underestimate the influence of $PM_{2.5}$.[16] Another recent study revealed that, in general, each 10 μg/m³ increase in the annual mean $PM_{2.5}$ level corresponded to a 3.8% increase in all-cause mortality.[11] Stratified analysis of the same study revealed that districts with lower SES experienced significantly greater health effects from $PM_{2.5}$ exposure. The analysis was conducted by dividing districts into quartiles based on key SES indicators, including literacy rate, university education rate, urbanization rate, and gross domestic product (GDP) per capita. The impact estimates for the lowest quartile of these indicators were 6.0%, 4.4%, 3.5%, and 4.9%, respectively, compared to their counterparts in the highest quartile. This demonstrates that populations in districts with lower SES are more vulnerable to the adverse health effects of $PM_{2.5}$ exposure, likely due to reduced access to healthcare, higher baseline exposure levels, and compounded environmental inequalities. These results were statistically significant ($P < 0.05$).[11]

Outdoor air pollution is also a public health problem for Türkiye. Research indicates that solely due to coal-fired power plants, Türkiye experiences approximately 2,876 premature deaths, 4,311 hospitalizations, and 637,643 instances of workplace absenteeism annually.[17] In a study conducted in Türkiye in 2018, it was found that a total of 44,617 individuals had premature mortality as a result of long-term exposure to $PM_{2.5}$. This study revealed that the provinces of Iğdır and Kahramanmaraş exhibited the highest estimated mortality rates associated with $PM_{2.5}$, while the provinces of Manisa and Afyonkarahisar recorded the highest estimated number of deaths per 100,000 population.[18]

Türkiye lacks a comprehensive analysis of $PM_{2.5}$ exposure and its associated burden on premature mortality, particularly in the context of socio-economic disparities. Existing studies often focus on global or regional scales, leaving country-specific data for Türkiye underrepresented. Moreover, the integration of socio-economic development indicators in assessing the health burden of $PM_{2.5}$ exposure remains limited. The aim of this study is to explore the relationship between $PM_{2.5}$-related mortality in Türkiye for 2019 and the socio-economic development levels of cities, using the WHO's AirQ+© software, providing a unique framework for understanding the interplay between air pollution and social determinants of health. By highlighting the regional disparities and the magnitude of the problem, this research aims to contribute to the existing literature and guide national strategies for air quality improvement and public health protection.

MATERIAL AND METHODS

This ecological study used WHO's AirQ+© (v.2.2) software (Regional Office for Europe, European Centre for Environment and Health, Bonn office, Germany), developed by the WHO Regional Office for Europe, to calculate the health impact of air pollution on specific populations.[19] AirQ+© has the ability to determine the proportion of a particular health outcome attributable to specific air pollutants in any urban area, country, or region. Additionally, it can predict potential changes in health impacts resulting from changes in air pollution levels compared to current conditions. Concentration/response functions and epidemiological studies provide the foundation for all of AirQ+©'s computations. The software's concentration/response functions are derived from a meta-analysis and systematic review of epidemiological studies. AirQ+© was employed to predict premature mortality from long-term $PM_{2.5}$ exposure.[20] Calculations involved using the annual average $PM_{2.5}$ level, converted from PM_{10} using WHO's conversion coefficient for Türkiye (0.66327),[21,22] since it is measured only in 16.6% of the stations. Additional components of the calculations included the region's surface area, the population aged 30+, and the mortality rate of this population, excluding external injuries. Data from 2019 were used to avoid Coronavirus disease-2019 impacts on air pollution levels and mortality rates. The annual average $PM_{2.5}$ levels for the provinces in 2019 were sourced from the Ministry of Environment, Urbanization, and Climate Change's air quality stations with sufficient data (90% and above).[23] The annual PM_{10} averages were obtained from the validated data shared in the 2019 Air Quality Bulletin.[24] According to these data, provinces with a data availability rate below 90% were excluded. To determine the annual average $PM_{2.5}$ concentration for a province in 2019, we summed the measured or converted annual average $PM_{2.5}$ concentrations from all air quality stations in that province and divided the total by the number of stations.

Provincial surface areas were sourced from the data in the document "Provincial and District Surface Areas" of General Directorate of Maps,[25] and population aged 30+ data from the Turkish Statistical Institute (TUIK) "Population by Age Groups-2019 Year" database.[26] The number of deaths for the 30+ population was calculated by excluding the total number of deaths from external injuries and poisonings in the 0-29 age group by using TUIK "Statistical Regional Units Classification, deaths by gender and age group, 2019" and "External injuries and poisonings" databases.[27] To obtain the death rate (per thousand) for the population aged 30+ years, excluding external injuries and poisonings, divide the number of deaths calculated according to provinces by the population aged 30+, and then multiply by 1,000. The map and graphic works were created using the Aldus FreeHand program.

The socio-economic development of the provinces was determined according to the index value of the "SEGE-2017" prepared by the Republic of Türkiye Ministry of Industry and Technology for the year 2017.[28] SEGE-2017 is a comprehensive study aimed at measuring the socio-economic development levels of districts in Türkiye. The research evaluates various indicators, including education, health, income levels, employment, infrastructure, social services, and environmental factors. Specifically, SEGE-2017 assesses income levels, literacy rates, accessibility and quality of health services, construction and infrastructure investments, industrial and commercial activities, and overall environmental conditions and quality of life at the district level. Since this study used publicly available air quality and statistical data and did not involve any human participants or identifiable personal information, it did not require ethical committee approval or informed consent.

Statistical Analysis

Data were analyzed statistically using IBM Statistical Package for the Social Sciences statistics, version 29.0 software (IBM Corp., Armonk, NY, USA), and correlation coefficient analyses were performed to assess relationships between variables.

RESULTS

Twenty provinces (Afyonkarahisar, Ağrı, Artvin, Bingöl, Bitlis, Bolu, Denizli, Elazığ, Eskişehir, Hakkari, Karabük, Kastamonu, Konya, Malatya, Mersin, Muğla, Muş, Tunceli, Uşak, Zonguldak) out of 81 were not included in the study due to the data rate being below 90%. Adana and Hatay were not included in the study due to the average $PM_{2.5}$ level being below 10 $\mu g/m^3$, which is the WHO-recommended limit value from 2005. As a result, the study contained data from 59 different cities. PM_{10} was measured in 64% of a total of 347 stations, and only 37.5% of these stations had measurement data covering more than 90% of the time period. $PM_{2.5}$ was not measured in 71% of the total 347 stations, and only about half (54.5%) of the measuring stations had sufficient $PM_{2.5}$ measurements. Overall, 16% of the total stations had measurements above 90%.

The annual mean $PM_{2.5}$ concentration for Türkiye in 2019, based on data from cities with adequate measurements, was found to be 32.2 $\mu g/m^3$. The provinces with the highest $PM_{2.5}$ concentration ($\mu g/m^3$), were Iğdır (78.93), Şırnak (54.27), Çorum (52.45), Düzce (44.14) and Kahramanmaraş (42.48) and the lowest ones were Hatay (8.84), Adana (9.31), Rize (15.61), Afyonkarahisar (16.08) and Nevşehir (16.75) (Figures 1, 2).

Iğdır (33.94), Şırnak (23.38), Çorum (22.56), Düzce (18.55), and Kahramanmaraş (17.76) were the provinces with the highest mortality rate (%) attributable to $PM_{2.5}$ exposure, while Rize (3.31), Nevşehir (3.95), Kırşehir (6.12), Bayburt (7.08), and Balıkesir (7.09) had the lowest rates (Table 1).

Erzurum (614.4), Çorum (263.7), Iğdır (228.8), Sinop (228.68), and Kütahya (196.05) were the provinces with the highest number of mortality cases per 100,000 population attributable to $PM_{2.5}$ pollution, while Rize (35.25), Nevşehir (40.11), Van (53.5), Diyarbakır (53.51), and Mardin (59.36) were the lowest (Table 1, Figure 3).

In provinces with adequate measurements, the total number of premature deaths attributed to air pollution in 2019 was found to be 37,768, with which 5,869 in İstanbul, 2,709 in Ankara, 2,534 in Bursa, 2,394 in Erzurum, and 2018 in İzmir (Table 1).

The correlation of premature deaths related to $PM_{2.5}$ with the socio-economic development index of the provinces was examined. There was no correlation found between the SES of the provinces and premature deaths related to $PM_{2.5}$.

DISCUSSION

In 2019, Türkiye continued to face significant air pollution issues, with annual average $PM_{2.5}$ levels exceeding WHO's recommended limits across all provinces and stations.

Short- and long-term PM exposure is a major cause of morbidity and mortality, linked to respiratory and cardiovascular diseases.[4,5,14] Additionally, PM and outdoor air pollution are classified as human group 1 carcinogens by the International Agency for Research on Cancer, correlating with bladder and lung cancer.[29] Pope et al.'s[30] study indicates a 4% increase in overall mortality and a 6% increase in heart-lung disease mortality for every 10 $\mu g/m^3$ increase in $PM_{2.5}$. In Türkiye, circulatory system diseases (36.8%), neoplasms (18.4%), and respiratory system diseases (12.9%) were the leading causes of death in 2019.[27] 39.1% of deaths from circulatory system diseases were attributable to ischemic heart disease, followed by cerebrovascular diseases (22.2%), other heart diseases (25.7%), and hypertensive disorders (7.9%). One important etiological factor of these common diseases, which are responsible for the majority of deaths that occurred in Türkiye in 2019, is continuous exposure to $PM_{2.5}$. Our findings align with these outcomes, highlighting that air pollution significantly reduces life expectancy, as shown by studies indicating a 0.61±0.20-year increase in life expectancy with a 10 $\mu g/m^3$ reduction in $PM_{2.5}$ levels.[5] That's why air pollution, particularly that which is caused by $PM_{2.5}$, represents a highly significant issue for public health, with its preventability being a crucial aspect.

Despite the severe health impacts, PM pollution monitoring in Türkiye was inadequate. PM_{10} was measured in 64% of stations,

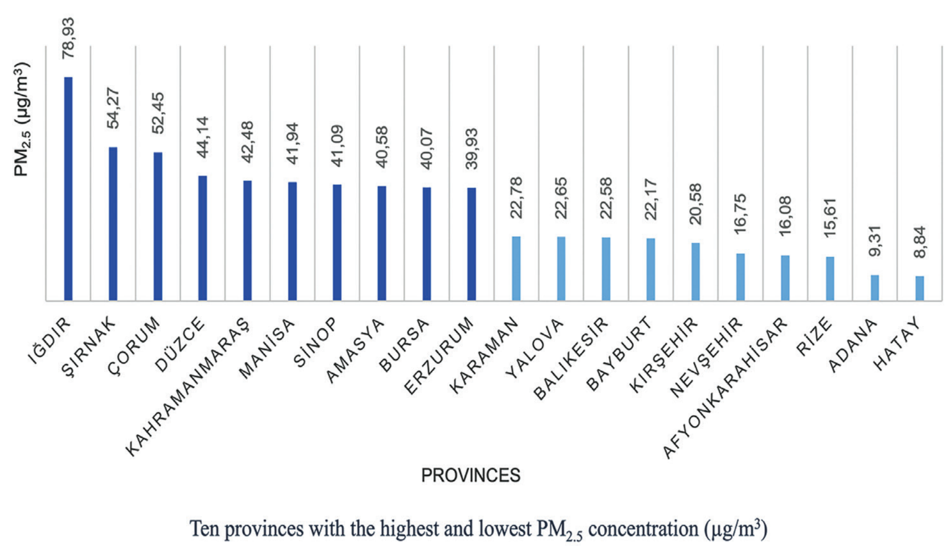

Figure 1. Ten provinces with the highest and lowest $PM_{2.5}$ concentration ($\mu g/m^3$)

$PM_{2.5}$: particulate matter

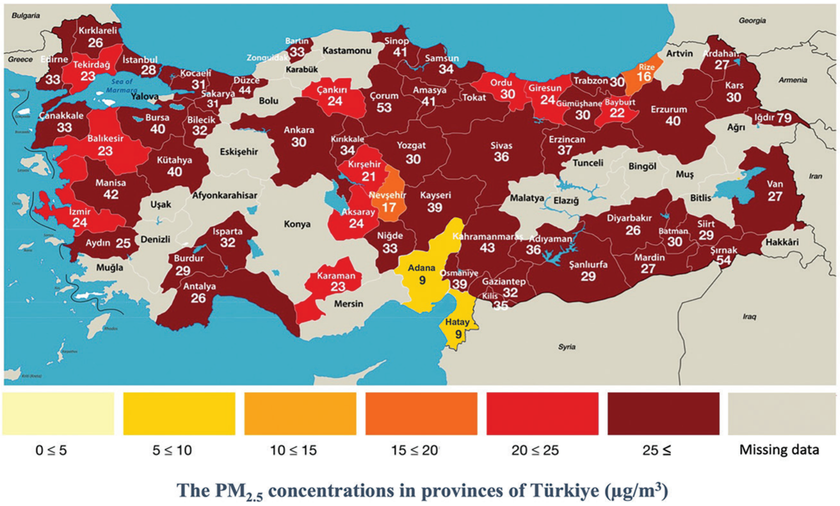

Figure 2. The $PM_{2.5}$ concentrations in provinces of Türkiye (µg/m³)

$PM_{2.5}$: particulate matter

Table 1. Estimated attributable proportion, the total number of premature deaths, premature mortality cases per 100,000 population and SES by province, attributed to $PM_{2.5}$ exposure (2019)

Province	Attributable proportion (%)	Number of attributable cases per 100,000 population at risk	Total number of attributable cases			Socio-economic status
	Central	Central	Central	Lower	Upper	
Adıyaman	14.28	105.26	335	224	434	-0.926
Aksaray	8.08	66.02	152	100	198	-0.271
Amasya	16.81	191.17	409	275	527	0.054
Ankara	11.18	80.30	2709	1803	3524	2.718
Antalya	9.34	62.08	948	629	1237	1.642
Ardahan	9.54	101.83	57	38	74	-0.983
Aydın	8.52	92.43	655	433	856	0.599
Balıkesir	7.19	90.15	740	489	970	0.476
Bartın	12.92	149.84	194	129	251	-0.14
Batman	11.05	64.48	165	110	215	-1.324
Bayburt	7.08	69.24	31	20	40	-0.629
Bilecik	12.50	138.38	188	125	244	0.556
Burdur	10.96	125.52	213	141	277	0.211
Bursa	16.41	136.43	2534	1703	3265	1.336
Çanakkale	12.61	150.28	537	358	697	0.548
Çankırı	7.69	101.56	126	83	165	-0.379
Çorum	22.56	263.70	890	606	1134	-0.262
Diyarbakır	9.25	53.51	419	278	547	-1.074
Düzce	18.55	176.47	409	276	524	0.2
Edirne	12.82	159.90	432	288	560	0.534
Erzincan	15.02	158.60	215	144	278	-0.15
Erzurum	16.50	614.40	2394	1610	3085	-0.531
Gaziantep	12.48	86.22	858	572	1114	0.25

Table 1. Continued

Province	Attributable proportion (%)	Number of attributable cases per 100,000 population at risk	Total number of attributable cases			Socio-economic status
	Central	**Central**	**Central**	**Lower**	**Upper**	
Giresun	8.13	102.28	299	198	392	-0.323
Gümüşhane	11.07	109.68	102	68	133	-0.623
Iğdır	33.94	228.80	217	152	271	-1.179
Isparta	12.18	134.63	361	241	469	0.564
İstanbul	9.99	64.61	5869	3896	7650	4.051
İzmir	7.86	72.38	2018	1334	2640	1.926
Kahramanmaraş	17.76	130.97	802	540	1031	-0.416
Karaman	7.30	68.42	100	66	131	0.177
Kars	11.40	148.60	210	140	274	-1.125
Kayseri	15.96	124.91	1001	672	1279	0.56
Kırıkkale	13.08	135.92	232	155	300	0.211
Kırklareli	7.63	107.72	256	170	334	0.557
Kırşehir	6.12	63.40	92	61	121	-0.085
Kilis	13.88	147.62	104	69	134	-0.57
Kocaeli	11.60	81.52	920	612	1196	1.787
Kütahya	16.21	196.05	715	481	922	0.17
Manisa	17.36	176.32	1577	1062	2028	0.49
Mardin	9.83	59.36	215	143	281	-1.396
Nevşehir	3.95	40.11	72	47	95	-0.015
Niğde	13.00	122.16	248	165	321	-0.395
Ordu	11.50	122.21	590	393	767	-0.486
Osmaniye	16.06	119.83	358	241	462	-0.367
Rize	3.31	35.25	76	50	100	0.174
Sakarya	11.97	115.00	698	465	906	0.832
Samsun	13.34	130.84	1079	721	1398	0.242
Siirt	10.70	64.70	85	57	111	-1.405
Sinop	17.06	228.68	332	223	427	-0.317
Sivas	14.22	153.18	569	381	736	-0.137
Şanlıurfa	11.02	60.42	498	331	648	-1.35
Şırnak	23.38	110.26	208	142	264	-1.788
Tekirdağ	7.58	62.10	395	261	517	1.014
Tokat	14.99	170.91	641	430	828	-0.381
Trabzon	11.07	108.20	538	358	700	0.389
Van	9.94	53.50	253	168	330	-1.452
Yalova	7.24	63.66	107	70	140	0.796
Yozgat	11.07	128.17	321	214	418	-0.589
	Total	**7280.14**	**37768**	**25211**	**48970**	

SES: socio-economic status, $PM_{2.5}$: particulate matter

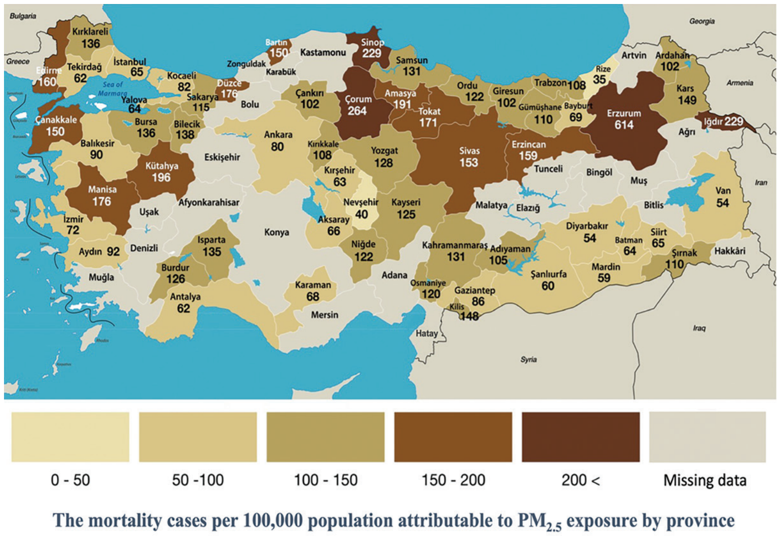

Figure 3. The mortality cases per 100,000 population attributable to $PM_{2.5}$ exposure by province

$PM_{2.5}$: particulate matter

with only 37.5% providing sufficient data. $PM_{2.5}$ was measured in only 16% of stations with sufficient data. The scarcity of reliable data, especially in regions with high pollution levels and vulnerable populations, clearly demonstrates the urgent need for improved and widespread monitoring capabilities to address the concrete reality of the public health crisis caused by air pollution in Türkiye.

The estimated mortality rate from long-term $PM_{2.5}$ exposure exceeded 20% in Iğdır, Şırnak, and Çorum, and surpassed 10% in 36 other provinces. We could not determine how $PM_{2.5}$ exposure contributes to Türkiye's leading causes of death due to insufficient data, highlighting the need for further research.

In 2019, $PM_{2.5}$ exposure led to an estimated 37,768 premature deaths in Türkiye (95% confidence interval 25,211-48,970). While this figure is lower than the 44,617 deaths estimated in 2018, it is important to note that the 2019 study covered fewer provinces (59 vs. 72) and used stricter data criteria (90% vs. 75% station data) (Table 2). These stricter criteria were implemented to ensure higher data accuracy but led to the exclusion of 20 provinces due to insufficient data coverage and two provinces due to average $PM_{2.5}$ levels falling below the limit value. These exclusions represent a significant portion of Türkiye, raising concerns about the underrepresentation of certain regions. These exclusions represent 20.3% of Türkiye's population aged 30+ and 31.2% of the country's total area, creating a significant gap in the study's geographic and demographic representation. The underrepresentation of these regions introduces significant uncertainty into the analysis. Many of the excluded provinces, especially in rural and industrialized areas, may have different pollution profiles or high exposure levels due to local $PM_{2.5}$ emission sources such as agricultural burning, industrial processes, or transportation corridors. Moreover, the population and geographic areas excluded from this study are not evenly distributed, which may skew the findings. For example, rural areas often lack adequate monitoring infrastructure despite potentially higher exposure levels due to unregulated pollution sources. On the other hand, urban centers such as İstanbul, Ankara, and İzmir, where most premature deaths are recorded, benefit from more comprehensive monitoring. This urban bias further emphasizes the need for even distribution of monitoring stations to ensure that the health impacts of air pollution are fully captured across all regions of the country. The lack of data from these regions may underestimate the true burden of premature $PM_{2.5}$-related deaths in Türkiye.

When compared to European Union (EU) member countries, where the highest annual mean $PM_{2.5}$ concentrations in urban areas were recorded in Bulgaria (19.6 μg/m^3), Poland (19.3 μg/m^3), and Romania (16.4 μg/m^3) in 2019, the findings in Türkiye indicate a substantially higher pollution burden.[31] The overall annual mean $PM_{2.5}$ concentration in Türkiye, based on cities with adequate measurements, was 32.2 μg/m^3-more than double the EU average (12.6 μg/m^3) and far exceeding the WHO-recommended limit of 10 μg/m^3. Additionally, certain provinces, such as Iğdır, Şırnak, Çorum, Düzce, and Kahramanmaraş, exhibit $PM_{2.5}$ levels that are significantly higher than those reported in the most polluted EU countries. In comparison with Poland, which holds the highest concentration of $PM_{2.5}$ among EU countries, where $PM_{2.5}$-related deaths ranged from 106 to 242 per 100,000, Türkiye's 11 largest cities (İstanbul, Ankara, İzmir, Kocaeli, Bursa, Konya, Şanlıurfa, Gaziantep, Antalya, Adana, Mersin) had $PM_{2.5}$ levels of 9.3-40.1 μg/m^3, with premature death rates between 60-176 per 100,000. Poland's geographical structure, energy resources, and industrial and heating policies may contribute to higher values compared to our country. From another point of view, if sufficient measurements were taken at the stations in these 11 largest cities in Türkiye, similar results could be obtained.

Despite a 23% decrease in air pollution-related deaths in 27 European countries between 2009 and 2019, Türkiye saw no reduction and ranked as the third worst in Europe for preventing air pollution-related premature deaths.[32] In 2019, European countries averaged 59.78 $PM_{2.5}$-related deaths per 100,000, while this study found rates in Türkiye between 35.25 and 614.40. A global meta-analysis estimated 25.3 $PM_{2.5}$-related

Table 2. Comparison of premature deaths attributable to long-term $PM_{2.5}$ exposure in Türkiye, 2018[18] and 2019

Features	2018	2019
Total number of stations, n	338	347
Number of provinces that included in the measurements, n	72	59
MD for 365 days a year (≥%)	75	90
Station measuring PM_{10} of over MD, n (%)	114 (33.7)	130 (37.5)
Station measuring $PM_{2.5}$ of over MD n (%)	63 (18.6)	57 (16.6)
Total number of premature deaths attributed to $PM_{2.5}$, n	44,617	37,768

MD: measurement data, $PM_{2.5}$: particulate matter

deaths per 100,000, which is a figure below Türkiye's lowest estimate, highlighting the country's challenges in addressing air pollution.[33]

In 2019, Türkiye's crude mortality rate was 5.3 per thousand, with 435,941 total deaths.[27] In other words, approximately one-ninth of the total number of deaths can be interpreted as premature deaths attributable to $PM_{2.5}$. Erzurum province had the highest estimated $PM_{2.5}$-related mortality, surpassing even the crude death rate of 530 per 100,000.

Vulnerable populations, particularly those of lower SES, are more susceptible to the effects of air pollution.[34] It is well known that SES and outdoor air pollution have a negative impact on the functioning of the respiratory and cardiovascular systems.[13,14] A study showed a 3.8% increase in all-cause mortality for every 10 μg/m^3 rise in $PM_{2.5}$, with greater impacts in districts with lower SES.[11] Districts with lower SES had greater health effects from exposure, according to stratified analysis. The districts with the lowest quartiles of literacy, university enrollment, urbanization rate, and GDP per capita were estimated to have had an impact of 6.0%, 4.4%, 3.5%, and 4.9%, respectively. There was strong evidence that districts in the lowest quartile compared to those in the highest quartile had a higher risk of $PM_{2.5}$-related mortality across all socio-economic factors ($P < 0.05$). A meta-analysis suggests that the negative effects of $PM_{2.5}$ on mortality may be underestimated if SES factors are disregarded.[16] However, this study found no correlation between SES and $PM_{2.5}$-related premature deaths in Türkiye. This may be sourced from several situations. First of all, in Türkiye, there is a need to investigate the relationship between SES, social classes, air pollution, and individual health levels in the smallest possible settlements. Another issue is that $PM_{2.5}$ was not measured at all stations, and the stations were far from representing the districts and the city. Additionally, the lack of correlation may stem from the geographic scale of the analysis. Most studies on SES and air pollution focus on smaller regions, such as neighborhoods or districts, where environmental inequalities are more pronounced. However, due to data availability and the current air pollution monitoring structure in Türkiye, province-level analysis remains the most feasible approach. While this broader scale may obscure localized disparities, it provides the best possible assessment within the existing framework. Future research incorporating finer spatial analyses would offer a more nuanced understanding of the relationship between SES and $PM_{2.5}$-related health outcomes, but this would require an extensive monitoring network, which is currently lacking.

WHO recommends a 5 μg/m^3 annual mean $PM_{2.5}$ limit and a 15 μg/m^3 annual mean PM_{10} limit.[35] In the relevant regulations, only a national limit is specified for PM_{10}. As of January 1, 2019, the national annual average limit for PM_{10} has been set at 40 μg/m^3, according to the Air Quality Assessment and Management Regulation (Official Gazette No: 26898, 2008). The lack of a national limit value for $PM_{2.5}$ in Türkiye is an important problem. Therefore, Türkiye should accept the PM_{10} limits recommended by WHO as soon as possible and determine the national $PM_{2.5}$ limit. This will be an important milestone toward preventing the morbidity and mortality caused by air pollution. According to WHO, national conversion coefficients can be used to calculate $PM_{2.5}$ values, over PM_{10} values in the event that $PM_{2.5}$ is not directly measured at stations. However, these calculated values may differ from region to region, and $PM_{2.5}$ calculations based on PM_{10} measurements may fail to reflect actual $PM_{2.5}$ concentrations.

Worldwide, several additional studies utilized the AirQ+© program. Cardito et al.[36] conducted an analysis of the concentration levels of six air pollutants (benzene, ground-level O_3, CO, nitrogen dioxide, and PM) that were observed by 37 stations in Campania, Italy, in the years 2019-2021. Based on the AirQ+© software's assessment of the health effects of air pollution, there was a notable decrease in adult mortality in 2020 compared to 2019 and 2021. The potential health benefits of reducing $PM_{2.5}$ exposure in Eastern Mediterranean Region (EMR), countries in 2019 were estimated by Faridi et al.[37] using WHO AirQ+© (v.2.1) software. In different EMR countries, it was estimated that lowering the annual mean $PM_{2.5}$ exposure level to 5 μg/m^3 would result in a 16.9-42.1% decrease in all natural-cause mortality in adults (ages 30+). Reaching the 25 μg/m^3 annual mean $PM_{2.5}$ would help all countries, as it would lower all-cause mortality by 3-37.5%. The health effects of long-term $PM_{2.5}$ exposure on years of life lost (YLL) and expected life remaining (ELR) indices in Ahvaz city between 2008 and 2017 were investigated by Zallaghi et al.[38] using the AirQ+© software. According to the results, over a ten-year period, the highest and lowest YLLs for all age groups were respectively, 137,760.49 (2010) and 5035.52 (2014). Additionally, the ELR index strongly correlated with the $PM_{2.5}$ concentration and was lower than the EPA and Iranian standards. Using PM data from 25 monitoring stations spread across the region between 2011 and 2019, Arregocés et al.[39] estimated the mortality rate attributed to yearly $PM_{2.5}$ exposure in Colombia's northern Caribbean region. An estimated 11.6% of acute lower respiratory disease deaths in children under 4 years old, 16.1% of deaths from chronic obstructive pulmonary disease (COPD), and 26.6% of deaths from ischemic heart disease in adults are attributed to prolonged exposure to $PM_{2.5}$. It was estimated that the annual rates of lung cancer and stroke attributable to PM exposure were 9.1% and 18.9%, respectively. It is estimated that PM pollution directly causes 738 deaths annually. The adult population (aged 18+) had the highest annual death rate, averaging 401 events. The annual average risk of bronchitis prevalence in children due to air pollution was 109 per 100,000 individuals.

In order to quantitatively estimate the number of specific health outcomes from long- and short-term exposure to atmospheric pollutants in São Paulo, Southeastern Brazil, Wikuats et al.[40] applied the AirQ+© model to analyze the 2021 data. Lowering São Paulo's $PM_{2.5}$ levels, as recommended by WHO, could avert 113 COPD deaths and 24 lung cancer deaths annually. Additionally, it might prevent 258 hospital admissions for respiratory disorders and 163 admissions for cardiovascular disorders, both, brought on by $PM_{2.5}$ exposure. The findings showed that O_3-related excess deaths from cardiovascular and respiratory illnesses were 228 and 443, respectively. In the Marmara Region, which is the area with the highest concentration of urban and industrial mobility in Türkiye between 2016 and 2019, Kahraman and Sivri[41] used AirQ+© software to estimate mortality rates in the metropolitan cities of İstanbul, Bursa, Kocaeli, Balıkesir, Sakarya, and Tekirdağ. From 2016 to 2019, a total of 46,920 premature deaths were attributed to exceeding the WHO limit values, with 11,895, 13,853, 11,748, and 9,429 recorded for each year. Thus, AirQ+© is a helpful software that facilitates the development and application of air pollution control measures, to reduce death and economic costs associated with $PM_{2.5}$ exposure in Türkiye.

The strength of our study lies in its contribution to the body of literature by using AirQ+© software to calculate, for the first time, the estimated number of premature deaths in Türkiye in 2019 that can be attributed to long-term exposure to $PM_{2.5}$. It is also unique in that it considers the particular conditions of Türkiye and employs data specific to that country. It serves as a catalyst for related research, helps clarify the impacts of air pollution, and establishes the framework for further investigation. This enables us to better comprehend the connection between public health outcomes and air pollution. Calculating the risk of premature death from $PM_{2.5}$ can help influence political changes such as updating environmental regulations and air quality standards, thereby improving the creation of health policies through public health measures.

This study has several notable limitations. Premature deaths attributable to $PM_{2.5}$ exposure could not be calculated for the entire population aged 30 and above, and across the entire area, due to data deficiencies and values falling below the threshold in some provinces. These excluded provinces account for a significant portion of Türkiye's population, meaning the overall burden of $PM_{2.5}$-related health outcomes may be underestimated.

Additionally, $PM_{2.5}$ was not measured in 71% of all air quality monitoring stations, and even where measurements were taken, only a small fraction (16%) had data above the 90% reliability threshold. Due to the limited availability of direct $PM_{2.5}$ measurements, $PM_{2.5}$ values were derived from PM_{10} using a conversion coefficient. This situation may limit the accuracy of the analysis. Understanding the actual $PM_{2.5}$ levels is essential for revealing the morbidity and mortality associated with long-term exposure. However, in Türkiye, there is currently no specified limit value for $PM_{2.5}$ in air quality regulations, which further complicates efforts to quantify the full scope of health impacts.

Lastly, the analysis was conducted at the provincial level, which may obscure localized environmental inequalities and their associated health impacts. Studies focusing on smaller geographic units, such as districts or neighborhoods, are needed to better capture these disparities.

CONCLUSION

Despite these limitations, this study is the first in Türkiye to estimate premature deaths attributed to $PM_{2.5}$ using AirQ+© software for 2019. The findings indicate that 37,768 premature deaths could have been prevented in 2019 alone if the $PM_{2.5}$ limit value recommended by the WHO had been adopted and implemented. Considering the limitations in $PM_{2.5}$ measurement capabilities, the actual number of deaths attributed to air pollution is likely underestimated. These findings highlight the necessity of establishing a more comprehensive air quality monitoring network and ensuring direct $PM_{2.5}$ measurements to enhance the reliability of health burden assessments. Expanding the measurement infrastructure would provide more accurate data, allowing for better estimation of the true health impacts of air pollution. Additionally, these findings reinforce the importance of annual measurement and control strategies to evaluate and improve national ambient air quality standards, which are critical for protecting public health and reducing premature mortality caused by air pollution. By addressing existing gaps, this study contributes to the scientific literature and strengthens advocacy efforts for improved air quality policies and monitoring infrastructure.

Ethics

Ethics Committee Approval-Informed Consent: Since this study used publicly available air quality and statistical data and did not involve any human participants or identifiable personal information, it did not require ethical committee approval or informed consent.

Acknowledgments

We would like to thank Ömer Erkmen who mapped estimated provincial $PM_{2.5}$ and related premature mortality findings.

Footnotes

Concept: N.A., A.T., C.H.Ç., K.P., Design: N.A., S.Ç.K., A.T., C.H.Ç., K.P., Data Collection or Processing: All authors, Analysis or Interpretation: All authors, Literature Search: N.A., S.Ç.K., M.E.K., O.T.S., S.S.O., N.K.Ç., A.T., C.H.Ç., K.P., Writing: S.Ç.K, N.A., M.E.K., O.T.S., S.S.O., N.K.Ç., A.T.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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