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Burden of Mortality Attributable to Long-Term Exposure to $PM_{2.5}$ in Addis Ababa, Ethiopia: A Health Impact Assessment Using AirQ+

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Abstract

Health impact assessments of ambient particulate matter remain far less developed in sub-Saharan African cities, despite fine particulate matter ($PM_{2.5}$) being a significant contributor to premature mortality globally. This study quantified the public health burdens of adult mortality associated with long-term $PM_{2.5}$ exposure in Addis Ababa, Ethiopia, under different counterfactual air quality scenarios. Hourly $PM_{2.5}$ data were collected across nine monitoring stations from 2022 to 2023. AirQ+ tool was utilized to estimate attributable natural-cause and cardiovascular disease (CVD) mortality among adults aged $\geq$ 30 years. Spatial analysis showed mean concentrations ranging from 15 $\mu g/m^3$ to 33 $\mu g/m^3$, with an overall mean of 26.74 $\mu g/m^3$, exceeding the WHO annual guideline by more than fivefold. Seasonal peaks occurred from June to August and diurnal maxima at 7:00 AM. In 2022, attributable natural-cause deaths ranged from 1489 (6.16%) at the less stringent WHO Interim Target 3 (15 $\mu g/m^3$) to 3169 (13.11%) at the WHO Air Quality Guidelines (5 $\mu g/m^3$). In 2023, the range was 1544 (6.40%) to 3218 (13.33%). For specific chronic endpoints, $PM_{2.5}$ concentration level was responsible for between 509 and 1071 CVD deaths in 2022, and between 535 and 1126 CVD deaths in 2023 across the counterfactual scenario. These results highlight the substantial health burden posed by ambient $PM_{2.5}$ in Addis Ababa and emphasize the urgent need for targeted interventions.

Keywords: AirQ+; mortality; Addis Ababa; air pollution; health impact assessment; cardiovascular disease

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1. Introduction

Air pollution is the most significant global environmental health threat, contributing to substantial morbidity and mortality worldwide. According to the State of Global Air 2025 report by the Health Effects Institute and the Institute for Health Metrics and Evaluation, air pollution was responsible for an estimated 7.9 million deaths globally in 2023, making it the leading environmental risk factor for mortality [1–3]. The majority of these deaths (86%) were attributable to non-communicable diseases, including ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), and lung cancer, with emerging evidence also linking exposure to dementia [1].

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Fine particulate matter ($PM_{2.5}$) remains the dominant contributor, accounting for approximately 4.9 million deaths, followed by household air pollution (2.8 million) and tropospheric ozone pollution (470,000) [1]. These findings underscore the pervasive and multisystem health impacts of air pollution.

The burden of air pollution is disproportionately concentrated in low- and middle-income countries (LMICs), where rapid urbanization, industrial growth, and limited regulatory capacity contribute to elevated pollution levels. In Africa, ambient air pollution alone was responsible for an estimated 394,000 deaths in 2019, reflecting a marked increase from 2015 [4]. Household air pollution further exacerbates this burden, particularly in settings reliant on solid fuels for cooking and heating [4]. Beyond health impacts, air pollution imposes significant economic costs, with losses exceeding 1% of gross domestic product in countries such as Ethiopia, Ghana, and Rwanda [4,5]. Moreover, $PM_{2.5}$ exposure has been associated with substantial losses in cognitive potential among children, posing long-term challenges for human capital development [4].

The causal relationship between long-term exposure to $PM_{2.5}$ and adverse health outcomes is well established. A comprehensive systematic review and meta-analysis conducted in support of the World Health Organization Air Quality Guidelines synthesized evidence from over 100 cohort studies and demonstrated consistent, statistically significant associations between $PM_{2.5}$ pollution level and all-cause, cardiovascular, and respiratory mortality [6–11]. These findings informed the 2021 revision of the WHO Air Quality Guidelines, which reduced the recommended annual mean $PM_{2.5}$ concentration from 10 $\mu g/m^3$ to 5 $\mu g/m^3$, reflecting growing consensus that no safe $PM_{2.5}$ pollution level threshold exists [12].

Health impact assessment (HIA) tools, particularly AirQ+, have become standard methods for quantifying the public health burden of air pollution. Developed by the WHO, AirQ+ applies concentration–response functions derived from epidemiological evidence to estimate attributable mortality and morbidity [13,14]. A global review identified 286 studies across 69 countries using AirQ/AirQ+, demonstrating its widespread application; however, significant gaps remain in the African context, particularly regarding data quality, spatial coverage, and uncertainty characterization [15].

Recent studies across African cities have reported consistently high $PM_{2.5}$ concentrations and substantial associated health burdens. In Kinshasa, annual mean $PM_{2.5}$ concentrations of 43.5 $\mu g/m^3$ were reported, with a large proportion of respiratory and cancer-related deaths attributable to air pollution [13]. Similarly, in Nairobi, personal exposure studies have documented high $PM_{2.5}$ levels, particularly among households using biomass fuels [16,17]. Despite these advances, the evidence base across sub-Saharan Africa remains limited, with relatively few studies providing high-resolution pollution level assessments [18].

Advances in air quality monitoring technologies provide new opportunities to address data gaps in resource-constrained settings. Satellite-derived estimates have improved understanding of regional trends but lack sufficient resolution for local health assessments. In contrast, low-cost $PM_{2.5}$ sensors enable expanded multi-site monitoring networks at relatively low cost and, when properly calibrated, can produce reliable data comparable to reference-grade instruments [17,19–23]. Validation studies in Ethiopia have demonstrated strong agreement between low-cost sensors and gravimetric methods, supporting their application in urban air quality assessment [24].

In Addis Ababa, PM concentration measurement has been limited by sparse monitoring infrastructure. However, several groups, including the city administration, have recently been installing low-cost sensors in different parts of the city, while functional reference-grade monitors are only available at the US Embassy. A foundational health impact assessment reported mean $PM_{2.5}$ concentrations of 42.4 μg/m^3 and estimated a substantial attributable mortality burden; however, the analysis relied on a single monitoring site, leaving it highly vulnerable to localized source biases [25]. Subsequent studies have similarly been constrained by limited monitoring coverage [26–28]. While establishing a perfectly uniform, high-density city-wide sensor network remains a logistical challenge in Addis Ababa, moving beyond single-site data to a distributed multi-site network is a critical next step to capture a more representative urban baseline for cumulative health assessments.

Given these limitations, there is a critical need for multi-site monitoring networks that capture diverse urban microenvironments to support more representative city-wide spatiotemporal assessments incorporating calibrated low-cost sensors along with two reference-grade monitors for robust health impact estimations. Integrating an expanded network of low-cost sensors offers a feasible approach to minimize the single-station biases of previous studies, providing a more robust, aggregated exposure baseline for public health interventions and air quality management.

Accordingly, the aim of this study was to characterize the spatiotemporal patterns of $PM_{2.5}$ across an expanded, multi-site sensor footprint and quantify the cumulative public health impacts in Addis Ababa, Ethiopia, using integrated monitoring data and the WHO AirQ+ model.

2. Materials and Methods

2.1. Description of Study Area

This study was conducted in Addis Ababa city in Ethiopia. The city is geographically situated between latitude 8.85° N and 9.05° N and longitudes 38.65° E and 38.90° E (Figure 1). It covers an area of about 540 km^2. According to the Ethiopian Statistical Service (ESS), the total population of the city was estimated to be 3,859,999 in 2022, reflecting a modest increase to 3,945,000 in 2023. The city is administratively divided into eleven sub-cities: Addis Ketema, Akaki Kaliti, Arada, Bole, Gullele, Kirkos, Kolfe Keranio, Ledeta, Nifas Silk Lafto, Yeka, and Lemi Kura.

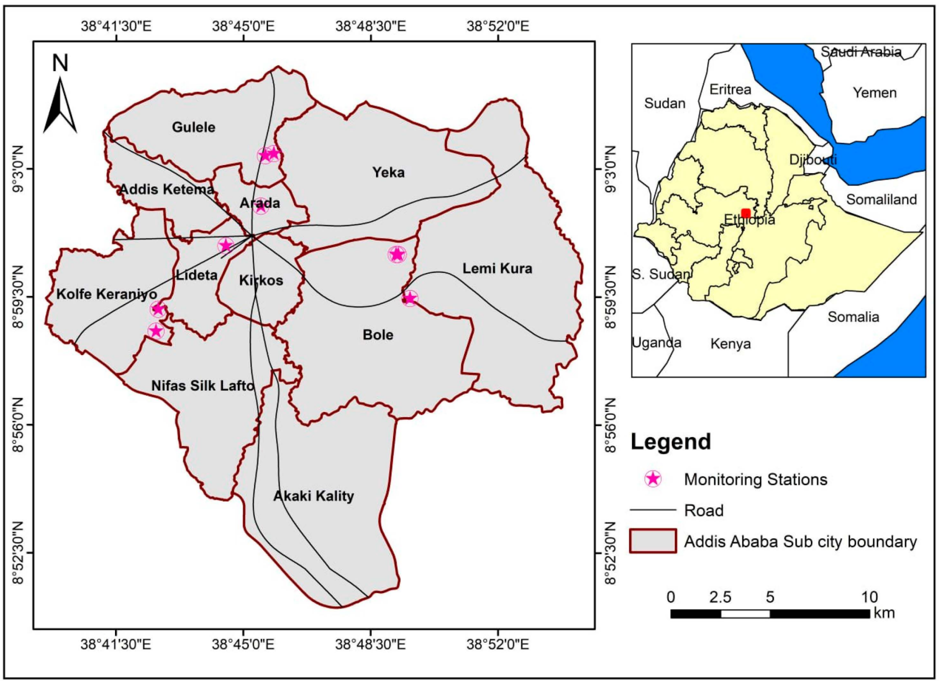

Figure 1. Description of the study area across the sub-cities of Addis Ababa, showing the road network and the spatial distribution of the nine air quality monitoring stations.

The city has an average altitude of 2400 m above sea level, with its highest point being Entoto Hill to the north, which rises to 3200 m. The city experiences a subtropical highland climate, with temperatures ranging from mild to cool. The long-term mean annual maximum and minimum temperatures of Addis Ababa are 25.8 °C and 12.6 °C, respectively. Over the past decades, the maximum temperature has increased by about 2.7 °C, while the minimum temperature shows smaller variations.

2.2. Air Pollution Data

Hourly $PM_{2.5}$ concentration data were downloaded directly from the PurpleAir online platform (www.purpleair.com) accessed on 15 June 2026 and the AirNow platform (www.airnow.gov) accessed on 15 June 2026 for the period 1 January 2022 to 31 December 2023 (Table 1). Data were cleaned by removing negative $PM_{2.5}$ values. Hourly $PM_{2.5}$ concentrations were retained only for days with at least 75% data availability ($\geq$18 h). No additional calibration or correction factors were applied to the PurpleAir data; the spatiotemporal analysis was conducted using the raw data to capture broader spatial variability. However, health impact estimates were derived exclusively from reference-grade BAM data to ensure toxicological and epidemiological robustness.

Table 1. Locations and land-use characteristics of the selected air quality monitoring sites.

Site	Longitude/Latitude	Land Use Characteristics	Monitoring Type
S1	38.758/9.033	Bare land, condominium, multi-story buildings, education facilities, perennial river and riverine vegetation	Low-cost sensor
S2	38.820/9.011	Asphalt, built-up area, open space	Reference-grade monitor
S3	38.760/9.056	Office buildings, parking, asphalt, green area, swimming pool	Reference-grade monitor
S4	38.711/8.986	Riverine area, hospital and road divider	Low-cost sensor
S5	38.764/9.057	Office buildings, asphalt	Low-cost sensor
S6	38.450/9.012	Traffic, hospital parking	Low-cost sensor
S7	38.821/9.011	Buildings, parking, green area, pedestrian pathways	Low-cost sensor
S8	38.710/8.976	Waste disposal/landfill	Low-cost sensor
S9	38.780/8.990	Asphalt, buildings, main road to airport, commercial and high-income residential area	Low-cost sensor

This study employed a two- tiered approach to assess air quality in Addis Ababa. Low-cost PurpleAir sensors (Purple Air LLC, Draper, Utah) captured spatiotemporal variations across urban microenvironments, while peer-reviewed calibration equations linked to reference-grade Beta Attenuation Monitor (BAM) standards were applied for the health impact assessment. This ensured reference equivalency.

$PM_{2.5}$ concentrations for the AirQ+ model minimized bias in mortality estimates.

2.3. Population and Mortality Data

The baseline demographic profile of Addis Ababa was structured using official government census data. The primary population datasets were obtained from the Population Projections for Ethiopia 2007–2037 report, published by the Central Statistical Agency (CSA) of Ethiopia [29] (historically referenced as the 2013 CSA report and subsequently restructured as the Ethiopian Statistics Service [ESS]).

Age-specific populations for 2023 were estimated via linear interpolation between the 2022 and 2027 ESS medium variant projections following standard demographic techniques (United Nations, Department of Economic and Social Affairs, Population Division (2022); World Population Prospects 2022: Methodology of the United Nations population estimates and projections [30]).

Due to the absence of empirical census or projection tables specifically for the year 2023, a linear interpolation model was executed using the medium-variant projection tracks from 1 July 2022 and 1 July 2027 to simulate the mid-interval demographic growth. The population for each specific age classification cohort in 2023 was determined using the following formula [31]:

$$\mathrm{P}_{2023} = \mathrm{P}_{\_2022} + \left(\frac{P_{2027} - P_{2022}}{5}\right) \times 1 \tag{1}$$

- P_{2023} = target population for 1 July 2023 (mid-interval year);
- P_{2022} = 3,859,638 (ESS medium variant, 1 July 2022);
- P_{2027} = 4,281,394 (ESS medium variant, 1 July 2027);
- 5 = number of years in the projection interval (2022 → 2027);
- 1 = forward step of exactly one year from the 2022 baseline.

Mortality data for Addis Ababa were obtained from the Global Burden of Disease (GBD) database developed by the Institute for Health Metrics and Evaluation (IHME). According to GBD estimates, the total population of Addis Ababa was approximately 3,859,638 during the study period. For the health impact assessment, the analysis focused on adults aged 30 years and older, as the exposure–response functions implemented in the AirQ+ model are derived from cohort studies conducted in this age group (Global Burden of Disease Study 2022 and 2023, retrieved from [32]). Detailed population and mortality data used in the analysis are presented in Table A1 (Appendix A).

2.4. Health Impact Assessment Using AirQ+

The public health burden of long-term ambient $PM_{2.5}$ exposure was quantified using the World Health Organization's AirQ+ software (version 2.2). This tool applies mathematically integrated concentration–response functions derived from global epidemiological cohort studies to estimate attributable mortality and morbidity fractions.

2.4.1. Model and Scenario Selection

For the present analysis, a log-linear model was selected to calculate the attributable proportion of mortality. This functional form is highly recommended for ambient exposure assessments across wide concentration fields where changes in relative risk follow a non-linear trajectory. The health impact of long-term ambient $PM_{2.5}$ exposure was estimated using the World Health Organization's AirQ+ software (version 2.2). AirQ+ is a quantitative tool that estimates the burden of disease attributable to air pollution using integrated exposure–response functions derived from epidemiological studies [13,33]. The software facilitates the calculation of $PM_{2.5}$ health impacts in accordance with the WHO Air Quality Guidelines [12], including interim targets, allowing for scenario-based assessments using different counterfactual concentrations [12].

For the present analysis, a log-linear model was employed to calculate the attributable proportion of mortality, as this functional form is recommended for long-term ambient $PM_{2.5}$ concentration assessments where the concentration–response relationship follows a non-linear pattern across a wide exposure range [13,34]. According to the AirQ+ glossary (August 2022 version), the log-linear function is expressed as

$$RR = Exp\Bigg(\alpha + \beta\log(X+1)/Exp\Bigg(\alpha + \beta\log(X_o+1)\left[\frac{X+1}{X_o+1}\right]\beta \tag{2}$$

where

RR = relative risk at exposure concentration; X = observed $PM_{2.5}$ concentration (μg/m^3); X_0 = counterfactual (cut-off) concentration (μg/m^3); β = coefficient representing the change in log relative risk per unit change in log-transformed exposure; and α is the intercept (constant term) in the log-linear model

In the log-linear model, the coefficient β quantifies the extent to which a one-unit increase in log-transformed exposure (log[X + 1]) is associated with an expected change in log relative risk by β units. For this analysis, β was derived from the integrated exposure–response (IER) functions embedded within AirQ+, which are based on a meta-analysis of global cohort studies [7].

For the present analysis, a log-linear model was employed to calculate the attributable proportion of mortality for long-term ambient $PM_{2.5}$ concentrations (2-year average). While this period is shorter than lifetime exposure assessments, it aligns with the integrated exposure–response functions in AirQ+ and captures near-term mortality burden.

The AirQ+ software enables users to calculate $PM_{2.5}$ impacts based on the WHO Air Quality Guidelines (2021) [35] including intermediate target values (Interim Target 3 = 15 μg/m3, Interim Target 4: 10 μg/m3, and the Air Quality Guideline (AQG): 5 μg/m^3). For specific calculations where impacts are quantified by selecting different cut-off points, the log-linear function is more appropriate than alternative models (e.g., linear or linear-log), particularly in the case of air pollution concentrations that are neither too low nor too high [12].

2.4.2. Attributable Proportion Calculation

The attributable fraction (AF) of health outcomes due to $PM_{2.5}$ exposure was calculated using [36]

$$AF = \sum\left[P_{(c)} \times \left(RR_{(c)} - 1\right)\right] / \sum\left(P_{\ (c)} \times RR_{(c)}\right) \tag{3}$$

where

RR(c) is the relative risk for the health outcome at exposure level cc, and P(c) is the proportion of the population exposed to level c.

Relative risk values were derived from the integrated exposure–response functions integrated into AirQ+, based on meta-analyses of global epidemiological studies.

2.4.3. Attributable Deaths Calculation

The number of attributable deaths (AD) per unit population was calculated as [13]

$$\mathrm{AD} = \mathrm{B} \times \mathrm{AF} \tag{4}$$

where B is the baseline reference frequency (number of deaths) for the health outcome in the population.

2.4.4. Air Pollution Reduction Scenarios

We modeled scenarios to estimate the potential health benefits of reducing $PM_{2.5}$ concentrations, focusing on two key targets. The WHO Air Quality Guidelines (AQG) of 5 μg/m^3 represents the optimal annual mean concentration for minimizing health risks, while the WHO Interim Target 3 (IT-3) of 15 μg/m^3 provides a more achievable intermediate goal. Comparing these levels allows assessment of both ideal and realistic reductions in air pollution and their corresponding health impacts.

3. Results

3.1. Spatial Variation in PM $_{2.5}$ Concentrations

Hourly $PM_{2.5}$ measurements were collected from nine monitoring stations across Addis Ababa, including seven PurpleAir low-cost public sensors for high spatial coverage and two reference-grade Beta Attenuation Monitors (BAMs) to provide benchmark-quality data for health impact assessment. A statistical summary of $PM_{2.5}$ concentrations recorded at nine monitoring stations in 2022 and 2023 is presented in Table 2. The Shapiro–Wilk test results showed that $PM_{2.5}$ concentrations were not normally distributed at all monitoring stations ($p < 0.05$).

Table 2. A statistical summary of $PM_{2.5}$ concentrations recorded at 9 monitoring sites.

Station	Year	Data Count (*n*)	Mean ± SD	Median (IQR)	Min–Max	CV (%)
S1	2022	7579	25.83 ± 13.07	23.08 (15.27–34.47)	1.21–66.44	50.61
	2023	7745	27.12 ± 14.35	25.15 (15.41–36.91)	0.26–71.97	52.93
S2	2022	7194	26.98 ± 12.81	24.00 (17.25–34.00)	1.00–65.00	47.48
	2023	6696	28.36 ± 12.76	26.00 (19.00–36.00)	2.00–66.00	44.99
S3	2022	2932	20.28 ± 8.02	19.00 (15.00–25.00)	0.10–44.00	39.53
	2023	7441	19.45 ± 10.88	17.00 (11.00–26.00)	0.90–51.00	55.95
S4	2022	5751	32.52 ± 16.77	30.16 (19.02–43.00)	1.72–84.19	51.56
	2023	2337	32.75 ± 18.34	31.58 (17.31–44.56)	1.90–88.55	55.98
S5	2022	7940	21.07 ± 11.36	18.09 (12.15–28.18)	0.61–54.40	53.90
	2023	7775	22.68 ± 12.75	20.01 (12.65–31.48)	0.09–61.06	56.22
S6	2022	4960	32.55 ± 18.07	28.35 (18.11–43.71)	3.14–88.99	55.53
	2023	6211	33.53 ± 20.42	30.43 (16.81–45.56)	0.08–97.19	60.90
S7	2022	6791	18.44 ± 9.64	16.20 (11.12–24.62)	1.66–47.03	52.28
	2023	3586	9.15 ± 6.82	7.21 (3.90–12.61)	0.05–30.11	74.57
S8	2022	5920	31.74 ± 15.44	29.55 (20.07–40.55)	1.88–82.84	48.65
	2023	5249	31.07 ± 16.25	28.76 (18.48–40.58)	2.87–81.57	52.30
S9	2022	7115	31.87 ± 11.61	29.91 (23.34–38.92)	4.84–67.61	36.42
	2023	7722	34.30 ± 12.11	32.59 (25.45–41.43)	4.79–70.64	35.30

The mean $PM_{2.5}$ concentrations ranged from 9.15 $\mu g/m^3$ at S7 in 2023 to 34.30 $\mu g/m^3$ at S9 in 2023, indicating substantial spatial heterogeneity. In 2022, the highest mean concentration was observed at S6 (32.55 $\mu g/m^3$), followed by S4 (32.53 $\mu g/m^3$) and S9 (31.87 $\mu g/m^3$), whereas S7 recorded the lowest mean (18.44 $\mu g/m^3$). In 2023, S9 showed the highest mean (34.31 $\mu g/m^3$), followed by S6 (33.54 $\mu g/m^3$) and S4 (32.75 $\mu g/m^3$), with S7 again exhibiting the lowest value (9.15 $\mu g/m^3$). Overall, the mean $PM_{2.5}$ concentration across all sites was 26.79 $\mu g/m^3$ in 2022 and 26.79 $\mu g/m^3$ in 2023.

Variability, reflected by the standard deviation, differed among stations and years. In 2022, S6 (18.07 $\mu g/m^3$), S4 (16.77 $\mu g/m^3$), and S8 (15.44 $\mu g/m^3$) exhibited higher fluctuations, while S7 (9.64 $\mu g/m^3$) showed moderate variability. In 2023, variability increased at several sites, notably S6 (20.42 $\mu g/m^3$) and S4 (18.34 $\mu g/m^3$), while S7 decreased (6.82 $\mu g/m^3$), indicating a sharper drop in mean $PM_{2.5}$. Comparison of mean and median values shows right-skewed distributions at S4, S6, S8, and S9, suggesting occasional high $PM_{2.5}$ spikes.

The spatial distribution of $PM_{2.5}$ concentrations appears closely linked to surrounding land use and anthropogenic activities. Stations with higher $PM_{2.5}$ levels, such as S4, S6, and S9, are in areas dominated by heavy traffic, commercial zones, high-income residential areas, waste disposal sites, and built-up infrastructure. For example, S6 includes traffic and building zones and hospital parking, while S9 is adjacent to major roads, commercial areas, and densely built high-income neighborhoods, which likely contribute to elevated emissions. S8, with moderate but still elevated concentrations, shares some of these urban characteristics.

In contrast, stations with lower $PM_{2.5}$ levels, particularly S7, are in areas with relatively more open spaces and pedestrian paths; reduced vehicular density may mitigate particulate concentrations. Similarly, S3 and S1, though urbanized, include green areas and riverine zones, which may help lower $PM_{2.5}$ through deposition and dispersion mechanisms.

Comparison of mean and median values indicates right-skewed distributions at most stations, particularly S4, S6, S8, and S9, suggesting occasional high $PM_{2.5}$ pollution episodes.

3.2. Temporal Variation in $PM_{2.5}$ Concentration

The overall mean $PM_{2.5}$ concentration was 26.73 $\mu g/m^3$ in 2022 and 26.76 $\mu g/m^3$ in 2023. The analysis of monthly mean $PM_{2.5}$ concentrations over the 2022–2023 period revealed a pronounced and consistent seasonal pattern (Figure 2A). Concentrations were relatively lower and stable during the months from October/November through May, with values ranging from 19 to 27 $\mu g/m^3$. A sharp and sustained increase was observed from June through September, forming a distinct peak period where monthly averages ranged from 29.53 to 36.61 $\mu g/m^3$.

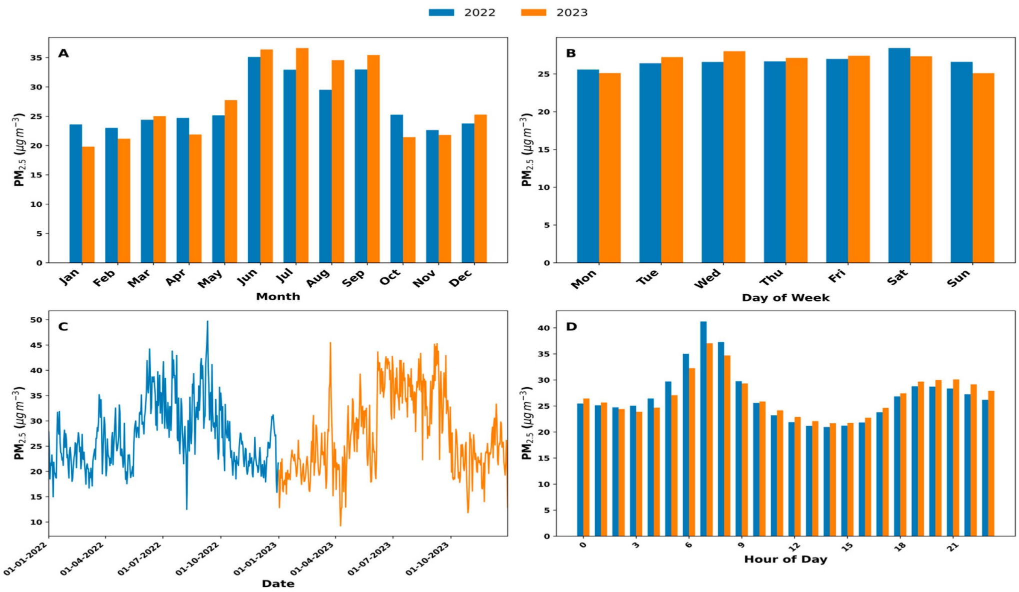

Figure 2. (**A**) Monthly average $PM_{2.5}$ concentration, (**B**) day-of-week average $PM_{2.5}$ concentration, (**C**) daily average $PM_{2.5}$ concentration, (**D**) hourly average $PM_{2.5}$ concentration.

This peak season was more severe and prolonged in 2023. Every month from June to September 2023 recorded a higher mean concentration than its 2022 counterpart. The highest single monthly mean of the study period was recorded in July 2023 (36.61 $\mu g/m^3$). In contrast, the lowest monthly mean was observed in January 2023 (19.85 $\mu g/m^3$).

A clear weekly cycle in $PM_{2.5}$ concentrations was evident (Figure 2B). In both years, the lowest mean concentrations occurred on Sundays (e.g., 24.88 $\mu g/m^3$ in 2023). Concentrations increased through the weekdays. A notable inter-annual shift in the peak pollution day was observed: the highest mean occurred on Saturday in 2022 (28.40 $\mu g/m^3$) but shifted to Wednesday in 2023 (28.08 $\mu g/m^3$).

The annual monthly mean values for both 2022 and 2023 are shown in Figure 2. In 2022, $PM_{2.5}$ concentrations varied across different stations, with notable peaks in the summer months. The highest $PM_{2.5}$ concentration was recorded as 47.17 $\mu g/m^3$ at station S6 in August, followed by station S9, which recorded a concentration of 40.81 $\mu g/m^3$ in September. In contrast, station S7 reported a comparatively lower PM $_{2.5}$ concentration of 12.95 $\mu g/m^3$. Similarly, there was a general increase in $PM_{2.5}$ concentration across most monitoring stations in 2023 during the wet season. The highest concentration was recorded at station S4 with a value of 47.00 $\mu g/m^3$ in September, followed by station S6 (42.98 $\mu g/m^3$). The highest value in July was recorded at station S9 (42.75 $\mu g/m^3$) followed by station S1 (37.64 μg/m^3). On the other hand, the lowest was recorded at station S7 in February (5.53 μg/m^3) and January (7.27 μg/m^3), which reflects a substantial reduction in pollution compared to the previous year.

3.3. Diurnal Variation in PM$_{2.5}$ Concentrations

The diurnal variation among all the monitoring stations showed a similar pattern in PM$_{2.5}$ concentrations, as shown in Figure 3. The results show generally higher concentrations in the early morning hours, particularly between 6.00 a.m and 8.00 a.m with a peak concentration observed at 7.00 a.m. The highest peak concentration of 37.67 μg/m^3 occurred on Friday, while the lowest relative concentration of 35.63 μg/m^3 was observed on Monday.

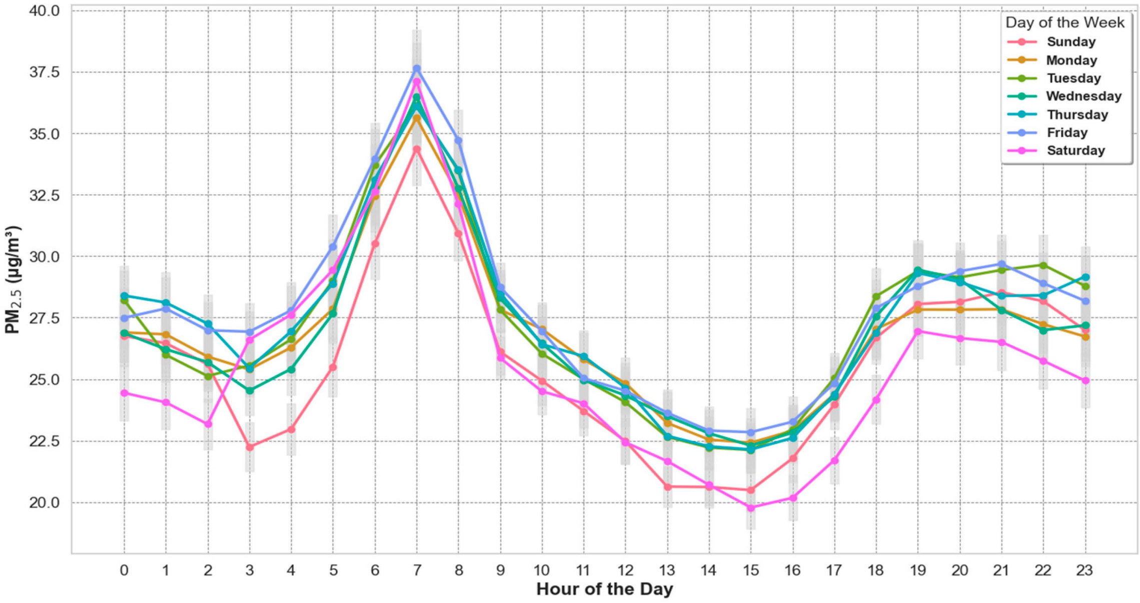

Figure 3. Average diurnal pattern of PM$_{2.5}$ concentration across all monitoring stations, aggregated by day of the week. Grey lines are error bars.

Following the morning peak, a noticeable decline in PM$_{2.5}$ concentrations was observed during the midday hours, specifically between 12:00 PM and 2:00 PM. On Monday, the concentration dropped to 24.83 μg/m^3 at 12:00 PM, while a similar concentration of 22.48 μg/m^3 was observed at the same time on Tuesday. In the evening, PM$_{2.5}$ concentrations typically increased, beginning around 5:00 PM and peaking between 7:00 PM and 8:00 PM. The minimum PM$_{2.5}$ concentration of 26.95 μg/m^3 was observed at 7:00 PM on Saturday, while the maximum value reached approximately 29.45 μg/m^3 by 7:00 PM on Wednesday. Significant differences in P$_{2.5}$ concentrations were observed across different hours of the day ($p < 0.05$).

3.3.1. Burden of Adult Mortality Attributable to Ambient PM$_{2.5}$ Level in 2022

Table 3 presents the estimated health impact attributable to health impacts attributable to ambient PM$_{2.5}$ concentrations among adults aged 30 years and older in 2022. The estimation was based on an annual mean PM$_{2.5}$ concentration of 23.26 μg/m^3 and a total population of 1,965,169. Assuming a cut-off of 5.0 μg/m^3 as recommended by the WHO Air Quality Guidelines, an estimated 13.11% (95%CL: 10.09–14.56%) of natural-cause mortality was attributed to PM$_{2.5}$ levels. This corresponded to approximately 3169 attributable deaths (95% CL: 2439–3519), equivalent to 161 deaths per 100,000 population (95%CL: 124–179).

Table 3. Estimated health impact attributable to long-term health impacts attributable to ambient $PM_{2.5}$ concentrations among adults (Aged 30+ Years) in Addis Ababa, 2022 (BAM Monitor Data: S2 and S3).

Cut-Off (μg/m^3)	Attributable Proportion (%) (95% CI)	Attributable Death (n) (95% CI)	Death per 100,000 (95% CI)
Scenario A (5.0)	13.11 (10.09–14.56)	3169 (2439–3519)	161 (124–179)
Scenario B (10.0)	9.70 (7.44–10.80)	2345 (1797–2610)	119 (91–133)
Scenario C (15.0)	6.16 (4.70–6.87)	1489 (1136–1661)	76 (58–84)

When counterfactual concentration was increased to 10.0 μg/m^3, the attributable proportion decreased to 9.70% (95% CI: 7.44–10.80%), which corresponds to 2345 attributable deaths (95% CI: 1797–2610) or 119 cases per 100,000 population (95% CI: 91–133).

At a cut-off of 15.0 μg/m^3, the estimated attributable proportion was 6.16% (95% CI: 54.70–6.87%), equivalent to 1489 attributable deaths (95% CI: 1136–1661) or 76 cases per 100,000 population (95% CI: 58–84).

3.3.2. Burden of Adult Mortality Attributable to Health Impacts Attributable to Ambient $PM_{2.5}$ Concentrations in 2023

In 2023, the health impact of long-term health impacts attributable to ambient $PM_{2.5}$ concentrations was assessed among adults aged 30 years and older. The assessment used an annual mean $PM_{2.5}$ concentration of 23.59 μg/m^3 and a total population of 20,019,691. The AIRQ+ tool was applied to estimate natural-cause mortality attributable to $PM_{2.5}$ using a log-linear model across three counterfactual scenarios (Table 4).

Table 4. Estimated health impact attributable to ambient $PM_{2.5}$ concentrations among adults (age 30+ years) in Addis Ababa, 2023 (BAM Monitor Data: S2 and S3).

Cut-Off (μg/m^3)	Attributable Proportion (%) (95% CI)	Attributable Death (n) (95% CI)	Cases per 100,000 (95% CI)
Scenario A (5.0)	13.33 (10.27–14.80)	3218 (2478–3573)	159 (123–177)
Scenario B (10.0)	9.93 (7.61–11.05)	2397 (1838–2668)	119 (91–132)
Scenario C (15.0)	6.40 (4.88–7.14)	1544 (1178–1722)	76 (58–85)

At a cut-off of 5.0 μg/m^3, an estimated 13.33% (95% CI: 10.27–14.80%) of natural-cause mortality was attributable to ambient $PM_{2.5}$ concentrations, corresponding to 3218 deaths (95% CI: 2478–3573), or 159 cases per 100,000 population (95% CI: 123–177). In contrast, at a cut-off of 10.0 μg/m^3 (Scenario B), the attributable fraction was 9.93% (95% CI: 7.61–11.05%), representing 2397 deaths (95% CI: 1838–2668), or 119 cases per 100,000 population (95% CI: 91–132%).

At a cut-off of 15.0 μg/m^3 (Scenario C), the estimated attributable proportion was 6.40% (95% CI: 4.88–7.14%), equating to 1544 deaths (95% CI: 1178–1722%), or 76 cases per 100,000 population (95% CI: 58–85). These results indicate that a substantial proportion of natural-cause mortality among adults in Addis Ababa is associated with long-term health impacts attributable to ambient $PM_{2.5}$ concentrations, with the largest burden observed when compared to the WHO guideline of 5 μg/m^3. The findings emphasize the public health importance of reducing ambient $PM_{2.5}$ to prevent premature deaths and highlight the potential benefits of air quality interventions in the city.

3.3.3. Attributable Cardiovascular Mortality Burden and Threshold Sensitivity (2022–2023)

The environmental health impact assessment evaluated the long-term ambient effects of fine particulate matter $PM_{2.5}$ on cardiovascular mortality among adults aged 30 and older in Addis Ababa across consecutive observation years. Based on projections in 2022, the number of adults in Addis Ababa (age $\geq$ 30 years) was about 1,965,169, including 6174.88 baseline cardiovascular deaths (mortality rate of 314.22 per 100,000). According to health impact assessment results, there was a significant health burden caused by environmental ambient $PM_{2.5}$ concentration in Addis Ababa under all counterfactual scenarios (Table 5).

Table 5. Health impact assessment of ambient $PM_{2.5}$ on cardiovascular mortality (adults $\geq$30 Years), Addis Ababa (2022).

Cut-Off (μg/m^3)	**Attributable Proportion (%) (95% CI)**	**Attributable Deaths (n) (95% CI)**	**Cases per 100,000 (95% CI)**
Scenario A (5.0)	17.35 (14.56–21.28)	1071 (899–1314)	42.8 (36.0–52.6)
Scenario B (10)	12.92 (10.80–15.95)	798 (667–985)	31.9 (26.7–39.4)
Scenario C (15)	8.25 (6.87–10.31)	509 (424–637)	20.4 (17.0–25.5)

Baseline cardiovascular deaths (2022): 6174.88. Adult population ($\geq$30 years): 1,965,169.

In Scenario A, for instance, the attributable fraction was 17.35% (95% CI: 14.56–21.28), which accounted for 1071 deaths (95% CI: 899–1314) or 42.8 per 100,000 (95% CI: 36.0–52.6). In Scenario B, $PM_{2.5}$ was responsible for 12.92% (95% CI: 10.80–15.95) of baseline deaths amounting to 798 deaths (95% CI: 667–985) or 31.9 per 100,000 (95% CI: 26.7–39.4), while Scenario C indicated that the attributable proportion was 8.25% (95% CI: 6.87–10.31) which led to 509 deaths (95% CI: 424–637) or 20.4 per 100,000 (95% CI: 17.0–25.5).

In 2023, the estimated adult population ($\geq$30 years) increased to 2,019,691, with total baseline cardiovascular deaths rising to 6489.90 (mortality rate: 321.33 per 100,000). Table 6 summarizes the findings for 2023 regarding the health impact of ambient $PM_{2.5}$ on cardiovascular mortality (adults $\geq$ 30 years). In Addis in 2023, there was an increase in the total adult population to 2,019,691, along with the number of cardiovascular deaths being 6489.90 (mortality rate: 321.33/100,000). The findings were similar in terms of $PM_{2.5}$-attributable cardiovascular mortality cases, but the total burdens were slightly higher compared to 2022. Using Scenario A, 17.35% (95% CI: 14.56–21.28) of the deaths were attributed to $PM_{2.5}$, accounting for 1126 deaths (95%CI: 945–1381) or 45.0 per 100,000 (95% CI: 37.8–55.2). Similarly, Scenario B generated 12.92% (95% CI: 10.80–15.95) of deaths due to $PM_{2.5}$ exposure, which translates to 838 deaths (95% CI: 701–1035) and 33.5 per 100,000 (95% CI: 28.0–41.4), and finally while Scenario C produced 8.25% (95% CI: 6.87–10.31), corresponding to 535 deaths (95% CI: 446–669) or 21.4 per 100,000 (95% CI: 17.8–26.8).

Table 6. Health impact assessment of ambient $PM_{2.5}$ on cardiovascular mortality (adults $\geq$ 30 Years), Addis Ababa (2023).

Cut-Off (μg/m^3)	**Attributable Proportion (%) (95% CI)**	**Attributable Deaths (n) (95% CI)**	**Cases per 100,000 (95% CI)**
Scenario A (5.0)	17.35 (14.56–21.28)	1126 (945–1381)	45.0 (37.8–55.2)
Scenario B (10)	12.92 (10.80–15.95)	838 (701–1035)	33.5 (28.0–41.4)
Scenario C (15)	8.25 (6.87–10.31)	535 (446–669)	21.4 (17.8–26.8)

Baseline cardiovascular deaths (2023): 6489.90. Adult population ($\geq$30 years): 2,019,691.

4. Discussion

This study presented air quality data collected from a total of nine monitoring stations distributed across Addis Ababa, including seven low-cost sensors (PurpleAir) and two BAM stations owned by the U.S. Embassy. For the spatiotemporal analysis, data from all available monitoring stations were utilized to accurately capture the spatial and temporal variability of $PM_{2.5}$ concentrations across the city. The inclusion of multiple monitoring sites allowed for enhanced characterization of urban air pollution patterns, which is particularly important in rapidly growing cities with diverse emission sources.

Across the entire study period, the overall mean $PM_{2.5}$ concentration was 26.76 $\mu g/m^3$, representing an exposure level 5.35 times higher than the WHO Air Quality Guidelines (AQG) of 5 $\mu g/m^3$. On an annual basis, air quality remained consistent, with an overall mean of 26.74 $\mu g/m^3$ in 2022 and 26.76 $\mu g/m^3$ in 2023. Considerable spatial variation was observed, with concentrations ranging from 15.23 to 33.14 $\mu g/m^3$. Although $PM_{2.5}$ levels in Addis Ababa remain above WHO standards, the mean concentration recorded in this study is lower than 42.4 $\mu g/m^3$ reported in the previous assessment [25]. The observed concentration is consistent with previous studies conducted in Addis Ababa. For instance, Sarath K. Guttikunda [37] reported annual ambient $PM_{2.5}$ concentrations ranging between 20 and 60 $\mu g/m^3$ across Addis Ababa using the WRF-CAMx chemical transport modeling system [37]. However, it remains slightly higher than the 23.6 $\mu g/m^3$ reported by Bulto and Berkessa [27]. A recent study conducted in Kinshasa, the Democratic Republic of Congo, another rapidly growing sub-Saharan African city, reported an annual mean $PM_{2.5}$ concentration of 43.5 $\mu g/m^3$ in 2019, which is nearly double the levels observed in Addis Ababa during our study period [13].

Stations located near hospitals (S4, S6), waste disposal areas (S8), and commercial corridors (S9) recorded the highest $PM_{2.5}$ concentrations, highlighting the strong influence of surrounding land use patterns. Sites adjacent to hospitals are typically situated along high-traffic roads with frequent vehicle movement, while commercial corridors are characterized by congestion and intensive fuel combustion. At the waste disposal site (S8), open burning and waste decomposition further contribute to elevated particulate levels. Similar spatial patterns have been reported in other urban studies such as Arba Minch, where $PM_{2.5}$ concentrations are significantly higher near roads, commercial centers, and waste-related activities due to localized emissions [38–41].

Our assessment revealed a peak in $PM_{2.5}$ concentrations during the wet season (June–August), consistent with a previous study conducted in Addis Ababa [25,26,42]. This seasonal increase can be attributed to low wind speeds, reduced pollutant dispersion, and enhanced secondary particle formation, which facilitate the accumulation of pollutants in the atmosphere [43]. In addition, increased reliance on biomass fuels such as charcoal and wood for cooking further elevates emissions [41,44]. Source apportionment evidence supports this pattern, showing that biomass burning contributions increase to 21.5% during the wet season (from 14% in the dry season), while vehicular emissions account for 31% of total $PM_{2.5}$ mass [41].

In contrast, studies from some Asian regions, such as India, report lower $PM_{2.5}$ concentrations during the monsoon season due to rainfall and stronger atmospheric mixing that remove particles from the air [45–48]. In a similar study in China, the summer wet season was associated with the lowest concentrations due to enhanced atmospheric diffusion and precipitation [49].

The persistence of elevated $PM_{2.5}$ levels in Addis Ababa during the wet season may be attributed to localized urban and infrastructural factors, including frequent flooding, inadequate drainage, and traffic congestion that sustain emissions despite rainfall. At the same time, the use of solid fuels remains widespread, as shown by Azanaw and Sisay Chanie [50], who reported that 87.1% of Ethiopian households rely on solid fuels, with 18.6% in urban areas. This emphasizes the continuing contribution of household energy practices to ambient air pollution. These findings suggest that urban infrastructure, energy consumption patterns, and local meteorological conditions interact to maintain elevated $PM_{2.5}$ levels during the wet season.

Average diurnal pattern of $PM_{2.5}$ concentration across all monitoring stations, aggregated by day of the week. The result showed a distinct diurnal bimodal profile, with a primary peak at approximately 7:00 AM. The observed morning peak in $PM_{2.5}$ concentrations is consistent with previous observations in Addis Ababa reported by Redi [43], where elevated pollutant levels during the early morning were associated with reduced atmospheric mixing and stable meteorological conditions [43,51]. This morning peak is highly indicative of the combined effects of morning traffic rush hours, domestic cooking activities, and a lower, stable atmospheric boundary layer height that limits pollutant dispersion early in the day.

Our analysis revealed that a significant proportion of natural-cause mortality among adults in Addis Ababa is attributable to ambient $PM_{2.5}$ concentrations. Under the strictest baseline counterfactual (5 $\mu g/m^3$), the $PM_{2.5}$ pollution concentration was responsible for 13.11% of natural-cause adult deaths in 2022 (3169 premature deaths) and 13.33% in 2023 (3218 premature deaths) (Tables 3 and 4), imposing an annual economic toll of over $2.04 billion and $2.07 billion. When evaluated against a moderate counterfactual threshold (Scenario B: 10 $\mu g/m^3$), the attributable proportion shifts to 9.70% in 2022 (2345 deaths) and 9.93% in 2023 (2397 deaths). This aligns closely with, but is slightly higher than, the 2043 deaths estimated by Kumie, Worku [25] the same threshold (10 $\mu g/m$). The escalation in absolute attributable deaths over time despite our slightly lower monitored $PM_{2.5}$ concentrations can be attributed to Addis Ababa's rapid demographic expansion and aging population (adults aged 30+ years rising to over 2 million by 2023). This demonstrates that population growth and urbanization can amplify the public health burden even during periods of modest ambient air quality stabilization.

At the least stringent counterfactual target (Scenario C: 15 $\mu g/m^3$), which corresponds to the WHO Interim Target 3, the model indicated that $PM_{2.5}$ still accounts for 6.16% (1489 deaths) and 6.40% (1544 deaths) of natural adults' mortality for 2022 and 2023, respectively.

The results from Addis Ababa are comparable to findings from other sub-Saharan African cities. A study conducted in Kampala, Uganda, using the WHO AirQ+ tool reported attributable proportions of approximately 18–20% for all-cause mortality associated with long-term $PM_{2.5}$ exposure, at annual concentrations near 39 $\mu g/m$ [52]. The slightly lower attributable fraction in Addis Ababa is consistent with its lower $PM_{2.5}$ concentration (approximately 23 $\mu g/m^3$ compared to 34.9 $\mu g/m^3$ in Kampala), reflecting the concentration–response function embedded in the AirQ+ model [21].

Our findings are also in line with the results from Kinshasa, the Democratic Republic of Congo, where an attributable proportion of 25.64% for all-cause mortality was reported at a much higher $PM_{2.5}$ concentration of 43.5 $\mu g/m^3$ [13]. The lower concentration in Addis Ababa (24–25 $\mu g/m^3$) logically results in a lower attributable proportion (13.1–13.5%). This gradient highlights the direct relationship between pollution levels and health impacts, suggesting that even the moderately high levels observed in Addis Ababa are associated with a considerable health burden.

Furthermore, a previous study in Addis Ababa using AirQ+ reported an attributable proportion of 17.7% for an annual $PM_{2.5}$ concentration of 42.4 $\mu g/m^3$ [25]. Our study, which uses more recent data and a lower baseline concentration, shows a lower attributable fraction, which is consistent with the expected non-linear relationship between exposure and health outcomes, especially when using the log-linear model recommended for such concentration ranges.

Quantitative health impact assessments, such as those performed using AirQ+, facilitate the estimation of potential benefits from improved air quality. Our analysis across different counterfactual scenarios demonstrates that adhering to stricter air quality guidelines would yield substantial health gains. Achieving the WHO's annual Air Quality Guideline of 5 $\mu g/m^3$ in Addis Ababa could prevent 13.1–13.5% of current adult deaths—representing over 3100 premature deaths annually. Even a more modest reduction to

15 μg/m^3 (WHO Interim Target 3) could prevent 6.2–6.6% of deaths, or approximately 1500 premature deaths each year.

Our specific assessment of cardiovascular mortality reveals that $PM_{2.5}$ exposure accounts for 17.35% of all baseline cardiovascular deaths in adults under 5 μg/m^3. This heavy cardiovascular burden strongly reinforces findings by Getachew, Mekonnen [52] who demonstrated that reducing $PM_{2.5}$ yields the highest absolute drop in mortality specifically for cardiovascular and ischemic heart diseases in Addis Ababa.

5. Limitations and Novelty

This study has several key strengths. It is one of the few studies in sub-Saharan Africa to utilize two consecutive years of reference-grade (BAM-1020) $PM_{2.5}$ monitoring data, which provides robust exposure estimates. The use of the WHO AirQ+ software ensures standardized, internationally comparable results, while the application of multiple counterfactual scenarios offers a nuanced assessment of potential health benefits arising from progressive air quality improvements.

Nevertheless, some limitations should be acknowledged. This study is limited by the use of low-cost $PM_{2.5}$ sensors, which have inherent measurement uncertainties compared to reference-grade instruments and can be influenced by environmental conditions such as temperature and relative humidity. The concentration–response functions embedded in AirQ+ are derived from North American and European cohorts and may not fully capture the exposure-disease relationship in Ethiopian populations. The absence of local cause-specific mortality data restricted the analysis to all-cause mortality, preventing detailed examination of respiratory disease-specific burdens. Moreover, the use of a city-wide annual mean $PM_{2.5}$ concentration obscures intra-urban exposure heterogeneity, which may result in exposure misclassification. Furthermore, the use of city-wide annual mean $PM_{2.5}$ concentrations may mask intra-urban exposure variability and introduce exposure misclassification. The ecological study design precludes causal inference at the individual level. Finally, the reliance on a two-year monitoring period may not fully capture long-term inter-annual meteorological variability and broader climatic influences on particulate matter dispersion within the Addis Ababa airshed.

5.1. Implications for Policy

The findings demonstrate that ambient $PM_{2.5}$ is a major contributor to premature adult mortality in Addis Ababa, with over 3100 attributable deaths annually. For policymakers, this evidence supports the urgent need to establish permanent air quality monitoring networks, enforce national ambient air quality standards in line with WHO guidelines, and implement targeted interventions in key sectors such as transportation, industry, waste management, and road infrastructure. Importantly, even incremental reductions in $PM_{2.5}$ concentrations can yield substantial health benefits, supporting a phased approach to policy implementation.

5.2. Future Research

Future research should prioritize the development of Ethiopia-specific concentration–response functions through local epidemiological cohort studies. Strengthening health information systems to capture cause-specific mortality and morbidity data is essential for more comprehensive burden assessments. High-resolution spatial exposure modeling would facilitate the identification of pollution hotspots and vulnerable subpopulations. Finally, evaluations of the health co-benefits of existing urban development and transportation policies would provide critical evidence for integrating health impact assessments into environmental decision-making frameworks.

6. Conclusions

This study demonstrates that long-term ambient exposure to $PM_{2.5}$ is responsible for a substantial and persistent burden of premature mortality among adults in Addis Ababa, with an estimated 13.1–13.5% of all-cause deaths attributable to air pollution, representing over 3100 preventable deaths annually. Progressive reductions in $PM_{2.5}$ concentrations would yield corresponding health benefits, with adherence to the WHO guideline of 5 $\mu g/m^3$ representing the optimal target. These findings add to the growing evidence across sub-Saharan African cities that air pollution constitutes a critical but modifiable public health priority. For policymakers, this study provides locally relevant, quantifiable evidence to support the development and implementation of air quality management strategies aimed at reducing the substantial health burden associated with urban air pollution.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The $PM_{2.5}$ datasets analyzed in this study are publicly available. Hourly $PM_{2.5}$ data from Addis Ababa were obtained from the PurpleAir Community API (Historical API endpoint, bulk downloads) and are accessible at (www.purpleair.com) accessed on 15 June 2026. BAM data were obtained from AirNow and are available at (www.airnow.gov) accessed on 15 June 2026. The processed datasets used for analysis in this study, including hourly averages and spatial summaries, are available from the corresponding author upon reasonable request.

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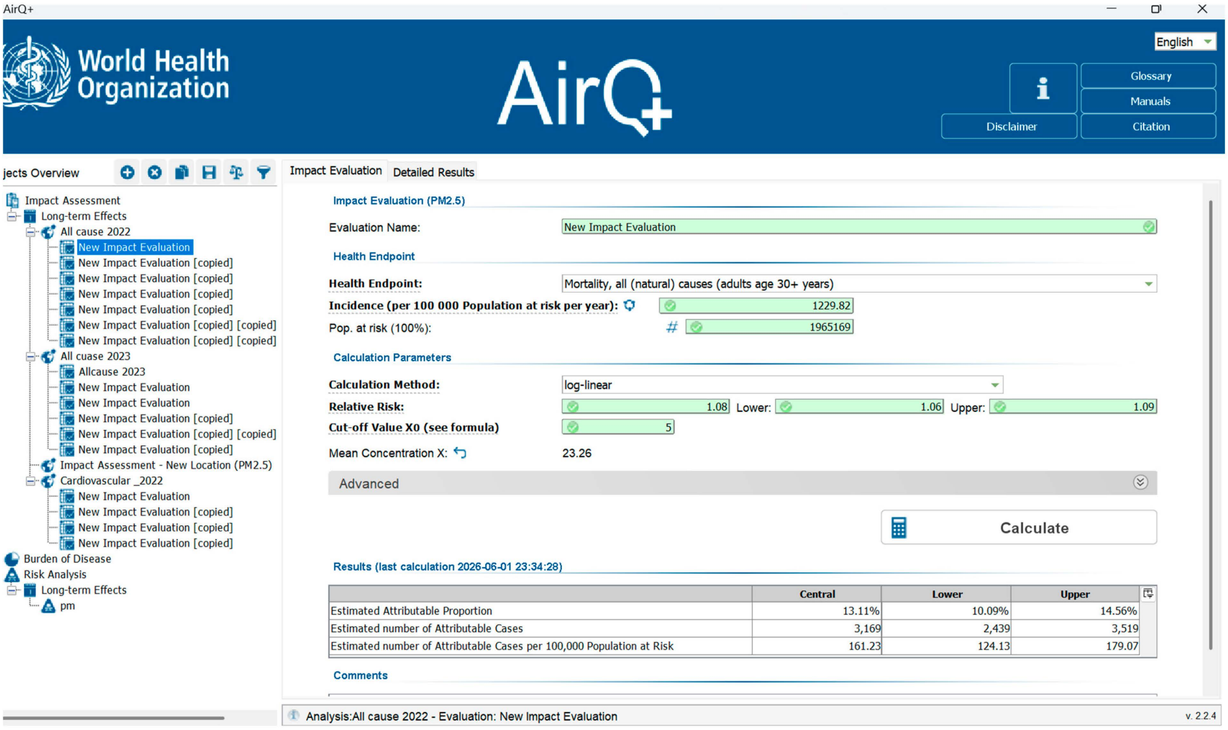
Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Baseline characteristics of the study population and exposure levels in Addis Ababa, Ethiopia, 2022–2023.

Framework Variable	Parameter/Data Metric	2022	2023
Demographics	National Population	125,384,287	128,691,692
	Addis Ababa Population	3,859,638	3,961,412
Health Metrics	All-Cause Mortality (Deaths)	24,168	24,137
	Cardiovascular Disease (CVD) Mortality (Deaths)	6174.88	6489.90
	Baseline Life Expectancy (L, Years)	67	67
Area (km^2)	Addis Ababa	527	527



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)

Incidence (per 100 000 Population at risk per year): 1229.82

Pop. at risk (100%): 1965169

Calculation Parameters

Calculation Method: log-linear

Relative Risk: 1.08 Lower: 1.06 Upper: 1.09

Cut-off Value X0 (see formula): 5

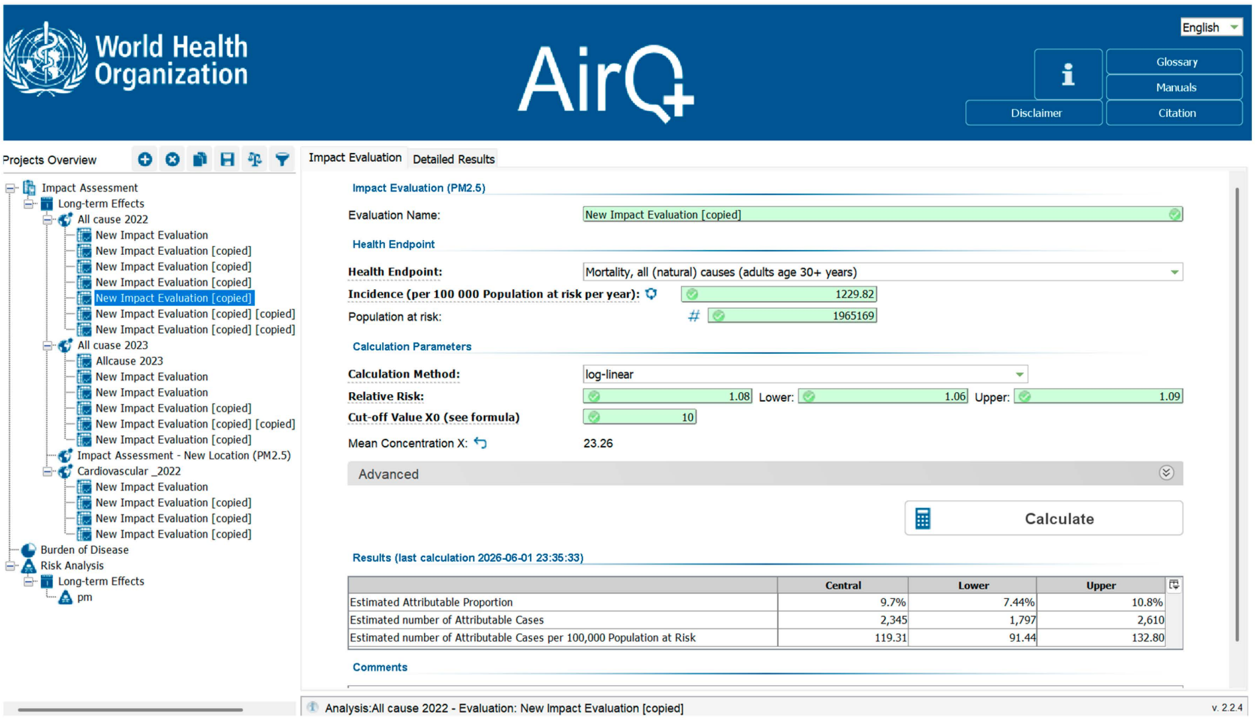
Mean Concentration X: 23.26

Results (last calculation 2026-06-01 23:34:28)

	Central	Lower	Upper
Estimated Attributable Proportion	13.11%	10.09%	14.56%
Estimated number of Attributable Cases	3,169	2,439	3,519
Estimated number of Attributable Cases per 100,000 Population at Risk	161.23	124.13	179.07

Analysis:All cause 2022 - Evaluation: New Impact Evaluation

Figure A1. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2022 data; counterfactual concentration: 5 µg/m^3).



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation [copied]

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)

Incidence (per 100 000 Population at risk per year): 1229.82

Population at risk: 1965169

Calculation Parameters

Calculation Method: log-linear

Relative Risk: 1.08 Lower: 1.06 Upper: 1.09

Cut-off Value X0 (see formula): 10

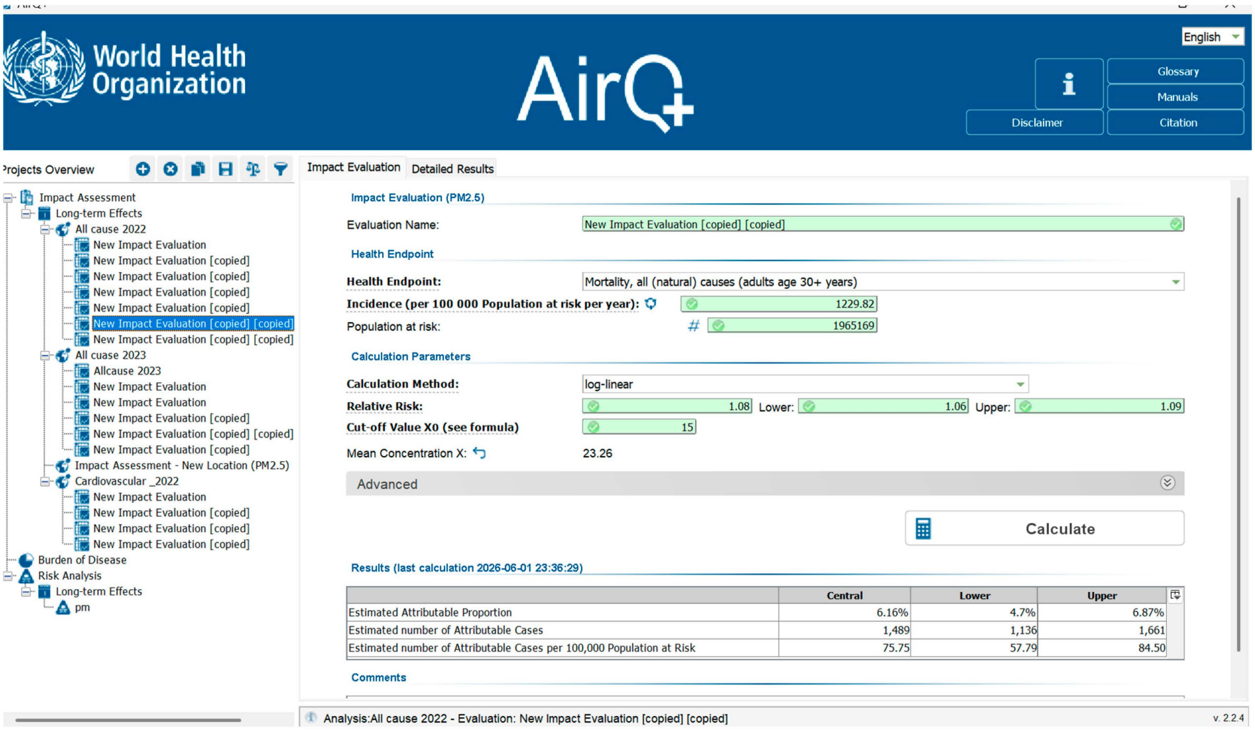
Mean Concentration X: 23.26

Results (last calculation 2026-06-01 23:35:33)

	Central	Lower	Upper
Estimated Attributable Proportion	9.7%	7.44%	10.8%
Estimated number of Attributable Cases	2,345	1,797	2,610
Estimated number of Attributable Cases per 100,000 Population at Risk	119.31	91.44	132.80

Analysis:All cause 2022 - Evaluation: New Impact Evaluation [copied]

Figure A2. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2022 data; counterfactual concentration: 10 µg/m^3).



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation [copied] [copied]

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)

Incidence (per 100 000 Population at risk per year): 1229.82

Population at risk: 1965169

Calculation Parameters

Calculation Method: log-linear

Relative Risk: 1.08 Lower: 1.06 Upper: 1.09

Cut-off Value X0 (see formula) 15

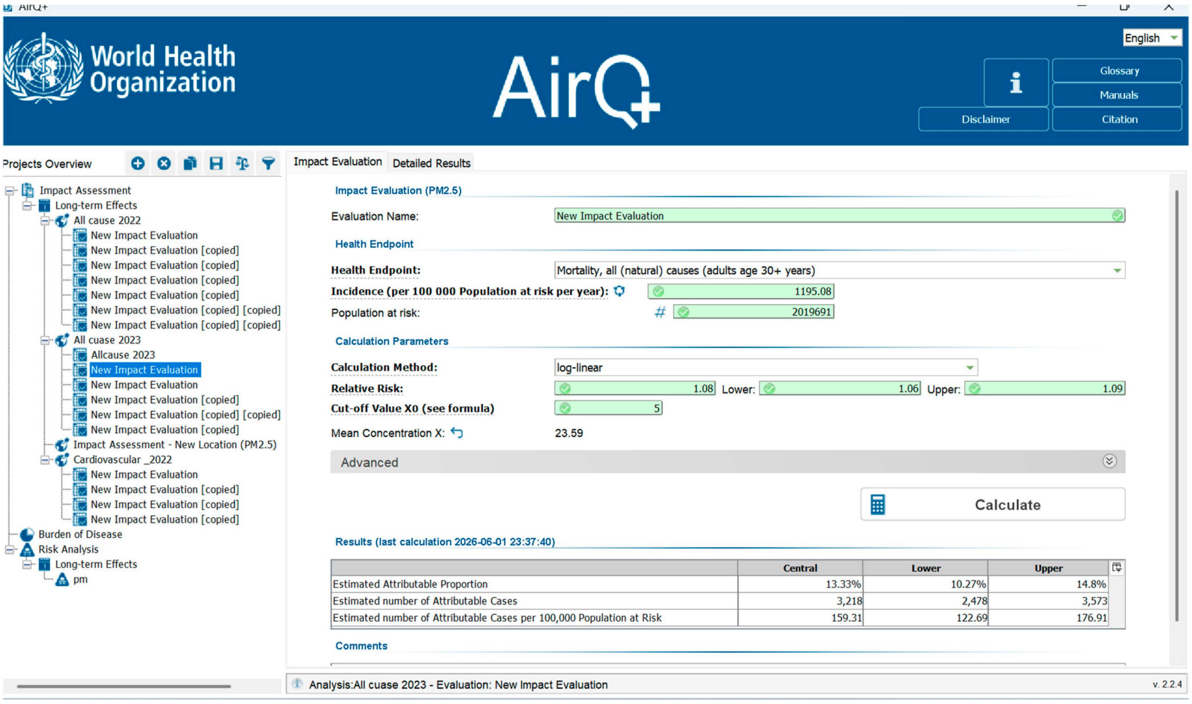
Mean Concentration X: 23.26

Results (last calculation 2026-06-01 23:36:29)

	Central	Lower	Upper
Estimated Attributable Proportion	6.16%	4.7%	6.87%
Estimated number of Attributable Cases	1,489	1,136	1,661
Estimated number of Attributable Cases per 100,000 Population at Risk	75.75	57.79	84.50

Analysis:All cause 2022 - Evaluation: New Impact Evaluation [copied] [copied]

Figure A3. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2022 data; counterfactual concentration: 15 μg/m^3).



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)

Incidence (per 100 000 Population at risk per year): 1195.08

Population at risk: 2019691

Calculation Parameters

Calculation Method: log-linear

Relative Risk: 1.08 Lower: 1.06 Upper: 1.09

Cut-off Value X0 (see formula) 5

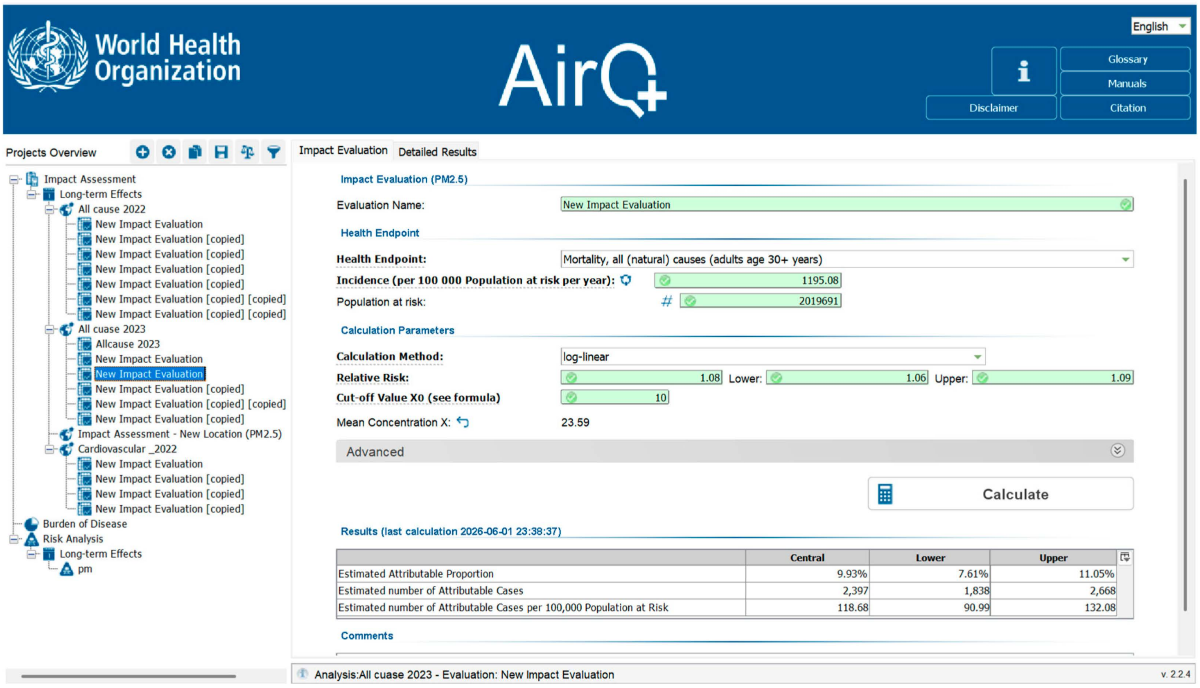
Mean Concentration X: 23.59

Results (last calculation 2026-06-01 23:37:40)

	Central	Lower	Upper
Estimated Attributable Proportion	13.33%	10.27%	14.8%
Estimated number of Attributable Cases	3,218	2,478	3,573
Estimated number of Attributable Cases per 100,000 Population at Risk	159.31	122.69	176.91

Analysis:All cuase 2023 - Evaluation: New Impact Evaluation

Figure A4. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2023 data; counterfactual concentration: 5 μg/m^3).



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)
Incidence (per 100 000 Population at risk per year): 1195.08
Population at risk: 2019691

Calculation Parameters

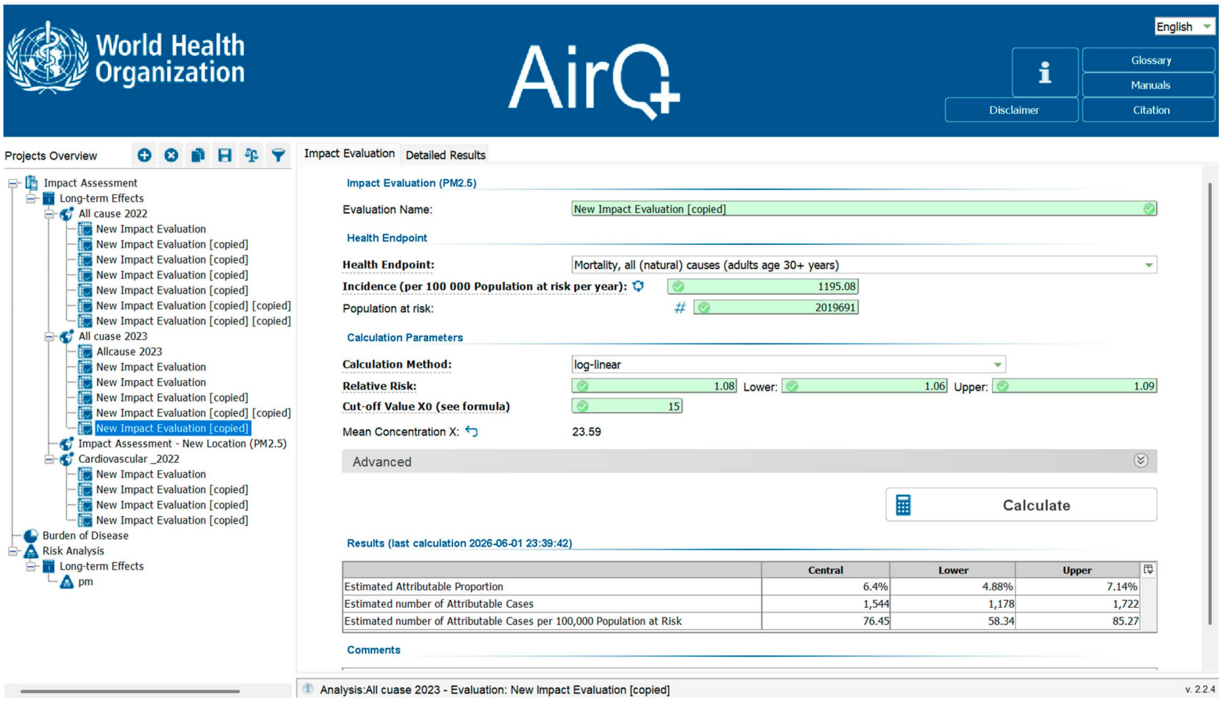
Calculation Method: log-linear
Relative Risk: 1.08 Lower: 1.06 Upper: 1.09
Cut-off Value X0 (see formula) 10
Mean Concentration X: 23.59

Results (last calculation 2026-06-01 23:38:37)

	Central	Lower	Upper
Estimated Attributable Proportion	9.93%	7.61%	11.05%
Estimated number of Attributable Cases	2,397	1,838	2,668
Estimated number of Attributable Cases per 100,000 Population at Risk	118.68	90.99	132.08

Analysis:All cuase 2023 - Evaluation: New Impact Evaluation v. 2.2.4

Figure A5. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2023 data; counterfactual concentration: 10 μg/m^3).



Impact Evaluation (PM2.5)

Evaluation Name: New Impact Evaluation [copied]

Health Endpoint

Health Endpoint: Mortality, all (natural) causes (adults age 30+ years)
Incidence (per 100 000 Population at risk per year): 1195.08
Population at risk: 2019691

Calculation Parameters

Calculation Method: log-linear
Relative Risk: 1.08 Lower: 1.06 Upper: 1.09
Cut-off Value X0 (see formula) 15
Mean Concentration X: 23.59

Results (last calculation 2026-06-01 23:39:42)

	Central	Lower	Upper
Estimated Attributable Proportion	6.4%	4.88%	7.14%
Estimated number of Attributable Cases	1,544	1,178	1,722
Estimated number of Attributable Cases per 100,000 Population at Risk	76.45	58.34	85.27

Analysis:All cuase 2023 - Evaluation: New Impact Evaluation [copied] v. 2.2.4

Figure A6. Analysis properties window in AirQ+ software illustrating the configuration for estimating all-cause mortality attributable to long-term ambient $PM_{2.5}$ exposure among adults aged 30+ years in Addis Ababa, Ethiopia (2023 data; counterfactual concentration: 15 μg/m^3).

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