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# $PM_{2.5}$ attributable health impact assessment across urban land-use areas: A comparative study using AirQ+ and BenMAP-CE in Surat, India

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## ABSTRACT

**Introduction:** Ambient fine Particulate Matter ($PM_{2.5}$) pollution is increasingly recognized as a critical environmental issue in rapidly urbanizing and industrializing cities of developing nations. This study aimed to quantify the zone-specific health burden attributable to $PM_{2.5}$ exposure in Surat, India.
**Materials and methods:** $PM_{2.5}$ data were obtained from a network of low-cost sensors operating across three major land-use zones: residential (West), commercial (Central), and industrial (South). $PM_{2.5}$ data collected over one year (October 2022 to September 2023) were combined with population projections and cause-specific mortality rates from national datasets. Two established Health Impact Assessment (HIA) tools, AirQ+ and BenMAP-CE, were utilized to estimate premature mortality associated with $PM_{2.5}$ levels exceeding WHO air quality standards.
**Results:** The industrial zone exhibited the highest annual mean $PM_{2.5}$ (86.6 $\mu g/m^3$) and correspondingly the most significant premature mortality burden, primarily from ischemic heart disease, chronic obstructive pulmonary disease, and stroke. The commercial and residential zones exhibited comparatively lower pollution levels; however, notable mortality impacts were associated with higher population densities. Both AirQ+ and BenMAP-CE models produced consistent mortality estimates, highlighting the relationship between pollution concentration and demographic factors in urban health risks. Elevated incidences of acute lower respiratory infections among children under five were also identified in the industrial zone.
**Conclusion:** In order to lower health hazards, the results highlight the necessity of zone-specific emission reduction measures and additional strengthening of Surat's particle emission trading scheme. The integrated framework offers a practical approach for evaluating urban health and air quality in developing nations.

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## Introduction

Rapid urbanization and industrial growth have pushed air pollution to the forefront of environmental and public health issues in many cities worldwide [1, 2]. Among various airborne contaminants, fine Particulate Matter ($PM_{2.5}$) stands out due to its small size and ability to penetrate deeply into the pulmonary system. An increasing amount of evidence currently connects a variety of harmful health effects to both acute and chronic exposure to $PM_{2.5}$ [3, 4]. These effects are especially evident in circulatory and respiratory domains, manifesting as increased rates of Ischemic Heart Disease (IHD), Chronic Obstructive Pulmonary Disease (COPD), stroke, and lung cancer, as well as a heightened risk for Acute Lower Respiratory Infections (ALRI), particularly in children [5–7]. $PM_{2.5}$ is a major cause of excess mortality and morbidity, disproportionately affecting vulnerable subgroups like children, the elderly, and people with pre-existing diseases, according to recent epidemiological and mechanistic research [8, 9].

India's rapid urbanization and industrialization have exacerbated exposure to air pollution, with major cities, including Surat, regularly exceeding both the national (40 $\mu g/m^3$) and World Health Organization (WHO) (5 $\mu g/m^3$) annual mean $PM_{2.5}$ limits [10]. Air quality monitoring data from recent years indicate persistent exceedances in urban centres and industrial corridors in India and other developing countries [11]. Surat, one of India's largest cities, exemplifies this issue with its dense industrial activity and vehicular emissions. The city's textile and allied industries, which primarily depend on coal and other combustion fuels, are major contributors to local $PM_{2.5}$ emissions. Notably, Surat is the pioneering site for India's first Emission Trading Scheme (ETS) for particulate matter reduction, a market-driven regulatory approach introduced in 2019, targeting industrial emissions [12]. Despite these advancements, intra-urban differences in pollution exposure and their associated health effects remain poorly understood due to low monitoring density and a lack of zone-specific epidemiological evaluations.

Traditional air quality monitoring in India relies on sparse reference-grade stations, which are often unable to capture the fine-scale spatial heterogeneity arising from complex land-use and emission patterns [13]. The deployment of Low-Cost Sensor (LCS) networks, particularly for $PM_{2.5}$ monitoring, has enabled unprecedented spatiotemporal resolution in measuring urban air pollution exposure. However, calibration and validation against reference methods remain crucial for ensuring data reliability [14–16]. Several recent studies emphasize the importance of validating and integrating LCS data for health impact assessment, given the recent developments in sensor technology and epidemiological analytics [17–19].

AirQ+ is a comprehensive software tool developed by the World Health Organization (WHO) that enables public health researchers to rigorously quantify the disease burden and health impacts due to exposure to air pollution, utilizing locally relevant air quality, population, and epidemiological data [20]. BenMAP-CE, developed by the U.S. Environmental Protection Agency (USEPA), allows users to estimate both the health impacts and the economic benefits associated with changes in air quality. It further facilitates spatial resolution assessments that directly support evidence-based policy formulation and regulatory decision-making [21]. Researchers may bridge critical knowledge gaps in urban pollution health dynamics by combining dense LCS networks with the Health Impact Assessment (HIA) frameworks, such as AirQ+ (WHO) and BenMAP-CE (US EPA), particularly when combined with contemporary demographic projections and detailed cause-specific mortality datasets. These approaches have been widely adopted in recent years across Asia and abroad, with comparative validation studies demonstrating their methodological consistency and relevance to the Indian environment [22–24].

The primary objective of this study is to evaluate the zone-specific health impacts associated with $PM_{2.5}$ exposure in Surat. Using LCS data, demographic estimates, and cause-specific death statistics from the Global Burden of Disease (GBD, 2021) dataset. Two established models, AirQ+ and BenMAP-CE, are utilized to evaluate mortality associated with $PM_{2.5}$ levels exceeding WHO guidelines. The analysis focuses on three major land-use zones: residential (West), commercial (Central), and industrial (South). The comparative evaluation of model outputs enhances understanding of exposure-response relationships in a rapidly industrializing urban environment.

## Materials and Methods

### *Study area*

Surat, situated along the western coast of India adjacent to the Arabian Sea, ranks as the eighth-largest city in the country. With an estimated population of approximately 6.8 million, Surat serves as a major urban and industrial hub in the state of Gujarat. Surat Municipal Corporation (SMC) area is subdivided into several zones reflecting diverse urban functions. For this study, three zones were selected to reflect major land-use types and emission profiles. The residential zone (West zone) is characterized by lower population density and predominantly residential land use. The Commercial zone (Central zone) has a high population density, commercial hubs, and traffic-congested areas. The Industrial Zone (South Zone) is an ETS compliance zone comprising textile and chemical industries. Fig. 1 shows the study area map of Surat city with wind rose diagram.

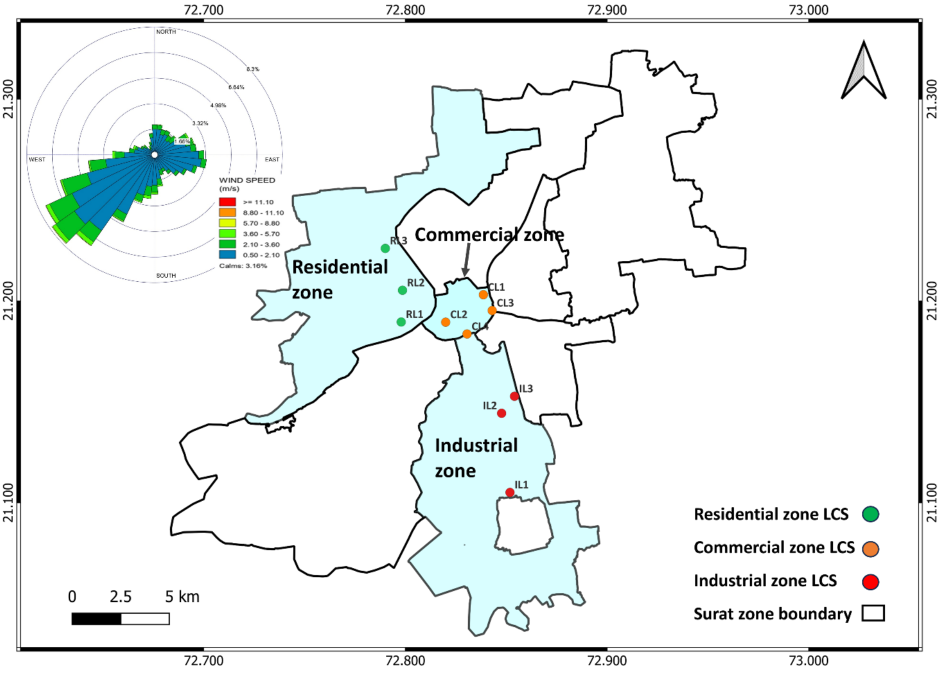

Fig. 1. Study area map of Surat city with wind rose diagram

### Low-cost sensor network and calibration

The spatial variability of Particulate Matter ($PM_{2.5}$) concentrations was examined using data collected from ten Atmos Low-Cost Sensor (LCS) monitors, equipped with Plantower PMS7003 sensors. These LCS monitors operated from October 2022 to September 2023 and were distributed across three zones: three in the Residential (west zone), four in the Commercial (central zone), and three in the Industrial (South zone) part of the study area. The PMS7003 sensor uses light-scattering nephelometry with a 650 nm laser diode to measure particle counts in size bins and estimate concentrations of $PM_1$, $PM_{2.5}$, and $PM_{10}$. The device specifications include a resolution of 1 $\mu g/m^3$, ±10% accuracy in the 0-1000 $\mu g/m^3$ range, a detection limit of 0.3 µm particle diameter, and operation within temperature ranges of –10 °C to 60 °C and humidity levels of 0-99% [25, 26]. Data were transmitted via IoT connectivity every 2 minutes and aggregated to hourly averages.

### Population and mortality data

Population data were sourced from the 2011 Census of India and extrapolated to 2021 using the corresponding demographic growth rates. Zone-wise projected populations for 2021 are summarized in Table 1. The South Zone exhibited the highest population (~1.21 million), and the Central Zone had the highest density (>76,000 persons/km²). As detailed age-specific data were unavailable, the population aged ≥30 years was approximated using national demographic ratios (≈ 50-55 % of the total population), consistent with the Census of India 2011 [27]. This pragmatic assumption is commonly applied in population-based health-impact assessments. Additionally, children under 5 years were separately identified for ALRI assessment, based on a 12.13% proportion from the 2011 Census [28].

Cause-specific mortality rates for Ischemic Heart Disease (IHD), Chronic Obstructive Pulmonary Disease (COPD), stroke, lung cancer, and Acute Lower Respiratory Infections (ALRI) in children were derived from the Global Burden of Disease (GBD) 2021 study (see Table 2). Gujarat state-level estimates were used to provide regional specificity. The data show that Gujarat has slightly higher all-cause mortality (836.65 per 100,000) compared to the national average (830.3 per 100,000). Mortality due to COPD and ischemic heart disease is notably higher in Gujarat than the overall rates for India, while stroke and lower respiratory infection rates are somewhat lower [29]. These variations underscore the importance of regional-level assessments, which recognize the heterogeneity in disease burden across populations.

Table 1. Zone-wise population details and the number of LCS used for the study

| Type of zone | Area ($Km^2$) | Population (Census of India 2011) | Projected Population in 2021 | Population density per $Km^2$ (in 2021) | Number of LCS |
|---|---|---|---|---|---|
| Residential zone | 87.169 | 449943 | 698716 | 8015 | 3 |
| Commercial zone | 8.285 | 408760 | 634763 | 76615 | 4 |
| Industrial zone | 84.039 | 781070 | 1212923 | 14432 | 3 |

Table 2. Mortality rate taken from the global burden of disease (GBD) study 2021

| **Mortality Due to** | **Baseline incidence (per 100,000 population)** |
|---|---|
| Mortality (all causes) | 836.65 |
| Chronic Obstructive Pulmonary Disease (COPD) | 92.22 |
| Ischemic Heart Disease (IHD) | 165.09 |
| Stroke | 42.71 |
| Lung cancer (LC) | 6.15 |
| Acute Lower Respiratory Infections (ALRI) (0 - 5 years) | 75.2 |

***Health impact assessment models***

The health impact assessment was conducted using two widely recognized tools: AirQ+, developed by the World Health Organization (WHO), and BenMAP-CE, developed by the United States Environmental Protection Agency (US EPA). Employing both models allowed cross-validation of results and enhanced confidence in the findings.

AirQ+ is an established tool developed by the World Health Organization (WHO) for estimating the burden of disease attributable to air pollution, with particular suitability for low- and middle-income countries due to its relatively simple input requirements. The model accepts data on population, baseline mortality rates, pollutant concentrations, and epidemiological risk coefficients to estimate the Attributable Proportion (AP) of cases, the number of attributable deaths, and mortality rates per 100,000 population. The tool utilizes Relative Risk (RR) functions derived from epidemiological research to calculate the Attributable Proportion (AP), which represents the fraction of cases in a population that can be attributed to exposure to pollutants [30].

$$AP = \frac{\sum(RR-1) \times P}{\sum RR \times P} \tag{1}$$

RR corresponds to the relative risk for a particular health endpoint under exposure to $PM_{2.5}$, and P is the proportion of the population exposed. The RR is modeled as RR=e^(β.Δc), where β represents the risk coefficient derived from concentration-response functions, and Δc is the pollutant concentration exceeding the counterfactual threshold. The AP is then integrated with baseline incidence (I) and exposed population size (N) to estimate the number of attributable cases

$$(\mathrm{NE} = \mathrm{I} \times \mathrm{N} \times \mathrm{AP}). \tag{2}$$

BenMAP-CE, in contrast, is a more comprehensive tool that enables not only the estimation of health impacts but also their economic valuation. It incorporates built-in population, incidence, and concentration–response databases, but allows for replacement with local inputs to increase specificity. BenMAP-CE supports grid-based and shapefile-linked spatial analysis, enabling more nuanced zone-level evaluations. The health impact was estimated using a log-linear exposure–response function expressed as:

$$\Delta Y = BI\,[1 - e^{\Delta PM\, -\beta}]\,.\,POP \tag{3}$$

Where ΔY is the number of premature deaths, BI is baseline incidence rate, ΔPM is the change in $PM_{2.5}$ concentration to the standard value, β is concentration-response coefficient, and POP is the population. Inputs included $PM_{2.5}$ concentrations, zone-specific population data, and GBD mortality rates [31]. For both tools, the counterfactual (cut-off) $PM_{2.5}$ concentration was set to 15 µg/m$^3$ for acute exposure scenarios and 5 µg/m$^3$ for chronic exposure scenarios, in accordance with the WHO air quality guidelines. Although the installed LCSs measure $PM_1$, $PM_{2.5}$, and $PM_{10}$ concentrations, $PM_{2.5}$ was selected for the present analysis due to its well-established association with adverse cardiovascular and respiratory outcomes [32]. Currently, specific national and international guidelines for $PM_1$ are not established in most countries, and the epidemiological evidence for $PM_{10}$-related mortality is less consistent than for $PM_{2.5}$. Moreover, international guidelines and widely used health impact assessment tools such as AirQ+ and BenMAP-CE are primarily based on $PM_{2.5}$ exposure metrics. This dual tool approach was adopted to cross-validate mortality estimates and assess consistency between the two models. BenMAP-CE provided a more spatially explicit and uncertainty-inclusive framework, whereas AirQ+ offered a simplified platform suitable for comparative evaluation of premature death estimates.

## Results and discussion

### *Diurnal and seasonal variations of $PM_{2.5}$ across urban zones*

Continuous $PM_{2.5}$ monitoring from October 2022 to September 2023 across Surat's industrial, commercial, and residential zones revealed marked intra-urban spatial and temporal variability in air quality (Fig. 2). The industrial South Zone persistently exhibited the highest $PM_{2.5}$ concentrations, with an annual mean of 86.62 µg/m$^3$, more than double the Indian National Ambient Air Quality Standard (NAAQS, 40 µg/m$^3$) and far exceeding the WHO guideline (5 µg/m$^3$). Seasonal maxima were especially pronounced during winter (mean 126.98 µg/m$^3$), driven by meteorological conditions such as temperature inversions and reduced wind speeds that restrict vertical mixing and promote pollutant accumulation. These effects were compounded by heightened industrial activity and biomass burning. In contrast, the commercial (Central) and residential (West) zones recorded annual means of 61.12 µg/m$^3$ and 53.10 µg/m$^3$, respectively, both exceeding national limits but reflecting moderate and comparatively lower emissions consistent with their land-use characteristics. Even in the residential zone, pronounced winter peaks underscored the citywide influence of unfavourable meteorological conditions.

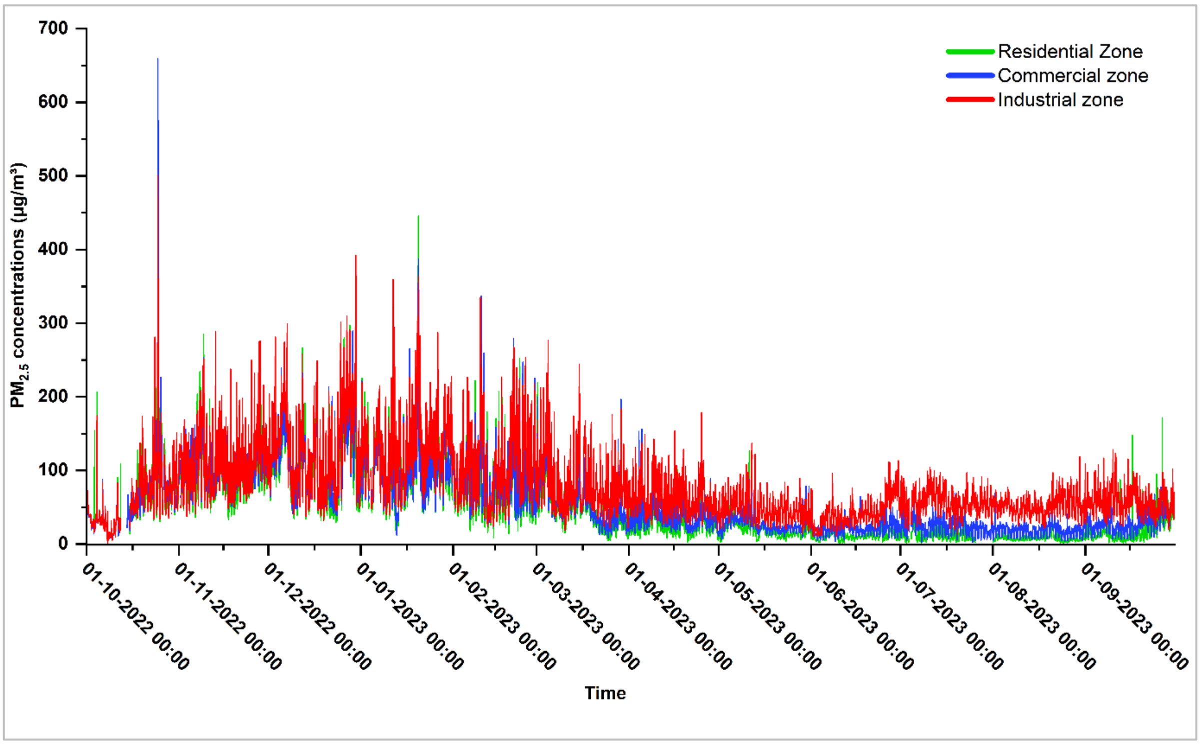

Fig. 2. Zone-wise hourly $PM_{2.5}$ concentration

Fig. 3 presents the zone-wise diurnal variations of $PM_{2.5}$ concentrations for four seasons: winter, summer, monsoon, and post-monsoon across residential, commercial, and industrial areas in Surat. Distinct seasonal contrasts were observed, with winter showing the highest concentrations across all zones and monsoon exhibiting the lowest. During the winter and post-monsoon seasons, $PM_{2.5}$ levels in all three zones consistently remained above the NAAQS of 40 µg/m$^3$, indicating severe pollution episodes. The industrial zone consistently recorded concentrations exceeding NAAQS throughout the year, highlighting its persistent emissions burden.

In all seasons, a characteristic bimodal diurnal pattern (morning: 07:00–09:00 h; evening: 19:00–21:00 h) was evident in every zone, attributable to the morning and evening rush hours, which coincide with shallow boundary-layer heights, low wind speeds, and peak combustion emissions. These factors are known to produce high ambient $PM_{2.5}$ due to both enhanced emissions and limited atmospheric dilution during stable conditions [33]. The elevated $PM_{2.5}$ levels in residential and commercial zones during winter and post-monsoon periods were primarily attributed to atmospheric stability and prevailing wind patterns [34]. During these seasons, winds predominantly blow from the east and southeast directions, transporting emissions from major industrial clusters toward densely populated urban areas. Post-monsoon dynamics also exhibited moderate diurnal peaks across all zones, reaching up to 90 µg/m$^3$ in industrial regions, reflecting the gradual reinstatement of atmospheric stability after the wet season. Conversely, during summer and monsoon periods, $PM_{2.5}$ levels decreased significantly across all areas due to enhanced vertical mixing, higher wind speeds, and rain-induced wet deposition. The monsoon season, characterized by south-west winds and frequent rainfall, produced the cleanest air conditions, with residential and commercial zones averaging below 25 µg/m$^3$. In contrast, the industrial zone still maintained elevated values, averaging 51.71

μg/m$^3$. Overall, the diurnal pattern remained bimodal across seasons, shaped by traffic emissions and boundary-layer dynamics. The persistence of high concentrations in industrial areas, even under favourable dispersion conditions, underscores the need for stringent emission control strategies targeting industrial and transport sources.

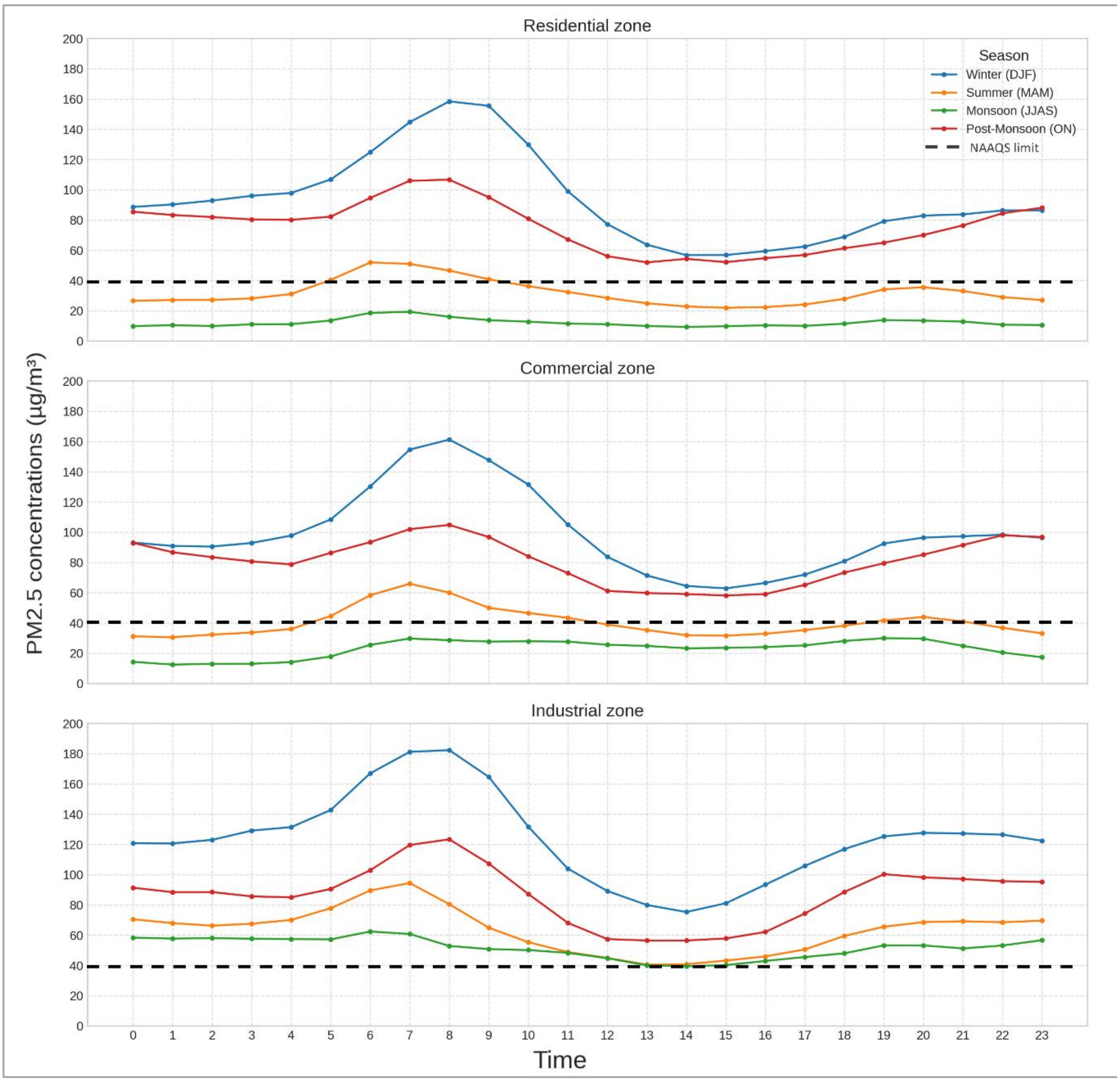

Fig. 3. Zone-wise seasonal diurnal PM$_{2.5}$ concentrations during the study period

### *Zone-specific premature mortality and population-adjusted risks from $PM_{2.5}$*

High-resolution, zone-specific estimates of premature mortality attributable to $PM_{2.5}$ exposure in Surat, visualized in Figs. 4 and 5, reveal pronounced spatial variation in both absolute and population-adjusted health burdens. These analyses, utilizing BenMAP-CE and AirQ+ models, demonstrate that demographic structure and local pollution intensities interact to shape public health outcomes in distinct ways. The industrial zone shows the most significant absolute number of premature deaths (BenMAP-CE: 2,201; AirQ+: 2,129 per year), with IHD and COPD contributing nearly 70% of this burden. Stroke and lung cancer, although representing a smaller fraction of total deaths, exhibit elevated attributable mortality, reflecting the systemic health impacts of chronic fine particulate exposure [35]. These findings indicate the industrial zone's higher ambient $PM_{2.5}$ levels and substantial population base, which together create a concentrated health burden.

Although the commercial zone experiences lower $PM_{2.5}$ concentrations than the industrial zone, its extremely high population density results in a substantial number of premature deaths (BenMAP-CE: 855; AirQ+: 785). However, when mortality is normalized by population size (Figure 4), the industrial zone exhibits higher mortality rates per 100,000 population (BenMAP-CE: 367; AirQ+: 355) compared to the commercial zone (BenMAP-CE: 272; AirQ+: 250), reflecting the compounded effect of intense pollution exposure and a sizeable resident population. Across both zones, cardiovascular and respiratory diseases, particularly IHD and COPD, dominate the attributable disease burden, consistent with established global epidemiological patterns linked to fine particulate matter exposure [36, 37]. The residential zone, as shown in both Figs. 4 and 5, exhibits the lowest premature mortality, reflecting both lower $PM_{2.5}$ concentrations and a relatively smaller, less densely populated area. All-cause deaths range from 735 to 802 annually, with per-capita rates (AirQ+: 213 per 100,000; BenMAP-CE: 232) continually lower than their commercial and industrial counterparts. These comparative gradients underscore the need for spatially explicit risk assessments that incorporate demographic weighting, rather than focusing exclusively on areas with the highest emissions.

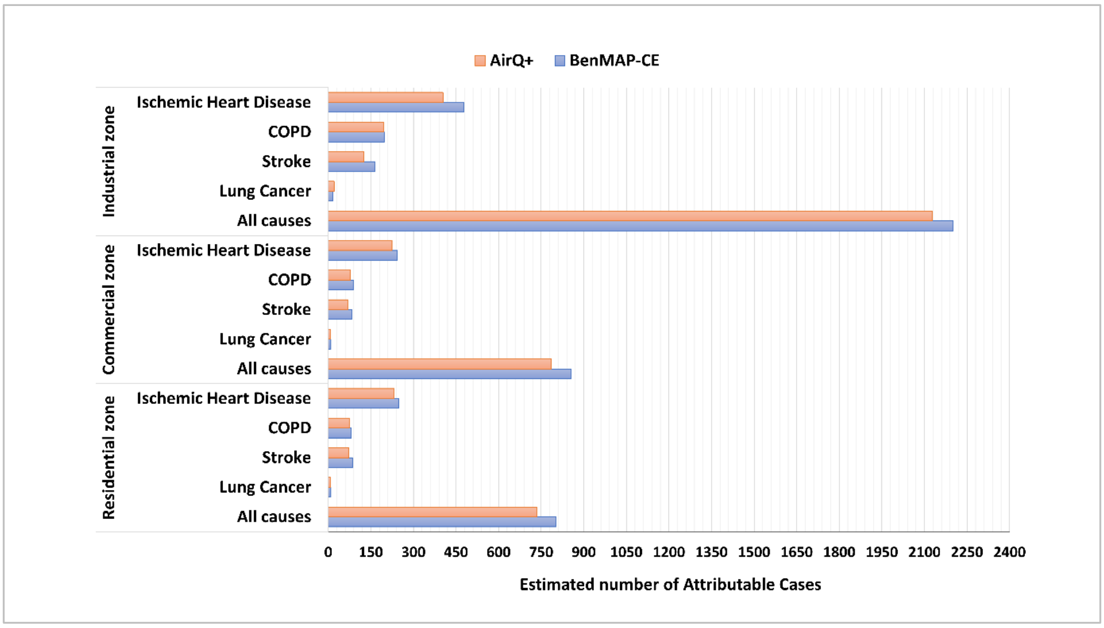

Fig. 4. Zone-specific estimated premature mortality attributable to $PM_{2.5}$ exposure in Surat city

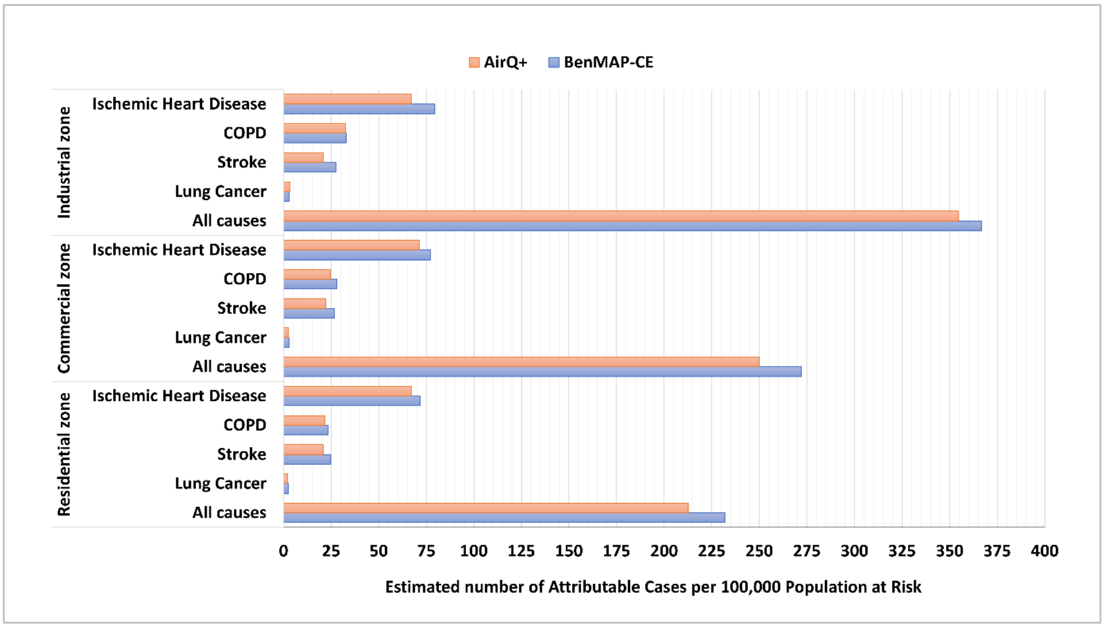

Fig. 5. Premature mortality rates per 100,000 population by zone attributable to PM$_{2.5}$ exposure in Surat city

A comparative assessment between BenMAP-CE and AirQ+ shows marginal differences, with BenMAP-CE consistently estimating mortality rates approximately 5-10% higher. These discrepancies are primarily attributable to differences in spatial population representation and the handling of uncertainty within each model. Both models exhibit strong agreement in zone-wise rankings and in identifying the most affected health endpoints, despite minor variations, which supports the validity and dependability of the findings.

### *Vulnerability of children under five years mortality using AirQ+*

Children under five years represent a uniquely vulnerable subpopulation to PM$_{2.5}$-induced Acute Lower Respiratory Infections (ALRI). Using separate demographic data subsets and GBD 2021 cause-specific mortality rates, the study estimated ALRI-related premature deaths attributable to PM$_{2.5}$ exposure above 5 µg/m$^3$ (acute exposure threshold), disaggregated by zone (see Table 3). The industrial zone recorded the highest child ALRI mortality with approximately 32 attributable deaths annually, corresponding to an Attributable Proportion (AP) of 28.94% and an incidence rate of 21.86 deaths per 100,000 children. This high burden reflects both pollutant concentrations and the increased number of children in the population. ALRI mortality estimates for the commercial and residential zones were lower in absolute terms (12.67 and 12.08 deaths, respectively) but still represented substantial APs exceeding 18%, indicating widespread vulnerability across urban typologies. These results highlight that, despite differences in overall pollution across zones, children’s respiratory health is consistently compromised throughout the city.

Table 3. Zone-wise estimated attributable premature deaths due to ALRI (0-5 years) associated with $PM_{2.5}$ concentration

| | **Residential zone** | **Commercial zone** | **Industrial zone** |
|---|---|---|---|
| Estimated Attributable Proportion in % | 18.87 | 21.68 | 28.94 |
| Estimated number of Attributable Cases | 12.08 | 12.67 | 32.17 |
| Estimated number of Attributable Cases per 100,000 Population at Risk | 14.26 | 16.37 | 21.86 |

### *Novelty and technical contributions*

This study advances urban air pollution health assessment in developing countries by integrating a city-wide LCS network with two robust HIA models, AirQ+ and BenMAP-CE, for zone-wise risk quantification. This approach addresses critical limitations in sparse monitoring and coarse epidemiological applications, offering fine-scale exposure and health burden mapping within a city. The use of dual HIA tools provides methodological cross-validation, a largely unexplored area in the context of developing countries, strengthening confidence in findings. Furthermore, combining population density data reveals that intra-urban demographic variation modulates health risks beyond pollution levels, underscoring the value of spatially explicit modelling and intervention prioritization.

### *Policy implications and ETS strengthening*

Surat's Emission Trading Scheme (ETS) is the first of its kind in India, targeting industrial particulate emissions through cap-and-trade mechanisms. Study results indicate that the South Zone, with the highest ETS compliance, is also associated with the highest $PM_{2.5}$ exposure and mortality burden. Emission reductions through enhanced ETS enforcement and extending the ETS to other sectors could prevent a certain number of premature deaths annually. Urban transport policies focusing on the Central zone's high density could further reduce population exposure and relative mortality. Integrating health-oriented metrics and zone-specific data into ETS performance frameworks could improve pollution control outcomes. Extending the ETS approach, with exposure-health modelling, offers a scalable framework for other industrial and densely populated cities in developing countries.

### *Limitations and future work*

Limitations include reliance on projected demographic data and GBD mortality rates, without validation from local hospitals or mortality registries. Morbidity outcomes, such as hospital admissions, could enhance the characterization of health burden. While calibration reduces the limitations of LCS, environmental variation may still introduce bias. Future work could integrate source apportionment, economic valuation via BenMAP-CE, socioeconomic vulnerability analysis, and AI-driven exposure prediction to enhance the granularity of assessments and policy utility.

## Conclusion

This study presents a zone-specific health impact assessment of $PM_{2.5}$ exposure in Surat, India, using LCS data and a dual-model epidemiological approach. The analysis highlights pronounced intra-urban disparities, with industrial and densely populated commercial zones exhibiting the highest $PM_{2.5}$ levels and associated premature mortality. The combined use of AirQ+ and BenMAP-CE enhances methodological robustness and improves confidence in the mortality estimates. Findings underscore that $PM_{2.5}$ levels impose a significant and uneven health burden across the city's land-use zones, reflecting the influence of emission intensity and population density. The dual-tool framework demonstrates a replicable approach for coupling high-resolution air quality monitoring with health risk assessment. Overall, the study provides actionable evidence to support targeted emission-control strategies and reinforces the need to strengthen Surat's Emission Trading Scheme and related urban air-quality management initiatives.

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## Competing interests

The authors declare no competing interests.

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## Ethical considerations

This study did not involve humans or animals as subjects, there was no harm anticipated to human or animal life. Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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