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Quantifying the Burden of $PM_{2.5}$ on Longevity and Healthy Aging: Life Expectancy and HALE in Gurugram

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ABSTRACT

Ambient fine particulate matter ($PM_{2.5}$) is a major environmental health risk, contributing to substantial mortality and morbidity worldwide. Rapidly urbanizing cities in India, such as Gurugram, experience persistent high $PM_{2.5}$ levels, yet limited research has quantified its impact on population longevity and healthy aging at the subnational level. This study provides the first city-level assessment of life expectancy (LE) and healthy life expectancy (HALE) in relation to ambient $PM_{2.5}$ exposure in Gurugram, integrating age- and sex-specific analyses using standard life table and Sullivan methods. Daily $PM_{2.5}$ concentrations (2020–2022) were combined with population and health data to estimate LE, HALE, and the LE-HALE gap across age cohorts. Results revealed a progressive decline in both LE and HALE with age, with LE at birth approximately 84 years and HALE 82 years for males, and 81 years for females. The LE-HALE gap widened with age, reaching 6–7 years in older adults, indicating a growing burden of disability. Notably, females lived longer but experienced higher morbidity, consistent with the "morbidity–mortality paradox." These findings highlight the compounded health risks of aging and air pollution and underscore the critical importance of air quality management, chronic disease prevention, and gender-sensitive health interventions. The study adds value by providing localized, actionable evidence linking environmental exposures to both longevity and quality of life, supporting sustainable urban health policies aligned with the UN Sustainable Development Goals.

Keywords: *Life expectancy, $PM_{2.5}$, Urban air pollution, Mortality, Morbidity, Sustainable development goals*

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INTRODUCTION

Ambient fine particulate matter ($PM_{2.5}$) is a leading global environmental health risk factor with substantial impacts on human mortality and longevity. The Global Burden of Disease (GBD) study estimated that long-term exposure to $PM_{2.5}$ caused approximately 4.1 million deaths and 104.9 million years of life lost worldwide in 2019, accounting for about 7.3% of total global mortality (Joshi *et al*., 2022). Numerous studies have linked $PM_{2.5}$ exposure to increased mortality, predominantly from cardiovascular, respiratory, and neoplastic diseases (Benchrif *et al*., 2021; Leao *et al*., 2021; Thangavel *et al*., 2022; Ghobakhalo *et al*., 2023). Reducing exposure to ambient $PM_{2.5}$ could therefore significantly enhance life expectancy, with estimates suggesting that a global reduction to 10 μg/m³, the WHO Air Quality Guideline (AQG) level could prevent nearly half of all $PM_{2.5}$-attributable deaths, especially in South-East Asia and Africa (WHO, 2020; Prasad, 2022; Gautam, 2023).

Beyond mortality, prolonged exposure to air pollution reduces human capital, productivity, and social well-being, particularly among the elderly. Ageing populations are biologically more susceptible to pollution-induced morbidity due to declining physiological resilience and higher prevalence of chronic diseases. Between 2000 and 2016, the global population aged 60 years and older grew by 50% (Yin *et al*., 2021). This demographic shift is most pronounced in low- and middle-income countries (LMICs), which simultaneously experience the world's highest air pollution levels (Singh *et al*., 2022). Consequently, the intersection of population ageing and environmental degradation poses an urgent public health challenge in such regions.

Life expectancy (LE) and healthy life expectancy (HALE) are widely used indicators to quantify population health status. While LE measures the average number of years an individual is expected to live, HALE accounts for years lived in good health, thereby incorporating the quality dimension of longevity. The difference between these two indicators (GAP = LE – HALE) reflects the average duration of life spent in poor health. Between 1995 and 2017, global averages for LE and HALE increased from 66.2 to 73.0 years and from 57.6 to 63.3 years, respectively, yet the GAP widened slightly from 8.6 to 9.7 years (Lakshmanan, 2023). This suggests that while people are living longer, they may also be spending more years with illness or disability. Regional disparities persist, with Africa showing the lowest LE and HALE, and women generally living longer but facing higher proportions of life spent in ill health (Dasgupta & Srikanth, 2020; Bar *et al*., 2021). These results highlight the importance of evaluating people's health as well as their lifespan.

Globally, several countries have incorporated HALE improvement into their public health policies. The World Health Organization introduced HALE in the World Health Report 2000 as a core measure of health system performance, and since

2004, the European Union has monitored HALE annually as part of its health reporting framework (Krishna, 2021). Nations such as the United Kingdom, France, Sweden, Japan, and the United States have included HALE as a strategic indicator for national health programs. Similarly, India's Healthy India 2030 and Healthy India Action Plan 2019–2030 identified HALE as a key indicator of population health progress (Maji *et al.*, 2023). Despite these developments, not much research has looked at the connections between life expectancy and air pollution, and healthy life expectancy at the subnational or city level in India. Gurugram, a rapidly urbanizing district within the National Capital Region, faces high $PM_{2.5}$ concentrations due to intense industrial and vehicular emissions. Understanding how air pollution influences LE and HALE in such areas is critical for developing targeted interventions and achieving the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 11 (Sustainable Cities and Communities). Therefore, this study aims to examine the patterns of life expectancy (LE) and healthy life expectancy (HALE) in Gurugram and explore their relationship with ambient air quality indicators.

Study region

Gurugram, located in the northern Indian state of Haryana (28.4595° N, 77.0266° E), is a major urban and industrial hub within the National Capital Region (NCR) of India **(Figure 1)**. The city covers an area of approximately 232 km^2 and had an estimated population of 1,726,452 in 2022 (Kumar *et al.*, 2022). Gurugram experiences a hot semi-arid climate characterized by four distinct seasons: Pre-monsoon (March–May): Hot and dry, with average temperature ≈ 27.6 °C and relative humidity ≈ 45%; Monsoon (June–August): Hot and humid, average temperature ≈ 31.4 °C and humidity ≈ 68%; Post-monsoon (September–November): Pleasant with mild temperature ≈ 33.8 °C and humidity ≈ 36%; Winter (December–February): Cool and foggy, average temperature ≈ 22 °C and humidity ≈ 75%; and, the annual average rainfall is about 714 mm, with monsoons contributing the majority. Rapid urbanization, heavy vehicular traffic, and construction dust are the main contributors to the city's poor air quality. The System of Air Quality and Weather Forecasting and Research (SAFAR) reported "very poor" Air Quality Index (AQI) levels of 303 in 2020 and 347 in 2021, indicating persistent particulate pollution (Kumar *et al.*, 2022).

MATERIALS AND METHODS

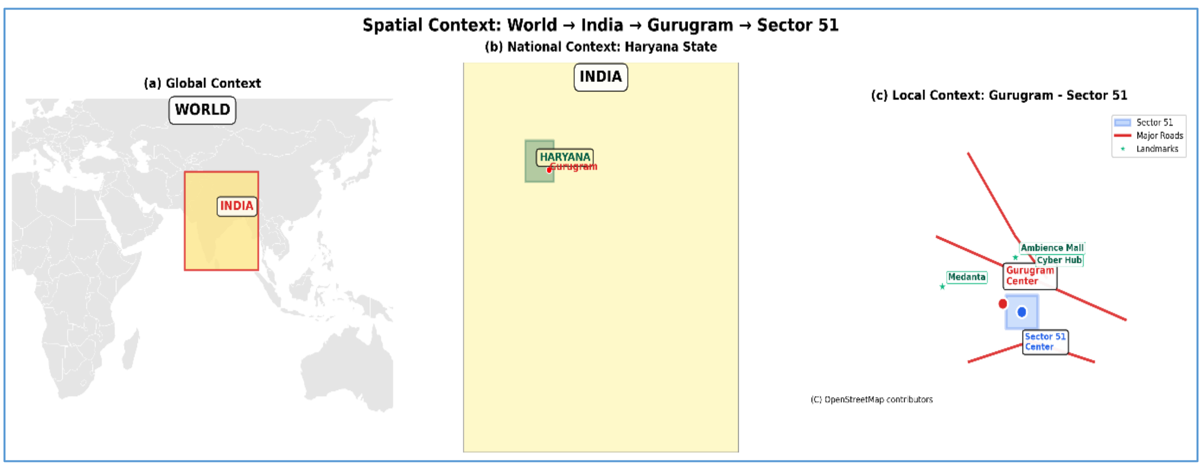

Figure 1. World map showing India, Haryana, and Gurugram city highlighting Sector 51 (study area).

Air quality data

Daily $PM_{2.5}$ concentration data for Gurugram were obtained from the Central Pollution Control Board (CPCB) online repository (https://cpcb.nic.in/) for the period March 1, 2020, to February 28, 2022. The selected monitoring station was Sector 51, located in a mixed residential-commercial zone. Data quality control involved removal of outliers, averaging multiple readings per day, and exclusion of days with > 25% missing hourly data.

Health data

Daily COVID-19 case data for the same period were collected from the official district Health Bulletin (https://gurugram.gov.in/health-bulletin/). The dataset was used to assess potential associations between $PM_{2.5}$ concentration and COVID-19 incidence.

All datasets were publicly available and required no ethical clearance.

Life expectancy (LE) estimation

Life expectancy was estimated using the standard life table method, which follows classical demographic principles for analyzing population survival and mortality (Preston *et al.*, 2001; Armitage, 2002;). The procedure involved computing age-specific death rates (ASDRs) from population and mortality data, followed by derivation of the survivorship function (lx) and the number of person-years lived (Lx). Subsequently, total person-years (Tx) lived beyond each age x were estimated. Finally, life expectancy (Ex) at a given age was calculated using the standard life table formula:

$$E_x = \frac{T_x}{l_x} \quad (1)$$

Where,

$$T_x = \sum_{i=x}^{n} L_i \quad (2)$$

and

$$L_x = l_{x-1} \cdot p_{x-1} \quad (3)$$

In these equations, lx represents the number of individuals surviving to age x, and p(x-1) denotes the probability of surviving from age x-1 to x. The computation was performed separately for males and females to reflect sex-specific mortality differences. All life table calculations were carried out using Microsoft Excel 2021, as the dataset size and structure were suitable for spreadsheet-based deterministic analysis. This approach enabled accurate estimation of life expectancy (LE) patterns across different age and sex groups within the study population.

Healthy life expectancy (HALE) estimation

Healthy Life Expectancy (HALE) was estimated using the Sullivan method, a widely accepted approach that adjusts total life expectancy for the proportion of time spent in various health states (Sullivan, 1971; Mathers *et al*., 2001). This method integrates mortality data with age-specific disability prevalence to quantify the expected number of years an individual lives in good health. The computation was conducted in two major stages: construction of the life table as described above, and adjustment of person-years lived by the prevalence of disability. The disability prevalence (Ux) data were obtained from national records available through the WeCapable database (https://wecapable.com/disabled-population-india-data/).

The healthy life expectancy at age x(HALEx) was derived from the following relationship:

$$HALE_x = \frac{HT_x}{l_x} \quad (4)$$

Where,

$$HT_x = T_x - \sum_{i=x}^{n} (U_i \times L_i) \quad (5)$$

Here, HTx represents the total years lived in good health beyond age x, Tx denotes total person-years lived beyond that age, and Ui indicates the age-specific prevalence of disability. The Sullivan method was chosen for this study due to its methodological simplicity, robustness, and international comparability, as well as its alignment with the World Health Organization's Health Statistics and Information Systems framework. All calculations were based on age- and sex-stratified population health data obtained from district health department records.

Analytical framework summary

The overall analytical process involved integrating environmental and health datasets to assess life expectancy (LE) and healthy life expectancy (HALE) trends for the Gurugram population. Daily $PM_{2.5}$ concentrations from the Central Pollution Control Board (CPCB) database for the period March 2020 to February 2022 were used to capture ambient air quality variations. Concurrently, daily COVID-19 case data were obtained from the District Health Bulletin to explore potential health interactions. Using these datasets, life expectancy was calculated via the life table method (Preston *et al*., 2001; Armitage, 2002), while HALE was computed using the Sullivan method (Sullivan, 1971; Mathers *et al*., 2001). All analyses were performed using Microsoft Excel 2021 to derive age- and sex-specific estimates of LE and HALE. The integration of these computations allowed for a comparative assessment of overall and healthy life expectancy, thereby illustrating the health implications of environmental and epidemiological factors in the study region.

RESULTS AND DISCUSSION

Life expectancy (LE) estimation

Age- and sex-specific life expectancy (LE) serves as a vital demographic indicator, reflecting the average number of remaining years an individual of a particular age and sex is expected to live under prevailing mortality conditions. In Gurugram, the estimated LE across age cohorts for both males and females, derived using the standard life table method (Preston *et al*., 2001; Armitage, 2002), revealed a distinct age-dependent decline **(Figure 2)**. At birth (age 0-4 years), LE was approximately 84 years for both sexes, indicating near parity in early-life survival. However, LE steadily declined with age, reaching 60 years at 30-34 years and 41 years for males and 42 years for females at 60-64 years. This progressive decline reflects the cumulative effect of age-related mortality risks and susceptibility to comorbidities, exacerbated during the COVID-19 pandemic.

The narrow sex gap in LE across all age groups suggests broadly comparable longevity between males and females, though slightly higher LE among older females may indicate a survival advantage consistent with global demographic patterns. These findings highlight the importance of age-sensitive and gender-informed health policies, particularly for the elderly, who exhibited the steepest decline in LE during the pandemic period. Moreover, the results align with prior evidence that environmental factors, such as $PM_{2.5}$ exposure, contribute to reduced survival and accelerated mortality risks in urban populations (Lelieveld *et al*., 2015; Cohen *et al*., 2017).

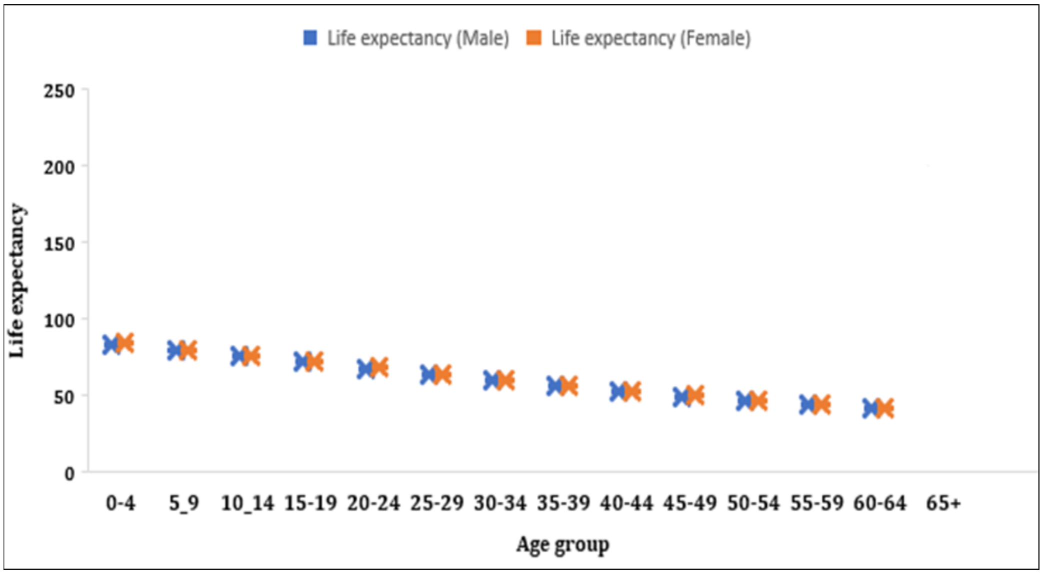

Figure 2. Age- and sex-specific life expectancy (LE) estimates for the Gurugram district, showing a progressive decline with increasing age and minimal disparity between males and females.

Healthy life expectancy (HALE) estimation

Healthy Life Expectancy (HALE) accounts for both mortality and morbidity, providing a more comprehensive measure of population health than LE alone. Using the Sullivan method (Sullivan, 1971; Mathers *et al.*, 2001), age- and sex-specific HALE estimates for Gurugram demonstrated a consistent decline with age **(Figure 3)**. At age 0-4 years, HALE was 82 years for males and 81 years for females, closely aligning with LE, indicating that early years are predominantly lived in good health. However, HALE declined to 58 years at age 30-34 and further to 35 years for males and 36 years for females by 60-64 years, reflecting an increasing burden of disability and chronic disease with age.

Despite having a longer life expectancy, women lived with poorer health for a greater number of years, revealing a modest gender gap. This finding aligns with the well-documented “morbidity-mortality paradox,” where women live longer but experience higher morbidity in later life. These results underscore the necessity of integrating morbidity prevention and functional health maintenance into public health strategies. Simply increasing lifespan is insufficient unless accompanied by improvements in health-adjusted life years, highlighting the importance of policies targeting chronic disease management, geriatric care, and gender-sensitive interventions.

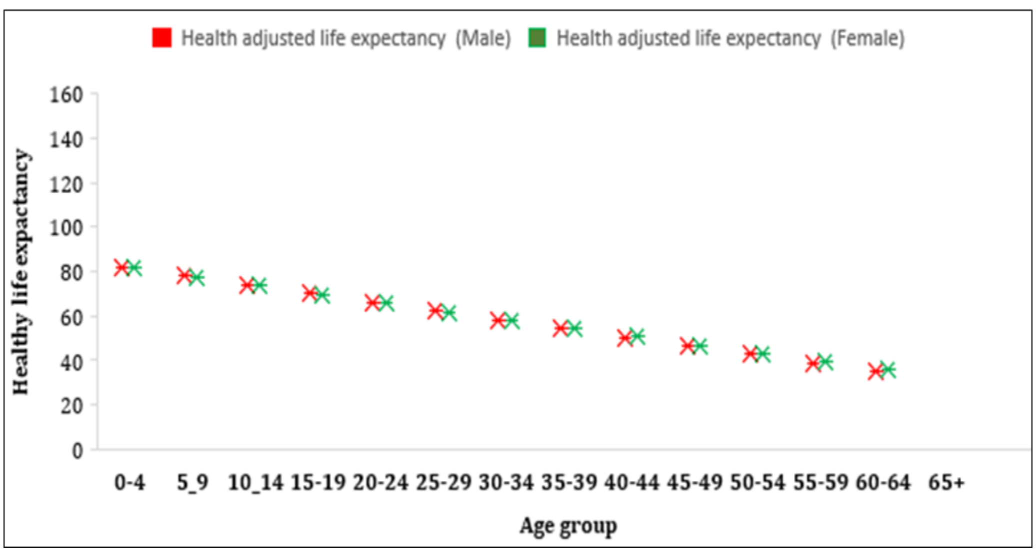

Figure 3. Age- and sex-specific Healthy Life Expectancy (HALE) estimates for Gurugram district, illustrating the reduction in healthy life years with age and the slightly higher morbidity burden among females.

Comparative Analysis of LE and HALE

Comparison of LE and HALE across age and sex reveals a widening gap between total and health-adjusted life expectancy with advancing age. In Gurugram, the LE–HALE gap increased from approximately 2 years at birth to 6–7 years among older adults, quantifying years lived in less-than-optimal health and signaling a substantial non-fatal disease burden in later life. While LE trends for males and females were largely similar, HALE revealed differentiated health experiences, with females experiencing higher disability prevalence despite longevity.

The intricate relationship between mortality and morbidity is illustrated by this combined LE and HALE analysis, which offers vital information for urban health planning. In rapidly developing cities like Gurugram, high $PM_{2.5}$ exposure and other environmental stressors may accelerate both mortality and morbidity, reinforcing the importance of pollution mitigation strategies. Prior studies have indicated that reductions in ambient particulate matter can meaningfully improve LE and HALE (Burnett *et al.*, 2018; Shaddick *et al.*, 2018), and our results provide localized evidence for these associations in India.

Implications for public health policy

To our knowledge, this is the first study assessing the impact of $PM_{2.5}$ exposure on LE and HALE in Gurugram. The findings highlight the urgent need for effective air quality management policies, as reducing pollution exposure can not only prevent premature mortality but also enhance quality of life by promoting healthier aging. Policymakers should incorporate HALE and the LE-HALE gap as comprehensive indicators of population health to identify inequalities and prioritize interventions.

Globally, public health indicators such as LE, HALE, and the LE-HALE gap have improved in most regions since 1995, but challenges remain in ensuring that life gains are spent in good health. Evidence suggests that risk factors such as tobacco use, unhealthy diets, alcohol consumption, and physical inactivity contribute substantially to years of life lost and the widening LE-HALE gap. Sustainable improvements in HALE require coordinated policies and programs empowering individuals to adopt healthy lifestyles while simultaneously addressing environmental determinants, such as air pollution, that disproportionately affect urban populations. Integrating these findings into urban health strategies aligns with global initiatives, including the UN Sustainable Development Goals, and emphasizes the need for localized, gender-sensitive, and age-focused health interventions.

CONCLUSION

This study provides the first comprehensive assessment of life expectancy (LE) and healthy life expectancy (HALE) in relation to ambient $PM_{2.5}$ exposure in Gurugram, a rapidly urbanizing district in India. The analysis revealed a clear age-dependent decline in both LE and HALE, with older adults experiencing the largest reductions, highlighting the compounded vulnerability of the elderly to environmental stressors. While LE was broadly similar between males and females, HALE analyses revealed that women, despite longer lifespans, experienced a higher burden of disability in later life, consistent with the "morbidity–mortality paradox."

The widening gap between LE and HALE with age underscores the growing number of years lived in poor health, reflecting the cumulative effects of chronic disease, environmental exposures, and age-related vulnerability. High $PM_{2.5}$ exposure in Gurugram likely contributes to both premature mortality and morbidity, emphasizing the critical need for air pollution mitigation as part of urban health strategies. Integrating HALE alongside LE in public health planning provides a more nuanced understanding of population health, allowing policymakers to design age-, gender-, and environment-sensitive interventions.

The study demonstrates that improving air quality and addressing modifiable lifestyle risk factors are essential not only to extend life expectancy but also to enhance the quality of those additional years, contributing to healthier aging and sustainable urban development. These findings support national and global public health goals, including the Sustainable Development Goals (SDG 3: Good Health and Well-being; SDG 11: Sustainable Cities and Communities), and provide actionable insights for targeted policy interventions in high-pollution urban areas.

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ETHICS STATEMENT: None

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