Economic Valuation of PM2.5-Attributable Mortality in Delhi, 2010-2030: A Benefit-Transfer Analysis Using the IER Model

Kajal Sharma[1]*, Prof. Himmat Singh Ratnoo[2]†, and Surender Kumar[3]†

[1] Research Scholar, Department of Economics, Maharshi Dayanand University, Rohtak, India

[2] Retired Professor, Maharshi Dayanand University, Rohtak, India

[3] Academic Administrator, Ashoka University, Sonipat, India

Corresponding author: Kajal Sharma, Email: kajalsharma.rs.eco@mdurohtak.ac.in

† These authors contributed equally as second authors.

Abstract

Delhi experiences persistently high concentrations of fine particulate matter (PM2.5), with substantial implications for public health and the economy. This study quantifies the economic value of mortality burdens attributable to PM2.5 exposure in Delhi over 2010-2030 using the Integrated Exposure-Response (IER) model and a benefit-transfer approach to the Value of a Statistical Life (VSL). A benchmark VSL of US\$9.4 million (2015 prices) is transferred to the Indian context via purchasing power parity (PPP)-adjusted GDP per capita and an income elasticity of 1.0; values are expressed in 2024 INR (₹) using the average exchange rate. Annual welfare losses are estimated for three exposure scenarios-Observed, Business-as-Usual (BAU), and WHO Air Quality Guideline (AQG)-and then aggregated to cumulative totals and avoided losses.

Results indicate that annual PM2.5-related welfare losses increased by ~40% between 2010 and 2020 (₹94,800 crore to ₹133,000 crore). Under BAU, losses rise to ~₹158,000 crore by 2030; under WHO-aligned air quality, they fall to ~₹80,500 crore. Cumulatively, the observed trajectory amounts to ~₹17.7 lakh crore (2010-2024), with an additional ~₹9.1 lakh crore projected for 2025-2030 under BAU; these losses are largely avoided under WHO compliance. Sensitivity checks varying income elasticity (0.8-1.2) and adjustment factors (0.3-0.5) preserve scenario rankings. The findings demonstrate large, quantifiable economic dividends from achieving WHO guidelines and provide a transparent baseline for policy evaluation in Indian megacities.

Keywords

PM2.5; mortality; value of statistical life; benefit transfer; air pollution; Delhi; IER model; cost-benefit analysis; welfare loss; WHO-AQG

Introduction

Ambient air pollution is one of the most significant environmental risks to health worldwide, with PM2.5 linked to increased mortality from cardiovascular, respiratory, and metabolic diseases. Indian megacities, particularly Delhi, regularly experience PM2.5 concentrations far exceeding health-based standards, making air pollution both a pressing public-health emergency and an economic concern. Over the past decade, Delhi has ranked among the world's most polluted cities, and exposure levels have remained consistently above the WHO-AQG values, placing millions at risk.

While epidemiological assessments have quantified the health burden of ambient air pollution in India, comprehensive evaluations of the economic value of mortality losses remain scarce, especially at the urban scale and over long-time horizons. Economic valuation of mortality risks is a critical input for cost-benefit analysis and environmental policy design, as it expresses health damages in monetary terms that

can be compared with the costs of air-quality improvement. Yet, for developing countries such as India, direct estimates of the VSL--a measure of society's willingness to pay for small reductions in mortality risk--are limited. As a result, researchers often rely on benefit-transfer approaches, in which benchmark VSL estimates from high-income economies are adjusted to local income levels using PPP and income elasticity parameters (Hammitt & Robinson, 2011; OECD, 2012; Narain & Sall, 2016).

This study provides a long-term, Delhi-specific economic valuation of PM2.5-attributable mortality for the period 2010-2030 using the IER model of long-term mortality risk (Burnett et al., 2014). The IER framework integrates epidemiological evidence from multiple exposure domains--including ambient and household air pollution, second-hand smoke, and active smoking--allowing risk estimation across a broad concentration range. Because the IER function exhibits a relatively flat slope at high exposures, it tends to yield conservative (lower-bound) estimates of risk and welfare loss. This characteristic makes the IER model particularly suitable as a baseline valuation framework for Delhi, where PM2.5 concentrations frequently exceed the upper range of many cohort studies.

The specific objectives of the paper are to:

(i) estimate annual PM2.5-attributable mortality in Delhi;

(ii) monetise these deaths using a VSL transferred from an OECD benchmark (US$9.4 million, 2015 prices) to Indian conditions via PPP-adjusted GDP per capita and an income elasticity of 1.0;

(iii) express the results in 2024 Indian Rupees (₹) under three exposure scenarios--Observed, BAU, and WHO-AQG; and

(iv) calculate cumulative and avoided welfare losses to assess the economic benefits of cleaner air.

Key findings (preview) Between 2010 and 2020, Delhi's PM2.5-related welfare losses increased by about 40%, rising from roughly ₹94,800 crore to ₹133,000 crore per year. If current trends persist, annual losses are projected to reach ₹158,000 crore by 2030 under the BAU scenario, while achieving WHO-compliant air quality would reduce losses to around ₹80,500 crore–a difference of nearly ₹78,000 crore per year by 2030. Over the full 2010-2030 period, the cumulative welfare loss amounts to approximately ₹26.8 lakh crore, of which around ₹9 lakh crore could be avoided through WHO guideline compliance. These magnitudes underscore that sustained exposure to high PM2.5 levels imposes a large and persistent economic cost on Delhi's population, while mitigation would yield substantial welfare gains.

Finally, this paper interprets the valuation as society's willingness to pay for marginal reductions in mortality risk rather than an intrinsic monetary value of human life. The estimates presented here aim to inform policy design by clarifying the scale of welfare benefits achievable through sustained air-quality improvement in Delhi and similar urban contexts

2. Literature Review

A large body of epidemiological research has firmly established the link between ambient air pollution and increased mortality. In particular, long-term exposure to PM2.5 is associated with elevated risks of premature death from cardiovascular and respiratory diseases, lung cancer, and type 2 diabetes (Pope et al., 2002; Cohen et al., 2017). Pope et al. (2002) found that each 10 μg/m^3 increase in PM2.5 was associated with approximately a 6% rise in cardiopulmonary mortality and an 8% rise in lung cancer mortality. Subsequent assessments, including those by Cohen et al. (2017) and the WHO, confirm that ambient PM2.5 exposure was responsible for about 4.2 million premature deaths globally in 2015 (95% CI: 3.7-4.8 million) and 4.2 million in 2019, with total air-pollution-related deaths (including household pollution) reaching 6.7 million annually. These figures make air pollution one of the largest contributors to the global burden of disease, particularly in low- and middle-income countries. The significant health

impacts also carry substantial economic costs. Converting mortality impacts into monetary terms enables comparison with mitigation expenses, typically using the VSL approach--a measure of a population's aggregate willingness to pay for small reductions in mortality risk. Studies in high-income economies introduced the VSL approach (Viscusi & Aldy, 2003; OECD, 2012), while in developing countries, limited local data have necessitated benefit-transfer approaches adjusting VSLs to national income levels (Narain & Sall, 2016; Shanmugam, 2019). The OECD recommends an income elasticity of VSL in the 0.8-1.2 range, and many Asian applications adopt a value near unity (Hammitt & Robinson, 2011; Viscusi, 2015).

Early attempts to measure VSL in India through labour-market and contingent-valuation studies found values far below those in wealthier countries. Madheswaran (2007) estimated a VSL of around ₹15 million (approximately US$0.3 million), while Shanmugam (2019) and others using wage-risk analyses reported similarly modest figures. Contingent valuation studies, such as Roy and De (2017), confirmed these lower magnitudes, reflecting differences in risk perception and income levels. Owing to the lack of local studies, analysts typically adopt benefit-transfer methods starting from OECD benchmarks and scaling by India's income ratio raised to an elasticity of about 1.0. Recent applications using this approach yield VSL values in the US$0.3-2.0 million range for India (Cropper & Sahin, 2009; Narain & Sall, 2016), depending on the chosen elasticity and whether PPP income is used. The lower end corresponds to higher elasticity assumptions (near 1.2) or lower-income populations, while the upper end reflects PPP-adjusted scaling. Despite the wide range, even conservative valuations indicate a large welfare cost of air pollution. The World Bank (Narain & Sall, 2016) concluded that applying appropriately adjusted international VSLs still produces substantial willingness-to-pay values for reducing mortality risk in India. Hence, while India's VSL is lower in absolute terms, it represents a significant share of income and underscores the magnitude of potential welfare gains from cleaner air.

Accurate estimation of pollution-related mortality depends on the exposure-response relationship between PM2.5 levels and health risk. The IER model developed by Burnett et al. (2014) integrates data from multiple sources--ambient and household air pollution, second-hand smoke, and active smoking--to estimate cause-specific mortality risks over a broad exposure range. The GBD studies adopted the model for global mortality estimation (Cohen et al., 2017), making it the standard for quantifying PM2.5-attributable deaths globally. Although the IER curve flattens at very high concentrations due to limited cohort data, it remains robust and transparent, providing conservative estimates that are particularly suited for highly polluted cities such as Delhi. Indeed, Apte et al. (2015) and Gurjar et al. (2016) noted that Delhi's PM2.5 levels--often exceeding 140-150 $\mu g/m^3$, about 15 times the WHO guideline--pose a massive public health challenge. The World Bank (2016) estimated that air pollution (ambient and household) cost India about 7.7% of GDP in 2013, while Pandey et al. (2021) found that lost output from air-pollution-related health impacts reached 1.4% of GDP in 2019. For Delhi specifically, Gupta et al. (2020) estimated annual losses of roughly ₹1 lakh crore (US$14 billion), reflecting its dense population and extreme exposure levels. Yet most previous studies evaluate single-year impacts rather than cumulative or scenario-based outcomes. The present study addresses this gap by applying the IER model over a 2010-2030 horizon to assess both the cumulative economic burden and the potential welfare gains from achieving WHO-compliant air quality in Delhi. This integrated epidemiological-economic framework offers a conservative, evidence-based foundation for cost-benefit evaluation of air-quality interventions.

3. Methods

3.1 Overview

The economic valuation of PM2.5-attributable mortality in Delhi integrates epidemiological exposure-response modelling with welfare-economic valuation. The analysis builds upon mortality estimates from the IER model and applies the VSL framework to monetise the health burden. The procedure follows established benefit-transfer and cost-benefit principles, progressing through four key stages: (i) transferring the reference VSL to India using income scaling, (ii) converting values into Indian rupees, (iii) estimating annual economic losses from attributable deaths, and (iv) aggregating cumulative and avoided losses across air-quality scenarios. This structure ensures consistency with international valuation standards while capturing context-specific economic implications for Delhi.

3.2 Valuation Procedure

The OECD benchmark VSL of US$9.4 million (2015 prices) was adopted as the reference and transferred to India using the standard income-elastic scaling rule:

$$VSL_{India} = VSL_{OECD} \times \left(\frac{Y_{OECD}}{Y_{India}}\right)^{\varepsilon}$$

where VSL_{OECD} is the OECD reference value (USD 9.4 million, 2015 prices), Y_{OECD} represents the average OECD per capita gross domestic product (GDP) in purchasing power parity (PPP) terms (~ USD 47,000 in 2015), Y_{India} denotes India's PPP GDP per capita (~USD 9,200 in 2024), and e=1.0 is the income elasticity of VSL. Although the OECD reference corresponds to 2015, the transfer employs India's 2024 PPP-adjusted per capita income to reflect current economic conditions. Because both Y_{OECD} and Y_{India} are expressed in PPP terms, the ratio Y_{OECD}/Y_{India} remains valid across years, ensuring real comparability. This approach aligns with standard benefit-transfer practice, allowing the 2015 OECD benchmark VSL to be appropriately scaled to India's contemporary income level. The use of PPP-adjusted GDP, rather than nominal exchange rates, ensures that the transfer captures real differences in living standards between countries. An elasticity of one is consistent with empirical evidence for middle-income economies, indicating a proportional relationship between income growth and willingness to pay for reductions in mortality risk.

The transferred VSL in USD was converted into Indian rupees using the 2024 average exchange rate of ₹83 = US$1, as follows:

$$VSL_{INR} = VSL_{India} \times ER_{2024}$$

where ER_{2024} is the rupee-dollar exchange rate used to convert the VSL into Indian Rupees. To maintain consistency and avoid over- or underestimation, a single baseline VSL value was adopted without applying additional adjustment factors. This approach ensures that the valuation reflects the central estimate of societal willingness to pay for mortality-risk reduction under prevailing economic conditions in Delhi.

Annual monetary losses were computed by multiplying the number of PM-attributable deaths in each year and scenario by the corresponding VSL:

$$Cost_{y,s} = D_{y,s} \times VSL$$

where $D_{y,s}$ is the number of attributable deaths in year y under scenario s (Observed, Business-as-Usual, or WHO). Results were expressed in crore INR (1 crore = 10^7 INR) for clarity. All calculations were

performed using the baseline VSL estimate to provide a consistent and transparent measure of the economic burden of air pollution–related mortality.

Cumulative welfare losses for the 2010-2030 period were obtained by summing annual losses:

$$C_{cum,s} = \sum_{y=2010}^{2030} Cost_{y,s}$$

The economic benefits of improved air quality were expressed as avoided losses, calculated as the difference between BAU and WHO-compliant scenarios:

$$Avoided\ Loss_s = Cost_{BAU} - Cost_{WHO}$$

These avoided losses represent the welfare gains, or the monetary value of lives saved, associated with achieving WHO guideline levels relative to the current trajectory.

All computations were performed using a harmonised dataset of annual PM2.5 concentrations, population exposure, and mortality data for Delhi. All values are expressed in 2024 constant rupees to maintain temporal comparability, with summary results reported in crore and lakh crore INR, and equivalent figures provided in billion USD for international comparison.

This framework provides a reproducible and conservative estimate of the welfare costs associated with PM2.5 exposure in Delhi and quantifies the economic gains achievable through cleaner air. It aligns with established international practice in environmental health economics and provides a robust empirical foundation for policy evaluation.

4. Results

4.1 Overview

The IER model provides a conservative yet robust framework for quantifying PM2.5-attributable mortality and associated welfare losses. Developed by Burnett et al. (2014), the IER function integrates evidence from multiple exposure sources--ambient, household, second-hand smoke, and active smoking--to estimate cause-specific mortality risks across a broad range of concentrations. In Delhi, where PM2.5 levels have long exceeded global safety thresholds, the IER model offers a lower-bound estimate of the health and economic burden of air pollution. Its relatively flat slope at very high concentrations ensures that results remain conservative, providing a cautious estimate of welfare losses.

4.2 Annual Economic Costs

Using annual mortality estimates derived from the IER model, the monetary valuation shows a steep rise in Delhi's air-pollution-related welfare losses from 2010 to 2020, followed by diverging trajectories under the BAU and WHO-AQG scenarios. Table 1 presents the estimated annual economic losses (base-case VSL) for 2010-2030, while Figure 1 illustrates their temporal evolution.

Table 1. *Annual Economic Cost of PM$_{2.5}$-Attributable Mortality in Delhi, 2010–2030 (Base Case, ₹ crore)*

Year	Observed	BAU	WHO
2010	94,777	—	—
2015	115,676	—	—
2020	132,980	—	—
2025	—	142,851	103,947
2030	—	158,392	80,513

Note. Values represent the annual economic cost of PM2.5-attributable mortality in Delhi (base-case VSL, expressed in 2024 constant rupees). Observed values correspond to historical years (2010–2020), while BAU (Business-as-Usual) and WHO (Air Quality Guideline) scenarios reflect projected estimates for 2025 and 2030. All figures are rounded to the nearest crore; detailed calculations are available upon request.

Figure 1. *Trends in Annual Economic Costs Attributable to PM2.5 Exposure (2010–2030)*
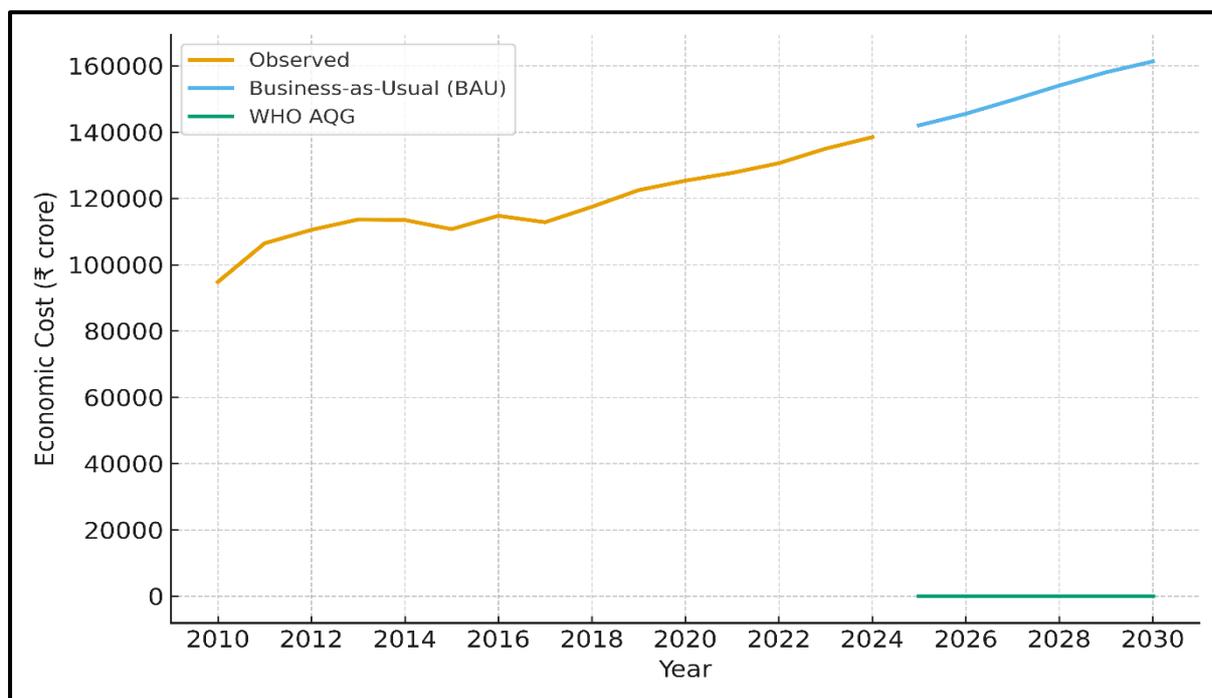
Between 2010 and 2020, Delhi's PM2.5-related welfare losses increased by nearly 40%, from approximately ₹94,800 crore to ₹133,000 crore annually. If current trends persist, losses are projected to reach ₹158,000 crore by 2030 under the BAU scenario, while achieving WHO-compliant air quality would reduce them to around ₹80,500 crore--a difference of nearly ₹78,000 crore per year. This gap reflects the economic value of a substantially cleaner environment under the WHO scenario. Because WHO-compliant air quality implies far lower PM2.5 exposure, the resulting decline in pollution-related mortality translates into markedly smaller welfare losses. Thus, the ₹78,000 crore difference is not a cost but an economic benefit--the monetary value of lives saved and health improvements from cleaner air.

Overall, the analysis shows that Delhi's pollution-related welfare losses more than doubled between 2010 and 2020 and continue to escalate under BAU. These results underscore that PM2.5 exposure imposes a growing financial burden on the city's economy, exceeding the pace of population and income growth.

4.3 Cumulative and Scenario Comparison

Aggregating annual losses over the study period highlights the magnitude of Delhi's long-term welfare burden and the potential economic savings achievable through air-quality improvements. Table 2 and Figure 2 summarise cumulative welfare losses from 2010–2030 across the three scenarios.

Table 2. *Cumulative Economic Cost of PM$_{2.5}$-Attributable Mortality in Delhi, 2010–2030 (Base Case, ₹ lakh crore)*

Scenario	Total (₹ lakh crore)	Description
Observed	17.7	Historical burden already incurred (2010–2024)
BAU	9.1	Additional projected losses if current trends persist (2025–2030)
WHO AQG	~0	Avoided burden under full guideline compliance

Note. Values represent cumulative welfare losses from PM2.5-attributable mortality in Delhi over the period 2010–2030, based on the base-case VSL expressed in 2024 constant rupees. The Observed scenario reflects the historical burden (2010–2024), while BAU (Business-as-Usual) and WHO (Air Quality Guideline) scenarios indicate projected outcomes for 2025–2030. Figures are rounded to one decimal place; detailed calculations are available upon request.

Figure 2. *IER-Based Cumulative Economic Costs of PM$_{2.5}$-Related Mortality, 2010–2030*
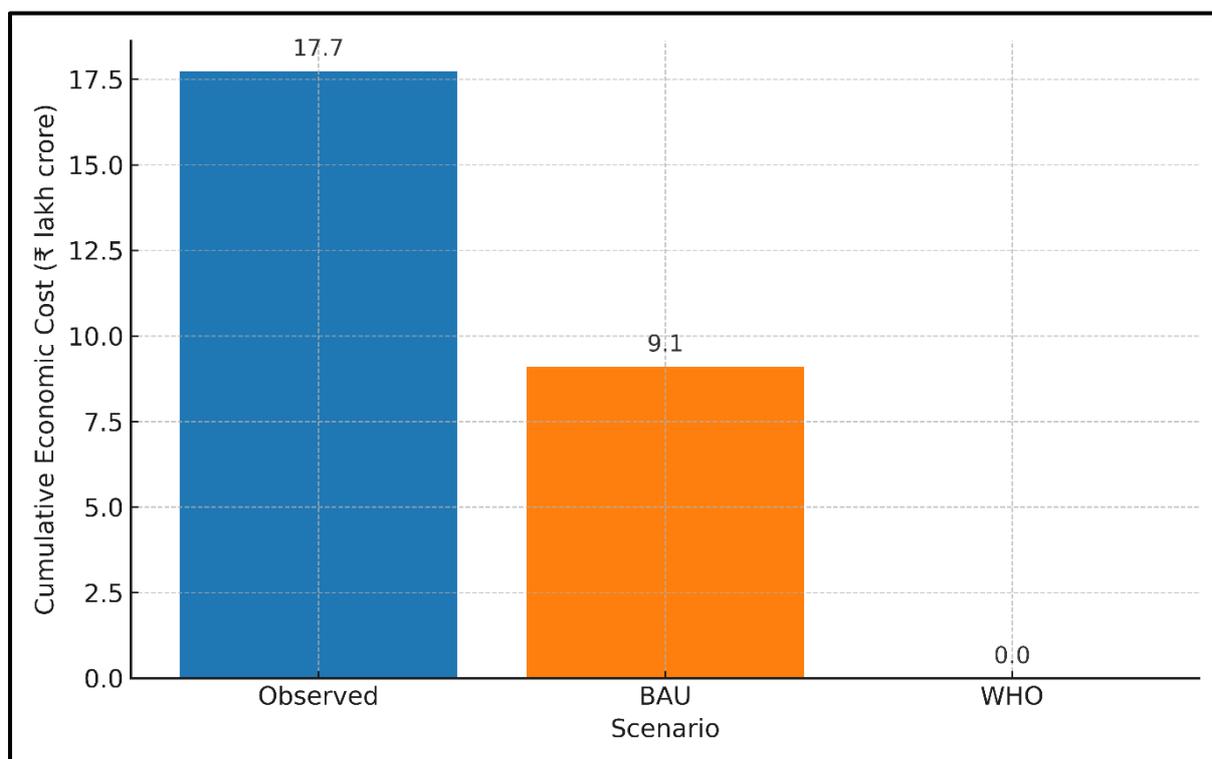
Over 2010-2030, Delhi's PM2.5-attributable mortality is estimated to result in a cumulative welfare loss of about ₹17.7 lakh crore under the observed trajectory. If current pollution trends persist, an additional ₹9.1 lakh crore in losses is projected between 2025 and 2030. Conversely, achieving the WHO Air Quality Guideline would avert nearly ₹9 lakh crore in losses relative to BAU--equivalent to the monetary value of lives saved during the same period.

Expressed differently, each year of delayed compliance with WHO standards could cost Delhi ₹1.5–2 lakh crore in foregone welfare benefits. These findings demonstrate that sustained air-quality improvements yield substantial and quantifiable economic dividends. The results reaffirm that pollution control in Delhi is not only a public health imperative but also a sound economic investment, offering significant welfare returns from reduced mortality and improved quality of life.

5. Discussion

This study provides one of the first long-term, scenario-based assessments of the economic burden of PM2.5-attributable mortality in Delhi using the IER model. The results show that welfare losses from PM2.5 exposure have grown rapidly since 2010 and are projected to reach ₹158,000 crore annually by 2030 under the BAU scenario. Achieving WHO-AQG compliance would reduce these losses to approximately ₹80,500 crore per year--a difference of about ₹78,000 crore annually, representing the economic value of avoided deaths. Cumulatively, the total welfare burden over 2010-2030 exceeds ₹26 lakh crore, with roughly ₹9 lakh crore in avoidable losses between 2025 and 2030 alone. These estimates underscore that the costs of inaction on air pollution far outweigh the investments required for mitigation.

The magnitude and trajectory of Delhi's pollution-related welfare losses align with previous national estimates while revealing sharper city-level impacts. The World Bank (2016) estimated India's combined welfare losses from ambient and household air pollution at 7.7% of GDP in 2013, while Pandey et al. (2021) calculated output losses of 1.4% of GDP in 2019. Delhi's annual loss--₹1-1.5 lakh crore--constitutes roughly 1.3% of India's total GDP, concentrated in a single city, reflecting its extreme exposure levels (Apte et al., 2015; Gurjar et al., 2016). Gupta et al. (2020) similarly found that PM2.5-related premature mortality in Delhi imposes annual economic losses exceeding ₹1 lakh crore, consistent with the present study's base-case results. The temporal analysis presented here extends those findings by quantifying both cumulative damages and avoided losses over two decades, offering a dynamic picture of welfare impacts under different policy pathways.

From a policy perspective, these findings demonstrate that improving air quality in Delhi yields substantial economic dividends alongside health benefits. Each year of delayed compliance with WHO standards could cost the city between ₹1.5 and ₹2 lakh crore in forgone welfare gains--equivalent to multiple years of Delhi's environmental expenditure. Investments in cleaner transport, industrial emission control, and household energy transition are thus not merely environmental actions but sound economic policies that prevent future losses. Moreover, as India urbanises further, city-level analyses can help prioritise air-quality management where population exposure and economic value are most concentrated.

At the same time, this study has a few important limitations. The IER model provides a conservative estimate of mortality risk, especially at high pollution levels (>100 $\mu g/m^3$), where relative risks tend to flatten due to limited cohort data. Consequently, the welfare losses reported here likely underestimate the true magnitude of damages. Uncertainty also arises from assumptions regarding income elasticity (e = 1.0), the exchange rate, and the range of applied VSL adjustment factors (0.3-0.5). However, these assumptions are consistent with OECD guidelines and widely used in Indian policy analyses, ensuring comparability. The focus on mortality further implies that the total welfare cost of air pollution--if morbidity, productivity loss, and healthcare expenditure were included--would be considerably higher.

Despite these limitations, the results clearly illustrate that cleaner air represents a major economic opportunity for Delhi. By integrating epidemiological and economic evidence, this study offers a framework adaptable to other Indian megacities facing similar pollution pressures. It strengthens the case

for urgent, data-driven air-quality policy, showing that achieving WHO-compliant PM2.5 levels is not only a public health necessity but also an economically rational goal.

6. Policy Implications

The findings of this study have clear and far-reaching implications for environmental, health, and economic policy in Delhi and other Indian megacities. The evidence demonstrates that the costs of inaction on air pollution are extraordinarily high: under a BAU trajectory, Delhi could lose nearly ₹9 lakh crore in welfare value between 2025 and 2030 alone. Achieving the WHO-AQG would convert these potential losses into quantifiable economic benefits, equivalent to roughly 1.5-2% of India's annual GDP over the same period. Such benefits far exceed the expected costs of pollution control measures, reinforcing that clean-air investments are fiscally prudent as well as socially equitable.

From a policy standpoint, three priorities emerge. First, targeted emission reduction from transport, industrial sources, and open burning must be accelerated through stricter enforcement, adoption of clean fuels, and electrification strategies. Second, integrated monitoring and data transparency should be institutionalised to enable performance tracking against WHO-aligned benchmarks. Third, economic valuation methods like those used in this study should be incorporated into cost–benefit analyses of air-quality interventions, allowing policymakers to internalise health-related welfare costs in economic planning.

Moreover, improving air quality delivers strong co-benefits for climate mitigation, energy efficiency, and public health equity. Given that PM2.5 exposure disproportionately affects low-income and vulnerable populations, cleaner air also contributes to India's broader goals under the Sustainable Development Goals (SDGs)--notably SDG 3 (Good Health and Well-Being) and SDG 11 (Sustainable Cities and Communities). Recognising pollution reduction as an economic development strategy can therefore catalyse both fiscal efficiency and social justice.

7. Conclusion

This study presents a comprehensive assessment of the economic burden of PM2.5-attributable mortality in Delhi from 2010 to 2030 using the IER model. By linking epidemiological risk functions with welfare economics through the VSL approach, it quantifies both historical and projected welfare losses under alternative air-quality scenarios. The results show that Delhi's annual economic cost of PM2.5-related mortality rose from approximately ₹94,800 crore in 2010 to ₹133,000 crore in 2020, and could reach ₹158,000 crore by 2030 under a BAU trajectory. In contrast, compliance with the WHO Air Quality Guideline would reduce annual losses to about ₹80,500 crore, yielding an economic benefit of nearly ₹78,000 crore per year by 2030.

Cumulatively, the total welfare loss over 2010-2030 is estimated at ₹26.8 lakh crore, of which nearly ₹9 lakh crore could be avoided through timely air-quality improvement. These findings make clear that air pollution is not merely a public health concern but a substantial economic liability. Every year of delayed mitigation imposes additional welfare losses equivalent to 1.5-2 lakh crore--resources that could otherwise strengthen healthcare, infrastructure, and climate adaptation.

By employing a conservative, policy-aligned framework, this study provides a lower-bound estimate of Delhi's pollution-related economic damages while highlighting the enormous potential for welfare gains from clean air. The approach can be readily extended to other Indian cities and integrated into national cost-benefit analyses. Ultimately, the evidence underscores that achieving WHO-compliant air quality in

Delhi is both a public health imperative and an economically rational objective--demonstrating that cleaner air translates directly into lives saved and wealth preserved.

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