



The health burden and economic costs averted by ambient PM_{2.5} pollution reductions in Nagpur, India



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ABSTRACT

National estimates of the health and economic burdens of exposure to ambient fine particulate matter (PM_{2.5}) in India reveal substantial impacts. This information, often lacking at the local level, can justify and drive mitigation interventions. Here, we assess the health and economic gains resulting from attainment of WHO guidelines for PM_{2.5} concentrations – including interim target 2 (IT-2), interim target 3 (IT-3), and the WHO air quality guideline (AQG) – in Nagpur district to inform policy decision making for mitigation. We conducted a detailed assessment of concentrations of PM_{2.5} in 9 areas, covering urban, peri-urban and rural environments, from February 2013 to June 2014. We used a combination of hazard and survival analyses based on the life table method to calculate attributed annual number of premature deaths and disability-adjusted life years (DALYs) for five health outcomes linked to PM_{2.5} exposure: acute lower respiratory infection for children <5 years, ischemic heart disease, chronic obstructive pulmonary disease, stroke and lung cancer in adults ≥25 years. We used GBD 2013 data on deaths and DALYs for these diseases. We calculated averted deaths, DALYs and economic loss resulting from planned reductions in average PM_{2.5} concentration from current level to IT-2, IT-3 and AQG by the years 2023, 2033 and 2043, respectively. The economic cost for premature mortality was estimated as the product of attributed deaths and value of statistical life for India, while morbidity was assumed to be 10% of the mortality cost. The annual average PM_{2.5} concentration in Nagpur district is $34 \pm 17 \mu\text{g m}^{-3}$ and results in 3.3 (95% confidence interval [CI]: 2.6, 4.2) thousand premature deaths and 91 (95% CI: 68, 116) thousand DALYs in 2013 with economic loss of USD 2.2 (95% CI: 1.7, 2.8) billion in that year. It is estimated that interventions that achieve IT-2, IT-3 and AQG by 2023, 2033 and 2043, would avert, respectively, 15, 30 and 36%, of the attributed health and economic loss in those years, translating into an impressively large health and economic gain. To achieve this, we recommend an exposure-integrated source reduction approach.

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1. Introduction

Ambient fine particulate matter (PM_{2.5}), which constitutes emissions from diverse combustion sources including transportation, power plants, industries and household use of solid fuels contributes substantially to increased risk of disease and death (Chafe et al., 2014; Lelieveld et al., 2015; Lim et al., 2012; Smith et al., 2014). Specific health outcomes linked with exposure to PM_{2.5} include mortality and morbidity from acute lower respiratory infection (ALRI) in children <5 years;

chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), lung cancer (LC) and stroke in adults ≥25 years (Burnett et al., 2014). A growing body of evidence also indicates increased risk of mortality from diabetes mellitus and preterm and underweight births (Coker et al., 2016; Dôâaz et al., 2016; Feng et al., 2016; Li et al., 2016; Meo et al., 2015; Nachman et al., 2016; Weinmayr et al., 2015), especially in developing countries where both exposure to PM_{2.5} and baseline mortality rates from these health outcomes are higher (IHME, Institute for Health Metric and Evaluation, 2015; WHO, 2015). The Global Burden of Disease (GBD) 2013 study estimates that the number of premature deaths and disability-adjusted life years (DALYs) attributable to ambient PM_{2.5} is approximately 3.0 and 70 million, respectively, per year (Forouzanfar et al., 2015; WHO, 2016a). The burden is borne disproportionately across the globe, with India having the second largest

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share after China, and accounts for about 18% of the global burden of disease (Giannadaki et al., 2016; Lelieveld et al., 2015). The estimates of PM_{2.5}-related premature deaths in the world's 20 topmost countries in 2010 are shown in Fig. 1. Pakistan, Nigeria and Bangladesh are the other three countries at the top 5 position (Giannadaki et al., 2016).

Although the burden in India is only about half the number in China, the trend in the former is increasing faster than the latter: ~12% and ~3% increase in number of death and life lost years, respectively, in India between 2005 and 2010, as compared to China's ~5% and ~0.5%, respectively (OECD, Organization for Economic cooperation and Development, 2014). The increasing number of deaths attributable to air pollution in India owes to a combination of high concentrations of PM_{2.5}, high population density and high disease prevalence (Apte et al., 2015). Death tolls in India are estimated to climb towards China's levels if India advances further along the same road of industrialization and motorization as China (OECD, Organization for Economic cooperation and Development, 2014). The estimated economic cost of the health impact of ambient PM_{2.5} in India was approximately USD 0.5 trillion in 2010 (OECD, Organization for Economic cooperation and Development, 2014).

Assuming the world attains the USEPA's ambient PM_{2.5} limit of 12 $\mu\text{g m}^{-3}$, an estimate of 1.443 million annual premature deaths would be averted globally, with China; India; Pakistan; Nigeria; Bangladesh, USA and the European Union having an estimate of 911,000; 281,000; 38,000; 13,000; 47,000 and 3000; 34,600 averted premature deaths per year, respectively (Giannadaki et al., 2016). Furthermore, attainment of WHO's PM_{2.5} air quality guideline (AQG) of 10 $\mu\text{g m}^{-3}$ in China and India combined, would avert ~1.4 million premature deaths per year (Apte et al., 2015).

Such air quality improvements would however depend largely on decisions and actions taken at the local, sub-national level (Chowdhury and Dey, 2016; COMEAP, Committee on the Medical Effects of Air Pollutants, 2012; Gowers et al., 2014). Therefore, local level estimates of attributed and averted disease burdens are critically important to inform policy decision-making and implementation. Indeed, they may justify the “cost” of improved or alternate technologies, or changes in policy required to meet global air quality standards, particularly in localities where the demand for economic development may supersede environmental considerations.

Hitherto, most local-level assessment of PM_{2.5}-related mortality in developing countries focused on the most polluted localities like Delhi,

Beijing, Yangtze River Delta, the Pearl River Delta and São Paulo (Abe and Miraglia, 2016; Dholakia et al., 2013; Guttikunda and Goel, 2013; Jiang et al., 2015; Wang et al., 2015; Zheng et al., 2015). The implication of this is that policymakers, who are also addressing pressing socio-economic and developmental needs, may overlook the impact of air pollution in less polluted localities. This is especially important since there is no safe limit below which the adverse health effects of PM_{2.5} do not occur (Pinault et al., 2016; WHO, 2005).

Therefore, in this study, we chose Nagpur district, which is believed to be the cleanest and second greenest district in India (Borkar et al., 2014; Wanjari, 2012) and conduct a detailed assessment of concentrations of ambient PM_{2.5} covering three distinct environments: urban, peri-urban, and rural, bearing in mind that the routine monitoring of air quality in India is presently nearly exclusively confined to urban areas (MoHFW, Ministry of Health and Family Welfare, Government of India, 2015). At the time of study, PM_{2.5} was not monitored in Nagpur district (CPCB, Central Pollution Control Board, Government of India, 2012); however, it is now being monitored in 1 out of the 7 air quality stations (all urban locations) in the district (MPCB, Maharashtra Pollution Control Board, 2016). Furthermore, we estimate the annual deaths, DALYs and economic cost attributed to ambient PM_{2.5} concentrations in 2013, and calculate the averted burdens and cost accruing from attainment of WHO interim targets and AQG under a planned mitigation scenario, for informed decision-making.

2. Methods

2.1. Site description

Nagpur district is located at the exact geographical centre of India (Fig. 2). It lies within Latitude 21°03'N and 21°21'N of the Equator and Longitude 78°57'E and 79°16'E of the Greenwich Meridian. It has an area of 9892 km² with an elevation of 310 m above sea level (Singh et al., 2011). It is the 3rd and 13th most populous city in Maharashtra and India, respectively (Census India, 2011). Its population is 4,653,570 of which 51 and 49% are male and female, respectively. Approximately 11% of its population is children ≤6 years (Census of India, 2011). It has population growth and literacy rates of 14.4 and 93.13%, respectively, and about two third of its population lives in urban areas (Census India, 2011). The district has a tropical climate

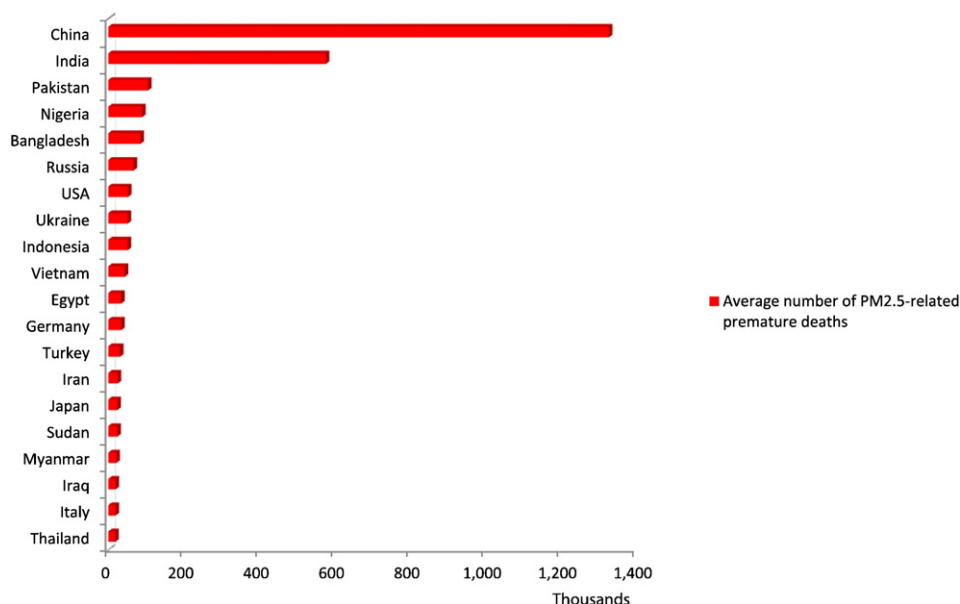


Fig. 1. Estimates of PM_{2.5}-related premature deaths in the world's topmost 20 countries in 2010 (Adapted from Giannadaki et al., 2016).

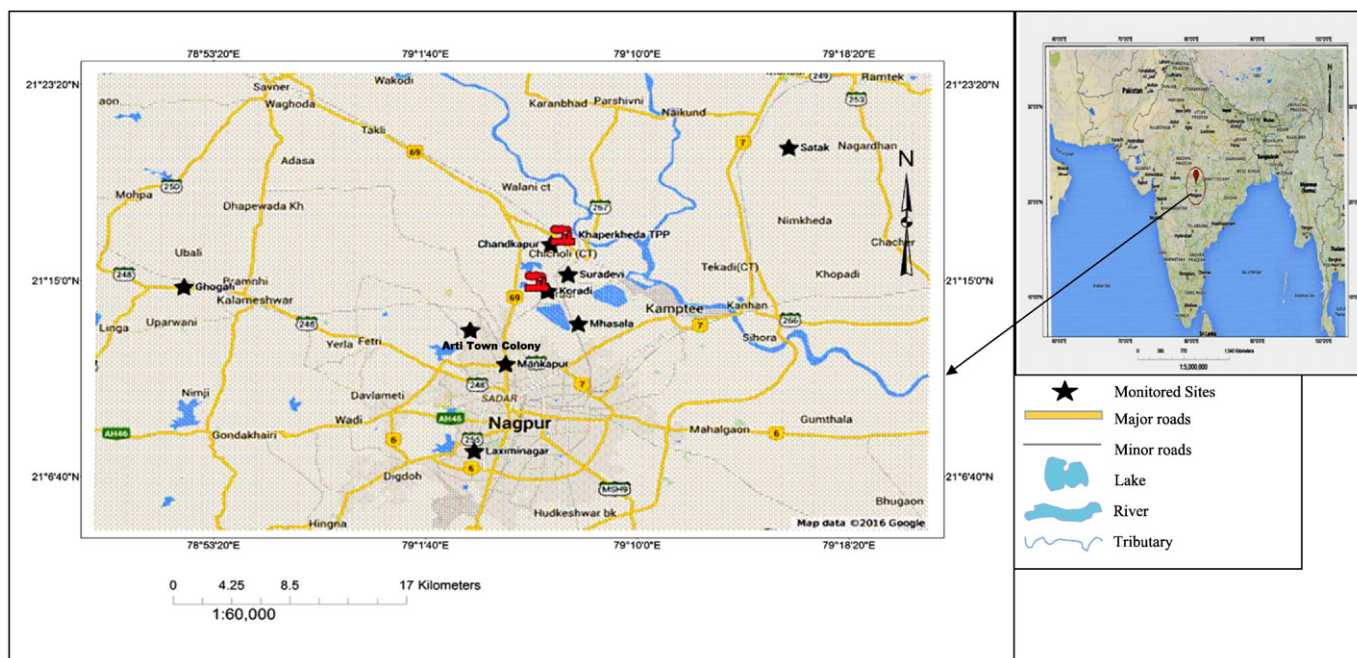


Fig. 2. Map of Nagpur district showing the monitored sites (adapted from Google map).

with four seasons: summer (April–June); monsoon (July–September), post-monsoon (October–November) and winter (December–March).

Nagpur district is a developing locality with high economic development, rapid urbanization, growing industrialization, and a developing technology sector. The district has been called one of the future global cities of the world (M.G.I., McKinsey Global Institute, 2011). Although Nagpur is regarded as one of the cleanest and greenest localities in India, it is a coal mining region that relies heavily on coal-fired thermal power plants for power generation. The district currently houses two coal-fired power stations and a third is currently under construction. It has a large vehicle fleet reliant on diesel and gasoline engines, most of which rely on two-stroke engines. It has a large population density of 470 persons per square kilometers (Census India, 2011).

In spite of the fact that more people live in the urban areas (~68%), the district has a very large number of villages (1859) scattered around a limited number of towns (41) (Census India, 2011). Most rural households use solid fuels (dung, crop residues, wood and coal) for cooking and heating. Furthermore, a source apportionment study conducted in traffic congested urban sites reports that the contributions of vehicular emissions, biomass burning, re-suspended dust and secondary inorganic aerosol to ambient air pollution range from 57 to 65%, 9–15%, 6–10% and 12–16%, respectively (Pipalatkhar et al., 2014). Thus, even in urban traffic hotspots, biomass burning contributes substantially to ambient $PM_{2.5}$ levels. No information could be obtained on the background concentration of $PM_{2.5}$ in Nagpur district.

2.2. Sampling protocol

We selected nine areas in Nagpur consisting of urban (Arti Town Colony, Laxminagar and Mankapur), peri-urban (Chandkapur, Ghogali and Koradi) and rural (Mhasala, Satak and Suradevi) locations. Each area has distinct characteristics within its category. For instance, even though Arti Town Colony, Laxminagar and Mankapur are all urban areas, Arti Town Colony is strictly a residential area, Laxminagar is a blend of commercial and residential areas, and Mankapur is a commercial hub with very high traffic congestion. Koradi, Chandkapur, Suradevi and Mhasala are peri-urban and rural areas close to two coal-fired thermal power plants. Ghogali and Satak vary in distance from the power plants (Fig. 1). The geographical positioning information, height and classification of sampled areas are shown in Table 1.

We collected continuous 24-h ambient $PM_{2.5}$ samples on pre-weighed polytetrafluoroethylene (PTFE) membrane filters (46.2 mm diameter), using pre-calibrated low volume air samplers (LVSS), with an average flow rate of 16.67 l min^{-1} (Dutt Fine Dust Air Sampler, Model: DFPM-2.5E; and Netel Fine Dust Sampler, Model: NPM-FDS-2.5A). The LVSS were placed on unobstructed roof-tops between 3.7 and 7.6 m high (Table 1). The LVSS were calibrated in-field using a rotameter, to ensure a standard flow rate of 16.67 l min^{-1} . No flow rate deviated by over 10% during the sampling period. After 24-h sampling, sample filters were transferred into glass cartridges, using clean forceps; covered, labeled, and placed in desiccators. We also collected

Table 1
Geographical positioning information, height and classification of sampled areas.

S/N	Sampled areas	Global positioning system coordinates	Sampled height (metre)	Area classification
1	Arti Town Colony	N21°12'33.9", E079°03'21.5"	7.6	Urban
2	Chandkapur	N21°17'15.4", E079°06'39.9"	3.7	Peri-urban
3	Ghogali	N21°16'00.0", E079°04'12.3"	4.3	Peri-urban
4	Koradi	N21°15'11.6", E079°04'55.5"	7.6	Peri-urban
5	Laxminagar	N21°07'13.0", E079°03'57.1"	7.6	Urban
6	Mankapur	N21°11'10.3", E079°04'55.8"	4.6	Urban
7	Mhasala	N21°12'48.6", E079°07'41.4"	3.7	Rural
8	Satak	N21°20'19.4", E079°14'45.5"	5.2	Rural
9	Suradevi	N21°14'50.7", E079°07'18.9"	4.6	Rural

continuous 24-h ambient PM with aerodynamic diameter $\leq 10 \mu\text{m}$ (PM_{10}), using collocated LVSS. Monitoring of PM_{10} was done in order to assess the ratio of $\text{PM}_{2.5}$ to PM_{10} .

Sampling was done for 7 consecutive days (Monday–Sunday) per site and season (winter, summer, monsoon and post-monsoon). The post-monsoon sampling was conducted several days before or after Diwali, an Indian festival in the post-monsoon season during which oil lamps are lit and fire-crackers are burnt. Therefore the sampling period for all sites did not coincide with Diwali. A total of 756 sample filters, 378 each for $\text{PM}_{2.5}$ and PM_{10} , were collected from February 2013 to June 2014. Concentrations ($\mu\text{g m}^{-3}$) of $\text{PM}_{2.5}$ or PM_{10} were determined gravimetrically in triplicate by dividing the PM mass (μg) deposited on the filter by the volume (m^{-3}) of air sampled during the 24-h period. The filters were equilibrated in a temperature and humidity controlled room, prior to pre- and post-weighing. Relative humidity and temperature were kept at a mean of 36% and 22 °C, respectively.

2.3. Statistical analysis

We assessed temporal and spatial variability of $\text{PM}_{2.5}$ or PM_{10} concentrations using repeated-measures multivariate analysis of variance (MANOVA, $p = 0.05$) using SPSS 17.0. The multivariate tests used were Pillai's Trace, Wilk's Lambda, Hotelling's Trace and Roy's Largest Root, while the post hoc tests were Least Significant Difference, Bonferroni adjusted comparisons and Dunnett T3.

2.4. Estimation of deaths, disease burden and cost of $\text{PM}_{2.5}$

We considered the contribution of five health endpoints linked to ambient $\text{PM}_{2.5}$ in the integrated exposure-response (IER) functions of Burnett et al. (2014): ALRI for children <5 years; COPD, IHD, LC and stroke for adult ≥ 25 years. The International Statistical Classification of Diseases, 10th Revision (ICD-10) codes for the health endpoints are presented in the Supplemental Material (Table S1). We calculated attributed and averted deaths and DALYs using reported relative risk values (Apte et al., 2015). Apte et al. (2015) derived age group and cause-specific relative risk values for $\text{PM}_{2.5}$ from 0 to $410 \mu\text{g m}^{-3}$ in $0.1 \mu\text{g m}^{-3}$ step, using the IER functions, assuming a counterfactual $\text{PM}_{2.5}$ concentration of $5.8 \mu\text{g m}^{-3}$.

We estimated the $\text{PM}_{2.5}$ attributed and averted deaths, DALYs and economic cost in Nagpur district, for the health endpoints, using hazards and survival analysis. We used the abridged life-table calculation method that separates the dimensions of age and calendar time in a system of Excel spreadsheets (Miller and Hurley, 2003). The hazard is the age-specific risks of dying, conditional on having survived to that age. Therefore the hazard rate for each age group was estimated as:

$$H_i = \left(\frac{RR_i - 1}{RR_i} \right) \times B_i \quad (1)$$

where: H_i is the hazard rate attributed to ambient $\text{PM}_{2.5}$ in Nagpur district for the health endpoint and age group RR_i is the relative risk of a health endpoint and specific age group at the annual average $\text{PM}_{2.5}$ concentrations; derived from IERs (Apte et al., 2015) (see Supplemental Material, Table S2, for details). B_i is baseline death or DALY rate for the health endpoint and age group in India, assuming same rates as Nagpur district. The values were downloaded from the Institute for Health Metrics and Evaluation GBD country database (IHME, Institute for Health Metric and Evaluation, 2015) (see Supplemental Material, Table S3, for details).

The hazard rate (H_i) for the health outcomes (except ALRI), were combined. The H_i for ALRI was analysed separately.

The probability of surviving (PS_i) and the probability of dying (PD_i) from the 5-year age interval were estimated from H_i using the following

algorithms (Mathers et al., 2001):

$$PD_i = \frac{5 \times H_i}{1 + 5(0.5 \times H_i)} \quad (2)$$

$$PS_i = 1 - PD_i \quad (3)$$

The probability of surviving (PS_i) for each age interval is then multiplied in chain, diagonally across the life table to calculate cumulative survival probabilities to the last age interval:

$$CSP_2 = CSP_1 \times PS_2 \quad (4)$$

$$CSP_1 = 1 \times PS_1 \quad (5)$$

where: CSP_1 is cumulative survival probabilities for the first age group considered (25–29 years) PS_1 is probability of surviving the first age group (25–29 years) CSP_2 is cumulative survival probabilities to the next age group (30–35 years) PS_2 is the probability of surviving for the next age group (e.g. 30–35 years) The cumulative survival at the end of each age interval is equivalent to the expected fraction of the life-year achieved in that interval, because it averages over the whole cohort the predicted contributions of those who survive to and through that age interval and those who die in it. Therefore, the population starting each next five-year interval ($P_{start_{i+1}}$) across a diagonal was estimated as:

$$P_{start_{i+1}} = P_1 \times CSP_i \quad (6)$$

where: P_1 is the 2013 population in each age interval in Nagpur district.

The values were adapted from United Nations population prospect (UN, 2013) and Maharashtra Population (MP, Maharashtra Population, 2016). Current population data was used for year 2013 estimation; while UN projected population for India, scaled to Nagpur, was used for the future years (2023, 2033 and 2043) estimations (see Supplemental Material, Table S4, for details).

The $\text{PM}_{2.5}$ -related deaths (or DALY when its hazard rate was used) in an age interval (D_i) were estimated as:

$$D_i = \frac{P_{start_i} \times PD_i}{5} \quad (7)$$

where: PD_i is the probability of $\text{PM}_{2.5}$ -related death (or DALY) for an age interval (Eq. (2))

We constructed excel spreadsheets that enabled us to separate the dimensions of age and calendar year over time. The spreadsheets method is flexible and allows monetary values to be estimated with or without discounting. Thus, we predicted the changes in the burden that might accrue in our planned mitigation scenario. Specifically, we calculate the number of $\text{PM}_{2.5}$ -related premature mortality, DALYs and the economic cost in Nagpur district for the year 2013 and the averted burden and cost per year supposing a planned mitigation achieved reductions from the current level to an annual average $\text{PM}_{2.5}$ concentration of $25 \mu\text{g m}^{-3}$ (interim target 2: IT-2) by 2023; $15 \mu\text{g m}^{-3}$ (IT-3) by 2033; and $10 \mu\text{g m}^{-3}$ (WHO AQG) by 2043. The economic cost was estimated using the value of statistical life (VSL) for India. The VSL represents an individual's willingness to pay for marginal reduction in risk of dying, and has been used extensively for cost benefit analysis to reducing air pollution (OECD, Organization for Economic cooperation and Development, 2014). The economic cost per year of premature deaths was estimated using the following equation:

$$EC_{mort} = n \times VSL_i \quad (8)$$

where: EC_{mort} is the economic cost per year of $\text{PM}_{2.5}$ -related premature mortality in Nagpur district n is the number of $\text{PM}_{2.5}$ -related premature mortality in the year VSL_i is the Indian value of statistical life.

The OECD (Organization for Economic cooperation and Development) (2014) gave an Indian VSLi value of USD 602,000 for 2010, while Ghude et al. (2016) reported an Indian value of USD 1.1 million for 2011. We use the former in our estimation, which is a conservative value. The economic cost for PM_{2.5}-related morbidity (EC_{morb}) was calculated as 10% of the estimated EC_{mort} (OECD, Organization for Economic cooperation and Development, 2014). We did not however apply discounting or age-weighting in our estimations.

3. Results and discussion

3.1. Concentrations of PM_{2.5} and PM₁₀ in Nagpur

The average concentrations ($\mu\text{g m}^{-3}$) of PM_{2.5} and PM₁₀ in urban, peri-urban and rural areas of Nagpur in four seasons are presented in Table 2. The multivariate tests (Pillai's Trace, Wilk's Lambda, Hotelling's Trace and Roy's Largest) revealed a significant difference ($p = 0.05$) in concentrations of PM_{2.5} or PM₁₀ across sites and seasons. Post hoc tests also showed significant ($p = 0.05$) variations in the concentrations of PM_{2.5} or PM₁₀ in any two seasons (see Supplemental Material, Table S5 and Fig. S1, for details). Specifically, the concentrations were significantly highest in post-monsoon, followed in decreasing order by summer, winter and monsoon. Studies conducted in different parts of India have also reported maximum and minimum levels of PM in post-monsoon and monsoon, respectively (Godri et al., 2010; Tiwari et al., 2012; Trivedi et al., 2014; Yadav et al., 2014).

High concentrations of PM in post-monsoon were mainly attributed to increased emissions from fireworks during Diwali (Mandal et al., 2012; Tiwari et al., 2014). Although, our sampling did not coincide with Diwali, the high concentrations we observed in post-monsoon could be attributed to emissions from pre and post-Diwali activities coupled with bad weather condition: low temperature, low wind speed and no rainfall (George et al., 2008). Majumdar et al. (2015) argue that Indian post-monsoon air pollution is not limited to the anthropogenic activities of Diwali festival alone, but on several other festivals celebrated during the season, wherein fireworks, bonfires, incense burning and open air community cooking with solid fuels occur. Mishra and Shibata (2012) attributed the pollution level to seasonal agricultural crop residue (straw) burning for crop rotation. Kaskaoutis et al. (2013) cited increased biomass burning for heating and cooking. Tiwari et al. (2014) and Yadav et al. (2016) believe it owes to a combination of increased biomass burning, vehicular traffic from festivals celebration and bad meteorological condition.

By contrast, low levels of PM in monsoon were attributed to precipitation (Pandey et al., 2013; Singla et al., 2012). Average ambient

concentration of PM was reported to decrease rapidly even in low to moderate rainfalls (Singla et al., 2012), indicating that precipitation has strong influence on concentration. Furthermore, our average PM level in post-monsoon or monsoon is substantially lower than the corresponding seasonal value reported for most Indian cities (Godri et al., 2010; Nirmalkar et al., 2013; Nirmalkar and Deb, 2016; Pandey et al., 2013; Singla et al., 2012; Tiwari et al., 2012; Trivedi et al., 2014; Yadav et al., 2014).

We observed significantly higher PM concentrations in summer compared to winter. This observation contrasts most reports from earlier studies which have mostly found higher PM concentrations in winter than in summer, and have attributed it to lower temperature and lesser dispersion and mixing in winter (Pandey et al., 2013; Singla et al., 2012; Tiwari et al., 2012). Therefore, although we report lower average PM concentration in winter compared to summer, we note however that neighborhood concentrations and personal exposure within emission hotspots may be higher in the former. Indeed, using ambient PM_{2.5} concentration values may underestimate health risks. Nevertheless, our average PM_{2.5} level in winter is lower than an 8-h winter value reported for Bhubaneswar of $61 \pm 20 \mu\text{g m}^{-3}$ (Panda et al., 2016).

Spatially, the post hoc tests show no significant difference ($p = 0.05$) in concentrations of PM_{2.5} or PM₁₀ in any two sites, except for the comparison of PM_{2.5} concentrations in urban ($36 \pm 16 \mu\text{g m}^{-3}$) and rural ($31 \pm 13 \mu\text{g m}^{-3}$) areas, where a significant difference was observed ($p = 0.05$) (see Supplemental Material, Table S5 and Fig. S1, for details). This may partly explain the rising and higher cases of cardiopulmonary diseases and decreased lung function in urban areas compared to rural (Pant et al., 2016). Our measured annual average PM₁₀ concentration exceeds the Indian NAAQS of $60 \mu\text{g m}^{-3}$, while our measured PM_{2.5} level is below the NAAQS of $40 \mu\text{g m}^{-3}$. This is consistent with the report of a recent review that average PM₁₀ concentrations in India often exceed NAAQS (Pant et al., 2016). Furthermore, none of the study area averaged below WHO's AQG of 10 or $20 \mu\text{g m}^{-3}$ for PM_{2.5} or PM₁₀ concentrations, or the USEPA's 12 or $50 \mu\text{g m}^{-3}$, respectively. The annual average concentration of PM_{2.5} in Nagpur district ($34 \pm 17 \mu\text{g m}^{-3}$) is however below WHO's interim target 1 (IT-1: $35 \mu\text{g m}^{-3}$); but exceeds the interim target 2 (IT-2), which is $25 \mu\text{g m}^{-3}$. The interim targets are incremental steps in a progressive reduction of air pollution in polluted localities and are intended to promote a shift from concentrations with acute serious health consequences to concentrations that if achieved, would result in substantial reduction in risks for acute and chronic effects (Krzyzanowski and Cohen, 2008). For instance, attainment of IT-1 ($15 \mu\text{g m}^{-3}$) from IT-2 ($25 \mu\text{g m}^{-3}$); or IT-2 from IT-3 ($35 \mu\text{g m}^{-3}$) was estimated to reduce risks of chronic effects of air pollution by about 6% (WHO, 2005).

Table 2
Spatio-temporal concentrations (mean \pm standard deviation) ($\mu\text{g m}^{-3}$) of tropospheric particulate matter and regulatory limits.

PM	Seasons	Sites			Annual average limits		
		Urban	Peri-urban	Rural	Indian NAAQS ^a	USEPA ^b	WHO ^c
PM _{2.5}	Winter	31 \pm 10	19 \pm 4	31 \pm 13	40	12	10
	Summer	42 \pm 10	52 \pm 19	35 \pm 6			
	Monsoon	19 \pm 9	17 \pm 4	17 \pm 5			
	Post-monsoon	51 \pm 13	53 \pm 15	42 \pm 9			
	Annual average	36 \pm 16	35 \pm 21	31 \pm 13			
PM ₁₀	Winter	124 \pm 49	75 \pm 18	103 \pm 38	60	50	20
	Summer	108 \pm 32	127 \pm 37	120 \pm 30			
	Monsoon	62 \pm 23	45 \pm 9	50 \pm 21			
	Post-monsoon	147 \pm 46	135 \pm 37	137 \pm 31			
	Annual average	110 \pm 50	95 \pm 46	102 \pm 44			
Ratio of PM _{2.5} to PM ₁₀	Winter	0.28 \pm 0.10	0.26 \pm 0.05	0.33 \pm 0.15			
	Summer	0.40 \pm 0.07	0.41 \pm 0.11	0.30 \pm 0.04			
	Monsoon	0.30 \pm 0.05	0.39 \pm 0.03	0.35 \pm 0.07			
	Post-monsoon	0.35 \pm 0.03	0.39 \pm 0.05	0.32 \pm 0.06			

^a NAAQS: National Air Quality Standard (CPCB, Central Pollution Control Board, Government of India, 2009).

^b USEPA, 2013.

^c WHO, 2005.

The WHO (2016b) stores data on annual average concentration of PM_{2.5} and PM₁₀ for different cities of the world, including 122 cities in India. Our annual average concentration of PM₁₀ ($103 \pm 47 \mu\text{g m}^{-3}$) is comparable to WHO's (2016b) value for Nagpur ($103 \mu\text{g m}^{-3}$). Our PM₁₀ value exceeds the levels in 39% of Indian cities in WHO database, but is lower than levels in most large Indian metropolises like Agra, Bangalore, Bhopal, Chandrapur, Faridabad, Mumbai, Delhi, Indore, Jaipur, Kolkata, Lucknow, and Raipur (WHO, 2016b). However, it exceeds levels in all high income European and American cities and in most South African cities, but is lower than levels in most cities in Bangladesh, China, and Nigeria (WHO, 2016b). Fig. 3 shows the range of ambient PM₁₀ concentrations in different regions of the world including our value for Nagpur district.

Our annual average PM_{2.5} concentration ($34 \pm 17 \mu\text{g m}^{-3}$) is comparable to a satellite derived PM_{2.5} estimate recently reported for Nagpur district ($33.6 \pm 20.5 \mu\text{g m}^{-3}$) (Chowdhury and Dey, 2016), but differs substantially from WHO (2016b) PM_{2.5} value for Nagpur ($51 \mu\text{g m}^{-3}$). Due to lack of data on PM_{2.5} concentration in Nagpur, the WHO (2016b) has derived its annual average PM_{2.5} concentration using measured concentration of PM₁₀ in Nagpur and reported ratio of PM_{2.5} to PM₁₀ in India. Therefore, the WHO may consider revising Nagpur's PM_{2.5} value in its database, because both the bias-adjusted satellite derived estimate and gravimetric measurements conducted in urban, peri-urban and rural areas of Nagpur for ~16 months have revealed that the value is $34 \mu\text{g m}^{-3}$. However, given that our value represents population-oriented exposures, which assumes that all individuals in a specific area have the same exposure to PM_{2.5}, we may have underestimated the exposure concentrations of some individuals in hotspots area. Such individuals may include women who cook with solid fuels and their children playing around them, or people including children residing, working, schooling or moving along busy roads. Their annual average PM_{2.5} exposure would very likely exceed our value. It is estimated that people commuting by vehicle, particularly in auto-rickshaw and cars with open windows are exposed to 1.5 to 4.0 times the ambient PM_{2.5} concentrations (Apte et al., 2011; Marshall et al., 2003). Similarly, Indian women cooking in households reliant on solid fuels have the highest mean [95% CI] 24-h PM_{2.5} exposure level ($337 [238, 479] \mu\text{g m}^{-3}$), followed in decreasing order by their under 5 years old children playing around them ($285 [201, 405] \mu\text{g m}^{-3}$), and their husbands who spend most time in the living room ($204 [144, 290] \mu\text{g m}^{-3}$) (WHO, 2014). The mean [95% CI] 24-h concentration of PM_{2.5} in the kitchen and living areas of such households is $450 [318, 640] \mu\text{g m}^{-3}$ and $113 [102, 127] \mu\text{g m}^{-3}$, respectively (Balakrishnan et al., 2013).

Annual mean concentration of ambient PM_{2.5} in Nagpur district and literature values for some localities within and outside India is presented in Fig. 4. The annual average PM_{2.5} concentration in Nagpur district

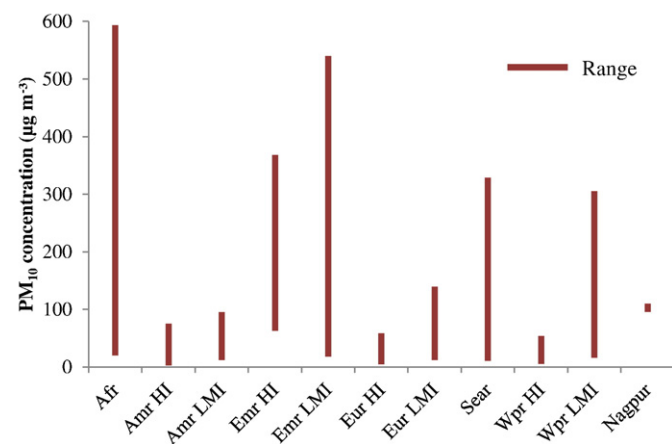


Fig. 3. Range of ambient PM₁₀ concentrations in different regions of the world including our value for Nagpur district.

($34 \pm 17 \mu\text{g m}^{-3}$) is lower than the annual average concentration reported for Chennai, Lucknow, Delhi, or Agra (Khare and Baruah, 2010; Kumar and Sarin, 2009; Massey et al., 2012; Pandey et al., 2013; Pant et al., 2015; Srimuruganandam and Nagendra, 2012; Tiwari et al., 2014). It is also lower than the values reported for Mumbai, Pune, Raipur, Kolkata and Hyderabad (Abba et al., 2012; Das et al., 2015; Giri et al., 2013; Guttikunda and kopakka, 2014; Yadav and Satsangi, 2013). Our average PM_{2.5} value is also lower than the levels reported for Lahore, Dhaka or Beijing (Begum and Hopke, 2013; Duan et al., 2014; Stone et al., 2010); but comparable to levels reported for Hong Kong, Escobedo and Santa Catarina (Martinez et al., 2012; Qiu et al., 2013). It however exceeds levels reported for Islamabad, Barcelona, Lagos or eight United States counties (Han et al., 2012; Minguillón et al., 2012; Owoade et al., 2013; Waheed et al., 2012).

3.2. Ratio of PM_{2.5} to PM₁₀ concentrations

Our aim of assessing PM₁₀ concentrations was to determine the ratio of PM_{2.5} to PM₁₀ (Table 2), because of its importance in air quality and health risk assessment. The ratio was highest in peri-urban areas, specifically Koradi and Chandkapur, where the coal-fired thermal power plants are located. Epidemiologic studies have reported that locations with higher PM_{2.5} to PM₁₀ ratios have stronger associations with mortality (Lippmann et al., 2013; Vedal et al., 2013). The observation corroborates reports of toxicological studies which attribute toxicity of PM_{2.5} to its hazardous chemical constituents and smaller particle size (USEPA, 2011). Due to its relatively smaller particle size, PM_{2.5} can be breathed deeply into the lungs and can penetrate deep into circulatory system, where its hazardous chemical constituents can exert systemic adverse health effects (Pope and Dockery, 2006). Studies conducted within the two thermal power plants in Nagpur district report significantly higher concentrations of mercury and other heavy metals in blood, milk and urine of cattle grazing within 5-km of the plants compared to control, with alteration in cattle's hemoglobin levels, blood urea nitrogen, serum glutamate oxaloacetate transaminase, albumin and creatinine, and mutation in bovine aminolevulinic dehydratase gene (Mahajan et al., 2012; Rajalaxmi et al., 2016), indicating potential risks to human health.

Our measured ratios of PM_{2.5} to PM₁₀ were generally highest in summer, followed in decreasing order by post-monsoon, monsoon and winter, except in rural areas where we measured the highest ratio in monsoon followed in decreasing order by winter, post-monsoon and summer. The ratio of PM_{2.5} to PM₁₀ is more likely to be lower in areas impacted more by crustal particles e.g. in rural areas with unpaved roads and with significant windy days, and in areas where windblown dust from infrastructural constructions contribute significantly to PM pollution. Such areas will have higher proportion of PM₁₀ as PM_{10-2.5} (Allen et al., 2013; Cohen et al., 2005; Ducret-Stich et al., 2013). Thus, the low ratio of PM_{2.5} to PM₁₀ in Nagpur district could be attributed to ongoing development. Nagpur is rapidly developing with several ongoing infrastructural construction works like roads, bridges and housing estates. Our ratios for urban (0.33 ± 0.08), peri-urban (0.36 ± 0.09) and rural (0.32 ± 0.09) locations are within the range of 0.31 ± 0.13 to 0.49 ± 0.17 reported for residential, heavy traffic, marine and industrial areas of Lagos (Owoade et al., 2013), indicating that both metropolises may have similar air pollution pattern and toxicity. Similar average ratio of 0.31, 0.34, 0.35, 0.34 and 0.35 was reported for Chennai, Dhaka, Rajshahi, the Ho Chi Minh City and in an arid valley in southern California, respectively (Begum et al., 2007; Hien et al., 2007; Oanh et al., 2006). Earlier GBD study (Cohen et al., 2005) assumed an average ratio of 0.35 for developing cities in Asia and Africa.

Developed cities with paved roads and reduced infrastructural construction sites would have higher ratio, because they would contain mainly PM_{2.5} from combustion sources. A ranged of 0.5 to 0.8 have been suggested for developed countries (Cohen et al., 2005). Studies conducted in urban areas of China and Korea have reported a range of

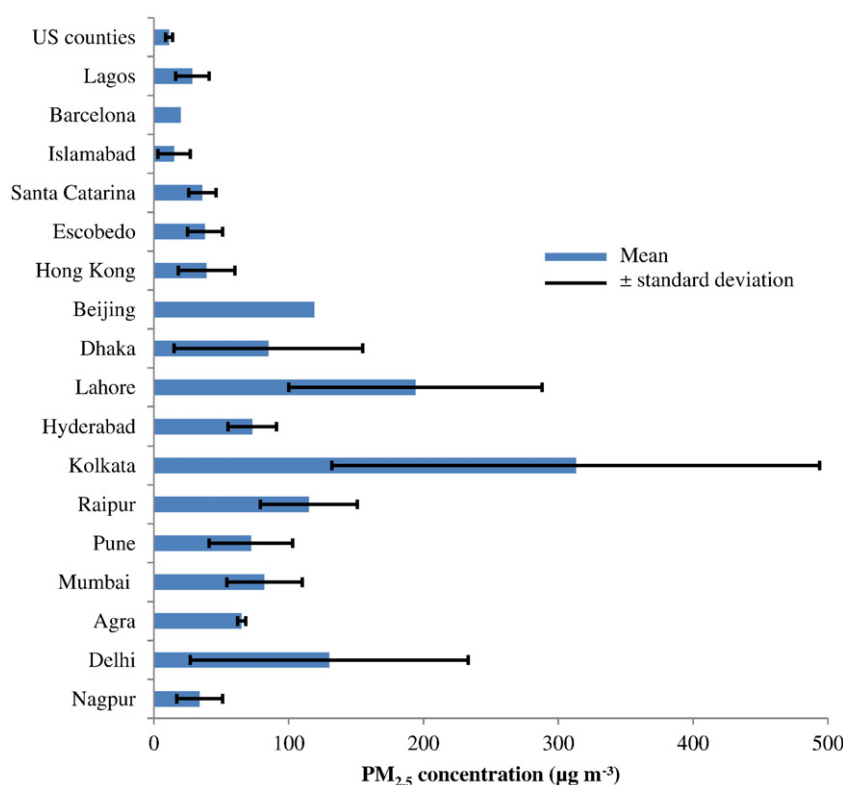


Fig. 4. Annual mean concentration of ambient PM_{2.5} in Nagpur district and literature values for some localities within and outside India.

0.51 to 0.78 (Oanh et al., 2006; Qian et al., 2001; Tsai and Chen, 2006; Wang et al., 2005).

3.3. Attributed burden and economic loss from PM_{2.5} pollution in Nagpur

The estimates of total and disease specific deaths and DALYs attributed to PM_{2.5} pollution in Nagpur district in 2013 is presented in Table 3. We estimate that 3.3 (95% confidence interval [95%CI]: 2.6, 4.2) thousand premature deaths and 91 (95CI: 68, 116) thousand DALYs is attributed to PM_{2.5} pollution in Nagpur district in 2013. This is equivalent to ~9 deaths and 250 DALYs per day. A recent study reported PM_{2.5}-related premature deaths in different districts in India, including Nagpur (Chowdhury and Dey, 2016). Their estimates were based on satellite derived PM_{2.5} concentrations, non-linear power law (NPL) and IER functions, and baseline mortality rate adjusted for different States using their per capita gross domestic product (GDP). Our estimate of PM_{2.5}-attributed premature deaths is substantially higher than their estimate for Nagpur district. Specifically, our mean value (3300 premature deaths) is about 1.4 times higher than theirs (2290 premature deaths) when IER was used and approximately 2.7 times higher for NPL (1240 premature deaths). The difference, particularly for their IER derived estimate is largely due to their assumption that baseline mortality rates for the health outcomes (except lung cancer) would be lower in Nagpur district than the national average because of the higher per capita income of

Maharashtra State. They did not however consider the adverse effect of higher provincial per capita GDP on health disparities particularly for people in the low income, education and occupation category.

High cost of living in wealthier provinces could disproportionately increase the level of exposure to air pollution and susceptibility to the health effects particularly for people in lower socioeconomic status (Clark et al., 2014; Hajat et al., 2015). They may be compelled to live in makeshift housing and work in neighbourhoods disproportionately located near dense traffic corridors, industrial areas including thermal power plants and waste dumpsites, since land in those locations are often cheaper (Adler and Newman, 2002). They are also more likely to use solid fuels for cooking and heating, leading to additional exposure from household air pollution and its effects (WHO, 2005). Disparity in susceptibility could result from inadequate nutrition, poor housing, poor quality of drinking-water and sanitation and predisposing health conditions like psychosocial stress, and behaviours such as smoking and alcohol misuse (WHO, 2005). They may also suffer more from health care deprivation (Regidor et al., 2006). Even in a universal health care coverage, persons with less income and education do not use health services in the same way that their wealthier better educated peers do in wealthy provinces (Adler and Newman, 2002). A study in Canada reported higher premature deaths among men with less income, less education and lower occupational status for different health outcomes, all of which were amenable to medical treatment (Wood

Table 3

Mean (95% confidence interval) of premature deaths and disability-adjusted life years (DALYs) attributed to ambient PM_{2.5} pollution in Nagpur in 2013.

Total attributed		ALRI		IHD		Stroke		COPD		LC	
Deaths	DALYs	Death	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths	DALYs	Deaths	DALYs
3300 (2600, 4200)	91,000 (68,000, 116,000)	130 (100, 170)	11,000 (8000, 14,000)	1800 (1500, 2300)	47,000 (36,000, 59,000)	900 (600, 1200)	21,000 (14,000, 29,000)	400 (300, 500)	11,000 (8000, 13,000)	40 (30, 50)	1100 (800, 1400)

The 95% confidence interval (95% CI) represents the statistical imprecision in PM_{2.5} concentrations (µg m⁻³) in Nagpur district [34.0 (95% CI: 32.5, 35.5) µg m⁻³]; ALRI: acute lower respiratory infection; IHD: ischemic heart disease; COPD: chronic obstructive pulmonary disease; LC: lung cancer.

et al., 1999). Therefore, higher provincial per capita GDP can cause increased baseline mortality particularly for this group of people, as their survival becomes more and more difficult.

Considering the fact that air pollution hotspots often coincide with lower socioeconomic position, we may have underestimated the actual health burden in our estimation when we made the assumption, by using population oriented-monitors, that all individuals in a location have the same level of exposure. Therefore, an additional assumption of lower baseline mortality burden in Nagpur district because of its better health care system resulting from higher provincial per capital income, may further underestimate the burden particularly for the socio-economically disadvantaged population. Furthermore, Chowdhury and Dey (2016) did not include PM_{2.5}-related deaths from pneumonia (ALRI) for children below 5 years of age in their estimation, which is a major health outcome in India and accounts for 130 (95% CI: 100, 170) premature deaths and 11 (95% CI: 8, 14) thousand DALYs in our estimation.

The number of people dying in Nagpur district because of PM_{2.5} pollution and the consequent lost years of healthy life substantially exceeds that reported for Sydney, Australia – 430 (90% CI: 310, 540) premature deaths and 5.8 (95% CI: 3.9, 7.6) thousand DALYs per year (Broome et al., 2015), or the estimate reported for Valladolid, Spain – 237 premature deaths (Arranz et al., 2014), but substantially lower than the estimate for Kerala, India – 6.1 (95% CI: 4.2, 7.8) thousand premature deaths and 96 (95% CI: 65, 123) thousand DALYs yearly (Tobollik et al., 2015). Our estimate is also lower than the estimate (range) in Beijing's central area of 6.4 (3.1–8.3) thousand premature deaths (Zheng et al., 2015) and the estimate (95% CI) reported for Yangtze River Delta of 13 (11, 16) thousand premature deaths (Wang et al., 2015). Our estimate is also lower than that for Taiwan of 6.3 (5.7, 6.8) thousand deaths (Lo et al., 2016) or for the Pearl River Delta of 12 thousand premature deaths (Jiang et al., 2015).

The burden from IHD dominates our overall estimation and accounts for 55.3% of the PM_{2.5}-related premature deaths and 52.0% of the DALYs, followed in decreasing order by stroke (27.2% of PM_{2.5}-related premature deaths and 23.1% of DALYs), COPD (12.3% of PM_{2.5}-related premature deaths and 11.6% of DALYs), ALRI (3.9% of PM_{2.5}-related premature deaths and 12.2% of DALYs) and LC (1.2% of PM_{2.5}-related premature deaths and DALYs). This is consistent with the pattern of disease contribution to total attributed deaths from PM_{2.5} pollution at the State-level in India (Ghude et al., 2016), but inconsistent with the pattern (COPD > IHD > Stroke > LC) for the GDP-adjusted baseline mortality (Chowdhury and Dey, 2016). It is important to state here that an estimate of PM_{2.5}-related attributed deaths does not represent the number of persons who died solely because of PM_{2.5} pollution, but rather, an estimate of the contribution of PM_{2.5} pollution to the death of a larger number of exposed persons.

The economic loss due to the health impact of PM_{2.5} pollution in Nagpur district in 2013 is USD 2.2 (95% CI: 1.7, 2.8) billion, per year. This is a huge economic loss and it is about 0.44% of the national estimate of the economic loss from ambient air pollution in India, which is USD 0.5 trillion per year (OECD, Organization for Economic cooperation and Development, 2014). Therefore, reducing PM_{2.5} pollution in Nagpur district has substantial economic benefit, in addition to the health benefit.

3.4. Averted burden and economic gain accruing from PM_{2.5} pollution improvements

By using standard life-table calculations that separates the dimension of age and calendar year, we could compare future changes in the distribution of health and economic burdens in two scenarios: a baseline scenario that assumes that annual average PM_{2.5} level remained unchanged; and a planned mitigation scenario that assumes gradual but purposive reductions from current level to 25 $\mu\text{g m}^{-3}$ (IT-2), 15 $\mu\text{g m}^{-3}$ (IT-3) and 10 $\mu\text{g m}^{-3}$ (AQG) by 2023, 2033 and 2043,

respectively (see Supplemental Material, Table S6, for details). Fig. 5 presents the distribution of PM_{2.5}-related premature deaths, DALYs and economic cost in Nagpur district under baseline and planned mitigation scenarios. We estimate that mitigation measures that achieves a reduction, from current annual average PM_{2.5} level to IT-2 by the year 2023, would avert 15% of the PM_{2.5}-attributed premature deaths (700 [95% CI: 500, 800]), DALYs (17 [95% CI: 13, 21] thousand) and economic cost (USD 400 [95% CI: 300, 600] million) in that year. Further reduction from IT-2 to IT3 by the year 2033 would avert about 30% of the PM_{2.5}-attributed premature deaths (1.6 [95% CI: 1.2, 2.0] thousand), DALYs (37 [95% CI: 29, 46] thousand) and economic cost (USD 1.1 [95% CI: 0.82, 1.3] billion) in that year. Attainment of the WHO AQG of 10 $\mu\text{g m}^{-3}$ by the year 2043, is estimated to avert about 36% of the PM_{2.5}-attributed premature deaths (1.7 [95% CI: 1.3, 2.2] thousand), DALYs (37 [95% CI: 29, 47] thousand) and economic cost (USD 1.1 [95% CI: 0.88, 1.4] billion) in 2043.

Our findings are consistent with similar analyses reported elsewhere. A state-level (range) estimate in India revealed that a 10% decrease in PM concentration in Kerala would avert 16 (11–20) thousand life years annually (Tobollik et al., 2015). Another study reports that a 17% reduction in average PM_{2.5} concentration in the Pearl River Delta region in China would avert >2.9 thousand deaths, annually (Jiang et al., 2015). A study in Brazil reports that a reduction from the annual average PM_{2.5} concentration in São Paulo, by 5 $\mu\text{g m}^{-3}$ would avert about 1.7 thousand premature deaths and results into an economic gain of USD 4.96 billion, annually (Abe and Miraglia, 2016). The study also reports that attainment of the AQG in São Paulo would avert >5 thousand premature deaths and 266 thousand DALYs and save USD 15.1 billion, annually (Abe and Miraglia, 2016).

Fig. 5 shows that under the planned mitigation scenario the residual health burden and economic cost in any year vary around the value at the start of the mitigation i.e. 2023. This indicates that the health and economic gains accruing from the planned mitigation would largely offset increases in the PM_{2.5}-related health and economic burdens arising from future changes in population demography. Put in other words, aging will increase the PM_{2.5}-related health burden and economic cost in Nagpur district by ~17% in every five years. This observation is consistent with earlier reports that the trends in PM_{2.5}-related premature mortality and the economic cost in India are increasing very fast and to keep them constant, average PM_{2.5} concentrations would need to decline by 20–30% over the next 15 years, merely to offset the increases resulting from aging populations (MoHFW, Ministry of Health and Family Welfare, Government of India, 2015; OECD, Organization for Economic cooperation and Development, 2014). Furthermore, we estimate that if our planned mitigation in Nagpur district is achieved, there would be an average (95% CI) gain in life expectancy of 9 (7, 11) months, 8 (6, 10) months and 2 (2, 3) months for the cohort in age group 25–29 by 2023, 2033 and 2043, respectively. Also, judging from the large residual health burden in 2043, there would be substantial gains going further below the AQG in the future. This is especially true as air pollution has no safe limit at least for some individuals (Krzyzanowski and Cohen, 2008), suggestive of the need to achieve the lowest concentrations possible in all microenvironments where population exposure occurs both outdoor and indoor.

To effectively reduce the health impacts and economic loss from air pollution in Nagpur district, we recommend an exposure-integrated source reduction approach, in line with the action plan adopted at the National level (MoHFW, Ministry of Health and Family Welfare, Government of India, 2015). This approach entails reduction of both emissions and exposures as much as possible with immediate priority given to sources that lead to the greatest levels of exposure and adverse health impacts. For Nagpur to attain an annual average ambient PM_{2.5} concentration of 25 $\mu\text{g m}^{-3}$ by 2023 (i.e. cutting current pollution level by ~26%), stakeholders would need to completely phase-out household use of solid fuel for cooking and heating. It is estimated that this pollution source alone contributes about 26% to ambient

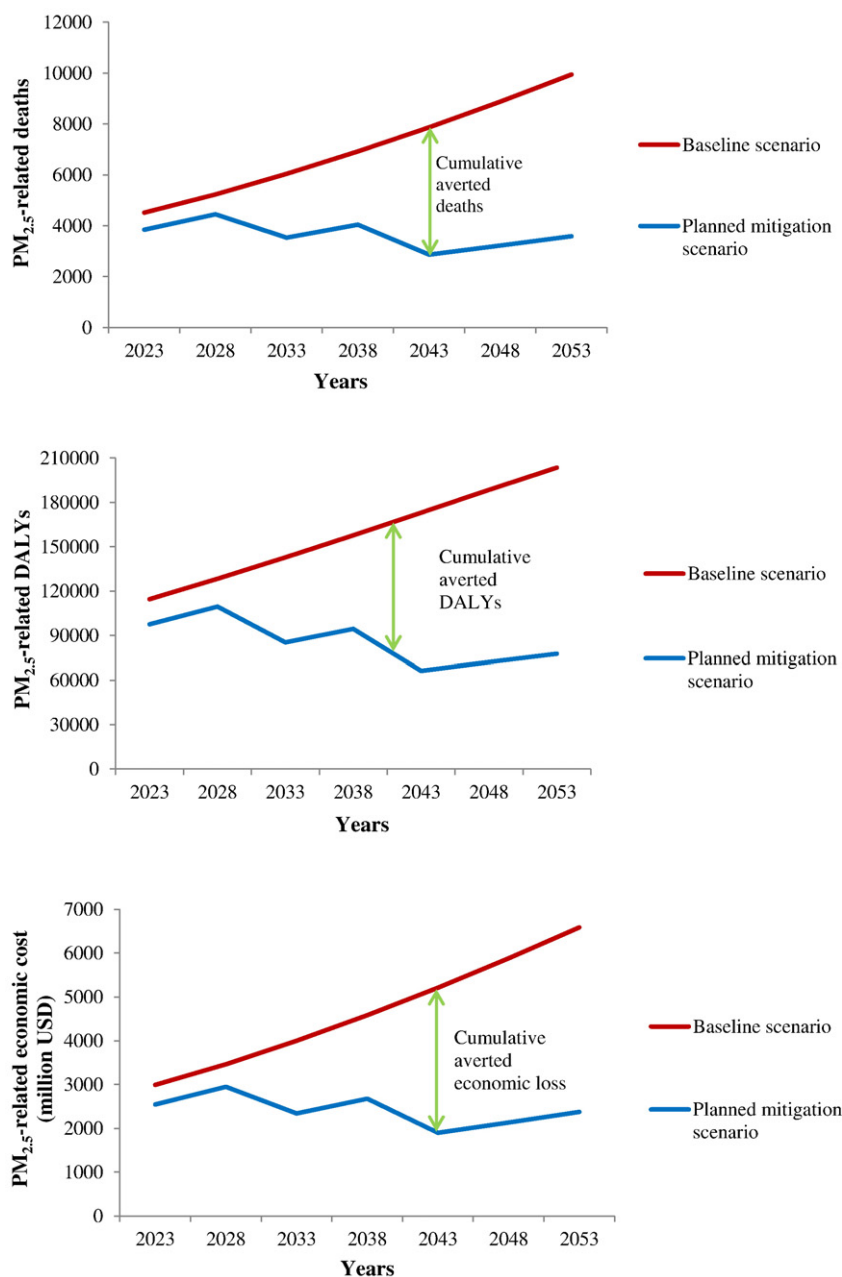


Fig. 5. Distribution of PM_{2.5}-related deaths, disability-adjusted life years (DALYs) and economic cost in Nagpur district under baseline scenario that assumes constant average annual PM_{2.5} concentration; and planned mitigation scenario that attains global interim target 2 ($25 \mu\text{g m}^{-3}$) by 2023, global interim target 3 ($15 \mu\text{g m}^{-3}$) by 2033 and global air quality guideline ($10 \mu\text{g m}^{-3}$) by 2043.

PM_{2.5} pollution in India (Chafe et al., 2014). This clearly is a substantial and important contribution particularly from exposure and health perspectives, since the emission is taking place where people are, especially those who may be more susceptible to the adverse effect. Thus, this source is probably contributing disproportionately to exposure and health effects from ambient air pollution.

Interventions should ensure a complete changeover, in all areas, to clean fuels for cooking, such as making electricity or liquefied petroleum gas available, affordable and accessible to all. It is high time the district moved beyond the age-old cooking methods that cause high pollution and exposure. Stakeholders would need to decide if to spend an average amount of USD 400 million every year to completely phase-out the use of dirty fuels, bypassing the so called “improved biomass cookstoves”, to gas and electric stoves by 2023, through intervention and awareness campaign, or loss the same amount or probably more to the adverse effect from continued exposure to the pollution. Furthermore, domestic

and agricultural trash burning, as well as burning of fireworks during festivals like Diwali should be strictly controlled with penalties for non-compliance, while providing suitable collection and disposal system for trash.

Another major contributor to ambient air pollution and exposure is vehicular emission, since this pollution is emitted in areas where there are many people including those travelling on or near roads, as well as those residing, working or schooling nearby. As a short to long-term goal, we recommend an “avoid-shift-improve approach” in-line with the initiative taken at the national level to prioritizing actions to manage the health burden from vehicles (MoHFW, Ministry of Health and Family Welfare, Government of India, 2015). The “avoid” means avoiding vehicle use as much as possible particularly in areas with large or dense populations based on financial disincentives. These may include higher taxes on fuels, congestion pricing, or increasing parking fees in densely populated areas, or making such areas vehicle free or

limiting vehicle use e.g. odd and even numbered license plates to be on the road only on alternate days. “Shift” refers to shifting to modes of transports that reduces pollution and health impact, such as mass transport like metro rail, battery powered rickshaws keeping free of emissions from petrol and diesel, or promoting non-motorized transport, such as bicycles. “Improve” refers to improvement of technologies of vehicles, by tighter emission and fuel standards and on-road vehicle checks so that they emit less pollution per kilometer travelled. Creation of alternate routes, such as city bypass roads that divert traffic away from populated areas, with zoning restrictions to prevent housing or commercial developments abutting the alternate routes, can reduce traffic congestions and reduce exposures. Vulnerable persons like children, pregnant women, elderly and people with pre-existing cardiopulmonary diseases should be counseled to limit leisure-time in traffic congested areas (Franklin et al., 2015).

Road dust could be substantially controlled by implementing street design guidelines for footpaths and cycle tracks with adequate vegetative cover and barriers like shrubs and trees and paving. Phasing in mechanical and vacuum based street sweeping and the sprinkling of recycled water to reduce dust circulation. Construction dust can be reduced by enforcing good construction practices and making construction industry accountable for construction and demolition wastes, safe disposal and recycling. Stringent emission standards should be enforced on thermal power plants, brick kilns and other local industries having high pollution potentials. For the long run, we recommend a more structural control strategy like the switch from coal to clean and renewable energy sources for power generation and changes in lifestyle and urban landscape, for further progress below the AQG.

4. Conclusion

We have, for the very first time in India, used a combination of hazard and survival analyses based on the life table method to present estimates of the health burden and economic costs attributed to ambient PM_{2.5} pollution in Nagpur district, which is believed to be one of the cleanest and greenest districts in India. The estimates revealed substantial PM_{2.5}-related health burden and economic loss in 2013, with increasing trend owing to future changes in population demography. It is estimated that a gradual but purposive improvements in ambient air quality from current annual average level ($34 \mu\text{g m}^{-3}$) to WHO interim target 2 ($25 \mu\text{g m}^{-3}$) by 2023, interim target 3 ($15 \mu\text{g m}^{-3}$) by 2033 and air quality guideline ($10 \mu\text{g m}^{-3}$) by 2043, would avert 15%, 30% and 36% of the PM_{2.5}-related health burden and economic loss, respectively, thereby increasing average life expectancy in the district by 9 months, 8 months and 2 months, respectively, in those years. However, most of the gains would mostly offset the increasing burden resulting from aging populations, indicative that going below the global air quality guideline of $10 \mu\text{g m}^{-3}$ in the future would result in substantial health and economic benefits, at least for some individuals.

In order to obtain optimum health and economic benefits however, immediate priority should be given to pollution sources that lead to the greatest level of exposure and adverse health effects. In this case, we recommend the total phasing-out of solid fuel use for cooking and heating in Nagpur district by 2023, alongside effective waste collection and disposal system and a comprehensive approach for reducing vehicular, industrial and construction emissions. For the long run, we recommend a more structural approach that focuses on the development and use of renewable energy sources and clean technologies for power generation, and changes in lifestyle and urban landscape. For emphasis, we state that if actions are not taken now to improve air quality in Nagpur district, thousands of people will continue to become sick and die very young. This situation will become worst in the future with more and more money spent to cure and manage illness, which would otherwise have been averted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.envint.2017.02.010>.

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