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Monitoring of construction dust and assessment of probable increment in mortality risks for exposed construction workers at Kolkata, India

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RESUMEN

El presente estudio evalúa el escenario de contaminación por polvo de construcción y riesgos para la salud asociados para obras de construcción en la metrópolis de Calcuta. Los niveles de partículas atmosféricas (PM, por su sigla en inglés) generados excedieron con creces los niveles diarios y anuales establecidos por los Estándares Nacionales de Calidad del Aire Ambiental (NAAQS) de la India (214.78-12 202.28 y 424.64-20 403.81 %, respectivamente, para PM_{10}, y 182.20-5847.92 y 323.29-8821.88 %, respectivamente, para $PM_{2.5}$). Se estimaron los riesgos de mortalidad asociados con la exposición a largo plazo de trabajadores de la construcción a niveles tan altos de PM. La naturaleza estocástica de las variables que influyen al calcular los riesgos para la salud se maneja mediante la Simulación de Monte Carlo (MCS). Los riesgos de mortalidad por diferentes causas debidos a la exposición elevada a PM_{10} ($RR\_Expos\_PM_{10}$), fluctuaron entre 1.25 (±1.20) (para el riesgo de accidente cerebrovascular para los trabajadores de movimiento de tierras) y 75.89 (±46.87) (para el riesgo de enfermedad pulmonar obstructiva crónica (EPOC) para los trabajadores de corte de paredes de ladrillo). Los riesgos de mortalidad por exposición a $PM_{2.5}$ ($RR\_Expos\_PM_{2.5}$) fluctuaron entre 1.96 (±0.40) para el riesgo de enfermedades respiratorias no malignas en trabajadores de movimientos de tierras y 19.04 (±8.82) para el riesgo de infecciones agudas del tracto respiratorio inferior (ALRI) para los trabajadores de corte de paredes de ladrillos. También se llevó a cabo un análisis de sensibilidad, el cual mostró que el riesgo de mortalidad asociado con la exposición a PM_{10} y $PM_{2.5}$ es más sensible a la concentración de PM_{10} durante las actividades de construcción y al riesgo relativo conjunto de $PM_{2.5}$, respectivamente. Se descubrió que el riesgo de mortalidad de los trabajadores de la construcción expuestos era considerablemente mayor (de 14.68% a 3548.56% para PM_{10} y de 61.60 a 1269,78% para $PM_{2.5}$) en comparación con la población promedio de la ciudad de Calcuta. Se necesitan intervenciones a nivel de políticas y de medidas locales para controlar y mitigar este alarmante escenario.

ABSTRACT

The present study assesses the construction dust pollution scenario and associated health risks for construction sites in the Kolkata metropolis. The generated PM levels well exceeded the daily and annual National Ambient Air Quality Standards (NAAQS) of India (214.78-12 202.28 and 424.64-20 403.81%, respectively for PM_{10} and 182.20-5847.92 and 323.29-8821.88%, respectively for $PM_{2.5}$). Mortality risks associated with long-term exposure to such high PM levels are estimated for construction workers. The stochastic nature of the influencing variables while calculating health risks is handled through the Monte Carlo Simulation (MCS). The mortality risks for different causes due to elevated PM_{10} exposure ($RR\_Expos\_PM_{10}$) ranged between 1.25 (±1.20) for the risk of stroke for earthwork workers to 75.89 (±46.87) for the risk of chronic obstructive pulmonary disease (COPD) for brick wall-cutting workers. The mortality risks for $PM_{2.5}$ exposure ($RR\_Expos\_PM_{2.5}$)

ranged between 1.96 (±0.40) for the risk of non-malignant respiratory diseases for earthwork workers to 19.04 (±8.82) for the risk of acute lower respiratory infections (ALRI) for brick wall-cutting workers. A sensitivity analysis was also carried out, which showed that the mortality risk associated with PM_{10} and $PM_{2.5}$ exposure is most sensitive to the PM_{10} concentration during construction activities and pooled relative risk for $PM_{2.5}$. The mortality risk of exposed construction workers was alarmingly higher (14.68-3548.56% higher for PM_{10} and 61.60-1269.78% higher for $PM_{2.5}$) than the average Kolkata City population. Policy-level and site-level interventions are necessary to control and mitigate the alarming scenario.

Keywords: construction site, fugitive emission, health impact, construction workers, Monte Carlo Simulation, sensitivity analysis.

1. Introduction

The construction sector worldwide is constantly growing, and India is no exception (Shah and Tiwari, 2010). India's construction sector will likely add approximately 40 billion m^2 of new construction space by 2050, with a construction growth rate of 9.2-10% compared to a global average of 5.2-5.5% (Dutta and Sengupta, 2014; Yu et al., 2017). The rapid and inevitable growth of the construction industry has potential environmental impacts, which include air pollution caused by construction dust generated during various construction activities. Dust exposure can occur in almost all construction activities, from foundation excavation to final sweeping before construction completion (Lumens and Spee, 2001). Due to the closed construction environment and poor ventilation system, tunnel construction projects are likely to generate more concentrated dust, and the workers involved are more susceptible to respiratory diseases (Arcangeli et al., 2004; Oliver and Miracle-Mcmahill, 2006). Flanagan et al. (2006) reported that concrete surface grinding was one of the activities that caused the most dust. Kinsey et al (2004) found that vehicles leaving construction sites can transport large amounts of dust and sediment to nearby roads, causing an increase in secondary dust due to external forcing. Akbar-Khanzadeh et al. (2010) reported that in 2008, more than 201 730 workers in the USA were directly exposed to concrete grinding while working with various hand and power tools. Ketchman and Bilec (2013) found that the majority of regional PM_{10} (89%) and $PM_{2.5}$ (90%) emissions were from soil movement during construction. According to Arocho et al. (2014), the concentration of particulate matter is much higher at the beginning of a construction project than that of other pollutants due to the excessive use of construction equipment such as bulldozers, loaders, and milling machines. The production of fresh concrete in a rotary drum mixer could generate a significant amount of fugitive dust (Azarmi et al., 2014). It was discovered that almost 17% of Germany's total PM_{10} emissions came from construction. According to specific calculations, 44% of Germany's total PM_{10} emissions from building activities came from earthworks (Faber et al., 2015). According to Othman (2015), PM_{10} concentrations in office buildings at construction sites were found to be 1.6-1.7 times higher than background levels both indoors and outdoors. Azarmi et al. (2014) closely observed the drilling, cutting, and mixing of concrete, and discovered that $PM_{2.5}$ and PM_{10} concentrations were, respectively, 14 and four times greater than the background. Construction equipment, including trucks, front-end loaders, backhoes, cranes, and cement mixers, has been linked to elevated particulate matter (PM) emissions in the construction sector, as demonstrated by Reddy and Arocho's (2018) research. PM ($PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, and PM_{10}) concentrations from two distinct building sites using various materials were measured by Ahmed and Arocho (2019). If construction-related particulate and dust emissions are not adequately controlled, they may also negatively affect the quality of indoor air in a nearby neighborhood as well as the health and well-being of those who live and work close to these sites (Wieser et al., 2021).

Adverse health effects for construction workers will be caused irrespective of whether construction work is being taken up in a rural or an urban area. Silica, a major component of construction dust, can cause serious ailments to exposed populations, including workers and nearby residents (Sauni et al., 2001; Torén et al., 2007; Singh et al., 2014; Torén and Järvholm, 2014; Chen et al., 2019). This leads to economic loss to the environment and society, particularly in developing countries where poor construction workers and laborers continue working in unhealthy environments due to poverty and ignorance (Singh et. al., 2014; Martínez et al., 2018). Silica, a major component of construction dust, is found in various materials on construction sites (Thar and Lofgren, 1993; Linch et al., 1998; Thorpe et al., 1999; Flanagan et al., 2006; van Deurssen et al., 2014; de Moraes et al., 2016). Quartz is a very common mineral found in many materials on construction sites, including sand, soil, granite, rock, concrete, masonry, and landscaping materials. Respirable silica can reach the gas exchange regions of the lungs when inhaled (Lumens and Spee, 2001). Exposure to high concentrations of respirable quartz can cause severe chronic diseases such as silicosis, pneumoconiosis, chronic obstructive pulmonary disease (COPD), chronic bronchitis, lung emphysema, lung cancer, rheumatoid arthritis, Sjogern's syndrome, scleroderma, lupus, and renal diseases (Castranova et al., 1996; Tjoe et al., 2003; Ruston, 2007; Brown et al., 2009; Akbar-Khanzadeh et al., 2010; Vida et al., 2010). In Hong Kong, silicosis has been the most common occupational disease for several decades, with up to 200 cases reported each year, mostly from the construction industry (Wong et. al., 1995). According to Thar and Lofgren's (1993) research, respirable silica exposure levels of 0.17 ± 8.3 mg m^{-3} were encountered by construction workers during concrete cutting. Workers exposed to concrete dust at levels below 1 mg m^{-3} of respirable dust with a respirable crystalline silica content of 10% showed minimal loss of lung function (Meijer et al., 2001). In the Netherlands, approximately 300 000 workers were employed in the construction industry in 2009, with nearly 60% potentially exposed to quartz (Lumens et al., 2009). Workers with more than 15 years of exposure were more affected by various disorders, including sinusitis, sneezing, shortness of breath, running nose, and asthma (Mariammal et. al., 2012).

Researchers have assessed the morbidity and mortality risks associated with long-term and short-term exposure to airborne PM. A meta-analysis of 110 peer-reviewed studies found that each 10 mg m^{-3} increase in $PM_{2.5}$ concentration was associated with a 1.04% increase in all-cause mortality (Atkinson et al., 2014). Chen and Hoek (2020) conducted a meta-analysis-based review study to determine the correlation between long-term exposure to $PM_{2.5}$ and PM_{10} and mortality from both causes and causes alone. These researchers discovered that the pooled risk ratio (RR) for mortality varied from 1.04 for circulatory illnesses to 1.19 for COPD when exposed to PM_{10}, and from 1.10 for respiratory diseases to 1.16 for acute lower respiratory infections (ALRI) when exposed to $PM_{2.5}$. The evaluation of health risks for construction workers exposed to dust has been the focus of numerous recent studies. Bergdahl et al. (2004) discovered that male construction workers in Sweden who were exposed to construction dust had a higher RR of 1.12 for COPD death when compared to a control group. Arndt et al. (2005) calculated the risk of disability for male construction workers in Germany, and discovered that the standardized incidence ratio (SIR) for cancer was higher, at 1.26 (cancer) and 1.27 (respiratory diseases) compared to the general workforce. A review study by Borup et al. (2017) found increased COPD occurrence in construction workers exposed to construction dust. According to Normohammadi et al. (2016), workers in Tehran, Iran who were highly exposed to demolition dust had a higher RR of developing silicosis and lung cancer-related mortality, at 22.64×1000^{-1} and $32\text{-}60 \times 1000^{-1}$, respectively, compared to 1×1000^{-1} for workers who were not as exposed. For residential developments in Beijing, China, Tong et al. (2018) evaluated the health risk in terms of the hazard index (R), which ranged from 0.49×10^{-7} to 11.42×10^{-7} at five distinct zones of superstructure construction. According to Chen et al. (2019), the overall health risk for tunnel construction workers in Chongqing, China, was evaluated to be $58.13 \times 1\,0^{-6}$, above the recommended limit of the United States Environmental Protection Agency (US-EPA). Male construction workers with respiratory and lung disorders had extra mortality risk ratios (MRR) of 1.44-1.80 for these conditions, according to Alicandro et al. (2019). Cheriyan and Choi (2021) and Khamarev et al. (2021) conducted a thorough analysis of the most recent research on the health risk assessment of PM in the construction sector.

Small and medium-scale construction sites, set up due to rapid urbanization and development in and around cities and towns in India, generate huge dust pollution posing serious health risks to exposed workers. The extremely necessary assessment of the same for construction sites at the Kolkata metropolis is still due. The present research has been undertaken to contribute to that area. The objective of the present study has been set to monitor and measure the extent of construction dust generation during different activities of building construction at different building construction sites in Kolkata. The monitored data has been further analyzed to find out the long-term exposure concentration of construction dust to which the involved construction workers are subjected and the probable associated causes and cause-specific mortality risks due to the exposure. The mortality risks of the exposed construction workers are further compared with the same for average Kolkata City residents and reported for understanding the gravity of the situation. The different variables influencing mortality risks are stochastic and Monte Carlo Simulation (MCS) is used in the present study to handle the risks involved with such variables. The uncertainties in these input variables are explored through sensitivity analysis to identify the critical parameter dependence of the estimated mortality risks due to PM exposure.

2. Methodology

2.1 The study program

2.1.1 Location of the study and monitored construction activities

A total of six construction sites with ongoing construction of multistoried residential apartment buildings at different locations of Kolkata City were chosen for monitoring the PM pollution scenario. Locations of Kolkata and surroundings are shown in Figure 1.

PM pollution scenarios were generated from a total of six construction activities. Earthwork, concrete mixing, brickwork, concrete chipping, brick wall-cutting, and marble cutting have been studied as per the study program as detailed in Table I. For all the sites, background concentrations of particulates were also monitored when no construction activities were taking place. The monitoring work spanned between November 2020 and May 2022. Each of the construction activities was monitored at multiple sites for more than one day. On each occasion, the sampling was done continuously for four hours. Wind velocity, ambient temperature, and relative humidity were recorded daily throughout the sampling period.

Table I. The study program.

Construction activity	Number of monitoring sites	Total days of sampling
Construction site background	Sites 1, 2, 3, 4, 5, and 6	16
Earthwork	Sites 1 and 3	10
Concrete mixing	Sites 1, 2, and 6	5
Brickwork	Sites 3 and 5	6
Concrete chipping	Sites 1 and 6	9
Brick wall cutting	Sites 4 and 5	6
Marble cutting	Sites 1 and 6	9

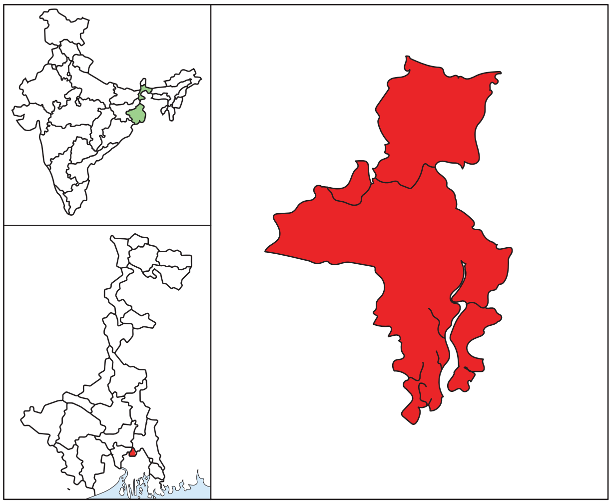

Fig. 1. Location of Kolkata and surroundings.

2.2 Instrumentation and sampling methodology

2.2.1 Sampling of particulates

Two particulate species, namely PM_{10} (particulates with a size ≤ 10 μm) and $PM_{2.5}$ (particulates with a size ≤ 2.5 μm) were monitored following the specifications of the Central Pollution Control Board, India (CPCB, 2013) using a fine particulate sampler (Envirotech, India, model APM 550M). The sampled air enters the APM 550M system through an omnidirectional inlet designed to provide a clean aerodynamic cut-point for particles greater than 10 μm. The airflow is then equally divided into two paths. In one path, air passes through a PM_{10} impactor, and the dust particulates of 10 μm get deposited on a specific Teflon (PTFE) membrane filter paper of 47 mm diameter (Whatman, 2 μm PTFE). In the other path, air passes through a nozzle of the well-shaped (WINS) impactor, designed to trap particulates between 2.5 and 10 μm. To avoid sampling errors, a 37 mm diameter GF/A paper (Whatman) immersed in silicone oil is used as an impaction surface. The air stream leaving the WINS Impactor consists of only fine particulates with an aerodynamic diameter ≤ 2.5 μm. These fine particles are collected on a specific Teflon (PTFE) membrane filter paper of 47 mm diameter (Whatman, 2 μm PTFE). The impactor is operated at an airflow rate of 1 $m^3 h^{-1}$. The lower detection limit of the mass concentration measurement range is estimated to be approximately 2 μg m^{-3} (Envirotech, 2022). The sampler was placed on a firm stand such that the inlets would collect the air samples from the breathing zone of the workers without creating any obstructions.

Mass concentrations of the sampled particulates were determined gravimetrically by calculating the difference in weights of the filter paper before and after sample collection using a high-precision electronic balance (Uni Bloc, model AUW220D) with a measurement range of 0.01-80 g). Appropriate precautions were taken to eliminate humidity effects.

2.3 Analysis and presentation of the study results

2.3.1 Assessment of the extent of particulate pollution for different construction activities at the monitored construction sites

Mass concentrations of two particulate species, namely PM_{10} and $PM_{2.5}$, were monitored for six different construction activities and at the construction site background for multiple days at different construction sites. The average concentrations of PM_{10} (*Act_Conc_*PM_{10}) and $PM_{2.5}$ (*Act_Conc_*$PM_{2.5}$) were calculated for six different activities. The average background concentrations at the construction sites for the species were also calculated (*Bck_Conc_*PM_{10} and *Bck_Conc_*$PM_{2.5}$, respectively). These are reported along with the respective average percentage increments over the 24-h and annual National Ambient Air Quality Standards (CPCB, 2009).

2.3.2 Estimation of the exposure

In Kolkata, construction workers spend about eight months annually at different construction sites. A group of workers engaged in a particular construction activity move from one site after completing their job to another during the working months, when they reside at the construction sites and get exposed to the prevailing air quality during working and non-working hours. The exposure, therefore, can be considered long-term.

A questionnaire-based survey was conducted amongst a total of 65 construction workers at the monitored sites to gather information about their daily and weekly working schedules, such as daily working hours (WH_Day) and weekly working days (*WD_Week*). The average values are calculated for each activity. The average weekly working hours (*WH_Week*) for construction workers involved in each activity are calculated using Eq. (1).

$$WH\_Week = WH\_Day \times WD\_Week \qquad (1)$$

During working hours, the respective construction workers remain exposed to PM concentration for a particular activity. During the remaining non-working hours of the day and off-days the worker's exposure is to the background particulate concentration at the construction site. The average particulate concentration to which a construction worker is exposed (*Expos_Conc_*PM_{10} and *Expos_Conc_*$PM_{2.5}$ respectively) throughout the week (7 × 24 = 168 h) during the working months is calculated using Eqs. (2) and (3).

$$Expos\_Conc\_PM_{10} = \frac{\begin{array}{l} Act\_Conc\_PM_{10} \times \\ WH_{Week} + \\ Bck\_Conc\_PM_{10} \times \\ \left(168 - WH_{Week}\right) \end{array}}{168} \qquad (2)$$

$$Expos\_Conc\_PM_{2.5} = \frac{Act\_Conc\_PM_{2.5} \times WH_{Week} + Bck\_Conc\_PM_{2.5} \times \left(168 - WH_{Week}\right)}{168} \quad (3)$$

2.3.3 Estimation of the mortality risks for construction workers due to long-term PM_{10} and $PM_{2.5}$ exposure

RR is a widely used parameter in epidemiological studies to represent the health impact of a particular cause in terms of the risk ratio for the population exposed compared to unexposed or control populations. It represents the number of times that disease is more (or less) likely to occur in the exposed as compared with the unexposed group (WHO Scientific Group, 2006).

Long-term exposure to high airborne particulate concentration increases the mortality risks of the exposed population. Many researchers all over the world have studied and estimated this risk. Chen and Hoek (2020) have done an extensive systematic review of such studies over recent years to support the derivation of World Health Organization (WHO) Global Air Quality Guidelines (WHO, 2021) to estimate the associations between long-term exposure to PM_{10} and $PM_{2.5}$ to all-cause and cause-specific mortality. The risk of mortality represented as RR or hazard ratio (HR) associated with long-term exposure per 10 µg m^{-3} increase in PM_{10} and $PM_{2.5}$ concentrations as estimated from the review are shown in Table II. These values are used in the present study to estimate the mortality risks for the construction workers in Kolkata subjected to long-term exposure to elevated PM_{10} and $PM_{2.5}$ concentrations.

The increment of the average long-term particulate concentration exposure of construction workers (estimated as $Expos\_Conc\_PM_{10}$ and $Expos\_Conc\_PM_{2.5}$, respectively) over the NAAQS (CPCB, 2009) specified annual standard values (60 and 40 µg m^{-3} for PM_{10} and $PM_{2.5}$, respectively). The all-cause and cause-specific mortality risks for exposed construction workers ($RR\_Expos\_PM_{10}$ and $RR\_Expos\_PM_{2.5}$) in Kolkata are then estimated using Eqs. (4) and (5).

$$RR\_Expos\_PM_{10} = 1 + \left[\left(RR\_PM_{10} - 1\right) \times \left\{ \frac{\left(Expos\_Conc\_PM_{10} - 60\right)}{10} \right\} \right] \quad (4)$$

Table II. Relative risk (RR) of all-cause and cause-specific mortality associated with long-term exposure to a 10 µg m^{-3} increase in PM_{10} and $PM_{2.5}$ concentrations.

Mortality cause	Long-term PM_{10} exposure			Long-term $PM_{2.5}$ exposure		
Parameter	Pooled RR per 10 µg m^{-3}			Pooled RR per 10 µg m^{-3}		
Symbol	RR_PM_{10}			$RR\_PM_{2.5}$		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
All non-accidental (natural) causes	1.04	1.03	1.06	1.08	1.06	1.09
Circulatory	1.04	0.99	1.10	1.11	1.09	1.14
Ischemic heart disease (IHD)	1.06	1.01	1.10	1.16	1.10	1.21
Stroke	1.01	0.83	1.21	1.11	1.04	1.18
Non-malignant respiratory	1.12	1.06	1.19	1.10	1.03	1.18
Chronic obstructive pulmonary disease (COPD)	1.19	0.95	1.49	1.11	1.05	1.17
Acute lower respiratory infection (ALRI)	–	–	–	1.16	1.01	1.34
Lung cancer	1.08	1.04	1.13	1.12	1.07	1.16

Source: Chen and Hoek, 2020; WHO, 2021.

$$RR\_Expos\_PM_{2.5} = 1 + \left[\left(RR\_PM_{2.5} - 1\right) \times \left\{ \frac{\left(Expos\_Conc\_PM_{2.5} - 40\right)}{10} \right\} \right] \tag{5}$$

2.3.4 Comparison of the mortality risks for construction workers to Kolkata City residents due to long-term PM_{10} and $PM_{2.5}$ exposure

Kolkata City residents also experience exposure to a high level of ambient particulate concentration. The West Bengal Pollution Control Board (WBPCB) regularly reports the average PM_{10} and $PM_{2.5}$ daily concentrations in Kolkata City (WBPCB, n.d.). The daily data was collected for three consecutive years (from April 1, 2017, to March 31, 2020), and the average PM_{10} and $PM_{2.5}$ concentrations a Kolkata City resident is exposed to are calculated (*Kol_Conc_PM*$_{10}$ and *Kol_Conc_PM*$_{2.5}$) and reported along with increment over the NAAQS (CPCB, 2009) specified standard values. As the city faced periodic lockdowns since March 2020 due to the COVID-19 pandemic disrupting normal activities, the particulate concentration level drastically slowed, and therefore the last two years' data was excluded.

Using the above data, all-cause and cause-specific mortality risks for an average Kolkata City resident (*RR_Kol_PM*$_{10}$ and *RR_Kol_PM*$_{2.5}$) are estimated using Eqs. (6) and (7).

$$RR\_Kol\_PM_{10} = 1 + \left[\left(RR\_PM_{10} - 1\right) \times \left\{ \frac{\left(Kol\_Conc\_PM_{10} - 60\right)}{10} \right\} \right] \tag{6}$$

$$RR\_Kol\_PM_{2.5} = 1 + \left[\left(RR\_PM_{2.5} - 1\right) \times \left\{ \frac{\left(Kol\_Conc\_PM_{2.5} - 40\right)}{10} \right\} \right] \tag{7}$$

Finally, the percent increment in all-cause and cause-specific mortality risks for exposed construction workers over average city residents (*Perent_Incr_RR_PM*$_{10}$ and *Perent_Incr_RR_PM*$_{2.5}$) of Kolkata is estimated using Eqs. (8) and (9). The obtained results helped to assess the increased mortality risks for local construction workers compared to the average residents of Kolkata City due to long-term PM_{10} and $PM_{2.5}$ exposure.

$$Perent\_Incr\_RR\_PM_{10} = \left\{ \frac{RR\_Expos\_PM_{10} - RR\_Kol\_PM_{10}}{RR\_Kol\_PM_{10}} \right\} \times 100\% \tag{8}$$

$$Perent\_Incr\_RR\_PM_{2.5} = \left\{ \frac{RR\_Expos\_PM_{2.5} - RR\_Kol\_PM_{2.5}}{RR\_Kol\_PM_{2.5}} \right\} \times 100\% \tag{9}$$

2.3.5 Handling of stochastic input data

The different variables used in the present study while determining the exposure durations, exposure concentrations, and mortality risks are stochastic. MCS is a widely used technique to handle models involving stochastic data in various fields of study, including health risk assessment due to air pollution (Tong et al., 2018, 2019; Hassan et al., 2022; Jiang et al., 2022; Jin et al., 2022; Khodadadi et al., 2022; Sahihazar et al., 2022).

In MCS analysis, the probability distributions of the input variables are fed to the model, and the simulations are run for numerous iterations. In the present study, during each stage of MCS, 10 000 iterations are run on the '@Risk' software v. 5.5 of Palisade Decision Tools Suite (2009), and the resultant outcomes are noted as probability distributions in terms of their mean and standard deviation. A schematic representation of the framework of the study is presented in Figure 2.

3. Results and discussion

3.1 Assessment of the extent of particulate pollution at monitored construction sites

The average mass concentrations of PM_{10} and $PM_{2.5}$ (*Act_Conc_PM*$_{10}$ and *Act_Conc_PM*$_{2.5}$, respectively) generated during the six construction activities are calculated and presented along with their average background concentration at the construction sites

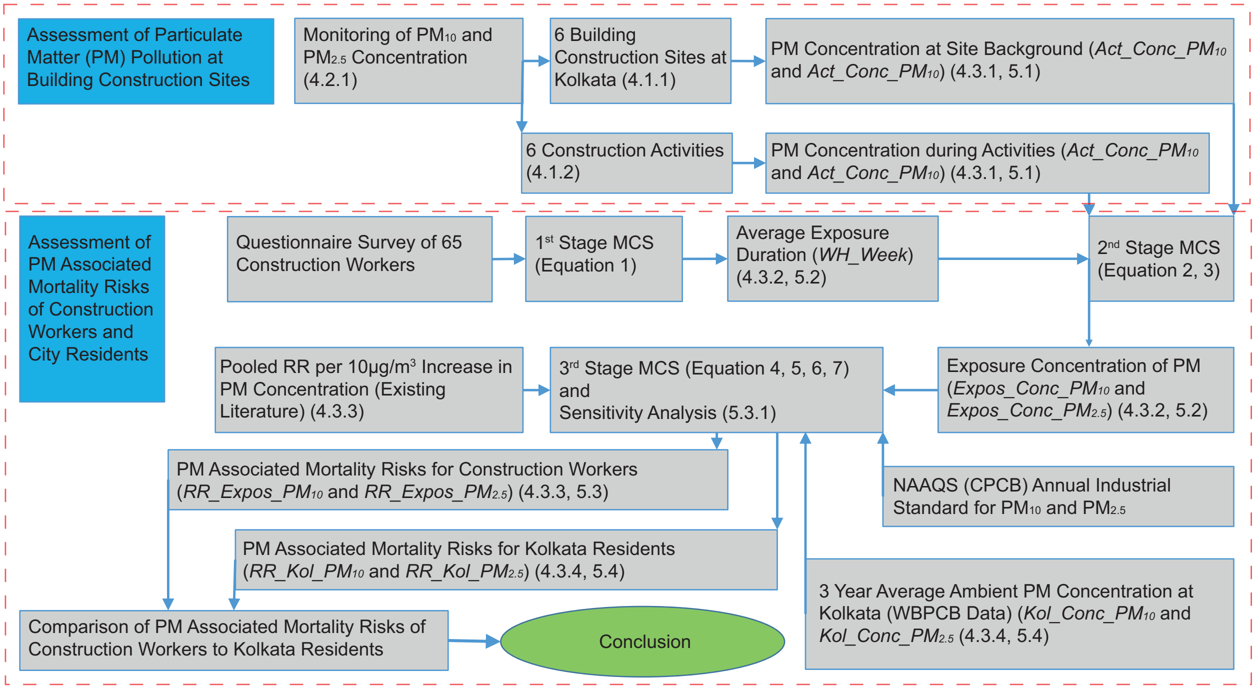

Fig. 2. The framework of the study.

($Bck\_Conc\_PM_{10}$ and $Bck\_Conc\_PM_{2.5}$, respectively) in Table III. These are compared with the NAAQS (CPCB, 2009) in terms of their increments over 24 h ($Incr\_NAAQS\_24\_PM_{10}$ and $Incr\_NAAQS\_24\_PM_{2.5}$, respectively) and annual ($Incr\_NAAQS\_An\_PM_{10}$ and $Incr\_NAAQS\_An\_PM_{2.5}$, respectively) industrial standards. The respective average percentage increments over 24-h NAAQS (CPCB, 2009) are shown in Figure 3.

The input variables for Eqs. (1) through (3) are all stochastic, and MCS was used to handle the involved risk. The long-term exposure concentrations ranged between 212.55 (±27.39)-3621.66 (±1063.21) $\mu g\ m^{-3}$ for PM_{10}. The same for $PM_{2.5}$ ranged between 133.18 (±26.83) and 1101.03 (±276.10) $\mu g\ m^{-3}$ for $PM_{2.5}$. These values will exceed the NAAQS-specified annual standards and are used in the subsequent sections to assess the associated mortality risks for the exposed construction workers.

Based on the daily air quality data of Kolkata City reported by the WBPCB, the three-year average (from April 1, 2017 to March 31, 2020) PM_{10} and $PM_{2.5}$ concentrations for Kolkata City are also calculated. These concentrations ($Kol\_Conc\_PM_{10}$ and $Kol\_Conc\_PM_{2.5}$) are reported in Table IV, along with the corresponding increments over the NAAQS (CPCB, 2009) specified standard values.

All six activities show elevated concentrations of both monitored particulate species compared to the daily and annual NAAQS standards (214.78-12202.28% and 424.64-20 403.81%, respectively, for PM_{10} and 182.20-5847.92% and 323.29-8821.88%, respectively, for $PM_{2.5}$), being the brick wall-cutting activity the highest polluter. Even the average construction site background concentrations were much higher than daily and annual NAAQS (80.97 and 201.62%, respectively, for PM_{10} and 103.29 and 204.94%, respectively, for $PM_{2.5}$). These concentrations are also much higher than the average concentrations in Kolkata City.

3.2 Assessment of the exposure of construction workers to particulate pollution at monitored construction sites

The activity and background particulate concentrations, as reported in Table IV, and the information about the exposure times (namely daily working hours [WH_Day], weekly working days [WD_Week], and average weekly working hours [WH_Week]), collected through a questionnaire survey amongst

Table III. Average particulate concentrations at monitored construction sites at background and during different construction activities.

Construction activity		PM_{10}			$PM_{2.5}$			$PM_{2.5}/PM_{10}$
	Parameters	Concentration	Increment over NAAQS_24	Increment Over NAAQS_Annual	Concentration	Increment over NAAQS_24	Increment over ZNAAQS_Annual	$PM_{2.5}$ / PM_{10} ratio
	Symbol	$\mathit{Act\_Conc\_PM}_{10}$	$\mathit{Incr\_NAAQS\_24\_PM}_{10}$	$\mathit{Incr\_NAAQS\_An\_PM}_{10}$	$\mathit{Act\_Conc\_PM}_{2.5}$	$\mathit{Incr\_NAAQS\_24\_PM}_{2.5}$	$\mathit{Incr\_NAAQS\_An\_PM}_{2.5}$	$\mathit{PM}_{2.5}\mathit{\_PM}_{10}\mathit{\_Ratio}$
	Unit	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)	
Earthwork	Mean	314.78	214.78	254.78	169.32	109.32	129.32	0.55
	S.D.	66.24	66.24	66.24	26.26	26.26	26.26	0.07
Concrete mixing	Mean	574.00	474.00	514.00	273.65	213.65	233.65	0.51
	S.D.	181.80	181.80	181.80	42.97	42.97	42.97	0.15
Brick work	Mean	425.54	325.54	365.54	211.05	151.05	171.05	0.50
	S.D.	71.58	71.58	71.58	43.64	43.64	43.64	0.04
Concrete chipping	Mean	1379.93	1279.93	1319.93	553.71	493.71	513.71	0.40
	S.D.	182.63	182.63	182.63	229.97	229.97	229.97	0.16
Brick wall cutting	Mean	12302.28	12202.28	12242.28	3568.75	3508.75	3528.75	0.30
	S.D.	2649.41	2649.41	2649.41	610.32	610.32	610.32	0.06
Marble cutting	Mean	1007.24	907.24	947.24	519.46	459.46	479.46	0.52
	S.D.	344.25	344.25	344.25	164.62	164.62	164.62	0.07
Background	Symbol	$\mathit{Bck\_Conc\_PM}_{10}$			$\mathit{Bck\_Conc\_PM}_{2.5}$			
	Mean	180.97	80.97	120.97	121.98	61.98	81.98	0.67
	S.D.	29.24	29.24	29.24	34.22	34.22	34.22	0.14
Kolkata average	Symbol	$\mathit{Kol\_Conc\_PM}_{10}$			$\mathit{Kol\_Conc\_PM}_{2.5}$			
	Mean	111.32	11.32	51.32	63.39	3.39	23.39	0.57
	S.D.	60.99	60.99	60.99	35.37	35.37	35.37	0.08
NAAQS_24 h*		100.00			60.00			
NAAQS_annual**		60.00			40.00			

NAAQS: National Ambient Air Quality Standards; CPCB: Central Pollution Control Board; S.D.: standard deviation.
*24-h and **annual industrial standard as per NAAQS (CPCB).

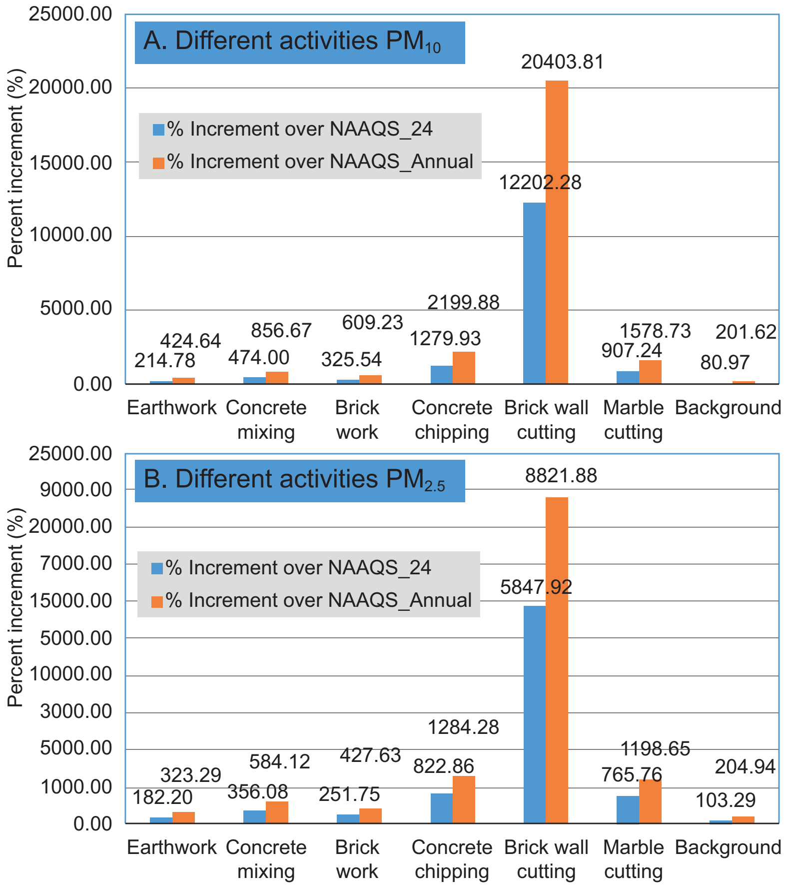

Fig. 3. Percent increment of average particulate concentrations for different construction activities over the NAAQS (CPCB). (NAAQS: National Ambient Air Quality Standards; CPCB: Central Pollution Control Board.)

Table IV. Exposure concentration of PM_{10} ($Expos\_Conc\_PM_{10}$) and $PM_{2.5}$ ($Expos\_Conc\_PM_{2.5}$) for construction workers.

Construction activity	Exposure time data					PM_{10}	$PM_{2.5}$
	Parameters	Number of workers surveyed	Daily working hours	Weekly working days	Weekly working hours	Exposure concentration	Exposure concentration
	Symbol	N_W	WH_Day	WD_Week	WH_Week	$Expos\_Conc\_PM_{10}$	$Expos\_Conc\_PM_{2.5}$
	Unit		Hours	Days	Hours	($\mu g\ m^{-3}$)	($\mu g\ m^{-3}$)
Earthwork	Mean	10	6.40	6.20	39.68	212.55	133.18
	S.D.		0.52	0.42	4.23	27.39	26.83
Concrete Mixing	Mean	13	7.54	6.08	45.80	288.06	163.33
	S.D.		0.52	0.28	3.75	54.88	27.93
Brick Work	Mean	12	8.00	6.00	48.00	250.86	147.43
	S.D.		0.00	0.43	3.44	29.67	27.51
Concrete Chipping	Mean	10	7.00	6.11	42.77	486.38	231.86
	S.D.		1.32	0.33	8.38	79.81	68.36
Brick Wall Cutting	Mean	10	7.67	6.22	47.71	3621.66	1101.03
	S.D.		1.41	0.67	10.25	1063.21	276.10
Marble Cutting	Mean	10	9.43	5.29	49.83	426.00	239.92
	S.D.		0.98	0.49	6.96	110.26	57.46
NAAQS_ annual*						60.00	40.00

NAAQS: National Ambient Air Quality Standards; CPCB: Central Pollution Control Board; S.D.: standard deviation.
**Annual industrial standard as per NAAQS (CPCB).

a total of 65 construction workers, are utilized to find out the exposure concentration of particulates ($Expos\_Conc\_PM_{10}$ and $Expos\_Conc\_PM_{2.5}$, respectively) for all the six activities. The results are reported in Table IV.

The input variables for Eqs. (1)-(3) are all stochastic, and MCS was used to handle the involved risk. The long-term exposure concentrations ranged between 212.55 (±27.39) and 3621.66 (±1063.21) µg m^{-3} for PM_{10}, and for $PM_{2.5}$ they ranged between 133.18 (±26.83) and 1101.03 (±276.10) µg m^{-3} for $PM_{2.5}$. These values exceed the NAAQS-specified annual standards and are used in the subsequent sections to assess the associated mortality risks for the exposed construction workers.

3.3 Assessment of the mortality risks for construction workers and Kolkata City Residents due to long-term PM_{10} and $PM_{2.5}$ exposure

The increment of these exposure concentrations of particulates over their NAAQS annual standards ($Incr\_NAAQS\_An\_PM_{10}$ and $Incr\_NAAQS\_An\_PM_{2.5}$) are calculated. The all-cause and cause-specific mortality risks (RR_PM_{10} and $RR\_PM_{2.5}$) associated with long-term exposure to a 10 µg m^{-3} increase in PM_{10} and $PM_{2.5}$ concentrations are obtained from existing literature as presented in Table II. These parameters estimate the mortality risks ($RR\_Expos\_PM_{10}$ and $RR\_Expos\_PM_{2.5}$) for the construction workers in Kolkata subjected to long-term exposure to elevated PM_{10} and $PM_{2.5}$ concentrations.

As reported in Table V, the mortality risks for different causes due to elevated PM_{10} exposure ($RR\_Expos\_PM_{10}$) are observed to be highest for workers engaged in brick wall cutting. Amongst the different causes, mortality risks for COPD and sroke are respectively observed to be the highest and lowest for PM_{10} exposure. Figure 4 summarizes the MCS output distributions of $RR\_Expos\_PM_{10}$ for different activities. The box-whisker charts show the 25-75% and 5-95% intervals of the distributions and the mean value. The mortality risks ranged between 1.25 (±1.20) (for risk of stroke for earthwork workers) to 75.89 (±46.87) (for risk of COPD for brick wall-cutting workers). For average residents of Kolkata City, the mortality risks due to PM_{10} exposure ($RR\_Kol\_PM_{10}$) are much lower and range between 1.09 (±0.63) (for risk of stroke) to 2.08 (±1.54) (for risk of COPD).

Table VI reports the mortality risks for different causes due to elevated $PM_{2.5}$ exposure ($RR\_Expos\_PM_{2.5}$), and brick wall-cutting workers face the highest risk. For $PM_{2.5}$ exposure, mortality risks for ALRI are the highest, and for non-malignant respiratory diseases are the lowest.

The box-whisker charts of (Fig. 5) summarize the MCS output distributions of the $RR\_Expos\_PM_{2.5}$ for different activities. The mortality risks ranged between 1.96 (±0.40) (for risk of non-malignant respiratory diseases for earthwork workers) to 19.04 (±8.82) (for risk of ALRI for brick wall-cutting workers). For average residents of Kolkata City, the mortality risks due to $PM_{2.5}$ exposure ($RR\_Kol\_PM_{2.5}$) are much lower and range between 1.20 (±0.38) (for risk of non-malignant respiratory diseases) to 1.39 (±0.66) (for risk of ALRI). Overall, the mortality risks for construction site workers are higher due to PM_{10} exposure than $PM_{2.5}$ exposure.

3.3.1 Sensitivity analysis

The mortality risks of construction workers ($RR\_Expos\_PM_{10}$ and $RR\_Expos\_PM_{2.5}$) are calculated from five input (independent) variables, anmely daily working hours (WH_Day), weekly working days (WD_Week), PM concentrations during construction activities ($Act\_Conc\_PM_{10}$ and $Act\_Conc\_PM_{2.5}$), PM concentrations at site background ($Act\_Conc\_PM_{10}$ and $Act\_Conc\_PM_{2.5}$), and relative risk of mortality associated with long-term exposure to per 10 µg m^{-3} increase in PM concentrations (RR_PM_{10} and $RR\_PM_{2.5}$).

The uncertainties in these input variables are explored through the iterative approach of a "what-if" kind of sensitivity analysis to identify the critical parameter dependence of the solution (dependent variable, i.e., mortality risk). The TopRank software v. 5.5 of Palisade Decision Tools Suite (2009) was used to carry out the analysis, and the results are presented in Figure 6 for $RR\_Expos\_PM_{10}$ and $RR\_Expos\_PM_{2.5}$. A tornado graph displays the range of an investigated output (dependent variable) as affected by the variation in each input (independent variables) as a stacked bar chart. The various inputs stacked on the vertical axis are sorted based on how strongly they affect the output. A larger swing indicates that the output variable is more sensitive to the variation of the input variable. A spider graph plots the range

Table V. All-cause and cause-specific mortality risks (Relative Risk) of Kolkata City residents and construction workers exposed to high PM_{10} concentrations.

Construction activity	Parameters	Increment over NAAQS_annual	All-cause and cause-specific mortality risks (relative risk) to exposed construction workers							
			All Non-accidental (natural) causes	Circulatory	Ischemic heart disease (IHD)	Stroke	Non-malignant respiratory	Chronic obstructive pulmonary disease (COPD)	Acute lower respiratory infection (ALRI)	Lung cancer
	Symbol	*Incr_NAAQS_ An_PM₁₀*	*RR_Expos_PM₁₀*							
	Unit	(μg m^{-3})								
Earthwork	Mean	152.55	1.66	1.66	1.86	1.25	2.88	4.20	-	2.27
	S.D.	27.39	0.15	0.37	0.33	1.20	0.53	1.80	-	0.36
Concrete mixing	Mean	228.06	1.99	1.99	2.29	1.38	3.81	5.78	-	2.90
	S.D.	54.88	0.28	0.57	0.53	1.83	0.91	2.81	-	0.62
Brick work	Mean	190.86	1.83	1.83	2.08	1.32	3.35	5.00	-	2.59
	S.D.	29.67	0.18	0.45	0.39	1.50	0.63	2.23	-	0.43
Concrete chipping	Mean	426.38	2.85	2.85	3.41	1.72	6.25	9.94	-	4.55
	S.D.	79.81	0.44	1.04	0.92	3.36	1.49	5.04	-	1.04
Brick wall cutting	Mean	3561.66	16.45	16.43	21.18	6.94	44.96	75.89	-	30.70
	S.D.	1063.21	5.19	9.54	9.08	29.18	16.51	46.87	-	11.24
Marble cutting	Mean	366.00	2.59	2.59	3.08	1.62	5.52	8.66	-	4.05
	S.D.	110.26	0.54	0.99	0.95	2.99	1.71	4.79	-	1.16
Kolkata average			*RR_Kol_PM₁₀*							
	Mean	51.32	1.22	1.22	1.29	1.09	1.63	2.08	-	1.42
	S.D.	60.99	0.27	0.32	0.38	0.63	0.78	1.54	-	0.52

NAAQS: National Ambient Air Quality Standards; S.D.: standard deviation.

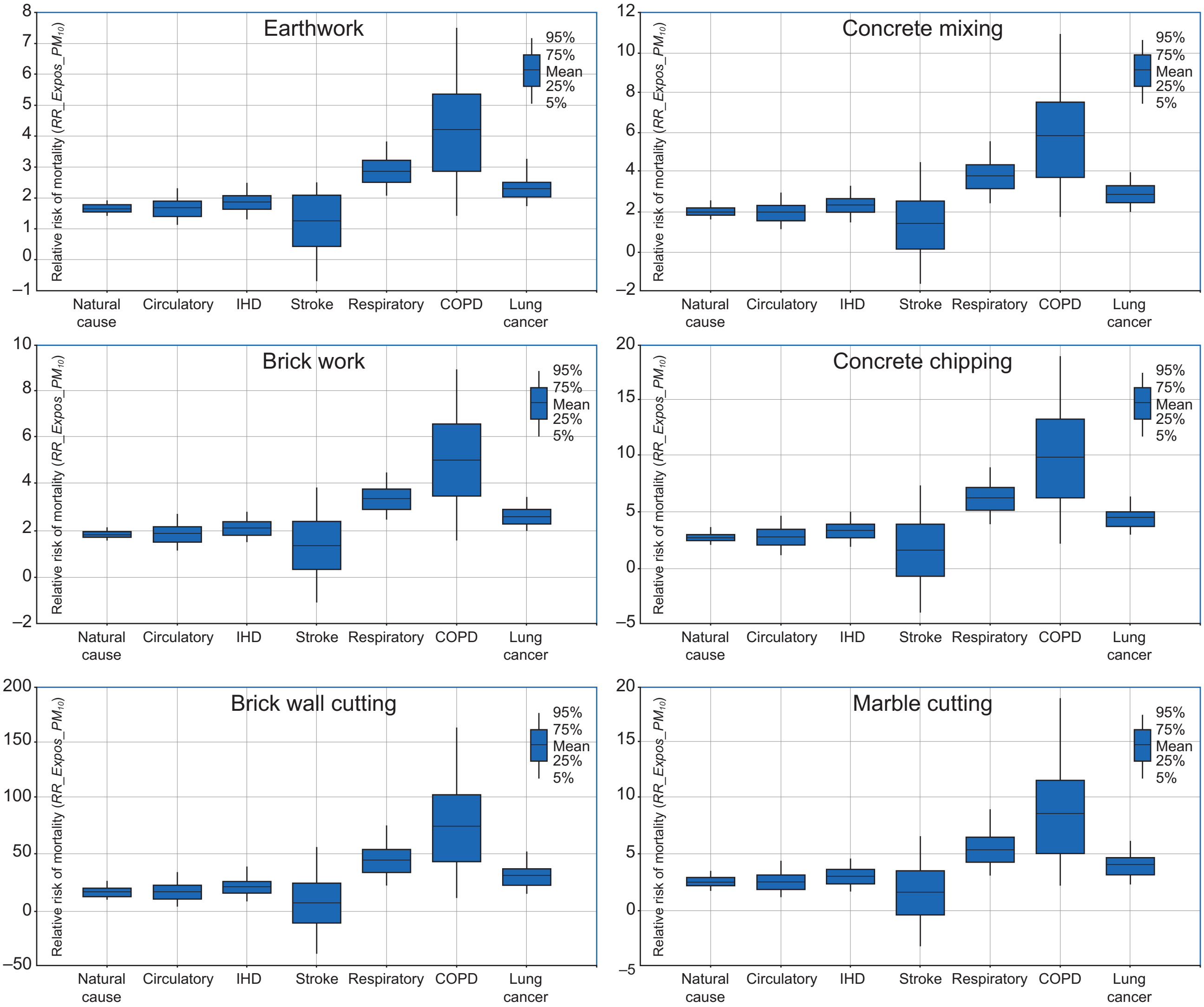

Fig. 4. Results of the Monte Carlo Simulation (MCS) in assessing mortality risks of exposed construction workers ($RR\_Expos\_PM_{10}$) to high PM_{10} concentrations.

(or sensitivity) of the output variable in response to the variation in the input variables creating a surface on the spider web. The bigger impact of an input variable is indicated by the closeness of the surface to that input variable's apex (S&P Global, 2016).

The mortality risk associated with PM_{10} exposure ($RR\_Expos\_PM_{10}$) is found to be most sensitive to PM_{10} concentration during construction activities ($Act\_Conc\_PM_{10}$). The mortality risk associated with $PM_{2.5}$ exposure ($RR\_Expos\_PM_{2.5}$) is, however, most sensitive to pooled relative risk ($RR\_PM_{2.5}$) followed by $PM_{2.5}$ concentration during construction activities and at the site background ($Act\_Conc\_PM_{2.5}$ and $Bck\_Conc\_PM_{2.5}$).

3.4 Comparison of the mortality risks for construction workers to Kolkata City residents due to long-term PM_{10} and $PM_{2.5}$ exposure

All-cause and cause-specific mortality risks for an average Kolkata City resident ($RR\_Kol\_PM_{10}$ and $RR\_Kol\_PM_{2.5}$) are also found in a similar way using the average PM_{10} and $PM_{2.5}$ concentrations. A Kolkata City resident is exposed to $Kol\_Conc\_PM_{10}$ and $Kol\_Conc\_PM_{2.5}$, obtained from three years of daily

Table VI. All-cause and cause-specific mortality risks (relative risk) of Kolkata City residents and construction workers exposed to high $PM_{2.5}$ concentrations.

Construction activity	Parameters	Increment over NAAQS_annual	All-cause and cause-specific mortality risks (relative risk) to exposed construction workers							
			All non-accidental (natural) cause	Circulatory	Ischemic heart disease (IHD)	Stroke	Non-malignant respirtory	Chronic obstructive pulmonary disease (COPD)	Acute lower respiratory infection (ALRI)	Lung cancer
	Symbol	*Incr_NAAQS_ An_PM*$_{2.5}$	*RR_Expos_PM*$_{2.5}$							
	Unit	(µg m^{-3})								
Earthwork	Mean	93.18	1.71	2.05	2.45	2.02	1.96	2.02	2.58	2.08
	S.D.	26.83	0.21	0.32	0.46	0.40	0.40	0.37	0.79	0.35
Concrete mixing	Mean	123.33	1.94	2.39	2.93	2.35	2.27	2.35	3.09	2.43
	S.D.	27.93	0.22	0.33	0.52	0.47	0.48	0.43	0.97	0.39
Brickwork	Mean	107.43	1.82	2.21	2.68	2.18	2.11	2.18	2.82	2.25
	S.D.	27.51	0.22	0.33	0.49	0.43	0.44	0.40	0.88	0.38
Concrete chipping	Mean	191.86	2.47	3.17	4.00	3.11	2.98	3.11	4.25	3.23
	S.D.	68.36	0.54	0.79	1.15	0.94	0.94	0.90	1.78	0.88
Brick wall cutting	Mean	1061.03	9.13	13.02	17.61	12.67	11.97	12.66	19.04	13.37
	S.D.	276.10	2.21	3.33	4.97	4.39	4.45	4.05	8.82	3.80
Marble cutting	Mean	199.92	2.53	3.26	4.13	3.19	3.06	3.19	4.40	3.33
	S.D.	57.46	0.45	0.69	1.01	0.87	0.87	0.80	1.71	0.77
Kolkata average			*Rr_kol_pm*$_{2.5}$							
	Mean	23.39	1.17	1.26	1.36	1.25	1.20	1.25	1.39	1.27
	S.D.	35.37	0.27	0.4	0.56	0.4	0.38	0.4	0.66	0.42

NAAQS: National Ambient Air Quality Standards; S.D.: standard deviation.

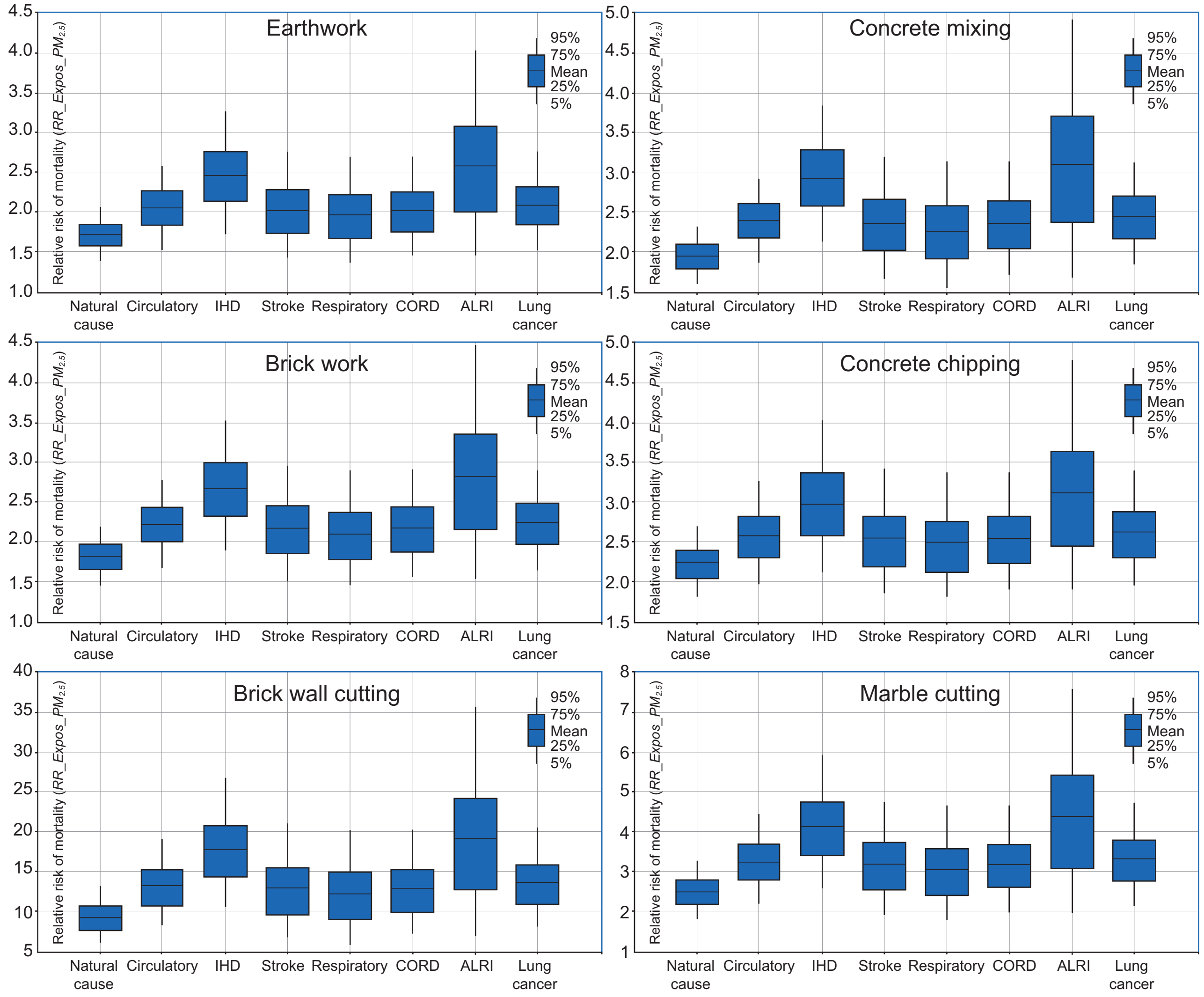

Fig. 5. Results of the Monte Carlo Simulation (MCS) in assessing mortality risks of construction workers exposed (*RR_Expos_PM*$_{2.5}$) to high PM$_{2.5}$ concentrations.

data provided by the WBPCB. The results are reported in Tables V and VI. Finally, the percent increment in all-cause and cause-specific mortality risks for exposed construction workers over average city residents (*Perent_Incr_RR_PM*$_{10}$ and *Perent_Incr_RR_PM*$_{2.5}$) of Kolkata are estimated and reported in Figure 7.

It can be observed that in all cases, mortality risks due to particulate exposure are much higher for construction workers in Kolkata when compared to average city residents, ranging from 14.68 to 3548.56% higher for PM$_{10}$ and 61.60 to 1269.78% higher for PM$_{2.5}$. PM$_{10}$ exposure is more damaging for non-malignant respiratory diseases, COPD, and lung cancer. PM$_{2.5}$ exposure has increased mortality risk for circulatory diseases, IHD, stroke, and ALRI. For workers engaged in brick wall cutting, however, PM$_{10}$ exposure is likely to cause more damage for all cause-specific mortality risks except for stroke, where PM$_{2.5}$ exposure is the dominant cause.

4. Conclusion

PM concentrations were measured at six construction sites in Kolkata, India, during six different construction activities like earthwork, concrete mixing, brickwork, concrete chipping, marble cutting, and

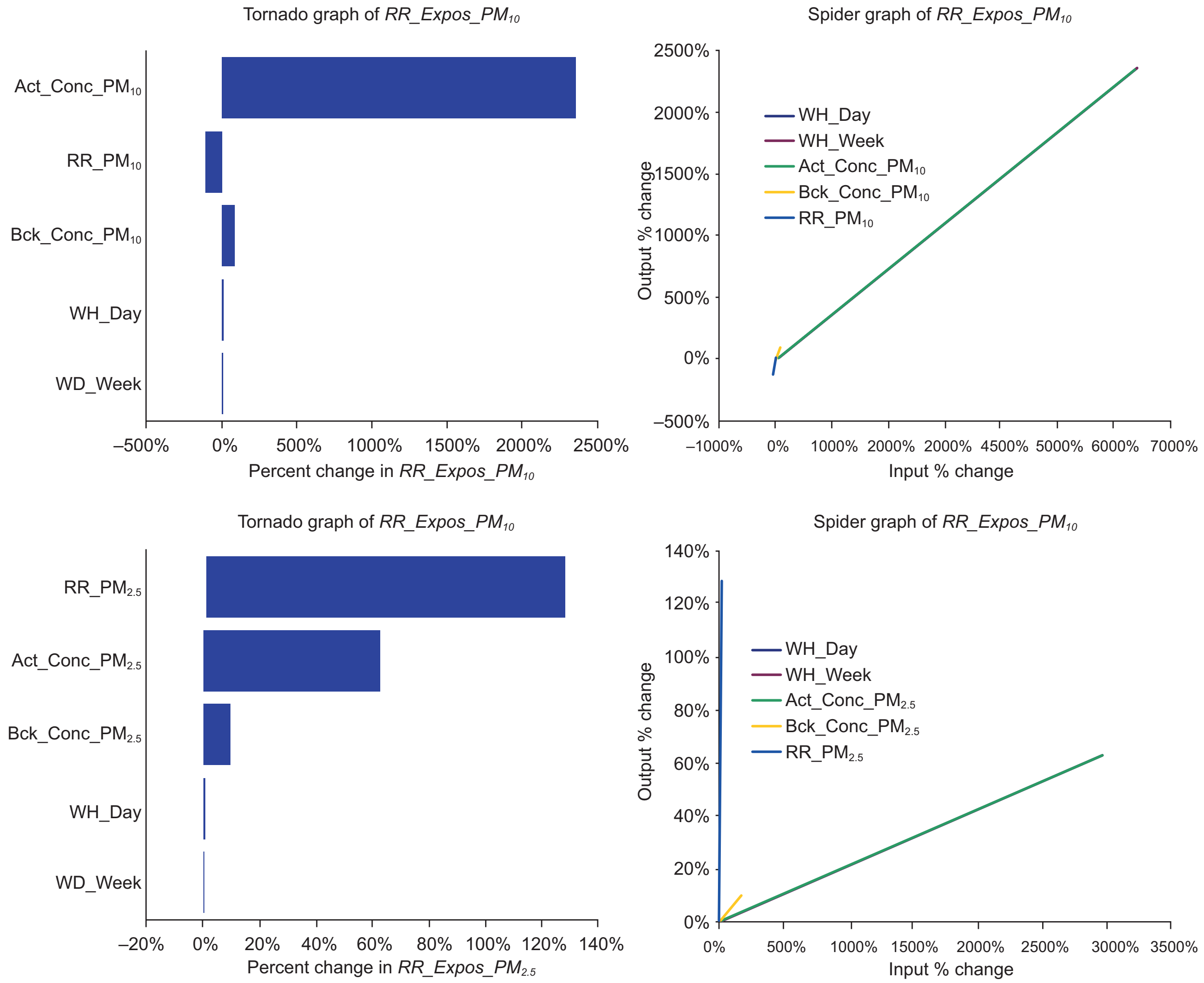

Fig. 6. Sensitivity of mortality risks of exposed construction workers (*RR_Expos_*PM_{10} and *RR_Expos_*$PM_{2.5}$) on different influencing variables.

brick wall cutting. The generated PM levels largely exceeded daily and annual NAAQS standards (214.78-12 202.28 % and 424.64-20 403.81%, respectively, for PM_{10} and 182.20-5847.92% and 323.29-8821.88%, respectively, for $PM_{2.5}$), the activity of 'Brick Wall Cutting' being the highest polluter and least amount of PM generated during "Earthwork". All these concentrations are much higher than the Kolkata City average concentrations. Such data on generated PM levels due to construction activities are scanty in this region of India, and the present study shows the serious air quality issues due to high PM levels around construction sites to which the construction workers are exposed.

All-cause and cause-specific mortality risks associated with long-term exposure to these high PM levels are estimated for the construction workers in Kolkata. The mortality risks for different causes due to elevated PM_{10} exposure (*RR_Expos_*PM_{10}) ranged between 1.25 (±1.20) (for risk of stroke for earthwork workers) to 75.89 (±46.87) (for risk of COPD for brick wall-cutting workers). The mortality risks for $PM_{2.5}$ exposure (*RR_Expos_*$PM_{2.5}$) ranged between 1.96 (±0.40) (for risk of non-malignant respiratory diseases for earthwork workers) to 19.04 (±8.82) (for risk of ALRI for brick wall cutting workers). Overall, the mortality risks for construction site workers are higher due to PM_{10} exposure than $PM_{2.5}$ exposure.

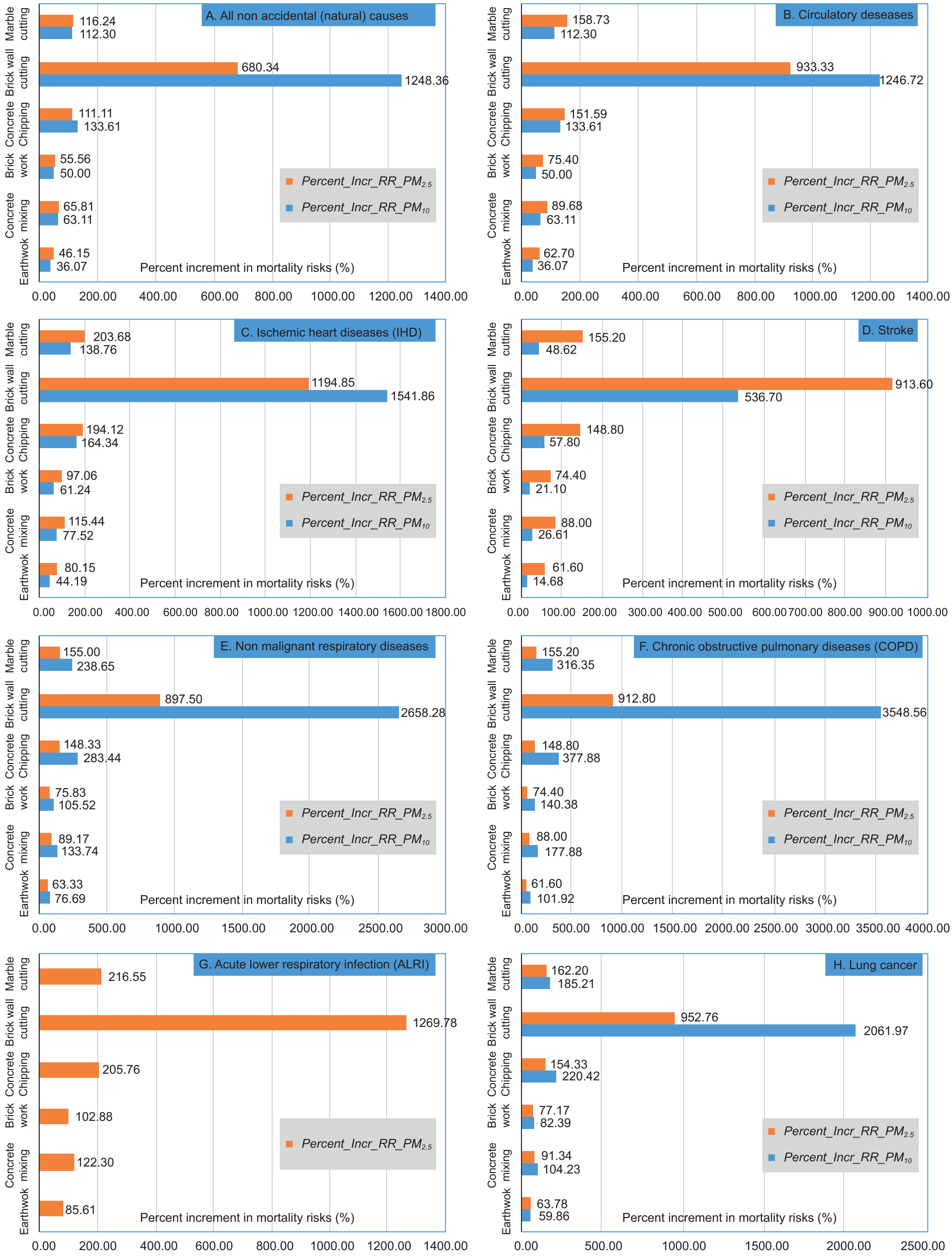

Fig. 7. Percent increment in all-cause and cause-specific mortality risks (relative risks) of construction workers compared to Kolkata City residents exposed to high PM_{10} and $PM_{2.5}$ concentrations.

The mortality risks of exposed construction workers are compared with average Kolkata City residents, and the results clearly show that PM exposure-associated mortality risks are alarmingly higher for Kolkata construction workers than for average city residents, ranging from 14.68 to 3548.56% higher for PM_{10}, and 61.60 to 1269.78% higher for $PM_{2.5}$. The situation demands immediate control and mitigation measures at the site level and policy-level interventions.

The results obtained in this study are based on data collected from six construction sites in Kolkata. Results obtained from a wider range of construction sites from different regions of the country with varying climatic conditions could provide deeper insight into the PM exposure pattern and associated health risks. Along with the two sizes of PM (PM_{10} and $PM_{2.5}$) considered in this study, assessment regarding other PM species such as PM_4 and PM_1 during construction work are also required. These issues could be addressed during future research.

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