REVIEW ARTICLE

Indian megacities as localities of environmental vulnerability from air quality perspective

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Abstract: Large proportions of the Indian population live in megacities (e.g., Delhi, Mumbai and Kolkata), which are vibrant centers of economic opportunities and offering better quality of social life. Due to increasing migration to these cities, Indian megacities are constantly expanding, which subsequently leads to strain on the environment with a range of impacts at local, regional and global levels. During the last few decades the anthropogenic emissions of greenhouse gases (GHGs) and other air pollutants have increased substantially, resulting in worsening ambient air quality of these cities. With respect to time span the concern over air pollutants has also changed in Indian megacities. Concern over particulate matter, black carbon, NO_x and ozone has heightened recently due to their local and regional impacts on air quality and environmental (including public) health and also because they contribute to global climate change. Although authorities have implemented several measures to reduce air pollution and its impacts in Indian megacities, much more is yet to be done to improve their ambient air quality. This paper focuses on major air pollution and GHGs emission issues in Indian megacities and associated problems within the framework of their role in environmental vulnerability.

Keywords: emission inventory, human health, Kolkata, Delhi, Mumbai, air pollution

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1. Introduction

The world is experiencing the biggest beckon of urban growth in the human history. Urban areas have emerged as centers of global efforts to curb climate change and improve the air quality. In 2008, 50% of the world's population was living in urban areas and this trend is likely to continue in the foreseeable future. As projected by United Nations, most of the world urban population growth between 2000 and 2030 will be in urban areas of developing countries and by 2030, 60% of the developing countries population will live in urban centers[1].

The striking offshoots of rapid and massive urbanisation are the megacities that emerged as a most visible physical sign of anthropogenic global change in the 20th century. In 1950, there were only two megacities, New York and Tokyo, with 12.4 and 11.3 million people respectively. By 2005, this number had increased to 20 and it is projected that there will be 22 megacities in 2015. Developing countries will have 17 of these 22 megacities in 2015[2]. Higher population and population densities, utmost development dynamics, as well as extreme and multifaceted interaction of diverse demographic, social, political, economic and ecological processes are the general characteristics of these giant urban areas. Furthermore, exceedingly dynamic processes executing together in the same place and reinforcing themselves through mutual interaction and feedback make these urban centers more complex and vulnerable. In the case of Indian megacities, uncontrolled expansion, higher vehicular populations, harsh scarcity of supporting infrastructure, severe pollution load, intense emission of greenhouse gases (GHGs), and extreme socio-economic disparities are the common features. These megacities are prone to growing air pollution vulnerability because of pronounced industrial and vehicle populations, solid waste generation, and power plant augmentation. In relationship with this, air pollution vulnerability can be defined as the condition in which people face exposure towards a certain health risk due to increasing air pollution.

The Indian megacities (Delhi, Mumbai and Kolkata) are the key centers of growing Indian economy. The last two decades are an onlooker of rapid increase in Indian urban population because of leading economic growth. According to the census of India[3], about 17% of the total Indian population was living in urban areas in 2001; this had increased to 31% by the year 2011[4]. The total number of inhabitants in the three Indian megacities is about 5% of the total national population (Figure 1). This trend of ongoing population explosion has placed a great strain on the environment and air quality of the megacities because of overburden on supporting infrastructures.

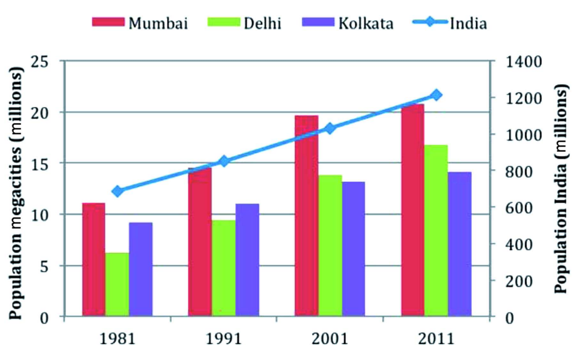

Figure 1. Population trends in India and megacities.

In view of the discussion above, it can be emphasized that air pollution is a serious and widespread problem in Indian megacities. Air quality of these urban areas is becoming poorer due to increasing vehicular, industrial, power plant and dust emissions. All these in turn lead to adverse effects on the health of people. The World Health Organisation (WHO) air quality guidelines are regularly being exceeded in Indian megacities to a great extent. Thus, Indian megacities are among the most polluted cities in the world and are paying heavily, both in terms of health and economic price for it[5].

2. Air Pollution in Megacities and Climate Change

Megacities in India are extremely diverse, with a wide variation in the air pollution sources, vulnerable population, fuel mix, industrial cluster, critical pollutants, climate and demography. Megacities have experienced an intense demand for fossil fuels to support their infrastructures which in turn has led to increased air pollution and GHGs emissions. Air pollutants and GHGs emissions originating from Indian megacities are recognised as increasing sources of regional and global-scale pollution[6].

Delhi was among the top five SO_2-emitting megacities of the world in the early 1990s. Thermal power plants and the transport sector were the prime culprits for it[7]. Garg *et al.*[7] estimated that emissions of SO_2 (in terms of per km^2) decreased from 48 to 47 Mg between the years 1990 to 1995. In terms of suspended particulate matter (SPM), Delhi ranked the fourth most polluted city in the world[8]. Gurjar *et al.*[9] and Reddy and Venkataraman[10] estimated that 15% of Delhi's respirable suspended particulate matter (RSPM) emission results from automotive traffic. Gurjar *et al.*[9] estimated the emissions of CH_4, CO, CO_2, N_2O, NH_3, non-methane volatile organic compounds (NMVOC), NO_x, SO_2 and total suspended particulate (TSP) from different sectors in megacity Delhi. They observed that emissions of most of the pollutants have increased during 1991 and 2000 in megacity Delhi. CO emissions increased from 361 Gg in 1990 to 503 Gg in 2000 (39% increase). N_2O and NH_3 emissions ranged from 1.4–1.7 and 10 Gg/year, respectively, in Delhi. NMVOC emissions showed an increase of 55% with 148 Gg in 1990 to 229 Gg in 1999. Similarly, SO_2 emissions showed an inter-annual variability, with values ranging between 90 and 113 Gg whereas TSP emissions in Delhi increased from 131 Gg in 1990 to 150 Gg in 2000 (15%). With respect to GHGs emissions, Delhi lies among the top emitter districts of India[11]. Anthropogenic sources contribute about 26.52 Tg of CO_2 in Delhi. According to Gurjar *et al.*[9], CO_2 emissions increased from 17 Tg in 1990 to 22 Tg in 2000 (increase by 30%). Power plants, transport and domestic fuel combustion were identified as significant emission sources. Similarly, CH_4 emissions increased about 40% from 133 Gg in 1990 to 192 Gg in 2000 in megacity Delhi. In the case of NO_x, emissions increased from 94 Gg in 1990 to 161 Gg in 2000. With respect to per capita emissions of GHGs and other pollutants, Delhi was the highest emitter during 1990 and 1995 (Figure 2).

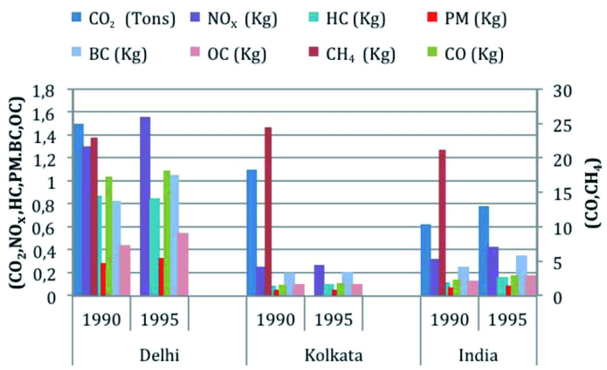

Figure 2. Per capita emissions of GHGs (CO_2; CH_4) and other air pollutants (NO_x; HC; PM; BC; OC and CO) in Delhi, Kolkata and India[42].

Mumbai is the financial and commercial capital of India with only 1% of the country population. However, it produced 17% of Indian GDP and contributed 25% of industrial output and 70% of capital transactions to India's economy in 2009[12]. Expansion of industries, increased foundry production and vehicular population has led to a severe air pollution problem in Mumbai. The World Bank suggests that in Mumbai, NO_x emission is rapidly increasing due to the rising vehicular and industrial population. It was estimated that during the years 1992–1993, annual NO_x emission was 37 Gg[13] where transport sector emerged as the major contributor. Garg *et al.*[7] stated in his study that the megacity Mumbai was the largest emitter (0.51 Tg) of CH_4 in 1995. It contributed almost 2.7% of the total CH_4 emitted in the country. Similarly, in the case of N_2O emissions, Mumbai was among the top five districts of India. The National Environmental Engineering Research Institute[14] estimated that the annual anthropogenic particulate emission in Mumbai was 16.5 Gg/year and Bhanarkar *et al.*[15] revealed that during 2000, Mumbai had significantly high SO_2 emissions in comparison to other South Asian and Southeast Asian megacities, with the emissions exceeding 200 Gg SO_2/year. Garg *et al.*[7] reported that among all the districts in India, Mumbai was the third largest emitter of SO_2 in terms of emission per unit area with 71,395 and 67,356 Gg/year in the years 1990 and 1995, respectively.

In 2004, Kolkata was the second largest metropolis in South Asia and was considered as one of the worst-polluted cities of the world[16]. It has been experiencing problems related to air pollution in all its severity over the past decades[17,18]. The air pollution problem of Kolkata is more serious because of less availability of open space for diffusion of air pollutants. About 2.4% of the Indian population was living in Delhi and Kolkata in 1990 while both cities contributed about 5% of the total national CO_2 emission in the same year. The CO_2 emission increased to 5.2% in 1995 and decreased to 4.7% in 2000 even though country level proportion of combined urban population of Delhi and Kolkata increased to 2.7% and 2.9% in 1995 and 2000, respectively[19]. In the case of CH_4 emissions, these cities' share was 2.5% of national emissions. Figure 2 shows the per capita emissions of GHGs and other pollutants in Delhi, Kolkata and India. It indicates that in 1990, the per capita emission of CH_4 in Kolkata was higher than that in Delhi and India while the per capita emission of CO_2 was highest in Delhi.

The air quality monitoring data of the Central Pollution Control Board (CPCB) indicates the real picture in Indian megacities (Figure 3). Between 1960 and 1980, SO_2 was considered the most critical pollutant[20]. However, it is observed that SO_2 concentration has been reduced in the recent years. Long-term data shows that SO_2 is under control in all three megacities (Figure 3), below the National Ambient Air Quality Standards (NAAQS) value. Substantial growth in SO_2 concentration has been noticed during 1991–1993 and 1995–1999 in Kolkata. Uncontrolled burning of coal and fossil fuels in industry and power plants might be held responsible for these trends in Kolkata. Significant changes in the urban fuel matrix, like low-sulfur diesel and Compressed Natural Gas (CNG) for transport sectors, the shift from biomass-based fuels to liquefied petroleum gas (LPG) and from coal to kerosene as a cooking fuel, have largely contributed in lowering SO_2 levels in megacities[20]. Because of effective implementation of such policies to reduce SO_2 emissions it is no longer a pollutant of concern in Indian megacities.

Conforming to the global trend, NO_x is emerging as the new challenge for Indian megacities. Vehicular emissions appear as significant source of NO_x in Indian megacities[76–80]. It is a highly reactive gas and has greater adverse health impacts. NO_x concentration trend shows a distinct rise after 2003 in Delhi and Mumbai and after 2005 in Kolkata (Figure 3). It exceeds the annual average standard at several occasions and locations. The high rise in ambient NO_x concentration has been noticed between 2000 and 2002 in Kolkata. Higher vehicular activities and uncontrolled fossil fuel burning in small-scale industries might be responsible for this growth in Kolkata.

The suspended particulate matter (SPM) concentration is at persistently high levels in all three megacities. Figure 3 reveals that SPM levels are above the standards in all three megacities. Although various interventions have taken place to mitigate ambient SPM levels, they have been dwarfed by emissions from constantly increasing vehicular population. The vehicles and windblown dust have been found as one of the major sources of SPM in megacities.

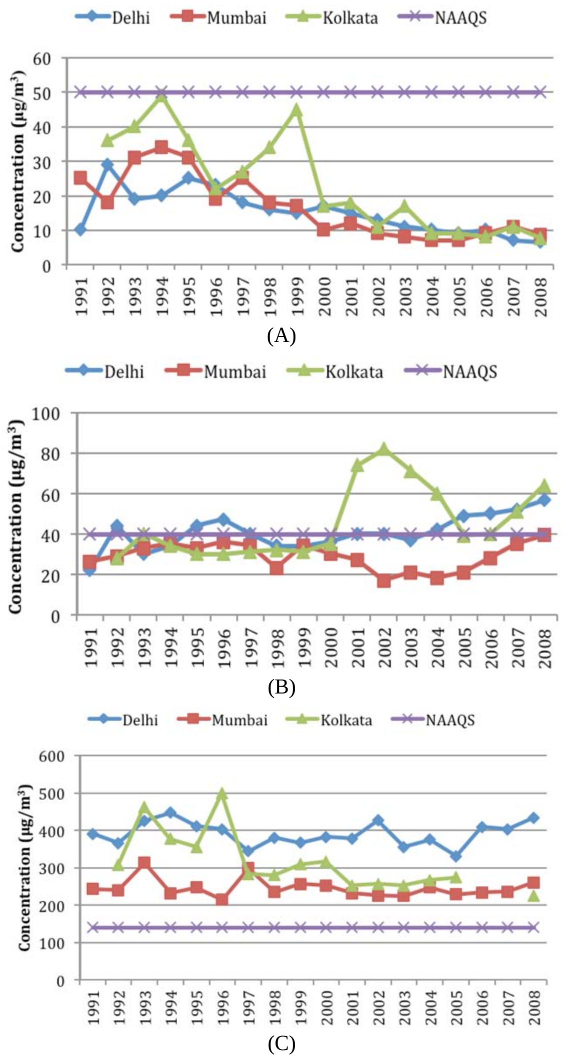

Figure 3. Trends of annual average concentration of (A) SO_2, (B) NO_x and (C) SPM in the Indian megacities Delhi, Mumbai and Kolkata.

3. Sources of Air Pollution and GHGs Emissions in Indian Megacities

Air pollution has become a serious problem in Indian megacities. It is not only changing the local climate and the environment but also negatively affecting the economy and public health. There are several sources of air pollution and GHGs emissions in Indian megacities but they vary according to the infrastructure, social aspects and economy of each megacity. Nevertheless, the main sources of air pollution are power plants, industries, motor vehicles and domestic sources[21–24]. While industrial air pollution is localised, automobile sources and power sector have emerged as the most significant contributors to regional air pollution. As per the census of India, Delhi households (HHs) are having the highest two-wheeler ownership, which is about 39% HHs, followed by 17% HHs in Mumbai and 12% HHs in Kolkata. Similar trends have been observed for car ownership. About 21% of Delhi HHs owned cars while 13% of HHs in Mumbai and 9% of HHs in Kolkata owned cars[3]. According to Gurjar *et al*.[9], in Delhi thermal power plants were the major sources of SO_2 and TSP from 1991 to 2000 while the transport sector contributed most to NO_x, CO and non-methane volatile organic compounds (NMVOC) emissions (80%). Furthermore, while CO_2 was largely emitted by power plants in the past (about 60% in 1990 and 48% in 2000), the contribution by the transport sector significantly increased (27% in 1990 and 39% in 2000). Furthermore, as per Guttikunda *et al*.[25] estimations, the transport sector dominates most of the direct and indirect emissions. Re-suspension of road dust is a major contributor for particulate matter (PM), followed by power plants and vehicular emissions. Similarly, in the case of SO_2, power plants and industries are the dominating sources while for NO_x, CO and NMVOC, vehicular emissions are the major source (Figure 4). A study conducted by the government of Delhi[26] showed that CO_2 emission from different sectors in Delhi was about 26 Tg during 2007–2008. Thermal power plants (TPPs) were the major point sources of CO_2 emissions in Delhi. The total CO_2 emission from these thermal plants in the year 2007–2008 was about 10 Tg (Figure 4). Ramachandra and Shwetmala[27] stated in their

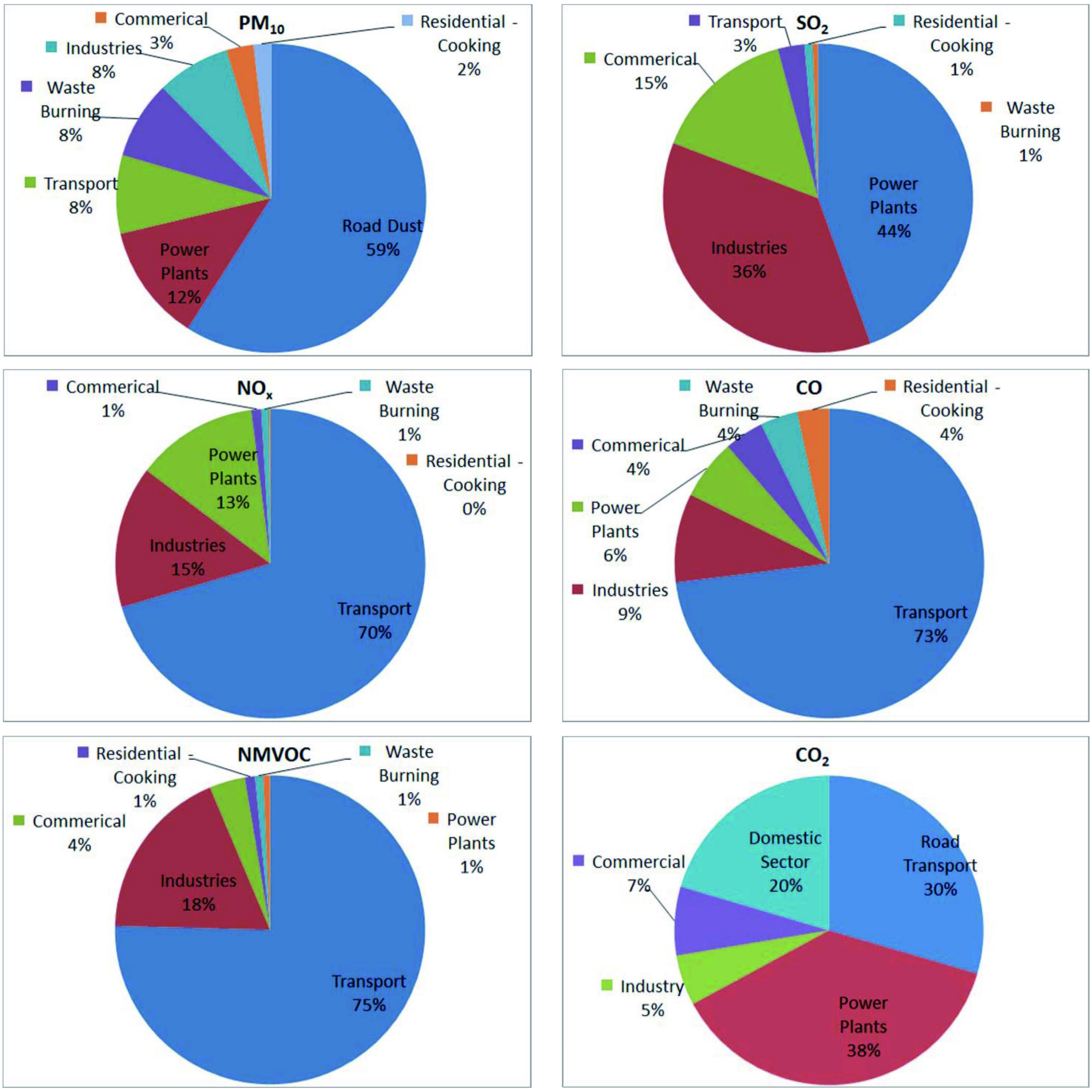

Figure 4. Contribution of different sectors for emissions of PM_{10}, SO_2, NO_x, CO, NMVOC and CO_2 pollutants in megacity Delhi[37].

study that vehicle transport in Delhi had contributed about 221 Gg of CO_2, 16 Mg of CH_4 and 130 Mg of NO_x in the area of one km^2. According to a recent study conducted by the CPCB[28], the predominance of private vehicles, especially cars and two-wheelers, is causing high GHGs emissions in Delhi. The CPCB[28] did a source apportionment study for various pollutants in megacity Mumbai. According to this study, particulate matter (PM) is mainly contributed from area sources (~37%) like bakeries, hotels, construction activities, etc. These area sources also contribute to ~69% and 68% of HC and CO concentration in the city. Industries (point source) contribute up to ~94% of SO_2, followed by a ~48% contribution to the total NO_x and 28% of PM. PM contributions are well distributed amongst vehicular, industries and road dust categories (~35%).

Figure 5 shows a clear picture of the source apportionment study of Mumbai. According to Guttikunda *et al*.[29] Kolkata was at the fourth position in terms of SO_2 emission among South Asian megacities for the period from 1990 to 2000. From 1980 to 1997, industries and power plants were the main sources. According to the West Bengal Pollution Control Board

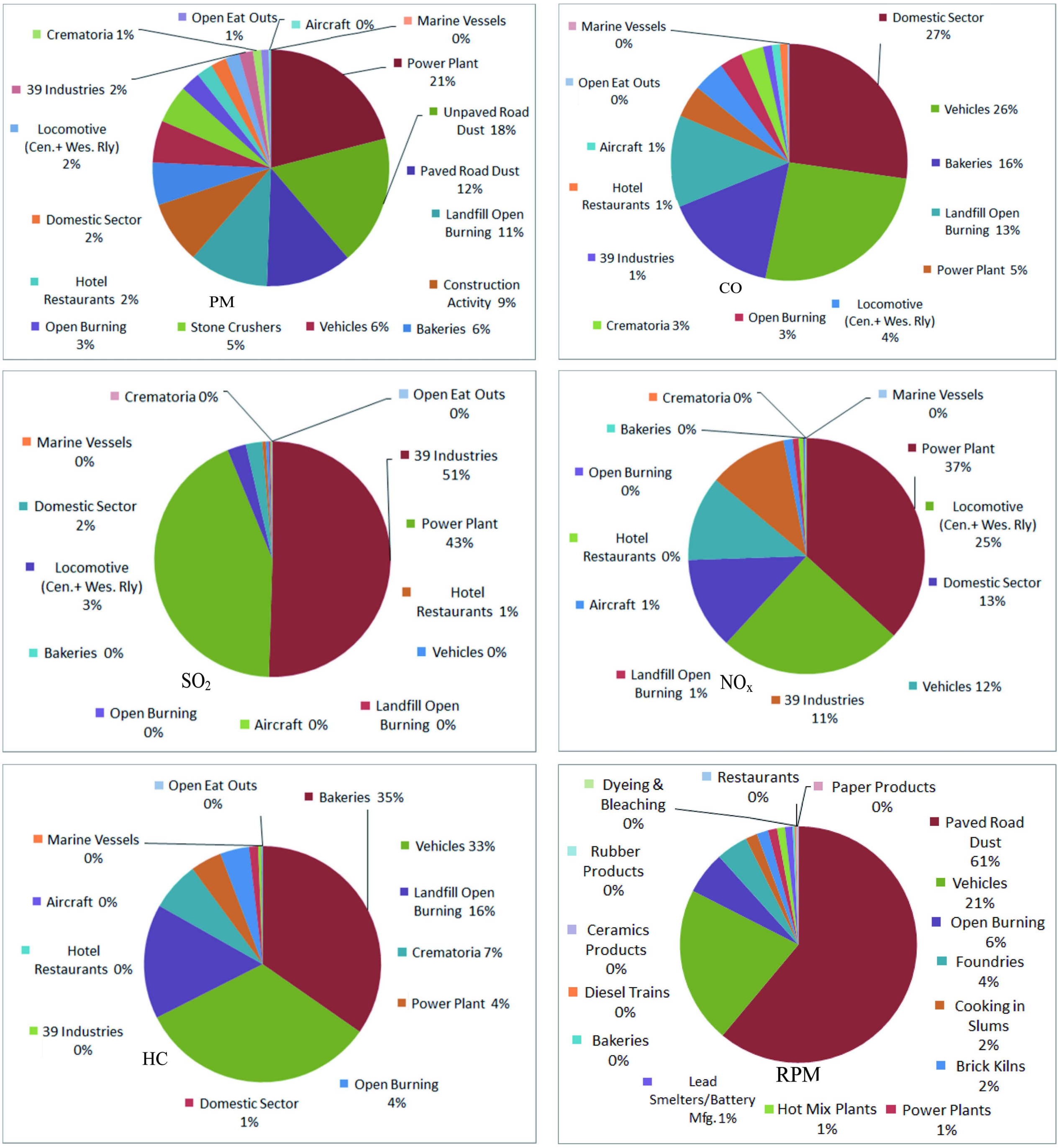

Figure 5. Contribution of different sectors for emissions of PM, CO, SO_2, NO_x, HC in megacity Mumbai[14] and RPM in Kolkata.

(WBPCB)[30], the presence of high-level particulate matter in the ambient air is a major problem for the megacity Kolkata. The major sources of air pollution in Kolkata are industrial emissions and automobile emissions. Asian Development Bank (ADB)[31] estimations suggest that for RPM (Respirable Particulate Matter), paved road dust is the major contributor in megacity Kolkata, followed by vehicles and open burning (Figure 5). ADB also suggests that in the case of NO_X. vehicles (74%) are the major source of NO_x, followed by industrial sources (26%). Ghose *et al*.[16] stated that approximately 70% of the total pollution load of the city is contributed by vehicles in Kolkata. Garg *et al*.[11] revealed in their study that in Delhi, Mumbai and Kolkata, large point source emissions contribute more than 50% to their individual CO_2

emissions, more than 80% to methane emissions and more than 70% to SO_2 emissions.

Black Carbon Emissions and Sources in Indian Megacities

Black carbon (BC) has been identified as a driver of important regional climatic impacts. It is directly accountable for the lessening of incoming short-wave solar radiation at the Earth's surface, and responsible for a rising atmospheric temperature[37–39]. Studies have identified Indian megacities as a very large source of BC emissions from contained combustion (such as combustion in engines, stoves, and kilns). BC emissions from megacities are also a major contributor to several large regional masses of haze or so-called atmospheric brown cloud (ABC)[32]. The South Asian ABC has important regional climate impacts in Asia. Due to extensive indoor and outdoor emissions of BC and its co-emitted pollutants, these are the third-leading contributors to the burden of disease in South Asia[32,33]. According to Venkataraman *et al.*[34], combustion of solid biofuels such as wood, agricultural waste and dried animal manure in cooking stoves, is the largest source of BC emission in India. BC emission was estimated as 1134 Gg/year in 2001 and reached up to 2293 Gg/year in 2011 from all sources in India[35]. Figure 6 shows the contributions of different sectors for BC emissions in India during the years 1991, 2001 and 2011. Maximum BC emission growth is found over the Indian Gangetic Plane which accounts for only 15% of the Indian geographical region but contributes more than 35% of India's total BC emission[35]. According to Beig[35], Delhi, Mumbai and Kolkata are having certain pockets or areas where emissions of BC are 20.01 to 62.98 Gg/box/year), which is the highest value in the whole country. Nevertheless, there are very few BC concentration measurements studies available for the Indian megacities. As per Venkataraman *et al.*[34], the average BC concentration in Mumbai was 12.5 μg/m^3 in 1999. Similarly, Rai *et al.*[36] suggest that during the years 2001–2002, BC concentrations at different sites of Delhi varied from 6.7 to 26.9 μg/m^3. Recently, Bano *et al.*[37] published their study and according to them, BC emissions in Delhi during 2006 ranged between 5.7 and 30.3 μg/m^3. According to Bano *et al.*[37], the annual average BC concentration in Delhi from January to December 2006 was 14.75 μg/m^3, which is very high compared to other Indian urban areas. The higher concentration over Delhi may be attributed to the greater influence of vehicular and industrial emissions[40]. Mitra *et al.*[40] estimated BC emissions from the energy sector in Delhi and Kolkata. According to their estimations, the transportation sector is one of the major contributors of BC emissions in Delhi and Kolkata. According to their analysis, emissions of BC from gasoline consumption in Delhi has increased from 0.5 Gg to 0.6 Gg during the years 1990–1995, and for diesel consumption it increased from 7.3 Gg to 11.5 Gg. For Kolkata their estimations suggest that BC emissions from gasoline consumption had increased from 5 Mg to 6 Mg during the years 1990–1995, while for diesel consumption it increased from 2.36 Gg to 3.00 Gg during the same period. Sahu *et al.*[41] suggested that increasing vehicle population and a higher demand of energy are responsible for high concentrations and high emissions of BC in Indian megacities.

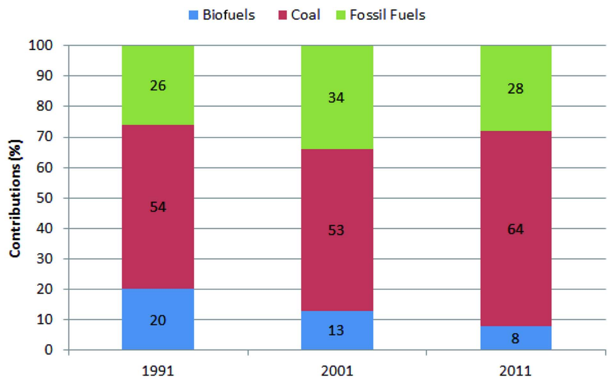

Figure 6. Contributions of various sectors for black carbon emissions in India[6].

4. Impact of GHGs Emission and Air Pollution in Megacities

Increasing GHGs emissions and air pollution episodes continue to pose a significant threat to local, regional and global environment and human health in Indian megacities. Their impact is gradually seen to be increasing with respect to smog, fog episodes, hydrological cycle, agricultural productivity, biodiversity, temperature, irregular rainfall, and an increase in the frequency of droughts and floods[41–46]. These impacts are not restricted locally but also significantly influence the regional economy, and the social, political and cultural environment.

4.1 Environmental Vulnerability

Increasing GHGs emissions and associated climatic impacts have resulted in major vulnerability issues and problems in Indian megacities. According to Nair's[47] analysis of rainfall in the Indian megacities during the last 50 years, there is no significant trend in the annual rainfall. Instead, its seasonal variation and changes in intensity causes reduction in ground water level and increase in the salinity of aquifers in the coastal megacities of Mumbai and Kolkata. In July 2005, Mumbai faced severe problems because of heavy rainfall (94 centimeters of rain in 24 hours), which resulted in 1000 deaths[48]. This event underscores the vulnerability to climate hazards faced by Mumbai[47,49,50]. The coastal cities of Mumbai and Kolkata are under threat from the predicted sea level variations. Occurrences of heat waves and cold waves have emerged as a routine phenomenon in Delhi, which is significantly affecting human health, especially for poor people. Nair[47] and Bhattacharya *et al*.[51] have observed that malaria-endangered area is likely to extend to Mumbai in the near future.

As discussed in earlier sections, escalating air pollution emissions due to immense consumption of fossil fuels and other activities in Indian megacities are causing cumulative impacts on their local environment. Elevated levels of ozone in megacities cause major air quality and environmental problems. Ground level ozone not only affects the human health but also severely damages vegetation and crops[52–57]. According to Guttikunda[58], increasing emissions in Delhi are leading to an increase in ground level concentration of ozone pollution. The impact of the ozone pollution is particularly high during forenoon rush hours, when the sunlight catalyses the interactions between NO_x and volatile organic compounds (VOC) to boost the production of ground level ozone[58,59]. Ground level ozone is very harmful for the human respiratory system. Acute bronchitis, asthma and chest pain, coughing, eye irritation, nausea, headaches and chest congestion are prime symptoms of ozone-caused diseases. Jain *et al*.[60] observed that the monthly average maximum ozone concentration in Delhi was 62–95 ppb in dry summer (April to June), whereas it was found to be 50–82 ppb in the autumn (October to November). Their analysis suggests that most of the time, surface ozone values at Delhi exceeded the World Health Organisation (WHO) ambient air quality standards (hourly average of 80 ppb) for ozone. Purkait *et al*.[61] analyzed concentrations of ozone and its precursors in megacity Kolkata. According to their observations, ozone levels in Kolkata are below threshold level but these levels are also responsible for eye irritation of local inhabitants. The ozone concentration level is at its maximum during autumn and winter and at its minimum during monsoon in Kolkata. Mittal and Sharma[62] conducted a study over all three Indian megacities for measuring the concentration of ozone. According to their observations, the concentration of ozone in Delhi was between 60 to 89 parts per billion by volume (ppbv), while in Kolkata the concentration was between 60 to 90 ppbv and in Mumbai the concentration was between 60 to 90+ ppbv.

Impact of Black Carbon

Global warming and ozone depletion are the major problems associated with air pollution, which adversely affect the global climate change. Atmospheric brown clouds (ABCs) are the new problem identified by researchers, which encompasses complex inter-linkages of several issues, including air pollution, haze, smog, and global warming[63]. In the atmosphere, BC reacts with other aerosols such as sulfates, nitrates, numerous organic acids and dust[64], and together the mix of such particles is referred to as atmospheric brown cloud[65]. BC absorbs the solar radiation reflected by the Earth's surface and clouds, which would have otherwise escaped to space. Because of their short lifetimes (days to weeks), ABCs are concentrated in regional and megacity hot spots. Ramanathan *et al*.[65] and United Nations Environment Programme (UNEP)[66] identified 13 megacities affected, and Mumbai, Delhi and Kolkata are among them. According to UNEP, BC levels in these cities make up 10% of the total mass of all carbon particles in the atmosphere that result from human activities[66]. According to Ramanathan *et al*.[67], absorbing aerosols in atmospheric brown clouds in the South Asian region are playing a major role in the observed regional climate and hydrological cycle changes and have masked as much as 50% of the surface warming due to the global increase in greenhouse gases. Their observation also expresses the possibility that, if current trends in BC and aerosol emissions continue, the subcontinent may experience a doubling of its current drought frequency in the coming decades.

4.2 Health Impacts

According to the estimates of the WHO and the World Bank, there was an increase in premature deaths due to air pollution in Indian cities in the years 1992–1995.

Studies like those of Chhabra *et al*.[68], Cropper *et al*.[69], Joshi[70], Pachauri *et al*.[71], Gurjar *et al*.[72] have discussed the adverse effect of air pollution on human health in Indian cities. The WBPCB[73] observed that there is a huge difference in respiratory disorders between the population of Kolkata and other rural inhabitants. According to their survey, about 13.5% and 35% of the rural population are suffering from upper and lower respiratory tract symptoms respectively, while these figures are 41.3% and 47.8% in Kolkata[74]. Similarly, Kazimuddin and Banerjee[75] stated in their study that more than 10,000 premature deaths occurred in Kolkata in 1995 due to SPM. According to the Health Care Institute of India, there is an alarming rise in the number of patients with respiratory problems in Delhi hospitals[39]. The lead (Pb) level in the blood was found to be 25.6 g/dL in Kolkata (compared with 6.0 g/dL in Tokyo)[16,81]. The CPCB conducted an epidemiological study for Delhi. According to their estimations, 33.2% of Delhi residents had one or more respiratory symptoms[82]. Lower respiratory symptoms (LRS) include recurrent dry cough, cough with phlegm (wet cough), wheezing, breathlessness on exertion and chest discomfort. Residents of Delhi had a 1.5-times greater prevalence of upper respiratory symptoms (URS) in comparison to the rural population. The prevalence of lower respiratory symptoms was 1.8-times higher among the residents of Delhi than their rural counterparts. The RSPM level was positively associated with lower respiratory symptoms (LRS)[82]. Lung function was reduced in 40.3% of all individuals in Delhi. Lung function reduction was more prevalent in women than in men, both in rural and urban settings of Delhi. Chronic obstructive pulmonary disease (COPD) was detected in 3.9% of the residents of Delhi, according to Central Pollution Control Board (CPCB)[82].

Gurjar *et al*.[9] developed a spreadsheet model, namely the "Risk of Mortality/Morbidity due to Air Pollution (Ri-MAP) model" to evaluate the direct health impacts of various criteria air pollutants present in urban air sheds. Here, the Ri-MAP model is applied in a case study to assess the health impacts of air pollution in Delhi, Mumbai and Kolkata during the period 1991–2008. The calculations take into account the effects of each pollutant individually, not considering the synergistic effects of two or more pollutants. The results obtained from the Ri-MAP model are presented below with respect to the megacities Delhi, Mumbai and Kolkata.

4.2.1 Total Mortality

The excess number of deaths (i.e., total mortality) in the megacities Delhi, Mumbai and Kolkata shown in Figure 7 has been calculated, taking into account the total sum of effects caused by the three criteria air pollutants TSP, SO_2 and NO_2. During 1991–2008, Delhi has been often associated with the highest number of total mortality cases. It is observed that there is an overall-increasing trend in incidents of total mortality in Delhi and Mumbai but it is not so for Kolkata.

4.2.2 Respiratory Mortality

Figure 7 shows the excess number of respiratory mortality cases estimated with the help of the Ri-MAP model owing to the total effect of the three pollutants considered (TSP, SO_2 and NO_2) in Indian megacities. A similar trend is observed for the excess number of respiratory mortality cases. Delhi shows the highest number of respiratory mortality cases during most of the time. The respiratory mortality incidents are increasing gradually in Delhi. The rising concentration of PM in Delhi might be responsible for that increasing trend.

4.2.3 Cardiovascular Mortality

Similar to the total mortality and respiratory mortality, cardiovascular mortality shows the same trend of excess number of cases. The number of excess cases of cardiovascular mortality was 3369, 2427 and 2954 in Delhi, Mumbai and Kolkata respectively in the year 1995. These figures became 5685, 3259 and 2393 in 2008 for the same cities.

4.2.4 Hospital Admissions due to Chronic Obstructive Pulmonary Disease (COPD)

As illustrated in Figure 7, the morbidity (hospital admission) cases due to chronic obstructive pulmonary disease (COPD) follow a pattern similar to that of cardiovascular mortality (Figure 7). Delhi has the highest annual average excess cases of 15,608 cases/year, while the figures for Kolkata (11,910 cases/year) and Mumbai (11,411 cases/year) are at the low end.

4.3 Socio-economic and Political Implications of Air Pollution

Experts suggest that the effects of air pollution and climate change may vary according to the socio-economic profile of the population. The impact of air pollution and its exposure with various socio-economic

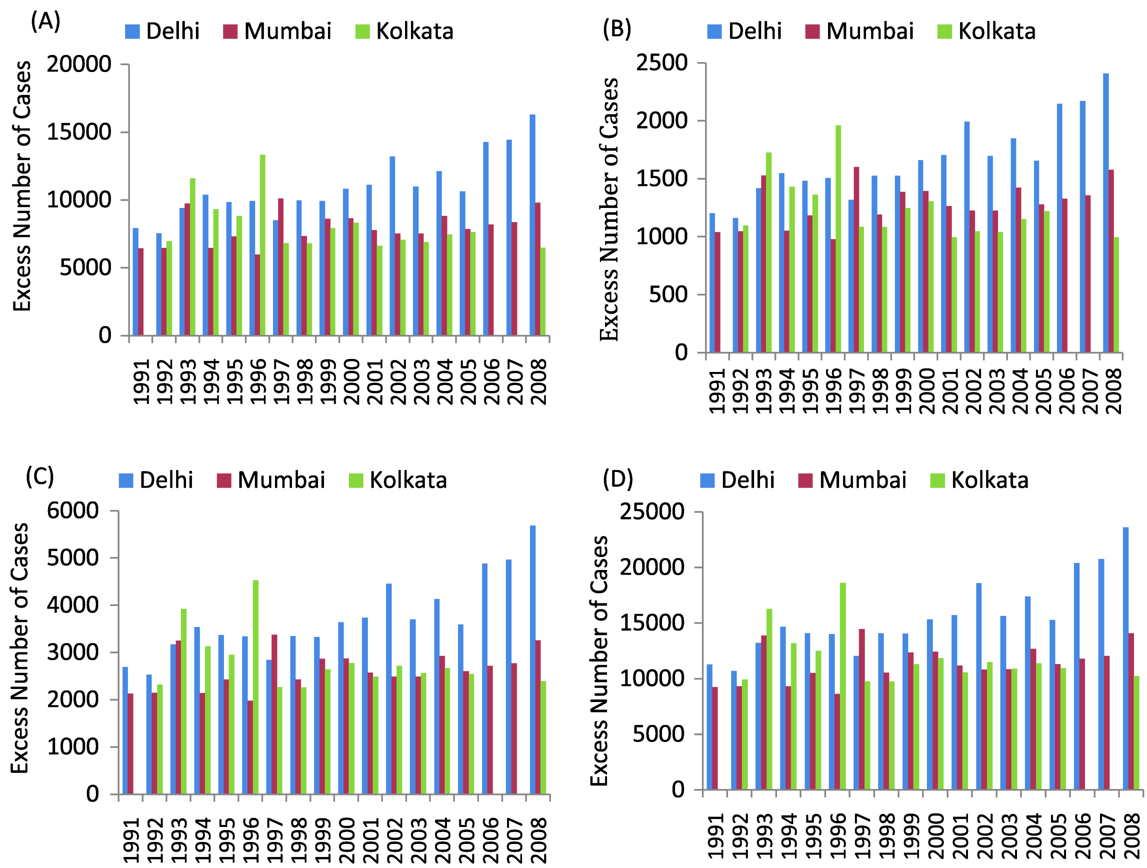

Figure 7. Excess number of cases of (A) total mortality, (B) respiratory mortality, (C) cardiovascular mortality and (D) hospital admission COPD in the megacities Delhi, Mumbai and Kolkata.

groups in India is not well studied, mainly due to the lack of suitable expertise and resources[83]. Nevertheless, Garg[84] has estimated the health benefits associated to different socio-economic groups in the population of Delhi, based on their income level. According to his estimations, social groups with a low and medium income in urban households have higher mortality rates (7.56 per 1000 persons in the low-income category, 4.8 in the medium-income category, and 4.61 in high-income category) and higher risks of suffering from asthma in comparison to those in the high-income category (18.82 for low-income, 12.98 for medium-income, and 11.14 for high-income). Lower income groups are exposed to higher concentrations of pollutants, and have higher baseline mortality and morbidity rates. Moreover there is unequal access to healthcare because of the expenditure required. All these factors contribute in reducing the capacity of lower income groups to deal with air pollution impacts on health[84]. It is also observed by Garg[84] that with respect to PM in Indian megacities, its sources are owned by higher income groups and their economic benefits also accrue to them, while the poor bear a disproportionately higher share of the resultant air pollution health burden.

Interestingly, air and water pollution are interlinked at several junctions of their cycles. For example, dry and wet depositions of air pollutants contaminate the water bodies, whereas gaseous and particulate emissions from wastewater treatment plants pollute the ambient air. Also, GHGs emissions from anaerobic digestion at the bottom of reservoirs and irrigated paddy fields contribute to climate change. Furthermore, an increasing impact of climate change and a high demand of water are significantly leading to water scarcity in Indian megacities. The gap between water demand and delivery has become a severe problem in Indian megacities and it is estimated that this situation will be worse in future[47]. The Intergovernmental Panel on Climate Change (IPCC) highlights that due to thermal stress and water scarcity in some regions in Asia, rice production could decline by nearly 4% by the end of the century and that substantial losses are likely in rain-fed wheat throughout

Southeast Asia. For example, a 0.5°C to 1.5°C rise in temperature would reduce wheat and maize yield potential by 2% to 5% in India. According to the WWF[85] climate change may affect the availability of food for Indian megacities.

For more than one decade, there has been a lively environmental debate along with a high degree of legislative activity in megacities and other cities of India. Air pollution in megacities and climate change are the prominent issues for the debate. It is the major policy issue for the higher level legislative bodies[86]. Due to worsening air pollution problems in Indian megacities, several local non-governmental organizations (NGOs), lawyers, and expert groups have joined hands to preserve the local environment[87]. Because of these activities, the Supreme Court of India directed the Delhi government to use Compressed Natural Gas (CNG) as an alternative fuel and implement its orders latest by March 1, 200l. Even though the implementation of this policy measure was not an easy task, this policy instrument along with other interventions such as the Metro, has recently improved the air quality of Delhi by significantly reducing particulate air pollution. However, due to constantly increasing vehicular population, air pollution levels at several locations still exceed the air quality standards prescribed by the CPCB.

5. Evaluation of Air Pollution and Climate Change Mitigation Strategies in Megacities

The period of the 1990s saw a rapid increase in pollution levels in Indian megacities. In fact, 1996 was considered the peak year in terms of air pollution load in megacities. The transport, industrial, thermal power plants and domestic sectors emerged as major contributors for increasing pollution in these cities. There are several policy measures taken by decision-making bodies to reduce air pollution and GHGs emissions in megacities. Since vehicular exhausts were identified as the major source of toxic emissions in megacities, a part of mitigation measures started in 1996 with reduced concentration of lead and benzene in gasoline. Similarly in 1998, the Supreme Court of India directed to replace the old auto-rickshaws and buses by new ones and to implement CNG for all new auto-rickshaws and buses in Delhi[88]. Looking at the slow progress in the implementation of the Court direction for CNG implementation, the Supreme Court of India again advised the government in March 31, 2001 to rapidly and strictly implement the CNG for all public transport in Delhi. In the same manner, on October 17, 2001, the Mumbai High Court ordered the phasing out of old commercial vehicles unless they are converted to run on LPG/CNG. So far various categories of old commercial vehicles have been phased out from the roads[89]. To reduce vehicular emissions, the government is scheduling more stringent emission norms in India, and large cities are their prime concerns. Recently in 2010, the implementation of the European Emission Standard Euro 4 in 11 cities of India is an example in this context.

To control industrial pollution in Delhi, the local government implemented some stringent rules for thermal power plants. Also, all stone crushers and hot mix plants have been closed down in Delhi and shifted to the outskirts of the city. As per the directions of the Supreme Court, 168 hazardous industries have been closed down in Delhi. The massive level of mass-awareness campaign was organized by the Delhi government with other groups to mitigate GHGs and air pollution in Delhi[89]. This helped in implementation of CNG in public transport system and commercial vehicles and also to adopt stringent emission norms in Delhi. Similarly, to reduce air pollution and GHGs emissions from the industrial sector in Mumbai, the government of Maharashtra implemented industrial location policy that relocated several industries outside Mumbai. Almost all the industries were provided with pollution control systems. All stone crushing and hot mix plants in Mumbai were shifted to the confirming zone. In Kolkata, the government has launched various policies to reduce emissions from the industrial sector. Some examples include stricter location policies for new industrial units, the mandatory use of clean fuels, and financial assistance for the installation of pollution control devices in small-scale industries[89].

6. Challenges and Opportunities of Climate Change and Air Pollution Mitigations in Megacities

There are various emerging challenges and opportunities that are important to be considered in the implementation and management of strategies to the improvement of air quality of Indian megacities, particularly in the context of their links with climate change and human health. Although measures have been taken in Indian megacities to improve the local and regional air quality and mitigate the climate change, these cities constantly face difficulties related to institutional and technological limitations. Economic constraints are one of the major challenges faced by cities to implement the advanced technologies to mitigate air pollution. In the case of Delhi, this has been experienced that multiple institutions with overlapping responsibilities result in chaotic and inefficient governance. A “no care” attitude (unless forced by the court of law), rapid and unplanned urbanisation, continued growth of the megacities[32], uncontrolled vehicular density on insufficient road space that is badly being cared for, lack of adequate parking facilities[75], low turnover of old vehicles with too frequent breakdowns, undisciplined drivers, and indifferent pedestrians together with a bad traffic management have taken the problems into a threatening stage[90]. These are in fact the major issues in megacities leading to the increasing air pollution[16, 73, 91–93].

Unaccountable interference and opposition of government policies by some groups having certain vested interests is also a major problem in megacities. For instance, the development of the Delhi Metro and the Bus Rapid Transit System (BRTS) faced tough opposition from certain local organizations/groups and media. Nevertheless, despite these obstacles, there are a large number of opportunities available in terms of implementing favorable policies for reducing air pollution to benefit the residents of these cities and also to mitigate their regional climatic implications.

7. Conclusion

The pressing air pollution and climate change issues associated with Indian urban agglomerations are closely linked problems sharing common causes and solutions. It is well known that air pollution and GHGs emissions are arising largely from the same sources in Indian megacities. Thus, co-benefits can be accomplished if one targets to reduce air pollution or GHGs emissions. Undoubtedly, it is the necessity of pursuing and coordinating among the researchers, regulatory bodies and policy makers that can support mitigating policies to achieve multiple benefits. The present study brings together the issues of air pollution, GHGs emissions, sources, impacts and many other consequences of air pollution and GHGs emissions in Indian megacities to understand their vulnerability in terms of local and regional scale impacts on air quality, environment, economy and human health. Although this paper has focused on the megacities in India (Delhi, Mumbai and Kolkata), the overall study indicates the status of urban emissions and their impacts in developing nations. Moreover, although measures to mitigate air pollution and GHGs emissions in Indian megacities are based on the best available scientific knowledge, the public participation, proper management, political will and capacity are prerequisites to transform these options into actions. In summary, air pollution problems and associated multiple effects in Indian megacities necessitate a great deal of integrated efforts from different walks of society that must be maintained to protect the environment and benefit the public welfare in a sustainable way.

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