Air Pollution, Climate Change, and Human Health in Indian Cities: A Brief Review

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Climate change and air pollution have been a matter of serious concern all over the world in the last few decades. The present review has been carried out in this concern over the Indian cities with significant impacts of both the climate change and air pollution on human health. The expanding urban areas with extreme climate events (high rainfall, extreme temperature, floods, and droughts) are posing human health risks. The intensified heat waves as a result of climate change have led to the elevation in temperature levels causing thermal discomfort and several health issues to urban residents. The study also covers the increasing air pollution levels above the prescribed standards for most of the Indian megacities. The aerosols and PM concentrations have been explored and hazardous health impacts of particles that are inhaled by humans and enter the respiratory system have also been discussed. The air quality during COVID-19 lockdown in Indian cities with its health impacts has also been reviewed. Finally, the correlation between climate change, air pollution, and urbanizations has been presented as air pollutants (such as aerosols) affect the climate of Earth both directly (by absorption and scattering) and indirectly (by altering the cloud properties and radiation transfer processes). So, the present review will serve as a baseline data for policy makers in analyzing vulnerable regions and implementing mitigation plans for tackling air pollution. The adaptation and mitigation measures can be taken based on the review in Indian cities to reciprocate human health impacts by regular air pollution monitoring and addressing climate change as well.

Keywords: air pollution, climate change, aerosols, urban, India, health

INTRODUCTION

Air pollution and climate change are major threats to rapidly growing cities in present times. The developing nations like India, which are switching from predominantly rural country to increasingly urban, have to face critical challenges in terms of climate action and sustainable development (Van Duijne, 2017; Singh C. et al., 2021). India is projected to have 53% of the national population as urban population by addition of 416 million urban dwellers by the year 2050 (UNDESA, 2018).

The change in land use land cover patterns in urban areas due to ongoing urbanization affects regional climate by altering the surface and boundary layer atmospheric properties (Shepherd, 2005; Ren et al., 2008; Yang et al., 2012). Further, the urbanization by changing land use land cover affects climate via increased anthropogenic emissions, extreme precipitation (that may cause
urban flooding), higher temperatures, and frequent heat waves with heat related human health impacts (Chestnut et al., 1998; Ramanathan et al., 2001; Shastri et al., 2015). The regional climate changes are reflected by different meteorological conditions such as changes in temperature and precipitation. The anthropogenic emissions such as greenhouse gas (GHG) emissions trigger these local climate changes.

In addition to the impact of urbanization on climate, the increasing urban population and vehicular traffic increases the pollutant emissions and aerosol load in the atmosphere. The increasing urbanization along with growing population and industrialization has been stated as one of the key reasons for high aerosol loading in the Indian sub-continent (Kaskaoutis et al., 2011; Ramachandran et al., 2012; Krishna Moorthy et al., 2013). Thus, the climate change and air pollution remain one of the biggest threats to human health and well-being in cities and are interlinked with each other as discussed later in this study.

According to a report by World Health Organization (WHO) more than seven million people across the world lose their lives due to diseases linked with PM$_{2.5}$ pollution (WHO, 2015). India, being a rapidly developing country with increasing population is suffering from severe air pollution; as among the world’s most polluted cities, nine of them lie in India [WHO Global Urban Ambient Air Pollution Database (Update 2016), 2016]. The increasing air pollution in most of the Indian megacities over last few decades and its consequential human health impacts (such as asthma and cardio-respiratory illness) have drawn prominent attention in recent years (Sarath and Ramani, 2014; Gautam et al., 2020; Shaw and Gorai, 2020).

CLIMATE CHANGE

The global change in climate has been reported by various workers in the last few decades. The natural process of climate change because of volcanic eruptions, continental drift, and astronomical cycles is now accelerated by human activities (IPCC, 2007). The emission of greenhouse gases (GHGs) is one of the major factors in altering climate by changing atmospheric concentration of certain gases. Further, the role of water vapors in altering the climate is also being well looked into by scientists (Jacob, 2001; Forster and Collins, 2004). Not only this, scientists are also looking into the role of black carbon in climate change due to their ability to strongly absorb incoming solar radiations (Jacobson, 2001; Ramanathan and Carmiche, 2008; Surendran et al., 2013). Menon et al. (2002) used a global climate model to investigate the role of aerosols in altered climate in India and China and reported that precipitation and temperature changes in the model could be correlated to large load of absorbing black carbon in the aerosols. Also, due to heating of air by black carbon aerosols, atmospheric stability is altered leading to changes in hydrologic cycle and large-scale circulations.

Climate change is known to alter the temperature, precipitation pattern and solar insolation over the planet. According to IPCC (2007) report, about 0.65°C increase has been observed in global average surface temperature over last 50 years and is projected to increase by 1.1–6.4°C. The rise in sea level has been observed with ongoing warming trend. Annual sea level rise between 2.5 and 3 mm along the coastline of Mumbai has been reported (Pramanik, 2017). Also, according to a study by NASA, this region has possessed increase in average temperatures by 2.4°C for the period from 1881 to 2015 (NASA, 2015). Further, an increase in frequency of extreme rainfall was analyzed that can cause flooding. This can also be seen in Mumbai, one of the Indian mega-city and home to the largest population threatened by coastal flooding (Intergovernmental Panel on Climate Change IPCC-SREX, 2012). Mumbai has been recognized as one of the world’s most vulnerable cities to climate change according to UN-HABITAT, 2010 (Mehta et al., 2019). The changes in rainfall in the past century (1901–2019) were observed over India by Kuttippurath et al. (2021). In the study of 119 years of rainfall measurements, a significant change in the rainfall pattern has been confirmed after 1973 with the declining trend of about 0.42 ± 0.024 mm dec$^{-1}$. The study shows that in recent decades, the wettest place of the world has shifted from Cherrapunji to Mawsynram.

Besides, the increasing temperature due to climate change can trigger melting of glaciers. A study conducted by Kumar et al. (2021) for monitoring glacier changes in Nanda Devi region of Central Himalaya, India, for three decades, shows the loss of about 26 km$^2$ (10%) of the glaciated area between 1980 and 2017. Additionally, the climate change causing extreme weather events causes increase in frequency and intensity of floods, storms, torrential rains, and droughts etc. that take thousands of lives and affect millions of people (Haines et al., 2006; Majra and Gur, 2009). The projected climate change estimates from 2036 to 2060 for 57 Indian cities show that 33 cities are likely to experience rise in extreme rainfall and exacerbated flood risk. The remaining 24 cities will observe precipitation declines, reflecting higher drought risk (Ali et al., 2014; Singh C. et al., 2021).

The land use land cover being an important factor in climate change has been focused in many studies over Indian cities such as Nath et al. (2021) that shows rapid expansion of built-up areas in Guwahati with an overall increase of 103% in area over the last 30 years (1990–2020). The expansion in urban areas causes decline in vegetated areas, cropland, and fallow land thereby contributing to climate change. Paul et al. (2021) also showed expansion in urban areas at annual rates of 38.6% with decline in agricultural area at rate of 2.1% for peripheral Delhi during the 1973–2017. So, climate change is one of the emerging threats to human health in Indian cities. With the increase in climate variability, there is an associated increase in health issues (Bush et al., 2011). Cities, due to UHI occurrence, are supposed to have higher effect of climate extremes such as precipitation extremes and heat waves than rural regions (Shepherd, 2005; Shastri et al., 2017; Chauhan and Singh, 2020).

Human Health Impacts Associated With Climate Change

The adverse impacts of climate change on human health have been documented in several studies and these effects are expected to increase with future climate change (Luber and McGeehin, 2008; Bell et al., 2018; Filippelli et al., 2020). The climate change
affects human health by problems induced from notable extreme weather conditions such as increased temperature, precipitation, increased intensity and frequency of heat waves, floods, droughts, strong winds, and landslides (Orimoloye et al., 2019). The change in temperature and precipitation causing severe heat, extreme cold, and unpredictable rain linked with climate change increases health related issues; as these climatic changes further induces water and air-borne infections, vector borne-infections, malnutrition, incidence of diarrhoeal diseases, and heat related morbidity and mortality (Haines et al., 2006; Dutta and Chorsiya, 2013).

Children, elderly people, and urban residents are more vulnerable to these health impacts (Haines et al., 2006; Ebi and Paulson, 2010; Filippelli et al., 2020). Nearly 150,000 deaths and about 5 million illnesses have been reported per year due to climate change (Dutta and Chorsiya, 2013).

The respiratory infections, chronic obstructive pulmonary disease, pneumothorax, asthma, allergies, hyperthermia, and dehydration are some of human health issues associated with climate change either directly or indirectly (D’Amato et al., 2011; Filippelli et al., 2020). About 6% of children in India are prone to respiratory tract infections and 2% of adults in India are also trapped in asthma disease (International Institute for population sciences (IIPS) Macro International, 2007).

Thus, these extreme weather conditions have adverse health impacts that can also result in loss of lives. If we look at the extreme heat related human health effects, it becomes imperative to understand the effects of rising temperature on biota.

The increase in temperature due to climate change is a major cause of heat-related diseases in cities such as skin cancer, heat stroke, heart disease, diarrhea, and increased mortality (Changnon et al., 1996; Honda and Barnett, 2014; Orimoloye et al., 2019). The heat related human health impacts also include dehydration, heat cramps, heat exhaustion, heat stroke, loss of fluids, heat injuries, eye, and skin diseases (Dutta and Chorsiya, 2013). The increase in urban temperature or the urban heat island (UHI) effect is an important implication of climate change. The UHI effect have been reported in many Indian cities (Ambinakudige, 2011; Kikon et al., 2016; Mathew et al., 2016; Kaur and Pandey, 2020) causing thermal discomfort to urban residents. This effect is linked with certain respiratory problems due to deterioration of air quality by cooling agents (Liu and Zhang, 2011).

Besides, the heat waves along with other frequent weather events are reported as significant evidence of climate change in eastern India (Patil and Deepa, 2007). The heat wave during 1998 and 2015 has taken lives of more than 2000 people each in India (Mukherjee and Mishra, 2018). Approximately 1,625 people lost their lives in Rajasthan, followed by Bihar, Uttar Pradesh, and Odisha during 1978 to 1999 due to heat wave (De, 2000); while the toll increased to 3,442 heat-related deaths during 1999–2003 (Chaudhury et al., 2000; Centers for Disease Control Prevention, 2006). The statistical data documented in a study by Dutta and Chorsiya (2013) states that more than 600 people have died due to heat wave in India in 2013. Besides, about 1,400 deaths were caused by high ambient temperature (50°C) in Andhra Pradesh in 2002. Similarly, in Ahmadabad high ambient temperature (46.8° C) took lives of many urban residents in 2010. Further, the heat waves significantly affected dozens of Indian states such as Rajasthan and Uttarakhand in 2009 (Dutta and Chorsiya, 2013). The climate variability and its relation with mortality due to heat in India were documented by Akhtar (2007), Dholakia et al. (2015) for Ahmedabad, Murari K. K. et al. (2015), and Mazdiyasni et al. (2017). Further, following the increasing frequency of hot days and nights during the period 1951–2016, 4-fold increase has been projected by 2050 and 12-fold by 2100 that will lead to increased heat-related mortality (Mukherjee and Mishra, 2018; Singh C. et al., 2021).

The climate change is known to trigger other extreme events such as drought, floods, tsunamis, and cyclones that are associated with negative human health impacts. Urban drought and floods caused by changing climate due to scarcity or excess of rainfall indirectly affects human health. Drowning, hypothermia, and trauma are some physical effects of floods on human health (Ahern et al., 2005; Du et al., 2010). Severe drought conditions resulting in scarcity of food caused high number of deaths due to starvation in India (Dutta and Chorsiya, 2013). Also, the high rainfall causing floods lead to destruction of crops that in turn causes shortage of food leading to malnutrition and public health issues. The malnutrition is a severe issue in India with about 47% of the children prone to this problem according to World Bank Report on Malnutrition in India (2009). The malnutrition can further cause anemia from which about 70% children, 55% women, and 25% of men population are suffering, in India (Majra and Gur, 2009).

The rising sea level due to climate change may cause flooding that can cause death (Dutta and Chorsiya, 2013). Moreover, the drought and flood conditions also decrease the availability of fresh water. The increase in risk of diarrheal diseases linked with floods has been reported for India (Mondal et al., 2001). The contaminated water can cause transmission of various water-borne infections leading to E. coli infection, cholera, typhoid, cryptosporidium, shigelgia, giardia, and viruses such as hepatitis A (Ghabastou et al., 2002; Kovats and Akhtar, 2008; Majra and Gur, 2009). Besides, floods also lead to certain rodent-borne diseases such as including tularemia, leptospirosis, and viral hemorrhagic diseases. Lyme disease, Hantavirus pulmonary syndrome, and tick-borne encephalitis are some other diseases linked with climatic variability for Baltimore and London (Wilson et al., 2001; Majra and Gur, 2009).

Besides, the extreme weather events due to climate change such as cyclones, tsunamis, and floods have taken thousands of lives and affected millions of population in many Indian states such as Assam, Bihar, West Bengal, Odisha, Uttar Pradesh, Himachal Pradesh, Rajasthan, and Gujarat (World Health Organization (WHO), 2005; Majra and Gur, 2009). These events also cause adverse health impacts on surviving population. Some of these extreme weather events reported in the past few years are:

Heat wave in Odisha in 1998 and 2004, Super cyclone in Odisha with wind speed over 300 km/h in October 1999, Heat wave in Andhra Pradesh in 2003, Cold wave in Uttar Pradesh and Uttarakanchal in 2004, Tsunami affecting Tamil Nadu, Andhra Pradesh, Kerala, and the Andaman-Nicobar Islands in 2004,
Heaviest rainfall in Indian metropolitan city of Mumbai in 2005, Cyclone in Andhra Pradesh in 2005, Floods in Gujarat and Madhya Pradesh in 2005 and cloudburst and flood in Uttarakhand in June 2013.

These disasters enhances the incidence and spread of diseases by increasing transmission of infectious vectors such as plague, Japanese encephalitis, malaria, dengue fever, chikungunya, and filariasis (Bhattacharya et al., 2006; Devi and Jauhari, 2006; Dhiman et al., 2008; Bush et al., 2011). Additionally, these calamities have badly affected Indian states such as Plague in Surat, malaria in Odisha, West Bengal, Jharkhand, Chattisgarh, Madhya Pradesh, and North East (Kumar et al., 2007). The coastal regions of India are prone to tsunamis and cyclones (Dutta and Chorsiya, 2013).

These disasters also lead to occurrence of water-borne diseases such as amoebiasis, cryptosporidiosis, giardiasis, typhoid, cholera, and other infections. According to The World Health Organization (WHO), 900,000 Indians die each year from drinking contaminated water and breathing polluted air (World Health Organization and United Nations Children’s Fund (WHO and UNICEF), 2000). Also, Indian Ministry of Health estimated 1.5 million deaths annually between 0- and 5-year-old children. Every year in India around 0.6-0.7 million children under 5 years of age die from diarrhea.

So, the potential health impacts related with climate change can be categorized as:

a) Direct factors: The factors such as thermal stress, death/injury in floods and storms are direct implication of climate change that affects human health.

b) Indirect factors: The indirect factors include vectors-borne diseases, water-borne pathogens, water and air quality, and food availability and quality that are indirectly caused by climate change.

**AIR POLLUTION**

Air pollution is a matter of serious concern in megacities where the pollution levels often exceed the permissible limits due to its associated health risks for city residents (Chattopadhyay et al., 2010; Debone et al., 2020). The metropolitan cities of India are exposed to unhealthy and unhygienic conditions due to air pollution (Dutta et al., 2021). The continuous and alarming increase of urban air pollution is an emerging environmental issue in the Indian megacities for the last few decades (Faheem et al., 2021).

Major outdoor and indoor air pollutants in urban areas can be primary or secondary air pollutants. Primary air pollutants that are emitted directly include particulate matter (PM$_{2.5}$, PM$_{10}$, suspended particulate matter (SPM), respirable particulate matter (RPM)), SO$_x$, NO$_x$, CO, ammonia, and dust particles while the secondary air pollutants involve ozone, smog, Peroxyacyl nitrates (PANs) etc.

The developing nations like India with ongoing urbanization are suffering from increased air pollution issues due to the lack of services such as adequate transportation management, suitable roads, and unplanned distribution of industries (Rumana et al., 2014). The congested roads in cities reduce average vehicular speed resulting in higher vehicular emissions adding to air pollution levels (West Bengal Pollution Control Board, 2010). The increasing and unplanned urbanization coupled with industrialization and population growth are posing threat to human health by increasing air pollution levels leading to number of health issues (Dutta et al., 2021). Additionally, the complex and intensive human activities in these urban areas are fueling the problem by increasing emission of pollutants.

In Indian cities, the air pollutants are either emitted from natural sources such as long-range transport of desert dust influx originated from the western arid regions of Africa, Middle-East, and Thar (Rajasthan) regions, predominately during summer and pre-monsoon season (El-Askary et al., 2006) or they can be of anthropogenic origin as given in Figure 1 (Ghose et al., 2005; Habib et al., 2006; Prasad and Singh, 2007; Badarinath et al., 2010; Sharma et al., 2010; Kharol et al., 2011; Danidotiya et al., 2020).

Vehicular emissions (95%) have been identified as prevalent source of high NO$_2$ concentrations followed by industries and fuel burning, thereby increasing air pollution in urban areas of India (Mondal et al., 2000; Ghose et al., 2004; ARAI, 2010). The combustion of low-quality fuel in Indian cities causes SO$_2$ emissions (Zou et al., 2007). Air pollutants are also emitted from crude oil wells and flared natural gas (Amakiri et al., 2009). Besides, open burning and landfill fires of municipal solid waste were recognized as chief source of air pollution for Mumbai, India in a study reported by National Environmental Engineering Research Institute (Central Pollution Control Board (CPCB), 2010). Open coal liming, fluoride mining, lime stone mining, thermal power plant, natural and domestic burning of coal, cement industry, and road dust were another primary source of air pollution in India (MPCB, 2010; Maji et al., 2016). Road dust (61%) was identified as major source of high particulate matter concentration followed by vehicular emissions, industrial emissions, vegetation, and solid fuel burning for another Indian city (Pune). Plastic industry, domestic waste burning, and food processing factories were the main sources of air pollution in Nashik city (Maji et al., 2016). Diesel generators, coal based industrial emissions, oil refinery emissions were major source of PM in Agra (Maji et al., 2016). Also, thermal power plants in most of the cities in addition to large- and small-scale industries are contributing to high air pollution levels. For Kolkata, 51.4% of the air pollution is contributed by motor vehicles followed by 24.5% emissions from industries and 21.1% dust particles (West Bengal Pollution Control Board, 2005).

The deterioration of air quality has been further aggravated by emission of toxic pollutants such as particulate matter, greenhouse gases like SO$_x$, NO$_x$, and O$_3$ (Rumana et al., 2014). Emission of aerosols from deserts, oceans, forest fires, and volcanoes into the atmosphere also adds to air quality depletion. Increase in population, urbanization, and industrialization has depleted air quality and hence adversely affects human health (Rumana et al., 2014).

Besides, Particulate matter, Black carbon (BC) has been studied by various workers around the globe. Singh A. et al. (2014) reported mass concentrations of BC in Indo-Gangetic Plains (IGP) that varied from 8.5 to 19.6, 2.4 to 18.2, and
2.2 to 9.4 \( \mu g \) m\(^{-3}\) during paddy-residue burning emission in the month of October-November, emission from bio- and fossil-fuel combustion during December-March months and wheat-residue burning emissions during April-May, respectively. In contrast, the mass concentrations of Elemental Carbon (EC) varied from 3.8 to 17.5, 2.3 to 8.9, and 2.0 to 8.8 \( \mu g \) m\(^{-3}\) during these emissions, respectively. Not only this, polycyclic aromatic hydrocarbons (PAHs) have been studied by Rajput et al. (2011) during paddy and wheat biomass burning emissions of Indo-Gangetic plains and reported 40 ng m\(^{-3}\) of total PAHs are reported from paddy residue burning and 7 ng m\(^{-3}\) during wheat burning season.

Human Health Impacts by Air Pollution

Since last few decades, there has been significant degradation of air quality in most of the Indian cities as many of the Indian cities are in grip of serious air pollution issue such as Kolkata, Delhi (Ghose et al., 2005) with the air quality above the standards provided by CPCB and WHO. The daily and annual average values were high for most of the gaseous pollutants in Indian cities (Dandotiya et al., 2020). The literature suggests the high load of ambient air pollution (specifically in the Indo-Gangetic plain) (Satheesh et al., 2002; Kharol et al., 2011; Ramachandran et al., 2012) has been identified as one of the important contributors to the air pollution related diseases burden in India (Prabhakaran et al., 2020). The literature has also discussed the high gaseous and particulate matter concentrations in air are significantly connected with premature mortality and hospitalizations for respiratory and post respiratory illnesses in cities (Burnett et al., 1997; Yang et al., 2004).

Air pollution is linked with short term, medium, or long term impacts on human health (Gumashita and Bijlwan, 2020). Several studies have been conducted regarding the short-term health effects of exposure to air pollution. Short term impacts include irritation to eyes, throat, and nose, and some respiratory infections such as pneumonia and bronchitis, while long term air pollution impacts involve chronic respiratory diseases, heart related problems, lung cancer, and even damage to the brain, liver, kidneys, or nerves (Faheem et al., 2021). Meanwhile Prabhakaran et al. (2020) reported that both short- and long-term exposure to air pollutants contributed to higher blood pressure and increased risk of incident hypertension. The associations between gaseous pollutants and health outcomes have also been discussed (Samoli et al., 2008, 2013; Stafoggia et al., 2013). The higher gaseous and particulate matter concentrations in air are significantly connected with premature mortality and hospitalizations for respiratory and post respiratory illnesses in cities (Burnett et al., 1997; Yang et al., 2004). Rajput et al. (2019) reported that coarse particles exhibited higher mass deposition fraction in extrathoracic region, whereas fine particles deposited...
significantly in pulmonary region. Intensification of biomass and biofuel burning emissions during post-monsoon and wintertime have implications to deeper penetration and higher mass deposition fraction of fine-particles in the PUL region.

The air pollution impacts are different in different people such as some individuals are more sensitive to air pollutants than others. Children, elderly people and pregnant women are more prone to health risks related with air pollutants. The studies revealed that the children on exposure to air pollution are highly affected as compared to adults as the lungs of children are comparatively less developed at birth and are not proper functional until about 6–8 years of age (Burri, 1984; Lee, 2010; Smith, 2013). Also, the people who are already suffering from health issues like heart, lung disease, asthma etc are having higher probability to suffer more. Moreover, the extent of impacts depends on duration of exposure and concentration of air pollutants as studied in the city of Agra (Faheem et al., 2021).

Various epidemiological studies conducted in this concern states that poor quality of air poses significant risk to human health creating problems such as decreased lung function, respiratory symptoms and increased asthma incidence, allergy, and cardio-respiratory illness [Ghose et al., 2005; Pope et al., 2009; Beckerman et al., 2012; Portnov et al., 2012; WHO, 2013; Cheng et al., 2014; Tsai and Yang, 2014; Carosino et al., 2015; Global Initiative for Asthma (GINA), 2015; Shaw and Gorai, 2020] with higher concentration of air pollutants. Chronic obstructive pulmonary diseases, influenza, bronchitis, asthma, upper track respiratory infection, and acute respiratory infections were some other health impacts observed for Indian cities due to air pollution (Haque and Singh, 2017). Further, air pollution is linked with several disease and even premature death. The air pollutants dispersed to a long distance and they react or damage the mechanisms by chemical reaction with the molecules of respiratory system and bringing about adverse chemical changes. The health issues such as genetic changes, impaired liver function, hematological abnormalities, and neurobehavioral problems were also associated with air pollution especially for the people exposed to higher vehicular emissions. These include traffic policeman, auto, and taxi drivers and roadside hawkers (Mukhopadhyay, 2009). Besides, detrimental health effects, such as lung cancer, cardiovascular disease risk, cardiopulmonary mortality, and pulmonary inflammation have been reported on exposure to particulate matter in several epidemiological studies (Pope et al., 2009; Huang et al., 2012; Gorai et al., 2014; Prabakaran et al., 2020).

Furthermore, the health impacts of NO2 involve irritation of the alveoli and resistance in airways and pulmonary function and decrease in pulmonary capacity reported for cities such as Agra and Taiwan (Mudgal et al., 2000; Yang et al., 2005; Saini et al., 2008). Respiratory health effects, lower birth rates, lower birth weights, and chronic bronchitis are health impacts associated with exposure to high SO2 concentrations (Ciccone et al., 1995; Dejmek et al., 2000; Rogers et al., 2000). Although gaseous air pollutants such as NO2 and SO2 are matter of increasing concern for human health; but particulate matter was observed as prominent reason for air pollution related mortality and morbidity rather than gaseous pollutants (Maji et al., 2016). High particulate matter concentration was observed in India with more than 50% of the population exposed to these higher concentrations (above NAAQs) (Ramya et al., 2021). The premature death due to SPM is reported to be very high and the children are the worst effected groups in Kolkata (Haque and Singh, 2017). Besides, abundance and variability of viable bioaerosols was reported by Rajput et al. (2017) in Indo-Gangetic Plains with very high concentration of Gram-positive bacteria (GBP), Gram-negative bacteria (GNB), and Fungi; having implications for human health.

The monitoring of ambient air quality for selected cities in India is conducted by The Central Pollution Control Board (CPCB). In 1984, CPCB initiated National Ambient Air Quality Monitoring (NAAQM) for monitoring air quality that was later renamed as National Air Monitoring Programme (NAMP). Also, the Government of India has prescribed The National Ambient Air Quality Standards (NAAQS). Health risk assessment has been conducted in various studies using formulae given by USEPA.

About 91% of world’s population has been found to be residing in areas with air quality higher than permissible limits according to WHO (Mostafavi et al., 2021). Air pollution has led to death of about 3.8 million people throughout the globe as reported by WHO, due to certain human health issues such as ischemic heart disease (27%), pneumonia (27%), chronic obstructive pulmonary disease (20%), stroke (18%), and lung cancer (8%) (Ramya et al., 2021). In India, about 1.24 million deaths have occurred due to air pollution. Out of this, 0.67 million cases were attributed to ambient air pollution and remaining 0.48 million cases were linked with household air pollution (Rumana et al., 2014; Balakrishnan et al., 2019). In India, about 0.62 million in 2005 and 0.69 million in 2010 premature death cases have occurred due to outdoor air pollution (OECD, 2014).

About 1.67 million (95% uncertainty interval) deaths were attributable to air pollution in India in 2019, accounting for 17.8% (15.8–19.5) of the total deaths in the nation. The majority of these deaths were due to ambient particulate matter pollution (0.98 million) and household air pollution (0.61 million). There was a decrease in death rate due to household air pollution by 64.2% from 1990 to 2019, whereas an increase was observed in death rate due to ambient particulate matter pollution by 115.3 and 139.2% increase in death rate due to ambient ozone pollution (GBD 2015 Risk Factors Collaborators).

Air pollution has led to respiratory diseases in about 70% of people in an Indian city, Kolkata as reported jointly by Chittaranjan National Cancer Institute, West Bengal Department of Environment and the Central Pollution Control Board (CPCB) (Mukhopadhyay, 2009). About 10,647 premature deaths were caused due to air pollution in Kolkata in 1995 (Ghose, 2002; Schwela et al., 2006). Adverse lung diseases and genetic abnormalities in exposed lung tissues were reported for children exposed to polluted air in Kolkata (Lahiri et al., 2000). The people residing in Kolkata city were facing seven times higher burden on their lungs due to air pollution as compared to their rural counterparts and about 47% of Kolkata’s residents were suffering from lower respiratory tract symptoms Roy et al., 2001; West Bengal Pollution Control Board (WBPCB), 2003; Schwela et al., 2006. Rajeev et al. (2018) reported
health risk assessment of PM1-bound carcinogenic hexavalent chromium [Cr (VI)] from central part of Indo-Gangetic plain (IGP) by assessing excess cancer risk (ECR) which was found to be 57 and 14.3 (in one million) for adults and children, respectively.

The human health impacts caused by air pollution result in high economic cost of about USD 80 billion in 2010, that is almost equal to 5.7% of India’s gross domestic product (GDP) (Maji et al., 2016).

Various studies have been conducted regarding air pollution and their associated health impacts for Indian cities such as for Delhi (Gurjar et al., 2010; HEI, 2011; Rizwan et al., 2013; Nagpure et al., 2014); Chandigarh (Gupta et al., 2001); Kolkata (Ghose et al., 2005; Gurjar et al., 2016; Haque and Singh, 2017); Rajasthan (Rumana et al., 2014); Lucknow (Lawrence and Fatima, 2014); Mumbai (Joseph et al., 2003; Maji et al., 2016); Maharashtra (Maji et al., 2016), Agra (Maji et al., 2017); Gwalior City (Dandotiya et al., 2020); Chennai (Jayanthi and Krishnamoorthy, 2006; HEI, 2011). Agarwal et al. (2018) studied mutagenicity and cytotoxicity of PM from biodiesel-fueled engines that were relatively higher compared to their diesel counterparts, indicating the need for exhaust gas after-treatment. The exhaust of chemical characterization revealed that biodiesel-fueled engines contained several harmful PAHs and trace metals, which affected the biological activity of PM.

Aerosols and Particulate Matter
Aerosols have been considered as one of the key air pollutants that significantly influence the air quality and affects public health (Xu et al., 2014). Aerosol optical depth (AOD), an optical property, have been determined in several studies using either ground based observations or satellite data to monitor the concentration of aerosols in the atmosphere. The AOD values are extensively used to represent air pollution level, reflect atmospheric conditions and define climatic effects as these values are closely linked with air pollutants such as PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and O$_3$ (Chu et al., 2003; Xu et al., 2014; Li et al., 2016; Awais et al., 2018; Ahmad et al., 2020). The monitoring of aerosols has been carried out in many of the Indian cities, as India has been recognized as one of the regional hot spots of aerosols because of increasing anthropogenic activities in the country. The high aerosols load in the atmosphere causes adverse human health impacts and reduces visibility due to poor air quality (Davidson et al., 2005). The exposure to particulate matter (especially PM$_{2.5}$ i.e., particles <2.5 µm in diameter) has been recognized as fifth leading risk factor throughout the globe and the third leading risk factor in India with about 1 million premature mortality per year across the nation (Chowdhury and Dey, 2016; GBD 2015 Risk Factors Collaborators, 2016; Conibear et al., 2018; Chen et al., 2020). The PM$_{2.5}$ can penetrate deep into the human body and hence can cause greater risk among all other air pollutants (Xing et al., 2016). In India, industrial and vehicular emissions, dust, emissions from biomass burning, open waste burning, household and power sector are major sources of high PM$_{2.5}$ concentrations (Guo et al., 2017; Conibear et al., 2018; Venkataraman et al., 2018). Domestic cooking and heating, dust from construction activities and industrial emissions are major urban sources of PM$_{2.5}$ (Guttikunda et al., 2019). Rajput et al. (2014) reported the PM$_{2.5}$ mass concentrations in Patiala region of Punjab during paddy-residue burning in the months of October and November in the range of 60–390 µg m$^{-3}$ with organic carbon (OC≈33%) contributing significantly; while, mass concentration of PM$_{2.5}$ during wheat-residue burning period of April–May varies from 18 to 123 µg m$^{-3}$.

Besides, emissions in the surrounding rural areas, also contribute to the urban pollution in India (Guttikunda et al., 2019; Ravindra et al., 2019), such as local sources (like traffic, power plants, industries) account for ~70% of total PM$_{2.5}$, but the non-local sources (agricultural crop burning in the neighboring states) contribute over 30% in Delhi (Guo et al., 2017; Prabhakaran et al., 2020). Moreover, the burning of firecrackers during Diwali festival in Delhi worsens the situation by adding more pollutants (Ganguly et al., 2019). With the ongoing urbanization, PM$_{2.5}$ pollution is expected to further increase in the coming decades (Chowdhury et al., 2018; Conibear et al., 2018).

The important studies conducted over Indian cities regarding aerosols and particulate matter are discussed in this section and average AOD values for some of the Indian cities are given in Table 1.

Kaskaoutis et al. (2012) conducted a decadal study (2001–2010) for analysis of variations and trends in aerosol properties over Kanpur, India using AERONET data. The study showed overall increase in column-integrated AOD on a yearly basis with significant increase in AOD during the months of November and December as well as for the months of March and April. The increase has been attributed to continuous increase in anthropogenic emissions during which are primarily due to fossil-fuel and biomass combustion over the IGP. Choudhary et al. (2021) studied the seasonal and spatial variability of Brown Carbon (BrC) and reported that water soluble organic carbon (WSOC) aerosols during winter exhibited ~1.6 times higher light absorption capacity than in the monsoon season at Kanpur, a central site in Indo-Gangetic Plains.

Further, the aerosols optical properties have been examined during the period 2010–2012 for Greater Noida, Delhi region, using ground-based sun photometer data by Sharma et al. (2014). In a study conducted for Varanasi, India by Murari V. et al. (2015), the annual mean concentration of particulate matter (PM$_{2.5}$ and PM$_{10}$) was higher than annual permissible limit (PM$_{10}$: 80%; PM$_{2.5}$: 84%) in a range of 8–9 times over than the approved standard values. The study states that high PM values pose a risk of developing cardiovascular and respiratory diseases as well as lung cancer. Further, Sahu and Kota (2017) showed 0.69% increase in non-accidental mortality per 10 µg m$^{-3}$ increase of PM$_{2.5}$ over Delhi in a study conducted during 2011–2014. Rajeev et al. (2016) attempted to characterize fine-mode ambient aerosols, and individual rain waters during the South-west monsoon (July–September 2015) in the central Indo-Gangetic Plain (IGP). Not only this, water-soluble ionic species (WSIS) were measured and characteristic mass ratios suggested that below-cloud scavenging was predominant mechanism of aerosols wash-out.
### TABLE 1 | PM values for some Indian cities during different years.

| Study area                              | PM values (µg/m³)                     | References                        |
|-----------------------------------------|--------------------------------------|------------------------------------|
| Jorhat, Northeast India                 | 24 h mean concentration              | Islam and Saikia, 2020             |
| PM$_{2.5}$ = 121 ± 49                   |                                      |                                    |
| PM$_{10}$ = 153 ± 45                   |                                      |                                    |
| Delhi (ITO)                             | 24-h mean concentration              | Shaw and Gorai, 2020               |
| PM$_{2.5}$ = 71.9                       |                                      |                                    |
| Bangalore (S. G. Halli)                | 24-h mean concentration              |                                     |
| PM$_{10}$ = 11.90                      |                                      |                                    |
| Kolkata                                 | 24-h mean concentration              |                                     |
| PM$_{10}$ = 97.00                      |                                      |                                    |
| Bhubaneswar                             | Annual mean concentration            | Mahapatra et al., 2018             |
| PM$_{2.5}$ = 30.6 ± 22.1                |                                      |                                    |
| PM$_{10}$ = 88.3 ± 30.6                 |                                      |                                    |
| Kanpur                                  | PM$_{1}$ average mass concentration  | Rajput et al., 2018                |
| During non-foggy conditions = 247 ± 113 |                                      |                                    |
| During foggy conditions = 107 ± 58      |                                      |                                    |
| Patiala                                 | PM$_{2.5}$ mass concentration = 60-390 (October–November) | Rajput et al., 2016 |
| Patiala                                 | PM$_{2.5}$ mass concentration = 18–123 (April–May) | Rajput et al., 2016 |
| Patiala                                 | Average concentration                | Sen et al., 2016                   |
| PM$_{2.5}$ = 55.4 ± 13.5                |                                      |                                    |
| Lucknow                                 | Average concentration                |                                     |
| PM$_{2.5}$ = 51.5 ± 17.7                |                                      |                                    |
| PM$_{10}$ = 182.2 ± 58.0                |                                      |                                    |
| Kolkata                                 | Average concentration                |                                     |
| PM$_{2.5}$ = 47.6 ± 9.3                 |                                      |                                    |
| PM$_{10}$ = 66.7 ± 17.0                 |                                      |                                    |
| New Delhi                               | Average concentration                |                                     |
| PM$_{2.5}$ = 61.8 ± 18.6                |                                      |                                    |
| PM$_{10}$ = 127.4 ± 62.2                |                                      |                                    |
| Nagpur                                  | Average concentration                |                                     |
| PM$_{2.5}$ = 35.2 ± 18.4                |                                      |                                    |
| PM$_{10}$ = 53.9 ± 23.7                 |                                      |                                    |
| Varanasi                                | Average concentration                |                                     |
| PM$_{2.5}$ = 52.5 ± 28.6                |                                      |                                    |
| PM$_{10}$ = 139.6 ± 68.0                |                                      |                                    |
| Mid-IGP region                          | Annual mean PM$_{10}$ concentration = 206.2 ± 77.4 | Sharma et al., 2016 |
| Varanasi                                | Annual mean concentration            |                                     |
| PM$_{2.5}$ = 100.0 ± 29.6                |                                      | Murari V. et al., 2015             |
| PM$_{10}$ = 176.1 ± 85.0                |                                      |                                    |
| Monthly average concentration           |                                      |                                    |
| PM$_{2.5} =$ 43.6-318.5 µg/m$^3$        |                                      |                                    |
| PM$_{10}$ =$ 50.1-154.0$ µg/m$^3$       |                                      |                                    |
| Delhi                                   | Mean mass concentrations             | Tiwari et al., 2015                |
| PM$_{2.5}$ = 118.3 ± 81.7               |                                      |                                    |
| PM$_{10}$ = 232.1 ± 131.1               |                                      |                                    |
| Vishakhapatnam                          | Annual average concentration         | Guttikunda et al., 2015            |
| PM$_{10}$ = 70.4 ± 29.7                 |                                      |                                    |
| Chennai                                 | Annual average concentration         |                                     |
| PM$_{10}$ = 121.5 ± 45.5                |                                      |                                    |
| Delhi                                   | PM$_{2.5}$ = 130.0 ± 103.0           | Tiwari et al., 2014                |
| PM$_{10}$ = 222.0 ± 142.0               |                                      |                                    |
| Pune                                    | Average mass concentration           | Yadav and Satsangi, 2013           |
| PM$_{2.5}$ = 72.3 ± 31.3                |                                      |                                    |
| PM$_{10}$ = 113.8 ± 51.6                |                                      |                                    |
| Barapani, foothills of NE–Himalaya      | Wintertime concentration of PM$_{2.5}$ = 39–348 | Rajput et al., 2013 |
| Rajpur                                  | Annual average concentrations (July 2009 to June 2010) | Deshmukh et al., 2013 |
| PM$_{2.5}$ = 150.9 ± 78.6               |                                      |                                    |
| PM$_{10}$ = 270.5 ± 105.5               |                                      |                                    |
| PM$_{1}$ = 72.5 ± 39.0                  |                                      |                                    |

(Continued)
Adding to PM studies, Singh V. et al. (2021) analyzed particulate matter (PM2.5) in five Indian megacities (Chennai, Kolkata, New Delhi, Hyderabad and Mumbai) for 6 years period (2014–2019). Among all cities, Delhi is found to be the most polluted city followed by Kolkata, Mumbai, Hyderabad, and Chennai. Chakraborty et al. (2017) reported high levels of water-soluble organic aerosols (WSOA) and total organic aerosols (OA) using Aerosol Mass Spectrometer in two cities of Indo-Gangetic Plains.

In addition, Chen et al. (2020) discussed the long-term and short-term effects of PM2.5 over four Indian megacities (Delhi, Chennai, Hyderabad and Mumbai) during 2015–2018. The results depict annual averaged PM2.5 concentration of 110 µg/m3 (Delhi), 60 µg/m3 (Mumbai), 50 µg/m3 (Hyderabad), and 33 µg/m3 (Chennai) during study period with worst air quality for Delhi. The study showed 75% increase in PM2.5 concentration during Diwali due to burning of firecrackers that causes 20 extra daily mortality. The long-term exposure to PM2.5 causes 17,200–39,400 premature mortality and 428,900–935,200 years of life lost each year in these four Indian cities. About 10,200, 2,800, 5,200, and 9,500 premature deaths occur each year in Delhi, Chennai, Hyderabad, and Mumbai, respectively, on long-term ambient PM2.5 exposures. Among the major diseases, cardiovascular diseases were dominant with ischaemic heart disease (IHD) contributing about 40% and cerebrovascular disease contributing about 30% in each city.

Dutta and Jinsart, 2020 analyzed the PM concentration over Guwahati city during three-year period (2016–2018) and observed high PM levels (>100 µg m⁻³) during winter season causing high air pollution. The study showed acute health risk to city residents during winter as analyzed from computed hazard quotients (>1). Sorathia et al. (2018) reported diurnal variability of Dicarboxylic Acids (DCAs) and levoglucosan in PM10 during winter over IGP indicating biomass burning emission and secondary transformations to be predominant sources of DCA during wintertime.

Meanwhile, Delhi has been recognized as one of the most heavily polluted cities of India suffering from air pollution caused by industrial and vehicular emissions, thereby possessing high levels of anthropogenic aerosols (Mishra et al., 2013; Singh B. P. et al., 2014). The dust aerosols during pre-monsoon period further worsens the air quality, reduces visibility and increases radiative forcing (Singh et al., 2005, 2010). According to urban air database by WHO in September 2011, high PM 10 (above permissible limits) was observed in Delhi. The high particulate matter concentration causes several respiratory issues that may lead to chronic diseases in Indian cities (Jayaraman, 2007). Tiwari et al. (2009) also reported that PM2.5 concentration (97 ± 56 µg m⁻³) was nine times higher than the air quality guidelines given by World Health Organization (WHO) (2005) over Delhi in 2007.

Besides, particulate matter concentration for Indian megacities during 2010 and 2016 has been discussed in Figure 2 depicting % increase in almost all the Indian megacities during 6 year period in cities such as Varanasi (Singh et al., 2017; Kumar A. et al., 2020). The increasing PM concentration is correlated with the rising urban population (Kumar P. et al., 2020).

Meanwhile, toxicological studies have established that the toxic effects of particulate matter arise from combined effects of PM size and chemical composition. The modifications in PM composition due to several factors also impart changes in health effects (Peng et al., 2005). These results suggesting that besides mass concentration, chemical composition of PM is also important in evaluation of toxicity on exposure to PM, were supported by Oeder et al. (2012), Kelly and Fussell (2012), and Mirowsky et al. (2013). Further, the source apportionment of aerosols during wintertime has been looked into by various researchers. Rajput et al. (2018) studied secondary formation processes, fog-processing and source-apportionment of PM1-bound species in IGP and reported that the foggy conditions were associated with higher contribution of PM1-bound organic matter alongwith approximately equal decrease in SO₄²⁻, NO₃⁻, and NH₄⁺ and mineral dust fractions.

**COVID-19 and Air Quality**

Besides the deteriorating air pollution conditions, the improvement in air quality has been reported globally during lockdown imposed due to COVID-19. The restrictions lead to reduction in anthropogenic emissions and hence decrease in PM and gaseous concentrations in most of the cities throughout the globe (Adams, 2020; Berman and Ebisu, 2020; Menut et al., 2020). The similar trend was observed in Indian cities such as for Delhi, Kolkata (Bera et al., 2020; Mahato et al., 2020; Sharma et al., 2020; Singh and Chauhan, 2020; Srivastava et al., 2020; Maji et al., 2021). According to the data provided by NASA, there has been 30% reduction in global NO₂ emissions with 70% decrease in NO₂ emissions in India (Gautam, 2020).

A lockdown period study was conducted by Vadvru et al. (2020) for analysis of spatio-temporal variations of air pollution (Singh B. P. et al., 2014) (using NO₂ and AOD) for 41 Indian cities. The study revealed about 13% reduction in NO₂ levels during the lockdown as compared to pre-lockdown period. The
NO$_2$ levels were reduced by 19% as compared to same duration of previous year. Further, Siddiqui et al. (2020) found 27% improvement in air quality index over 8 five million plus cities of India with an average decrease of 46% in NO$_2$ levels. The closures of industrial and construction activities during lockdown were reason for improved air quality.

Adding to the research in this field, Srivastava et al. (2020) conducted air pollution study over Lucknow and New Delhi during 21-day lockdown in India by analyzing available data for primary air pollutants (PM$_{2.5}$, NO$_2$, SO$_2$, and CO). Significant decrease in air pollutants with an improvement in air quality was observed for both the Indian cities. Further, Bera et al. (2020) in a study conducted for Kolkata city stated the reduction in air pollutants such as CO, NO$_2$, and SO$_2$ along with particulate matter for the study area as shown in Table 2. The decrease in fossil fuel combustion, vehicular and industrial emissions contributed to significant reduction in air pollutants (CO, NO$_2$, and SO$_2$) levels during Covid-19 lockdown. The study further stated the decrease in biomass burning, construction activities and vehicular movement contributed to about 17.5% decrease in PM concentration during Covid-19 lockdown. The improvements in air quality with 30–40% reduction in CO$_2$ levels with significant temporal variation were observed for Kolkata also by Mitra et al. (2020).

Moreover, the improvement in air quality (PM$_{2.5}$, NO$_2$, and AQI) during Covid-19 lockdown was reported by Karuppasamy et al. (2020) revealing improved mortality rates with less number of deaths in India and worldwide due to air pollution. Further, Kant et al. (2020) analyzed decrease in AOD levels during the COVID-19 lockdown period for Eastern Indo-Gangetic planes, peninsular India and North India. On comparison of PM$_{2.5}$ levels over five Indian cities, Kumar A. et al. (2020) observed 50% reduction in PM$_{2.5}$ concentrations over five Indian cities during this period. Goel et al. (2020) in a study conducted for Ludhiana city of India revealed decline in PM$_{2.5}$, PM$_{10}$, NH$_3$, SO$_2$ concentrations with an overall improvement in air quality index.

Meanwhile, Delhi, the most polluted megacities of India was focused in many of the lockdown period studies. Gupta et al. (2020) reported decrease in CO, SO$_2$ and ozone levels over Delhi that was supported by significant improvement in air quality over Delhi reported by Kotnala et al. (2020). Significant decrease in PM concentrations was observed for Delhi even in the initial days of lockdown (Maji et al., 2021). Goel V. et al. (2021) analyzed 78% decrease in black carbon during the lockdown and unlock phases for Delhi as compared to the pre-lockdown period. Mahato et al. (2020) also discussed the reduction in the concentration of seven pollutants (PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, CO, O$_3$, and NH$_3$ gases) over Delhi during lockdown period. The study revealed more than 50% reduction in PM$_{10}$ and PM$_{2.5}$ concentrations. About 40–50% improvement in air quality was observed using the data collected in Table 2.

**TABLE 2 | Percent reduction in air pollutants for Indian cities during COVID-19 lockdown.**

| Parameter | Location | % reduction | References |
|-----------|----------|-------------|------------|
| NO$_2$    | New Delhi| 61.74%      | Vadrevu et al., 2020 |
| NO$_2$    | Delhi    | 60.37%      |            |
| NO$_2$    | Bangalore| 48.25%      |            |
| PM$_{2.5}$, PM$_{10}$ | Ahmedabad | 46.20% | Bera et al., 2020 |
| PM$_{2.5}$, PM$_{10}$ | Nagpur | 46.13% |            |
| PM$_{2.5}$, PM$_{10}$ | Gandhinagar | 45.64% |            |
| PM$_{2.5}$, PM$_{10}$ | Mumbai | 43.08% |            |
| PM$_{2.5}$, PM$_{10}$ | Kolkata | 17.5% |            |
| AOD       | Eastern Indo-Gangetic planes, peninsular India and North India | 20–37% | Kant et al., 2020 |
| PM$_{2.5}$ | Ghaziabad | 85.1% | Lokhandwala and Gautam, 2020 |
| PM$_{2.5}$ | Delhi | 35% | Chauhan and Singh, 2020 |
| PM$_{2.5}$ | Mumbai | 14% |            |
from 34 monitoring stations. The reduction in levels of various air pollutants for more Indian cities during COVID-19 lockdown period have been presented in Table 2.

Such reduction in air pollutant concentration during COVID-19 lockdown is associated with several health benefits. The study conducted by Goel A. et al. (2021) in this concern over Indian cities stated highest health benefits during phase 1 of the lockdown (initial 21 days) due to least PM$_{2.5}$ concentrations during this period. The average pollutant reduction of 44.6% was observed in Uttar Pradesh and about 58.5% decline in Delhi-NCR as compared with year 2019. The traechobronchial particle deposition was reduced by 30.14% during lockdown. The mortality reduction of 29.85 per 100,000 persons was observed due to declined PM concentrations during 1st phase of lockdown. Also, the decrease in mortality of 8.01 per 100,000 people was analyzed during phase 1 in comparison with the pre-lockdown period in Ghaziabad.

**NEXUS BETWEEN URBANIZATION, CLIMATE CHANGE, AIR POLLUTION AND HUMAN HEALTH**

The interactions between urban climate, air pollution, and human health in cities need to be explored. The cities in developing nations like India are facing high pressure due to air pollution and climate change. Limited studies have been performed on the combined effects of weather, climate variability, increased air pollution, and health impacts in India (Agarwal et al., 2006; Karar et al., 2006).

Climate plays a considerable role in spatial and temporal distribution of air pollutants. Greenhouse warming and ozone depletion in stratosphere are vital factors of climate change. Climate change can influence the air pollutant concentration and catalyze the formation of secondary pollutants. Also, the climatic conditions in addition to atmospheric parameters, topography and urban settlements influence the dispersion, accumulation and transformation of pollutants in the atmosphere. The dispersal of these air pollutants may cause respiratory disorders such as emphysema, asthma, allergy problems and chronic bronchitis (D’Amato et al., 2002).

According to the World Health Organisation (WHO) estimation, in past 30 years, the precipitation and warming trends due to anthropogenic climate change had taken 150,000 lives annually. The alterations in climate had caused many prevalent human diseases such as cardiovascular mortality and respiratory illnesses due to heat waves etc.

Besides, the nexus between urbanization, climate change and air pollution lies in a way such that some of the atmospheric pollutants (aerosols) can enhance the climate change because of their direct and in-direct effects (Ramachandran and Cherian, 2008). These air pollutants not only degrade the air quality with certain human health impacts but also have a considerable impact on climate by heating lower and mid troposphere, causing sea-land temperature gradients, monsoon circulation, distribution of rainfall solar dimming and cloud microphysics (Lau et al., 2006; Gautam et al., 2010; Sharma et al., 2014) thereby modifying the heat wave frequency, intensity of storms and precipitation patterns. These small sized particles can weaken the UHI effect by up to 1 K under heavily polluted conditions (Wu et al., 2017). So, the increased concentrations of air pollutants (such as aerosols) have an impact on global climate change as the increased air pollution (aerosol load) in the atmosphere is associated with the climate system and hydrological cycle (Ramanathan et al., 2001; Jirak and Cotton, 2006). In addition to this, the indirect effect of aerosols can also be seen on optical properties of clouds. Aerosols can affect the surface energy balance by either scattering or absorbing the incoming solar radiations that may cause surface cooling and atmospheric heating (Kaufman et al., 2002; Wu et al., 2017). This influences the radiation equilibrium of Earth via radiative forcing and chemical perturbations (Rosenfeld et al., 2007; Wang et al., 2009; Zhu et al., 2010; Zhang S. et al., 2016; Zhang W. et al., 2016).

Besides, the atmospheric structure and climate is influenced by concentration of atmospheric pollutants that are emitted by human activities (Fischer et al., 2003; Jaffe and Ray, 2007; Yan et al., 2008).

Commercial and high traffic regions have higher concentration of gaseous pollutants than vegetated areas. Also, the concentration of pollutants varies with the seasons and other atmospheric parameters (Dandotiya et al., 2020). The estimation of pollutant concentration is influenced by atmospheric conditions of that urban area such as temperature, relative humidity and wind speed etc.

The greenhouse gases (GHGs) emissions are estimated mainly by consumption patterns in cities of the developed world that causes climate change. According to IPCC report, ~20% of global emissions were attributed by buildings. Further, transportation was estimated to contribute to 13% of GHG emissions (Diarmid Campbell-Lendrum and Corvala). It can be seen that both buildings and transportation are eminent factors of cities. Also, the cities face higher pollution issues than rural areas with higher vegetation due to higher emissions from transportation and fossil fuel burning in highly populated regions with high vehicular traffic (Dandotiya et al., 2019).

Further, it is notable that the urbanization phenomenon plays important role in both climate change and air pollution either directly or indirectly. The increase in air pollutant emissions and their concentration in the atmosphere increases with the urbanization. The urban characteristics, materials used, vegetation, vehicular traffic etc alters the climatic conditions of an urban area thus leading to formation of strong spatial gradients of heat and air pollution. These conditions exacerbate the risks for human health.

The expanding urban areas with inadequate or improper management accompanied by land use land cover changes, deforestation and decrease in vegetation cover and alterations in climate variables can influence or modify urban climate by transformation of natural land surface to impervious surfaces (Balica et al., 2012; Jha et al., 2012). The urban heat island effect by increased urban temperature due to climate change increases the demand of energy requirement for cooling in cities. The air conditioners used for reducing the high temperature in cities in turn emits harmful GHGs that cause urban air pollution. Also, the concentration of certain pollutants, such as ozone, is influenced by atmospheric conditions and tends to be higher.
on warmer days. Moreover, the higher demand of electricity consumption leads to higher burning of fossil fuels that also increases air pollution. Certain respiratory issues can be caused by UHI effect due to depleted air quality by certain cooling agents (Liu and Zhang, 2011). The city residents also suffer from thermal discomfort due to elevated urban temperature by UHI effect resulting in exacerbation of heat-waves (Ohashi et al., 2007). The UHI effect influences air quality as the differential heating generates mesoscale winds that facilitate pollutant movement and circulation causing urban air pollution issues (Agarwal and Tandon, 2010). So, air pollution and climate change are interlinked with adverse impacts on human health in cities.

**CONCLUSION**

The present review highlights high air pollution levels over most of the Indian megacities with air pollutant levels lying above the permissible limits. The continuous emissions from both anthropogenic as well as natural sources causing high PM concentration with adverse human health impacts highlight the necessity of continuous monitoring of air pollutants over the Indian subcontinent using measurements and remote sensing satellite data.

The essential information regarding air pollutant levels in different megacities of India, provided in this review can help in design of effective mitigation strategies for each city by analyzing vulnerable regions. The data can facilitate a baseline data for air quality modeling studies to predict air pollution levels for effective preparedness, adaption and mitigations plans in tackling air pollution. The high disease burden and mortality linked with air pollution in Indian cities should be emphasized to effectively control air pollutant concentration throughout the nation. Besides, the results depicting reduction in air pollution during COVID-19 lockdown period suggest adoption of such short-time restrictions for pollution mitigation across different cities of India to improve the air quality and thus benefit human health.

Further, as stated in the review, India being a developing country is experiencing adverse human health impacts due to climate change. Indian cities are exposed to extreme weather events such as high precipitation, floods, droughts, heat waves with increased temperatures induced by climate change. The increase in health surveillance for heat waves, floods and for vector-borne diseases linked with climate change can help in combating severe human health impacts in near future in Indian cities. Also, the high population density with ongoing urbanization and industrialization are some of the primary factors to be considered to avoid negative health impacts associated with climate change in India. So, essential mitigation and adaptation strategies are required for current and projected climate change impacts mentioned in the review to avoid myriad human health effects in Indian cities because of climate change.

To conclude, the use of advanced technologies such as satellite data with geospatial techniques can be of great help in monitoring and mapping of spatial-temporal distribution patterns of the air pollution and climate change and associated health impacts. So, while focusing on building smart cities in developing nations like India, proper urban planning and sustainable measures should be taken for sustainable urban environment to avoid adverse health impacts.

**AUTHOR CONTRIBUTIONS**

RK was involved in review of the chapter and preparation of the manuscript. PP was involved in overall supervision of the manuscript and manuscript review and editing. Both authors contributed to the article and approved the submitted version.

**REFERENCES**

Adams, M. D. (2020). Air pollution in Ontario, Canada during the COVID-19 state of emergency. *Sci. Total Environ.* 742:140516. doi: 10.1016/j.scitotenv.2020.140516

Agarwal, A. K., Singh, A. P., Gupta, T., Agarwal, R. A., Sharma, N., Rajput, P., et al. (2018). Mutagenicity and cytotoxicity of particulate matter emitted from biodiesel-fueled engines. *Environ. Sci. Technol.* 52, 14496–14507. doi: 10.1021/acs.est.8b03345

Agarwal, M., and Tandon, A. (2010). Modeling of the urban heat island in the form of mesoscale wind and of its effect on air pollution dispersal. *Appl. Mathematical Modell.* 34, 2520–2530. doi: 10.1016/j.apm.2009.11.016

Agarwal, R., Jayaraman, G., Anand, S., and Marimuthu, P. (2006). Assessing respiratory morbidity through pollution status and meteorological conditions for Delhi. *Environ. Monit. Assess.* 114, 489–504. doi: 10.1007/s10661-006-4935-3

Ahern, M., Kovats, R. S., Wilkinson, P., Few, R., and Matthies, F. (2005). Global health impacts of floods: epidemiologic evidence. *Epidemiol. Rev.* 27, 36–46. doi: 10.1093/epirev/mx004

Ahmad, M., Tariq, S., Alam, K., Anwar, S., and Ikram, M. (2020). Long-term variation in aerosol optical properties and their climatic implications over major cities of Pakistan. *J. Atmos. Solar-Terrestrial Phys.* 210:105419. doi: 10.1016/j.jastp.2020.105419

Akhtar, R. (2007). Climate change and health and heat wave mortality in India. *Glob. Environ. Res.* 11, 51–57.

Ali, H., Mishra, V., and Pai, D. S. (2014). Observed and projected extreme rainfall events in India. *J. Geophysical Res.* 119, 12–621. doi: 10.1002/2014JO022264

Amakiri, A. O., Monsi, A., Terme, S. C., Ede, P. N., Owen, O. J., and Ngodigha, E. M. (2009). Air quality and micro-meteorological monitoring of gaseous pollutants/flame emissions from burning crude petroleum in poultry house. *Toxicol. Environ. Chem.* 91, 225–232. doi: 10.1080/02772240802131551

Ambinakudige, S. (2011). Remote sensing of land cover’s effect on surface temperatures: a case study of the urban heat island in Bangalore, India. *Appl. GIS* 7, 1–12.

ARAI (2010). *Air Quality Monitoring and Emission Source Apportionment Study for City of Pune*. Pune: The Automotive Research Association of India, [ARAI/IOCLAQM/R-12/2009-10]. Retrieved from: https://www.mpceb.gov.in/sites/default/files/focus-area-reports-documents/pune_report_cpcb.pdf (accessed April 15, 2021).

Awais, M., Shahzad, M. I., Nazeer, M., Mahmood, I., Mehmood, S., Iqbal, M. F., et al. (2014). Observed and projected urban temperatures: a case study of the urban heat island in Bangalore, India. *Appl. GIS* 7, 1–12.

Badarinath, K. V. S., Kharol, S. K., Kaskaoutis, D. G., Sharma, A. R., Ramaswamy, V., and Kambezidis, H. D. (2010). Long-range transport of dust aerosols over the Arabian Sea and Indian region—A case study using satellite
data and ground-based measurements. *Glob. Planetary Change* 2, 164–181. doi: 10.1016/j.gloplacha.2010.02.003

Balakrishnan, K., Dey, S., Gupta, T., Dhalwilal, R. S., Brauer, M., Cohen, A. J., et al. (2019). The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. *Lancet Planetary Health* 3, e26–e39. doi: 10.1016/S2542-5196(18)30261-4

Balica, S. F., Wright, N. P., and Van der Meulen, F. (2012). A flood vulnerability index for coastal cities and its use in assessing climate change impacts. *Nat. Hazards* 64, 73–105. doi: 10.1007/s11069-012-0234-1

Beckerman, B. S., Jerrett, M., Finkelstein, M., Kanaroglou, P., Brook, J. R., Arain, M. A., et al. (2012). The association between chronic exposure to traffic-related air pollution and ischemic heart disease. *Toxicol. Environ. Health* A 75, 402–411. doi: 10.1016/j.se mar.2012.07.0899

Bell, J. E., Brown, C. L., Conlon, K., Herring, S., Wang, L., D’Amato, M., et al. (2018). Changes in extreme events and the potential impacts on human health. *J. Air Waste Manage. Assoc.* 68, 265–287. doi: 10.1080/10406026.2017.1401017

Bera, B., Bhattacharjee, S., Sengupta, N., and Saha, S. (2020). Significant impacts of COVID-19 lockdown on urban air pollution in Kolkata (India) and amelioration of environmental health. *Environ. Dev. Sustain.* 23, 1–28. doi: 10.1007/s10668-020-00898-5

Berman, J. D., and Ebusu, K. (2020). Changes in US air pollution during the COVID-19 pandemic. *Sci. Total Environ.* 739, 139864. doi: 10.1016/j.scitotenv.2020.139864

Beckerman, B. S., Jerrett, M., Finkelstein, M., Kanaroglou, P., Arain, M. A., and van der Meulen, F. (2012). Urban climate and health in India. *Curr. Sci.* 90:369–375.

Bush, K. F., Luber, G., Kotha, S. R., Dhaliwal, R. S., Kapil, V., Pasqual, M., et al. (2011). Impacts of climate change on public health in India: future research directions. *Environ. Health Perspect.* 119, 765–770. doi: 10.1289/ehp.1003000

Chattopadhyay, S., Gupta, S., and Saha, R. N. (2010). Spatial and temporal distribution of and exposure to fine particulate matter (PM2.5) in four Indian megacities. *Atmosph. Environ.* X 5, 100052. doi: 10.1016/j.aeaoa.2019.100052

Cheng, Y., Li, X., Li, Z., Jiang, S., and Jiang, X. (2014) “Fine-grained air quality monitoring based on gaussian process regression,” in *Neural Information Processing. ICONIP 2014. Lecture Notes in Computer Science*, Vol. 8835, eds C. K. Loo, K. S. Yap, K. W. Wong, A. Teoh, and K. Huang (Cham: Springer). doi: 10.1007/978-3-319-12640-1_16

Chowdhury, S., Dey, S., and Smith, K. R. (2018). Ambient PM2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. *Nat. Commun.* 9:318. doi: 10.1038/s41467-017-02775-y

Choudhary, V., Raiput, P., and Gupta, T. (2021). Absorption properties and forcing efficiency of light-absorbing water-soluble organic aerosols: Seasonal and spatial variability. *Environ. Pollut.* 272:115932. doi: 10.1016/j.envpol.2020.115932

Chowdhury, S., and Dey, S. (2016). Cause-specific premature death from ambient PM2.5 exposure in India: estimate adjusted for baseline mortality. *Environ. Int.* 91, 283–290. doi: 10.1016/j.envint.2016.03.004

Chowdhury, S., Dey, S., and Smith, K. R. (2018). Ambient PM2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. *Nat. Commun.* 9:318. doi: 10.1038/s41467-017-02775-y

Chowdhury, S., Dey, S., and Smith, K. R. (2018). Ambient PM2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. *Nat. Commun.* 9:318. doi: 10.1038/s41467-017-02775-y

D’Amato, G., Riccardi, D., G’Amato, M., and Cazzola, M. (2002). Outdoor air pollution, climatic changes and allergic bronchial asthma. *Eur. Respir. J.* 20, 763–776. doi: 10.1183/09031936.02.004102

D’Amato, G., Rottem, M., Dahl, R., Blais, M. S., Ridolo, E., Cecchi, L., et al. (2011). Climate change, migration, and allergic respiratory diseases: an update for the allergist. *World Allergy Organ*. J. 4, 121–125. doi: 10.1097/WOX.0b013e3182260a37

Dandotiya, B., Sharma, H. K., and Jadon, N. (2019). Role of urban vegetation in particulate pollution control in urban areas of Guwahati City with special reference to SPM. *Adv. Biore*. 10, 97–103. doi: 10.15515/abt.0976-4585.10.1.97103

Dandotiya, B., Sharma, H. K., and Jadon, N. (2020). Ambient air quality and meteorological monitoring of gaseous pollutants in urban areas of Gwalior City India. *Environ. Claims* 32, 248–263. doi: 10.1064/010626.2020.1744854

Davidson, C. I., Phalen, R. F., and Solomon, P. A. (2005). Airborne particulate matter and human health: a review. *Aerosol Sci. Technol.* 39, 737–749. doi: 10.1080/02786820500191348

De, U. S. (2000). Weather and climate related impacts on health in megacities. *WMO Bull.* 49, 340–348.

Debene, D., Leirião, L. F. L., and Miraglia, S. G. E. K. (2020). Air quality and health impact assessment of a truckers’ strike in São Paulo state, Brazil: a case study. *Urban Climat* 34:100687. doi: 10.1016/j.uclim.2020.100687

Dejmek, J., Jelinek, R., Solansky, I., Benes, I., and Sram, R. (2000). Fecundability and parental exposure to ambient sulphur dioxide. *Environ. Health Perspect.* 108, 647–654 doi: 10.1289/ehp.00108647

Deshmukh, D. K., Deb, M. K., and Mkomma, S. L. (2013). Size distribution and seasonal variation of size-segregated particle matter in the ambient air of Raipur city, India. *Air Qual. Atmosp. Health* 6, 259–276. doi: 10.1007/s11869-011-0169-9

Devi, N. P., and Jauhari, R. K. (2006). Climatic variables and malaria incidence in Dehradun, Uttarakanchal, India. *J. Vector Borne Dis.* 43:21–28.

Dhiman, R. C., Pahwa, S., and Dash, A. P. (2008). Climate change and Malaria in India: interplay between temperature and mosquitoes. *Regional Health Forum* 12:27–31.

Dholakia, H. H., Mishra, V., and Garg, A. (2015). Predicted Increases in Heat Related Mortality Under Climate Change in Urban India. *Environ. Res.* 6, 259–276. doi: 10.1016/j.envres.2020.109634

Du, W., FitzGerald, G. J., Clark, M., and Hou, X. Y. (2010). Health impacts of floods. *Prehosp. Disaster Med.* 25, 265–272. doi: 10.1017/S1049020X00008141

Dutta, A., and Jinsart, W. (2020). Risks to health from ambient particulate matter (PM2.5) to the residents of Guwahati city, India: an analysis of....
of prediction model. *Human Ecol. Risk Assess. Int. J.* 27, 1094–1111. doi: 10.1080/10807039.2018.1807902

Dutta, P., and Chorsiya, V. (2013). Scenario of climate change and human health in India. *Int. J. Innovat. Res. Dev.* 2, 157–160.

Dutta, S., Ghosh, S., and Dinda, S. (2021). Urban Air-quality assessment and inferring the association between different factors: a comparative study among Delhi, Kolkata and Chennai Megacity of India. *Aerosol Sci. Eng.* 5, 93–111. doi: 10.11810/020-00087-x

Ebi, K. L., and Paulson, J. A. (2010). Climate change and child health in the United States. *Curr. Prob. Pediatric Adoles. Health Care* 40, 2–18. doi: 10.1016/jcpped.2009.12.001

El-Askary, H., Gautam, R., Singh, R. P., and Kafatos, M. (2006). Dust storms detection over the Indo-Gangetic basin using multi sensor data. *Adv. Space Res.* 37, 728–733. doi: 10.1016/j.asr.2005.03.134

Faheem, M., Danish, M., and Ansari, N. (2021). Impact of Air Pollution on Human Health in Agra District.

Filippelli, G. M., Freeman, J. L., Gibson, J., Jay, S., Moreno-Madrinjañ, M. J., Ogashawara, I., et al. (2020). Climate change impacts on human health at an actionable scale: a state-level assessment of Indiana, USA. *Climate Change* 163, 1985–2004. doi: 10.1007/s10584-020-02710-9

Fischer, H., Kormann, R., Klupfel, T., Gurk, C., K Ö ongstedt, R., Parchatka, U., et al. (2003). Ozone production and trace gas correlations during the June 2000. *MINATROC intensive measurement campaign at Mt. Cimone. Atmos. Chem. Phys.* 3, 725–738. doi: 10.5194/acp-3-725-2003

Forster, P. M. de F., and Collins, M. (2004). Quantifying the water vapour feedback associated with post-Pinatubo global cooling. *Climate Dynam.* 23, 207–214. doi: 10.1007/s00382-004-0431-z

Gabastou, J., Pesantes, C., Escalente, S., Narvez, Y., Vela, E., Garcia, L., et al. (2014). Contribution of a severe air pollution episode in India during Diwali festival-a nationwide approach. *Atmosphinera* 32, 225–236. doi: 10.20937/ATM.2019.32.03.05

Gautam, R., Hsu, N. C., and Lau, K. M. (2010). Premonsoon aerosol

Ganguly, N. D., Tzanis, C. G., Philippopoulos, K., and Deligiorgi, D. (2019). Analysis of a severe air pollution episode in India during Diwali festival-a nationwide approach. *Atmosphinha* 32, 225–236. doi: 10.20937/ATM.2019.32.03.05

Gupta, D., Boffetta, P., Gaborieau, V., and Jindal, S. K. (2001). Risk factors of lung cancer in Chandigarh, India. *Indian J. Med. Res.* 113, 142–150.

Gupta, N., Tomar, A., and Kumar, V. (2020). The effect of COVID-19 lockdown on the air environment in India. *Global J. Environ. Sci. Manage.* 6, 31–40. doi: 10.22034/GJESS.2019.06.SI.04

Gurjar, B. R., Jain, A., Sharma, A., Agarwal, A., Gupta, P., Nagpure, A. S., et al. (2010). Human health risks in megacities due to air pollution. *Atmos. Environ.* 44, 4666–4613. doi: 10.1016/j.atmosenv.2010.08.011

Gurjar, B. R., Ravindra, K., and Nagpure, A. S. (2016). Air pollution trends over Indian megacities and their local-to-global implications. *Atmos. Environ.* 142, 475–495. doi: 10.1016/j.atmosenv.2016.06.030

Guttikunda, S. K., Goel, R., Mohan, D., Tiwari, G., and Gadepralli, R. (2015). Particulate and gaseous emissions in two coastal cities—Chennai and Vishakapatnam, India. *Air Qual. Atmos. Health* 8, 559–572. doi: 10.1007/s11869-014-0303-6

Guttikunda, S. K., Nishad, K. A., Gota, S., Singh, P., Chanda, J., Jhawar, P., et al. (2019). Air quality emissions, and source contributions analysis for the Greater Bengaluru region of India. *Atmos. Pollut. Res.* 10, 941–953. doi: 10.1016/j.apr.2019.01.002

Habib, G., Venkataraman, C., Chiapello, I., Ramachandran, S., Boucher, O., and Reddy, M. S. (2006). Seasonal and interannual variability in absorbing aerosols over India derived from TOMS: relationship to regional meteorology and emissions. *Atmos. Environ.* 40, 1909–1921. doi: 10.1016/j.atmosenv.2005.07.077

Haines, A., Kovats, R. S., Campbell-Lendrum, D., and Corvalán, C. (2006). Climate change and human health: impacts, vulnerability and public health. *Public Health* 120, 585–596. doi: 10.1016/j.puhe.2006.01.002

Haque, M., and Singh, R. B. (2017). Air pollution and human health in Kolkata, India: a case study. *Climate* 5:77. doi: 10.3930/ci504001

HEI (2011). Public Health and Air Pollution in Asia (PAPA): Coordinated Studies of Short-Term Exposure to Air Pollution and Daily Mortality in Two Indian Cities. Research Report 157. Boston, MA: Health Effects Institute.

Honda, D. M., and Barnett, A. G. (2014). Heat-related morbidity in Brisbane, Australia: spatial variation and area-level predictors. *Environ. Health Perspect.* 122, 831–836. doi: 10.1289/ehp.1307496

Huang, W., Cao, J., Tao, Y., Dai, L., Lu, S. E., Hou, B., et al. (2012). Seasonal variation of chemical species associated with shortterm mortality effects of PM2.5 in Xi'an, a Central City in China. *Am. J. Epidemiol.* 175, 556–566. doi: 10.1093/aje/kwj342

Intergovernmental Panel on Climate Change IPCC-SREX (2012). "Managing the risks of extreme events and disasters to advance climate change adaptation, a special report of working groups I and II of the Intergovernmental panel on climate change," in Field, eds C. B. V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. (Cambridge, New York, NY: Cambridge University Press), 1–52.

International Institute for population sciences (IIPS) and Macro International (2007). *National Family Health survey (NFHS-3).* 2005-06: Volume 1. Mumbai: IIPS.

IPCC (2007). “Summary for policymakers,” in *Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the IV Assessment Report of the Intergovernmental Panel on Climate. Intergovernmental Panel on Climate Change (IPCC) (Cambridge: Cambridge University Press).
pollution in India taking Agra as a model city. *Aerosol Air Qual. Res.* 17, 831–842. doi: 10.4209/aaqr.2016.02.0067

Maji, K. J., Namedeo, A., Bell, M., Goodman, P., Nagendra, S. S., Barnes, J. H., et al. (2021). Unprecedented reduction in air pollution and corresponding short-term premature mortality associated with COVID-19 Lockdown in Delhi, India. *J. Air Waste Manage. Assoc.* 1–17. doi: 10.1080/10962247.2021.19 05104

Majra, J. P., and Gur, A. (2009). Climate change and health: why should India be concerned? *Indian J. Occupat. Environ. Med.* 13, 11–16. doi: 10.4103/0971-5278.50717

Mathew, A., Khandelwal, S., and Kaul, N. (2016). Spatial and temporal variations of urban heat island effect and the effect of percentage impervious surface area and elevation on land surface temperature: study of Chandigarh city, India. *Sustain. Cities Soc.* 26, 264–277. doi: 10.1016/j.scs.2016.06.018

Mazidiyani, O., Aghakouchak, A., Davis, S. J., Madadgar, S., Mehran, A., Rago, E., et al. (2017). Increasing probability of mortality during Indian heat waves. *Sci. Adv.* 3:e1700066. doi: 10.1126/sciadv.1700066

Mehta, L., Srivastava, S., Adam, H. N., Bose, S., Ghosh, U., and Kumar, V. V. (2019). Climate change and uncertainty from ‘above’and ‘below’: perspectives from India. *Region. Environ. Change* 19, 1533–1547. doi: 10.1007/s11356-014-3418-2

Menon, S., Hansen, J., Nazarenko, L., and Luo, Y. (2002). Climate effects of black carbon aerosols in China and India. *Science* 297, 2250–2253. doi: 10.1126/science.1075159

Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., and Cholakian, A. (2020). Impact of lockdown measures to combat Covid-19 on air quality over western Europe. *Sci. Total Environ.* 741:140426. doi: 10.1016/j.scitotenv.2020.140426

Mirojsky, J., Hickey, C., Horton, L., Blaustein, M., Galdanes, K., Pelter, R. E., et al. (2013). The effect of particle size, location and season on the toxicity of urban and rural particulate matter. *Inhalat. Toxicol.* 25, 747–757. doi: 10.3109/08958378.2013.846443

Mishra, A. K., Srivastava, A., and Jain, V. K. (2013). Spectral de pendency of aerosol

Mukhopadhyay, K. (2009).

Murari, K. K., Ghosh, S., Patwardhan, A., Daly, E., and Salvi, K. (2015). Temporal variability of MODIS aerosol optical depth and chemical characterization of airborne particulates in Varanasi, India. *Environ. Sci. Pollut. Res.* 22, 1329–1343. doi: 10.1007/s11356-014-3418-2

Nagpure, A. S., Gurjar, B. R., and Martel, J. C. (2014). Human health risks in national capital territory of Delhi due to air pollution. *Atmosp. Pollut. Res.* 5, 371–380. doi: 10.5094/APR.2014.043

NASA (2015). GISS Surface Temperature Analysis. Available online at: https://www.nytimes.com/2014/02/14/opinion/indias-air-pollution-emergency.html (accessed April 1, 2021).

Nath, R., Ni-Meister, W., and Choudhury, R. (2021). Impact of urbanization on land use and land cover change in Guwahati city, India and its implication on declining groundwater level. *Groundwater Sustain.* Dev. 12:100500. doi: 10.1016/j.gsd.2020.100500

NYT (2014). *India’s Air Pollution Emergency* [online]. The New York Times. Retrieved from: http://www.nytimes.com/2014/02/14/opinion/indias-airpollutionemergency.html?r=0

OECD (2014). *The Cost of Air Pollution: Health Impacts of Road Transport.* Paris: OECD Publishing. doi: 10.1787/9789264210448-en

Oder, S., Dietrich, S., Weichenmeier, I., Schober, W., Pusch, G., Jorres, R. A., et al. (2012). Toxicity and elemental composition of particulate matter from outdoor and indoor air of elementary schools in Munich, Germany. *Indoor Air* 22, 148–158. doi: 10.1111/j.1600-0668.2011.07 43.x

Ohashi, Y., Genchi, Y., Kondo, H., Kikegawa, Y., Yoshikado, H., and Hirano, Y. (2007). Influence of air conditioning waste heat on air temperature in Tokyo during summer: numerical experiments using an urban canopy model coupled with a building energy model. *J. Appl. Meteorol. Climatol.* 46, 66–81. doi: 10.1175/JAM2441.1

Orimoloye, I. R., Mazzino, S. P., Kalumba, A. M., Ekundayo, O. Y., and Nel, W. (2019). Implications of climate variability and change on urban and human health: a review. *Cities* 91, 213–223. doi: 10.1016/j.cities.2019.01.009

Patil, R. R., and Deepa, T. M. (2007). Climate change: the challenges for public health preparedness and response-an Indian case study. *Indian J. Occup. Environ. Med.* 11, 113–115. doi: 10.4103/0119-5278.38460

Paul, S., Saxena, K. G., Nagendra, H., and Lele, N. (2021). Tracing land use and land cover change in peri-urban Delhi, India, over 1973–2017 period. *Environ. Monit. Assess.* 193, 1–12. doi: 10.1007/s10661-020-08841-x

Peng, R. D., Dominici, F., Pastor-Barriuso, R., Zeger, S. L., and Samet, J. M. (2005). Seasonal analyses of air pollution and mortality in 100 US cities. *Am. J. Epidemiol.* 161, 585–594. doi: 10.1093/aje/kwi075

Pope, C. A. III, Ezzati, M., and Dockery, D. W. (2009). Fine-particle air pollution and life expectancy in the United States. *N. Engl. J. Med.* 360, 376–386. doi: 10.1056/NEJMc0805646

Portnov, B. A., Reiser, B., Karkabi, K., Cohen-Kastel, O., and Dubnov, J. (2012). High prevalence of childhood asthma in Northern Israel is linked to air pollution by particulate matter: evidence from GIS analysis and Bayesian Model Averaging. *Int. J. Environ. Health Res.* 22, 249–269. doi: 10.1080/09603123.2011.634387

Prabhakaran, D., Mandal, S., Krishna, B., Magsumbol, M., Singh, K., Tandon, N., et al. (2020). Exposure to particulate matter is associated with elevated blood pressure and incident hypertension in urban India. *Hypertension* 76, 1298–1299. doi: 10.1161/HYPERTENSIONNAHA.120.15373

Pramanik, M. K. (2017). Impacts of predicted sea level rise on land use/land cover categories of the adjacent coastal areas of Mumbai megacity, *Indian Environ. Dev. Sustain.* 19, 1343–1366. doi: 10.1007/s10668-016-9804-9

Prasad, A. K., and Singh, R. P. (2007). Changes in aerosol parameters during major dust storm events (2001–2005) over the Indo-Gangetic Plains using AERONET and MODIS data. *J. Geophys. Res.* 112:C9. doi: 10.1029/2006JD007778

Rajeve, P., Rajeve, P., and Gupta, T. (2016). Chemical characteristics of aerosol and rain water during an El Niño and PDO influenced Indian summer monsoon. *Atmos. Environ.* 145, 192–200. doi: 10.1016/j.atmosenv.2016.09.026

Rajeve, P., Rajeve, P., Singh, D. K., Singh, A. K., Singh, A. K., and Gupta, T. (2018). Risk assessment of submicron PM-bound hexavalent chromium during wintertime. *Human Ecol. Risk Assess. Int.* J. 24, 1453–1463. doi: 10.1080/10807039.2017.1414581

Rajput, P., Anjum, M. H., and Gupta, T. (2017). One year record of bioaerosols and particles concentration in Indo-Gangetic Plain: implications of biomass burning emissions to high-level of endotoxin exposure. *Environ. Pollut.* 224, 98–106. doi: 10.1016/j.envpol.2017.01.045

Rajput, P., Izhar, S., and Gupta, T. (2019). Deposition modeling of ambient aerosols in human respiratory system: health implication of fine particles
penetration into pulmonary region. Atmos. Pollut. Res. 10, 334–343. doi: 10.1016/j.apr.2018.08.013
Rajput, P., Mandalia, A., Kachawa, L., Singh, D. K., Singh, A. K., and Gupta, T. (2016). Chemical characterisation and source apportionment of PM1 during massive loading at an urban location in Indo-Gangetic Plain: impact of local sources and long-range transport. Tellus B Chem. Phys. Meteorol. 68, 1–10. doi: 10.3402/tellusb.v68.30659
Rajput, P., Sarin, M., and Kundra, S. S. (2013). Atmospheric particulate matter (PM2.5). EC, OC, WSOCC and PAHs from NE–Himalaya: abundances and chemical characteristics. Atmosp. Pollut. Res. 4, 212–214. doi: 10.5094/APR.2013.022
Rajput, P., Singh, D. K., Singh, A. K., and Gupta, T. (2014). Characteristics and emission budget of carbonaceous species from post-harvest agricultural-waste burning in source region of the Indo-Gangetic Plain. Tellus B Chem. Phys. Meteorol. 66,121026. doi: 10.3402/tellusb.v66.21026
Rajput, P., Sarin, M. M., Rengarajan, R., and Singh, D. (2011). Atmospheric polycyclic aromatic hydrocarbons (PAHs) from post-harvest biomass burning emissions in the Indo-Gangetic Plain: isomer ratios and temporal trends. Atmosp. Environ. 45, 6732–6740. doi: 10.1016/j.atmosenv.2011.08.018
Rajput, P., Singh, D. K., Singh, A. K., and Gupta, T. (2018). Chemical composition and source-apportionment of sub-micron particles during wintertime over Northern India: new insights on influence of fog-processing. Environ. Pollut. 233, 81–91. doi: 10.1016/j.envpol.2017.10.036
Ramachandran, S., and Cherian, R. (2008). Regional and seasonal variations in aerosol optical characteristics and their frequency distributions over India during 2001–2005. J. Geophys. Res. 113,D8. doi: 10.1029/2007JD008560
Ramachandran, S., Kedia, S., and Srivastava, R. (2012). Aerosol optical depth trends over different regions of India. Atmos. Environ. 49, 338–347. doi: 10.1016/j.atmosenv.2011.11.017
Ramanathan, V., and Carmichael, G. (2008). Global and regional climate changes due to black carbon. Nat. Geosci. 1, 221–227. doi: 10.1038/ngeo156
Ramanathan, V. C. P. J., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D. (2001). Aerosols, climate, and the hydrological cycle. Science 294, 2119–2124. doi: 10.1126/science.1064034
Ramya, A., Nivetha, A., and Dhevagi, P. (2021). “Overview of indoor air pollution: a human health perspective,” in Spatial Modeling and Assessment of Environmental Contaminants (Cham: Springer), 495–514. doi: 10.1007/978-3-030-63422-3_25
Ravindra, K., Singh, T., Mor, S., Singh, V., Mandal, T. K., Bhatti, M. S., et al. (2019). Real-time monitoring of air pollutants in seven cities of North India during crop residue burning and their relationship with meteorology and transboundary movement of air. Sci. Total Environ. 690, 717–729. doi: 10.1016/j.scitotenv.2019.06.216
Ren, G., Zhou, Y., Chu, Z., Zhou, J., Zhang, A., Guo, J., et al. (2008). Urbanization effects on observed surface air temperature trends in Northern China. J. Climate 21, 1333–1348. doi: 10.1175/2007JCLI3148.1
Ritzw, S. A., Nongkynrih, B., and Gupta, S. K. (2013). Air pollution in Delhi: its magnitude and effects on health. Indian J. Community Med. 38, 4–8. doi: 10.4103/0970-0218.106617
Rogers, J. F., Thompson, S. J., Addy, C. L., McKeown, R. E., Cowen, D. J., and Decoulle, P. (2000). Association of very low birth weight with exposures to environmental sulfur dioxide and total suspended particulates. Acta Cytol. 45, 958–964. doi: 10.1159/000328371
Singh, R. P., and Chauhan, A. (2020). Impact of lockdown on air quality in India during COVID-19 pandemic. Air Qual. Atmos. Health 13, 921–928. doi: 10.1007/s11869-020-00863-1
Singh, R. P., Rajput, P., Sharma, D., Sarin, M. M., and Singh, D. (2014). Black carbon and elemental carbon from postharvest agricultural-waste burning emissions in the Indo-Gangetic Plain. Adv. Meteorol. 2014, 1–10, doi: 10.1155/2014/197901
Singh, B. P., Srivastava, A. K., Tiwari, S., Singh, S., Singh, R. K., Bisht, D. S., and Madhavan, M., et al. (2021). Climate change adaptation in Indian cities: a review of existing actions and spaces for triple win. J. Environ. Sci. Eng. 12, 1–9. doi: 10.1186/s12524-017-0256-9
Singh, C., Madhavan, M., Arvind, J., and Bazaz, A. (2021). Climate change adaptation in Indian cities: a review of existing actions and spaces for triple wins. Urban Climate 36,100783. doi: 10.1016/j.uclim.2021.100783
Singh, R., Sharma, C., and Agrawal, M. (2017). Emission inventory of trace gases from road transport in India. Transport. Res. Part D Transp. Environ. 52, 64–72. doi: 10.1016/j.trd.2017.02.011
Singh, R. P., and Chauhan, A. (2020). Impact of lockdown on air quality in India during COVID-19 pandemic. Atmos. Environ. 212, 406–422. doi: 10.1016/j.atmosenv.2020.108.001
Singh, S., Nath, S., Kohli, R., and Singh, R. (2005). Aerosols over Delhi during pre-monsoon months: Characteristics and effects on surface radiation forcing. Geophys. Res. Lett. 32:L18808. doi: 10.1029/2005GL023062

Singh, S., Soni, K., Bano, T., Tanwar, R. S., Nath, S., and Arya B. C. (2010). Clear-sky direct aerosol radiative forcing variations over mega-city Delhi. Ann. Geophys. 28, 1157–1166. doi: 10.5194/angeo-28-1157-2010

Singh, V., Singh, S., and Biswal, A. (2021). Exceedances and trends of particulate matter (PM2.5) in five Indian megacities. Sci. Total Environ. 750:141461. doi: 10.1016/j.scitotenv.2020.141461

Smith, K. R. (2013). Biofuels, Air Pollution, and Health: A Global Review.

Sorathia, F., Samoli, E., Alessandri, E., Cadum, E., Ostro, B., Guter, A., et al. (2013). Short-term associations between fine and coarse particulate matter and hospitalizations in Southern Europe: results from the MED-PARTICLES project. Environ. Health Perspect. 121, 1026–1033. doi: 10.1289/ehp.1206151

Surendran, D. E., Beig, G., Ghude, S. D., Paniker, A. S., Manoj, M. G., Chate, D. M., et al. (2013). Radiative forcing of black carbon over Delhi. Int. J. Photoenergy 2013:13652. doi: 10.1155/2013/13652

Tiwari, S., Bisht, D. S., Srivastava, A. K., Pipal, A. S., Taneya, A., Srivastava, M. K., et al. (2014). Variability in atmospheric particulates and meteorological effects on their mass concentrations over Delhi, India. Atmos. Res. 145, 45–56. doi: 10.1016/j.atmosres.2014.03.027

Tiwari, S., Hopke, P. K., Pipal, A. S., Srivastava, A. K., Bisht, D. S., Tiwari, S., et al. (2015). Intra-urban variability of particulate matter (PM2.5 and PM10) and its relationship with optical properties of aerosols over Delhi, India. Atmos. Res. 166, 223–232. doi: 10.1016/j.atmosres.2015.07.007

Tiwari, S., Srivastava, A. K., Bisht, D. S., Bano, T., Singh, S., Behura, S., et al. (2009). Black carbon and chemical characteristics of PM10 and PM2.5 at an urban site of North India. J. Atmos. Chem. 62, 193–209. doi: 10.1007/s10874-010-9148-z

Tsi, S.-S., and Yang, C.-H. (2014). Fine particulate air pollution and hospital admissions for pneumonia in a subtropical city: Taipei, Taiwan. J. Toxicol. Environ. Health A 77, 192–201. doi: 10.1080/15287394.2013.853337

UNDESA (2018). 2018 Revision of World Urbanization Prospects.

UN-HABITAT (2010). State of the World’s Cities 2010/2011: Bridging the Urban Divide. London: Earthscan. doi: 10.3425/9781849774846

Vadrevu, K. P., Eaturu, A., Biswas, S., Lasko, K., Sahu, S., Garg, J. K., et al. (2013). Diurnal and seasonal cycles of ozone precursors observed from continuous measurement at an urban site in Taiwan. Atmos. Environ. 69, 2229–2242. doi: 10.1016/j.atmosenv.2013.02.003

Zhang, S., Wang, M., Ghan, S. J., Ding, A., Wang, H., Zhang, K., et al. (2016). On the characteristics of aerosol indirect effect based on dynamic regimes in global climate models. Atmosp. Chem. Phys. 16, 2765–2783. doi: 10.5194/acp-16-2765-2016

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