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

Rajveer Kaur and Puneeta Pandey*

Department of Environmental Science and Technology, School of Environment and Earth Sciences, Central University of Punjab, Bathinda, India

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-2019 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 alongwith 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 10 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 Carmichae, 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; Hondula 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 2,100 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, shigella, giardia, and viruses such as hepatitis A (Gabastou 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 Uttaranchal 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, crytosporidiosis, 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)}, SOx, NOx, 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; Dandotiya 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 SOx, NOx, 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

FIGURE 1 | Major sources of air pollution in Indian cities.
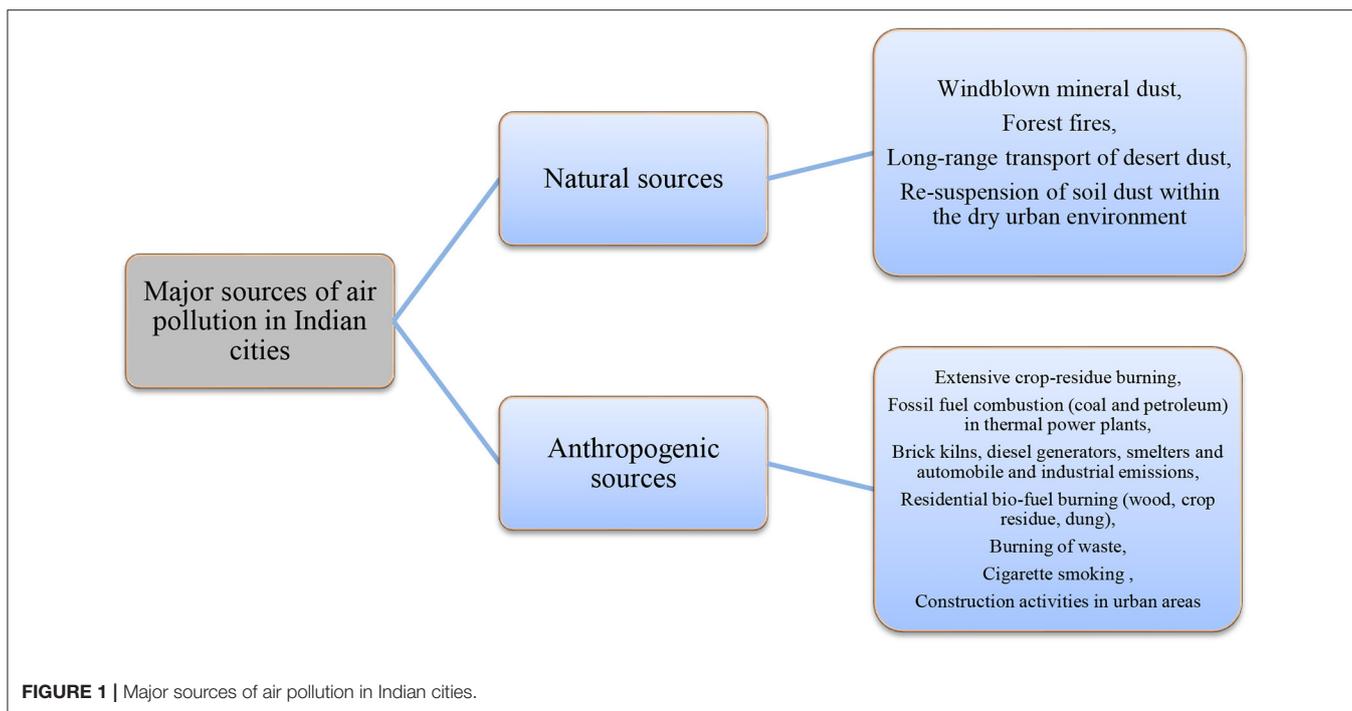
2.2 to 9.4 μg m^{-3} during paddy-residue burning emission in the month of October-November, emission from bio- and fossil-fuel combustion during December–March months and wheat-residue burning emissions duringApril-May, respectively. In contrast, the mass concentrations of Elemental Carbon (EC) varied from 3.8 to 17.5, 2.3 to 8.9, and 2.0 to 8.8 μg 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 ngm^{-3} during wheat burning season.

Human Health Impacts by Air Pollution
Since last few decades, there has been signification 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). Rajput et al. (2016) assessed temporal variability and source contributions of PM1, trace metals, five major elements, and four water-soluble inorganic species (WSIS) in the Indo-Gangetic Plains (IGP). Total WSIS contributes about 26% to PM$_1$ mass concentration. Secondary aerosols (contributing as high as) were predominantly

derived from stationary combustion sources and contributed ~60% to PM$_1$ loading. Further, atmospheric fog prevalent during wintertime can have a severe impact on atmospheric chemistry in the air-shed of IGP.

The health issues linked with air pollution is a topic of major concern specially for developing Indian cities. In India, the outdoor air pollution has become fifth eminent reason of death after high blood pressure, indoor air pollution, poor nutrition and tobacco smoking in 2012 causing about 0.62 million premature excess number of death cases (NYT, 2014; Maji et al., 2016).

Air pollution is linked with short term, medium, or long term impacts on human health (Gumashta 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; Prabhakaran et al., 2020).

Furthermore, the health impacts of NO_2 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 SO_2 concentrations (Ciccone et al., 1995; Dejmek et al., 2000; Rogers et al., 2000). Although gaseous air pollutants such as NO_2 and SO_2 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 (GPB), 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 $<2.5\,\mu m$ 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 PM2.5 mass concentrations in Patiala region of Punjab during paddy-residue burning in the months of October and November in the range of 60–390 μgm^{-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 μgm^{-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 μgm^{-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/m^3)	References
Jorhat, Northeast India	24 h mean concentration $PM_{2.5} = 121 \pm 49$ $PM_{10} = 153 \pm 45$	Islam and Saikia, 2020
Delhi (ITO)	24-h mean concentration $PM_{2.5} = 71.9$	Shaw and Gorai, 2020
Banglore (S. G. Halli)	24-h mean concentration $PM_{10} = 11.90$	
Kolkata	24-h mean concentration $PM_{10} = 97.00$	
Bhubaneswar	Annual mean concentration $PM_{2.5} = 30.6 \pm 22.1$ $PM_{10} = 88.3 \pm 30.6$	Mahapatra et al., 2018
Kanpur	PM_1 average mass concentration During non-foggy conditions $= 247 \pm 113$ During foggy conditions $= 107 \pm 58$	Rajput et al., 2018
Patiala	$PM_{2.5}$ mass concentration $= 60$-390 (October–November) $PM_{2.5}$ mass concentration $= 18$–123 (April–May)	Rajput et al., 2016
Patiala	Average concentration $PM_{2.5} = 55.4 \pm 13.5$	Sen et al., 2016
Lucknow	Average concentration $PM_{2.5} = 51.5 \pm 17.7$ $PM_{10} = 182.2 \pm 58.0$	
Kolkata	Average concentration $PM_{2.5} = 47.6 \pm 9.3$ $PM_{10} = 66.7 \pm 17.0$	
New Delhi	Average concentration $PM_{2.5} = 61.8 \pm 18.6$ $PM_{10} = 127.4 \pm 62.2$	
Nagpur	Average concentration $PM_{2.5} = 35.2 \pm 18.4$ $PM_{10} = 53.9 \pm 23.7$	
Varanasi	Average concentration $PM_{2.5} = 52.5 \pm 28.6$ $PM_{10} = 139.6 \pm 68.0$	
Mid-IGP region	Annual mean PM_{10} concentration $= 206.2 \pm 77.4$	Sharma et al., 2016
Varanasi	Annual mean concentration $PM_{2.5} = 100.0 \pm 29.6$ $PM_{10} = 176.1 \pm 85.0$ Monthly average concentration $PM_{10} = 43.6$–318.5 μg/m3 $PM_{2.5} = 50.1$–154.0 μg/m3	Murari V. et al., 2015
Delhi	Mean mass concentrations $PM_{2.5} = 118.3 \pm 81.7$ $PM_{10} = 232.1 \pm 131.1$	Tiwari et al., 2015
Vishakhapatnam	Annual average concentration $PM_{10} = 70.4 \pm 29.7$	Guttikunda et al., 2015
Chennai	Annual average concentration $PM_{10} = 121.5 \pm 45.5$	
Delhi	$PM_{2.5} = 130.0 \pm 103.0$ $PM_{10} = 222.0 \pm 142.0$	Tiwari et al., 2014
Pune	Average mass concentration $PM_{2.5} = 72.3 \pm 31.3$ $PM_{10} = 113.8 \pm 51.6$	Yadav and Satsangi, 2013
Barapani, foot–hills of NE–Himalaya	Wintertime concentration of $PM_{2.5} = 39$–348	Rajput et al., 2013
Raipur	Annual average concentrations (July 2009 to June 2010) $PM2.5 = 150.9 \pm 78.6$ $PM10 = 270.5 \pm 105.5$ $PM1 = 72.5 \pm 39.0$	Deshmukh et al., 2013

(Continued)

TABLE 1 | Continued

Study area	PM values (μg/m^3)	References
Mumbai	Average concentration PM$_{2.5}$ = 42	Kothai et al., 2011
Agra	PM 2.5 = 104.9 PM10 = 154.2	Kulshrestha et al., 2009
Kolkata	PM$_{10}$ = 140	Karar and Gupta, 2006

Adding to PM studies, Singh V. et al. (2021) analyzed particulate matter (PM$_{2.5}$) 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 PM$_{2.5}$ over four Indian megacities (Delhi, Chennai, Hyderabad and Mumbai) during 2015–2018. The results depict annual averaged PM$_{2.5}$ concentration of 110 μg/m^3 (Delhi), 60 μg/m^3 (Mumbai), 56 μg/m^3 (Hyderabad), and 33 μg/m^3 (Chennai) during study period with worst air quality for Delhi. The study showed 75% increase in PM$_{2.5}$ concentration during Diwali due to burning of firecrackers that causes 20 extra daily mortality. The long-term exposure to PM$_{2.5}$ 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 PM$_{2.5}$ 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 PM$_{2.5}$ concentration (97 $\pm$ 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 PM$_1$-bound species in IGP and reported that the foggy conditions were associated with higher contribution of PM$_1$-bound organic matter alongwith approximately equal decrease in SO_4^{2-}, NO_3^-, and NH_4^+ 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 NO$_2$ emissions with 70% decrease in NO$_2$ emissions in India (Gautam, 2020).

A lockdown period study was conducted by Vadrevu et al. (2020) for analysis of spatio-temporal variations of air pollution (Singh B. P. et al., 2014) (using NO$_2$ and AOD) for 41 Indian cities. The study revealed about 13% reduction in NO$_2$ levels during the lockdown as compared to pre-lockdown period. The
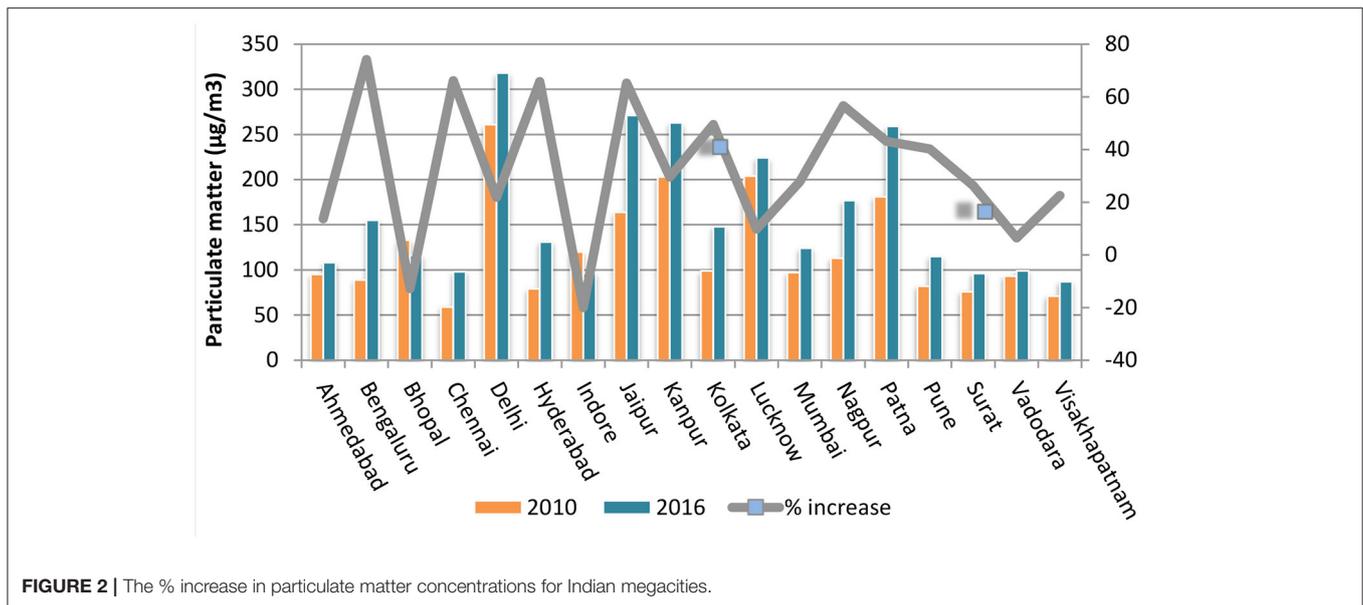
FIGURE 2 | The % increase in particulate matter concentrations for Indian megacities.

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.

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
	Delhi	60.37%	
	Bangalore	48.25%	
PM$_{2.5}$, PM$_{10}$	Ahmedabad	46.20%	Bera et al., 2020
	Nagpur	46.13%	
	Gandhinagar	45.64%	
	Mumbai	43.08%	
	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
	Mumbai	14%	

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

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 tracheobronchial 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.

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