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ORIGINAL PAPER

Urban Air-Quality Assessment and Inferring the Association Between Different Factors: A Comparative Study Among Delhi, Kolkata and Chennai Megacity of India

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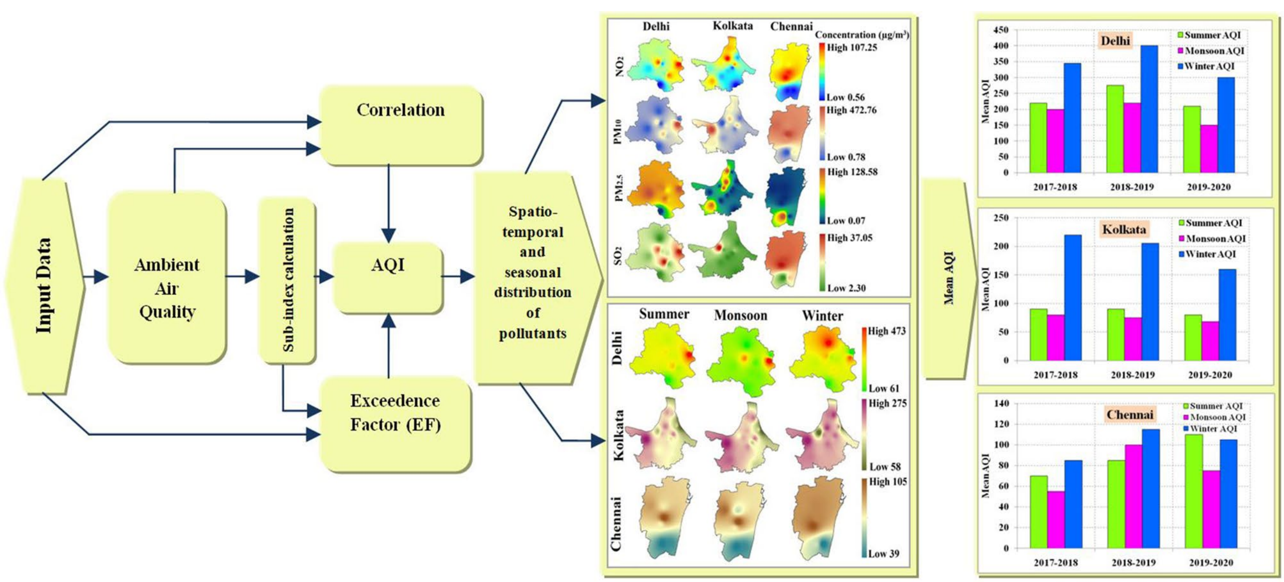
Abstract

The continuous increase of air pollution is an emerging environmental issue in the Indian megacities for the last few decades. Rapid and uncontrolled urbanization coupled with population growth, rising vehicle population, and growth of industries has been fuelling this problem. The present study analyzed the trend and pattern of air pollution of three Indian megacities: Delhi, Kolkata, and Chennai in a spatio-temporal frame using a comparative approach. To develop the air pollution scenario, air-quality data have been collected from the Central Pollution Control Board and also the State Pollution Control Board of respective cities. Four major pollutants (PM_{10}, $PM_{2.5}$, NO_2, and SO_2) have been selected to develop the air-quality index (AQI) from the period of 2017 to 2020. The meteorological parameters have been used to correlate with AQI. Moreover, exceedance factor has been calculated to analyze the level of pollution in comparison to the national standards. The results demonstrate that Delhi and Kolkata are most affected by air pollution. The seasonal distribution shows that higher concentrations of pollution were found during the winter season. The results of this analysis will be helpful in the assessment of air pollution and to investigate the way out through proper policies.

Graphic Abstract



Keywords Ambient air quality · Seasonal variation · Exceedance factor · Meteorological parameters · Sustainable management

Extended author information available on the last page of the article

1 Introduction

In the last few decades, air pollution has become a matter of great concern for the city people all over the world (Chattopadhyay et al. 2010; Debone et al. 2020). According to the World Health Organization (WHO), pollution is considered as the reason behind the deaths of more than 25% of people around the world (Sharma et al. 2019; Halim et al. 2020). Air pollution is being a major concern in most cities. In the case of India, mainly the large metropolitan cities including other urban areas are experiencing unhealthy, unhygienic conditions due to air pollution. It is reported that, due to outdoor air pollution, 1.2 million people lose their lives every year (Guttikunda et al. 2014). From the economic point of view, the World Bank estimates that India loses its GDP at about 3% due to air pollution (Kanawade et al. 2020). This makes air pollution one of the important issues to discuss concerning save peoples' lives, health, and the country's economy.

The major contributors to air pollution consist of mainly two types: gaseous air pollutants (SO_2, NO_2, CO, etc.) and suspended particulate matters (PM_{10}, $PM_{2.5}$, etc.). Depending on the regions and climatic conditions, the pollutants' source, their behavior, and concentration may differ from one city to the other. However, the major sources which contribute to air pollution in the regions are the combustion of fossil fuels from vehicles, power plants, industrial processes, etc. (Mohan and Kandya 2007). In India, air pollution is not concentrated in the cities alone, peri-urban and rural areas also have a contribution to pollution (Mouli et al. 2004; Guttikunda et al. 2014). But still, the major four metropolitan cities in India, i.e., Delhi, Kolkata, Chennai, and Mumbai, are attracting attention to most of the researchers to focus on air quality (Haque and Singh 2017). From the geographical point of view, the locations of all the four cities are distinct and different from each other. Delhi is a landlocked region, surrounded by states from all sides, while Kolkata is a lowland area for being the part of Bengal delta, and Chennai and Mumbai belongs to India's east and west coasts, respectively. All of them being highly populated regions have more or less similar pollution sources and whether the air quality in the cities is similar or not, is the major intention of the present study.

Day by day, air pollution is emerging as a critical issue in most of the urban areas, which needs proper planning to solve the problems (Rumana et al. 2014; Jain et al. 2020). Due to rapid urbanization, industrialization, migration of people from rural to urban areas has increased. Anthropogenic activities like burning fossil fuels use of natural gas, emissions from automobiles have enhanced at a large scale in recent days, specifically in urban metropolitan areas (Singh et al. 2007; Yadav et al. 2020). As a result, most of the Indian cities are suffering from poor air quality. Urban land use also affects the air quality of the cities because different types of land use, their spatial distribution, human activities release different impacts in the atmosphere as well as in the concentration of air pollutants (Xu et al. 2016; Kayes et al. 2019). Urban land expansion significantly influences air pollution. It is also reported that air pollutants are positively correlated with built-up areas, negatively correlated with vegetation and water bodies (Halim et al. 2020). Another study suggests that air quality has a significant relation with urban form in terms of urban continuity, sparseness, forest area ratio, urban fragmentation and included that there is a positive relationship between air quality and forest area ratio while a negative relationship with urban continuity at spatial scales (Li et al. 2020). In developing countries, rapid urban population growth along with land-use changes due to urban expansion is one of the driving forces for the deterioration of urban air quality (Rajamanickam and Nagan 2018).Thus, a high level of air pollution would induce to raise diverse effects on human health and cause instability towards the environment (Gorai et al. 2017; Chiarini et al. 2020). In the present context, air pollution is one of the focal concern of the decision-making bodies or government.

In India, there are no such places that comply with the standards given by WHO and National Ambient Air Quality (NAAQS), because most of the cities are facing a critical level of pollution (Dholakia et al. 2013). Except for a few places in Southern India, the entire country is experiencing a public health crisis mainly respiratory problems, due to air pollution levels. To address this issue, most of the countries have developed the Air Quality Index (AQI) for the past several years (Rajamanickam and Nagan 2018). In the case of Indian megacities like Delhi, Kolkata, and Chennai, the concentration of pollutants, their distribution over space, seasonal characteristics, and variation of the pollutants are some of the major concerns over the last few years (Singh et al. 2007). In the present study, four major air pollutants are taken into consideration to get the results, i.e. NO_2, SO_2, PM_{10}, and $PM_{2.5}$ because these are carrying significant roles in respect to the amount of concentration of pollutants. Though other pollutants like Ozone (O_3), Carbon Monoxide (CO), etc. have significant roles in affecting air quality, they are not included in the present study. Along with that, climatic variation is also considered regarding the air pollution study (Mohan and Kandya 2007). Thus, with the varying climatic parameters including temperature, rainfall, relative humidity, and wind speed, there is a possible variation in the behavior of pollutants over the regions (Jain et al. 2020). However, the relationship between those climatic variables and the level of AQI would be taken into account as another matter of concern. Comprehensive studies have been done worldwide from different perspectives to address this issue (Biswas et al. 2011; Jayamurugan et al. 2013; Halim et al.

2020). A large number of people in India are economically dependent on megacities. So, it is indispensable to understand the sources of air pollution, the spatio-temporal distribution of the pollutants over the cities, the AQI, and its relationship with meteorological parameters. Significantly, a comparative study among the three megacities is rarely observed, so the present study may draw the attention to focus on the air quality of the cities with the distribution of concerning air pollutants. Moreover, such studies would empower the policymakers to deal with the issues to make a sustainable environment in the future.

2 Methodology

2.1 Study Area

Many cities in India are facing the problem of pollution and are listed under the most polluted categories in the world. About 80% of the cities are not paying attention to the prescribed standards of ambient air quality. Most of the pollution is attributed to the uncontrolled growth of the vehicle population, and poor inspection and maintenance systems in the study areas (Singh et al. 2007). The present study relates to the three megacities of India, Delhi, Kolkata, and Chennai, and discusses their levels of air pollution with the help of AQI (Fig. 1).

Delhi is one of the largest metropolis by area and the second-largest metropolis by population. It is one of the largest metropolises in the world according to population with more than 16.75 million residents in the territory and with nearly 22.2 million inhabitants in the National Capital Region (NCR). Delhi has now more vehicles than the three megacities Chennai, Kolkata, and Mumbai, put together. It is adding some 1400 new vehicles to its roads every day, which contribute to the sources of air pollution (Amann et al. 2017). According to the Census of India (Census. 2011), Kolkata, the capital city of West Bengal had 4.5 million population, with the urban agglomeration, consists of the city and its suburbs, home to approximately 14.1 million people, which makes it the third most densely populated metropolitan area in the country (Haque and Singh 2017).

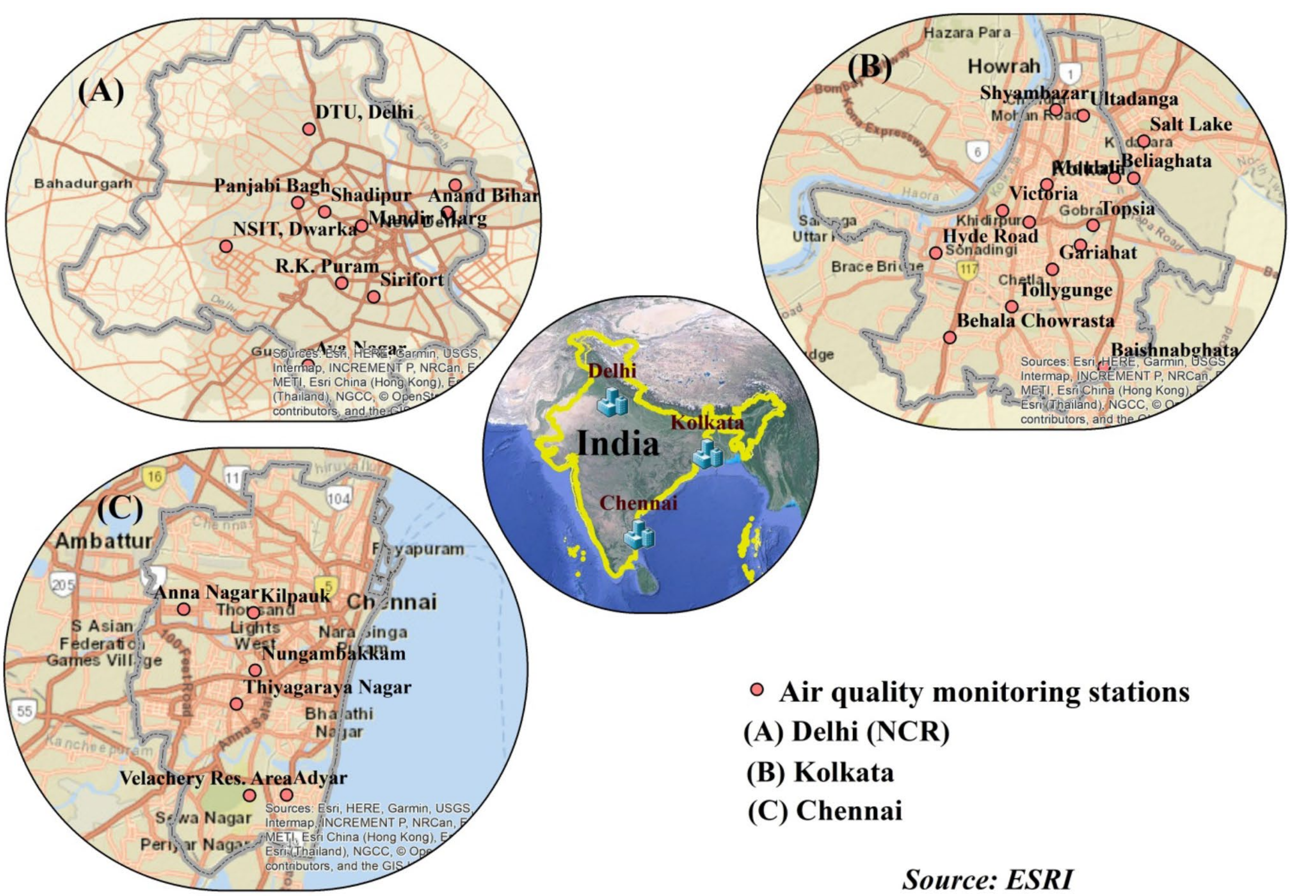


Fig. 1 Location map of three megacities: **a** Delhi NCR, **b** Kolkata, **c** Chennai showing their administrative boundaries and air-quality monitoring stations

Originally, Kolkata was a vast low-land that lies on the bank of Hooghly River, now is one of the most populated and one of the most polluted cities of the world with high levels of particulate matter in the atmosphere, creating a major health hazard (Dinda et al. 2020). A joint study by the West Bengal Department of Environment and the Central Pollution Control Board (CPCB), Chittaranjan National Cancer Institute (CNCI) has found that due to air pollution, around 70% of people in the city of Kolkata suffer from respiratory disorders (Spiroska et al. 2011). Insufficient road space, uncontrolled vehicular density, lack of adequate parking facilities, indifferent pedestrians together with a poor traffic management strategy, low turnover of old vehicles with too frequent breakdowns, undisciplined drivers, which is far from the ideal have a profound effect on urban air pollution (Ghosh et al. 2005). As the capital city of Tamil Nadu, Chennai is one of four metropolitan cities of India with more than 10 million inhabitants. With its proximity to the Bay of Bengal and thus access to markets in East Asia, it is also an important port city. The built-up area of Chennai is about 522 sq km. The sources contribute to highlight transport (including on-road dust), industries (including the coal-fired power plants), and open waste burning as the key air pollution sources in the urban areas of Chennai (Rajamanickam and Nagan 2018). In the present study, spatio-temporal pattern, trend, and distribution of air pollution are analyzed in the context of the Indian megacities.

2.2 Materials and Methods

2.2.1 Ambient Air Quality

The ambient air-quality monitoring network measures the number of air pollutants at different strategic locations in the country. The task of any monitoring network thus involves the selection of pollutants, their locations, frequency, sampling techniques, duration of sampling, manpower, infrastructural facilities, operation, and maintenance (Haque and Singh 2017; Sharma et al. 2019). In India, National Ambient Air Quality Monitoring (NAMP) is implemented by Central Pollution Control Board (CPCB) through a network consisted of 544 operating ambient air-quality stations covering 224 cities/towns in 26 States and 5 Union territories of the country in association with the command under the Air (Prevention and Control of Pollution) Act, 1981 for the collection, compilation and dissemination of the information on ambient air quality (Rajamanickam and Nagan 2018). For the present study, on three megacities, i.e. Delhi, Kolkata, and Chennai, the daily data on air pollutant concentration was collected from CPCB, West Bengal Pollution Control Board (WBPCB), and Tamil Nadu Pollution Control Board (TNPCB) websites to analyze the air-quality data under National Ambient Air Quality Standards (NAAQS) for the year of 2017–2020. The number of ambient air-quality monitoring stations in Delhi, Kolkata, and Chennai is 10, 13, and 6, respectively, and the stations are selected on a random basis.

2.2.2 Seasonal Variation

For the study of seasonal variation, the entire year is divided into three seasons: Summer (May to June), Monsoon (July to October), and Winter (November to February) as per regional climatic conditions. The concentration of air pollutants is analyzed in different seasons of the year from March 2017 to February 2020 at all the monitoring stations.

2.2.3 Air Quality Index (AQI)

The Air Quality Index (AQI) is a composite index that is used to convert the individual values of air pollutants into a uniform index with nomenclature and different color shades (Mouli et al. 2004; Sharma et al. 2019). It informs people about the level of ambient air quality, and the potential health risks, particularly for vulnerable groups, such as elderly people, children, and people having cardiovascular and respiratory diseases (Rajamanickam and Nagan 2018). To calculate AQI, two steps should be followed, i.e. sub-index development for individual pollutant and their combination to generate AQI. Sub-index functions were used to generate sub-indices of n number of pollutants. It can be expressed as:

$$I_i = f(X_i), \quad i = 1, 2, 3 \ldots, n \tag{1}$$

where I_i represents the sub-index and X_i represents the concentration of pollutants. Therefore, a similar numerical function should be used to obtain AQI:

$$\mathrm{AQI} = F(I_1, I_2, \ldots, I_n) \tag{2}$$

However, the AQI for the different stations of the three cities has been computed based on the following equation:

$$\mathrm{AQI}_i = \frac{I_{\mathrm{HI}} - I_{\mathrm{LO}}}{B_{\mathrm{HI}} - B_{\mathrm{LO}}}(C_i - B_{\mathrm{LO}}) + I_{\mathrm{LO}} \tag{3}$$

where AQI implies Max (i) (where $i = 1$, 2…n; whereas n denotes no. of pollutants), C_i represents the pollutant concentration, B_{HI} and B_{LO} represent the breakpoint concentration greater and smaller to C_i, respectively; I_{HI} represent AQI value corresponding to B_{HI} and I_{LO} represents to AQI value corresponding to B_{LO} (subtract one from I_{LO}, if I_{LO} is greater than 50).

AQI is represented as a numeric value that varies from 0 to 500. If the score is 0, it is the best air quality and if the score is 500, it is the worst air quality (Higher AQI leads to higher pollution). There are six AQI categories, namely good, satisfactory, moderate, poor, very poor, and severe (Table 1). Each of these categories is decided based on ambient concentration values of air pollutants and their likely health impacts (known as health breakpoints) (CPCB 2011). Eight pollutants (PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, and Pb) are considered under the Air Quality sub-index and health breakpoints, short-term (up to 24 h) National Ambient Air Quality Standards are also prescribed for them. Based on ambient pollutant concentration measurement, the sub-index is calculated; (e.g. the sub-index for $PM_{2.5}$ will be 145 at concentration 87 μg/m^3, 90 at concentration 54 μg/m^3, and 327at a concentration of 196 μg/m^3). The worst sub-index determines the overall AQI (in the case of the above example, the AQI value would be 327 for $PM_{2.5}$). AQI categories and health breakpoints for the eight pollutants are given in Table 2.

2.2.4 Illustration of Sub-Index Calculation

In case of Moulali Commercial area of Kolkata, shows the concentration of $PM_{10}=110.5$ μg/m^3, $SO_2=4.6$ μg/m^3, $NO_2=39$ μg/m^3, $PM_{2.5}=53$ μg/m^3. The PM_{10} falls in the breakpoint range of 0–50 μg/m^3 and the corresponding AQI range is 0–50, SO_2 falls in the breakpoint range of 0–40 μg/m^3 and the corresponding AQI range is 0–50, NO_2 falls in the breakpoint range of 0–40 μg/m^3 and the corresponding AQI range is 0–50 and $PM_{2.5}$ falls in the breakpoint range of 0–30 μg/m^3 and the corresponding AQI range is 0–50. Therefore,

Sub index for PM_{10} (AQI_i)

$C_i=110.5$ μg/m^3, $B_{LO}=0$ μg/m^3, $B_{HI}=50$ μg/m^3, $I_{LO}=0$, $I_{HI}=50$

$$AQI_i = \left[\left\{\frac{50-0}{50-0}\right\} * (110.5-0)\right] + 0$$

So, $AQI_i=110.5$

Sub index for SO_2 (AQI_i)

$C_i=4.6$ μg/m^3, $B_{LO}=0$ μg/m^3, $B_{HI}=40$ μg/m^3, $I_{LO}=0$, $I_{HI}=50$

$$AQI_i = \left[\left\{\frac{50-0}{40-0}\right\} * (4.6-0)\right] + 0$$

So, $AQI_i=5.75$

Sub index for NO_2 (AQI_i)

$C_i=39$ μg/m^3, $B_{LO}=0$ μg/m^3, $B_{HI}=40$ μg/m^3, $I_{LO}=0$, $I_{HI}=50$

$$AQI_i = \left[\left\{\frac{50-0}{40-0}\right\} * (39-0)\right] + 0$$

So, $AQI_i=48.75$

Sub index for $PM_{2.5}$ (AQI_i)

$C_i=53$ μg/m^3, $B_{LO}=0$ μg/m^3, $B_{HI}=30$ μg/m^3, $I_{LO}=0$, $I_{HI}=50$

$$AQI_i = \left[\left\{\frac{50-0}{30-0}\right\} * (53-0)\right] + 0$$

So, $AQI_i=88.33$.

Table 1 Health statements for AQI categories. (*Source*: CPCB Website)

NAQI categories	Impact	NAQI categories	Impact
Good (0–50)	Minimal Impact	Poor (201–300)	Breathing discomfort to people on prolonged exposure
Satisfactory (51–100)	Minor breathing discomfort to sensitive people	Very poor (301–400)	Respiratory illness to the people on prolonged exposure
Moderate (101–200)	Breathing discomfort to the people with lung, heart disease, children and older adults	Severe (> 401)	Respiratory effects even on healthy people

Table 2 Breakpoints for AQI scale 0–00 (units: μg/m^3 unless mentioned otherwise)

AQI category (range)	PM_{10} 24-h	$PM_{2.5}$ 24-h	NO_2 24-h	SO_2 24-h	O_3 8-h	CO 8-h (mg/m^3)	NH_3 24-h	Pb 24-h
Good (0–50)	0–50	0–30	0–40	0–40	0–50	0–1.0	0–200	0–0.5
Satisfactory (50–100)	51–100	31–60	41–80	41–80	51–100	1.1–2.0	201–400	0.6–1.0
Moderate (101–200)	101–250	61–90	81–180	81–380	101–168	2.1–10	401–800	1.1–2.0
Poor (201–300)	251–350	91–120	181–280	381–800	169–208	10.1–17	801–1200	2.1–3.0
Very poor (301–400)	351–430	121–250	281–400	801–1600	209–748[a]	17.1–34	1201–1800	3.1–3.5
Severe (> 401)	430+	250+	400+	1600+	748+[a]	34+	1800+	3.5+

[a]One hourly monitoring (for mathematical calculation only)

Thus, the AQI for the station Moulali will be Max (110.5, 5.75, 48.75, 88.33) = 110.5.

2.2.5 Meteorological Parameters

In the present study, meteorological parameters have taken a significant role in determining the air quality of an area. Kayes et al. (2019) stated that not only seasonal variations are responsible for the seasonal fluctuation of pollutants, but also meteorological parameters play a distinct character to make the difference. The selected meteorological parameters include temperature (in °C), rainfall (in mm.), Wind Speed (in m/s), relative humidity (in %), and wind direction. To study the relationship between AQI and the meteorological parameters, the data are collected from the CPCB website in the year 2017–2020 for the three cities. The data are arranged in RStudio 2010 with average annual values for the subsequent seasons of summer, monsoon, and winter; and then computed the *r* value to get the correlation coefficient.

2.2.6 Pearson's Correlation Coefficient

For the assessment of the strength of the relationship between the air pollutants (PM_{10}, $PM_{2.5}$, NO_2, and SO_2) and local meteorological parameters, i.e., temperature, rainfall, relative humidity, and wind speed), the following calculation was used:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n(\sum x^2) - (\sum x)^2][n(\sum y^2) - (\sum y)^2]}} \tag{4}$$

where *n* implies sample size, and *x* and *y* are the individual samples.

2.2.7 Calculation of Exceedance Factor (EF)

The exceedance factor is an important tool to analyze and represent the condition of air pollution level of a particular region (Rajamanickam and Nagan 2018). It is the ratio between the annual mean concentration of pollutants and the annual standard for that particular pollutant. In the present study, annual mean concentrations of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ are calculated for the year 2017–2018, 2018–2019, and 2019–2020 for Delhi, Kolkata, and Chennai. According to the CPCB standards and classes, the range of concentration of pollutants' can be calculated with the help of exceedance factor (EF) (CPCB 2011):

$$\mathrm{EF} = \frac{\mathrm{CP}_{\text{annual, mean}}}{P_{\text{annual, standard}}} \tag{5}$$

where $\mathrm{CP}_{\text{Annual, Mean}}$ means annual concentration of pollutants and $P_{\text{Annual, Standard}}$ represents the annual standard value of the pollutants. The air pollution can be analyzed using the following criterion:

Low pollution (LP): EF < 0.5
Moderate pollution (MP): EF 0.5–1.0
High pollution (HP): EF 1.0–1.5
Critical pollution (CP): EF > 1.5.

3 Results

3.1 Spatio-Temporal Distribution of Pollutants

3.1.1 Distribution of Pollutants in Kolkata

The result shows that Kolkata is mostly affected by suspended particulate matter (SPM), as expected in a megacity, which adversely affects the health of its citizens (Spiroska et al. 2011). From Fig. 2, it is clear that among the four pollutants, the concentration level of PM_{10} is the highest, which ranges between the values of 65 μg/m^3 in Victoria and 175 μg/m^3 in Hyde Road. The concentration of NO_2 ranges between 32 μg/m^3 (Baishnabghata) and 45 μg/m^3 (Moulali). Likewise, the concentration of SO_2 ranges between 3 μg/m^3 (Picnic Garden) and 7.4 μg/m^3 (Moulali). Being a commercial area, Moulali is experiencing the highest concentrations of NO_2 and SO_2 due to excessive congestion and movement of transportation. The concentration of $PM_{2.5}$ is found to be highest in the Picnic Garden having a value of 77 μg/m^3 and the lowest is found at Behala Chowrasta (38 μg/m^3). As Hyde Road is an industrial area, the level of PM_{10} indicates the highest value, which can impact human health. The concentration of NO_2 and SO_2 is lowest in the station Picnic Garden having the value of 33 μg/m^{3}and 3.4 μg/m^3, respectively, and highest in the Victoria and Hyde Road with the value of 55 μg/m^3 and 8 μg/m^3, respectively. The major contributor PM_{10} is found to be above the permissible limit of NAAQS (100 μg/m^3) which is highest in Hyde Road (163 μg/m^3) and lowest in Picnic Garden (102 μg/m^3). Among the available data on the above five stations, Shyambazar is showing the highest concentration of $PM_{2.5}$ i.e. 80 μg/m^3, while Victoria is showing the lowest concentration of $PM_{2.5}$ i.e. 66.5 μg/m^3. The stations having the highest and lowest concentration of pollutants have been changed slightly. The concentration of PM_{10} is highest in Hyde Road (150 μg/m^3) and lowest in Gariahat (70 μg/m^3). The NO_2 and SO_2 concentrations are also found to be highest in Hyde Road (50 μg/m^3 and 11 μg/m^3, respectively); while they are found lowest in Tolly Gunge (40 μg/m^3) and Victoria (6.5 μg/m^3), respectively. Concentration of $PM_{2.5}$ is highest at Moulali (57 μg/m^3) and lowest at Behala Chowrasta (39 μg/m^3).

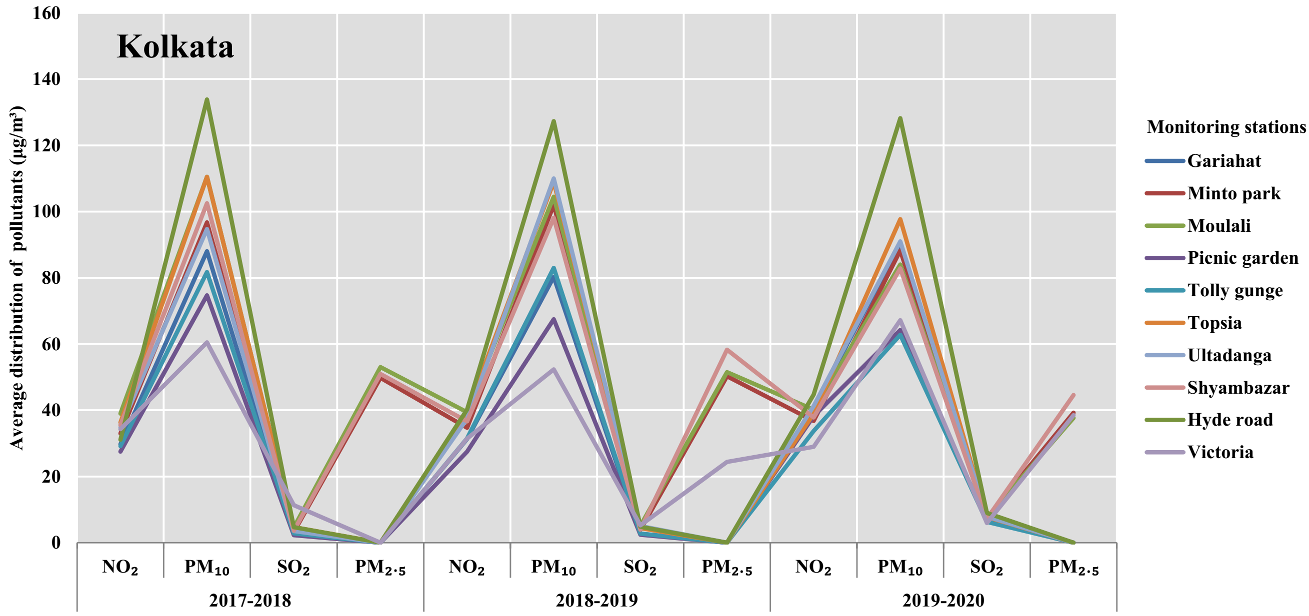


Fig. 2 Average distribution of pollutants (NO_2, PM_{10}, SO_2 and $PM_{2.5}$) in various monitoring stations of Kolkata during 2017–2018, 2018–2019 and 2019–2020. (*Data Source*: CPCB)

3.1.2 Distribution of Pollutants in Delhi

Being the capital city of India, Delhi is facing a much higher level of pollution than the other two megacities. The major sources of emission in Delhi were vehicular exhaust, road dust, fossil fuel combustion along biomass burning (Amann et al. 2017; Gorai et al. 2017). The increasing anthropogenic activities like vehicular, industrial, construction, and solid waste incineration along with increased incidents of post-harvest agricultural residue burning were attributed to the increase in the concentration of pollutants (Jain et al. 2020). The monitoring sites of Delhi are showing a variety of distributions in the concentrations of air pollutants in Fig. 3. In the case of NO_2 and SO_2, the highest values are observed in the site Punjabi Bagh (149 µg/m^3 and 30.5 µg/m^3, respectively), while the lowest in Aya Nagar (16 µg/m^3) and NSIT Dwarka (10 µg/m^3). Being a mixed area, Punjabi Bagh is experiencing the highest concentrations whereas Aya Nagar for being a residential area, gets less amount of pollutants concentrations. The concentration of PM_{10} and $PM_{2.5}$ is found to be highest in Anand Vihar (500 µg/m^3 and 215 µg/m^3, respectively) and the lowest is found in Sirifort (180 µg/m^3) and IHBAS, Dilshad Garden (89 µg/m^3). The concentrations of PM_{10} and $PM_{2.5}$ have reduced than the previous year. Here, the highest values of PM_{10} and $PM_{2.5}$ are found to be 235 µg/m^3 and 231 µg/m^3 in Anand Vihar and Shadipur, respectively, and the lowest are 163 µg/m^3 at Mandir Marg and 91 µg/m^3 at Aya Nagar. The concentrations of NO_2 and SO_2 are highest in Punjabi Bagh (96 µg/m^3 and 25 µg/m^3, respectively), while the lowest are in Aya Nagar (29 µg/m^3) and Sirifort (11 µg/m^3). The concentrations of PM_{10} and $PM_{2.5}$ are largest at Sirifort and Anand Vihar having the values of 271 µg/m^3 and 161 µg/m^3 and lowest at Aya Nagar (159 µg/m^3 and 82 µg/m^3). In the case of NO_2, the highest value is 83 µg/m^3 at Anand Vihar and the lowest is 22 µg/m^3 at Aya Nagar. Panjabi Bagh is showing the highest value of SO_2 (17.4 µg/m^3) and Mandir Marg is showing the lowest value (6.4 µg/m^3). For being residential areas, Aya Nagar and Mandir Marg have shown the lowest values among all.

3.1.3 Distribution of Pollutants in Chennai

The annual average values for NO_2, SO_2, and PM_{10} are shown in the different monitoring stations of Chennai (Fig. 4). Among the six stations, the concentrations of PM_{10} are in the range of 51–100 µg/m^3; where the highest and lowest concentrations are observed at Nungambakkam (100 µg/m^3) and Adyar (51 µg/m^3). The values of NO_2 and SO_2 range between 13–19 and 5–10 µg/m^3, respectively. The highest concentrations of NO_2 and SO_2 are found at the station Thiyagaraya Nagar (19.2 µg/m^3 and 9.8 µg/m^3), whereas the lowest concentrations of NO_2 and SO_2 are found at Adyar (13.3 µg/m^3) and Velachery (4.7 µg/m^3), respectively. $PM_{2.5}$

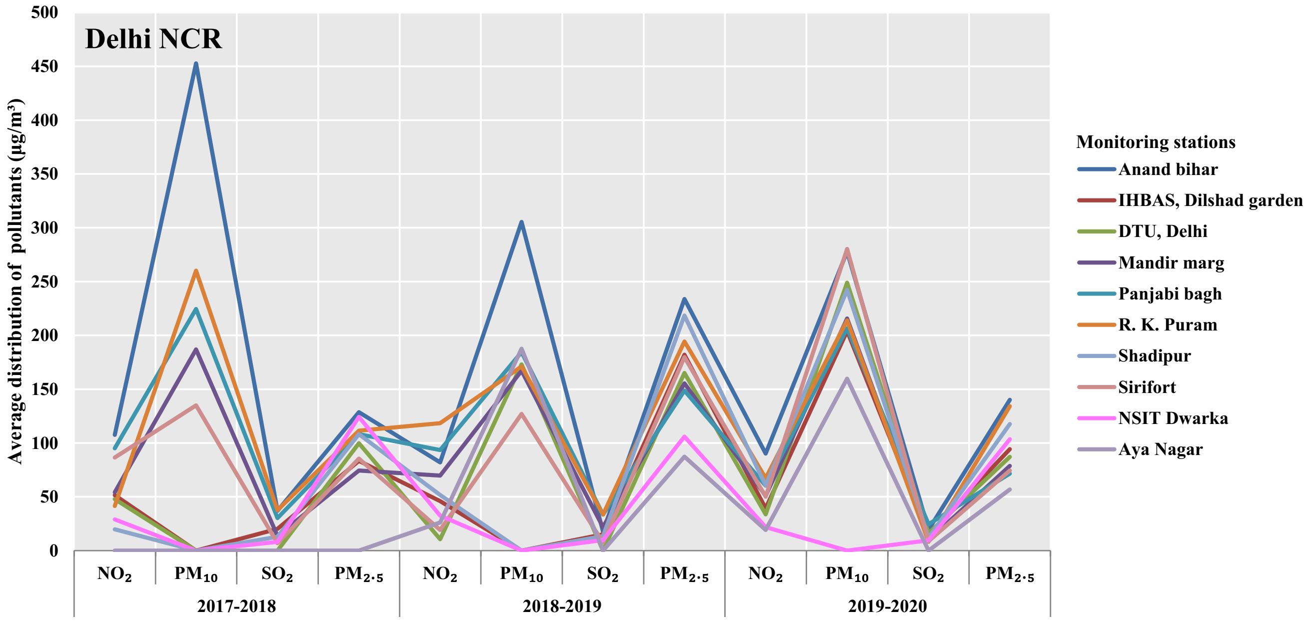


Fig. 3 Average distribution of pollutants (NO_2, PM_{10}, SO_2 and $PM_{2.5}$) in various monitoring stations of Delhi NCR during 2017–2018, 2018–2019 and 2019–2020. (*Data Source*: CPCB)

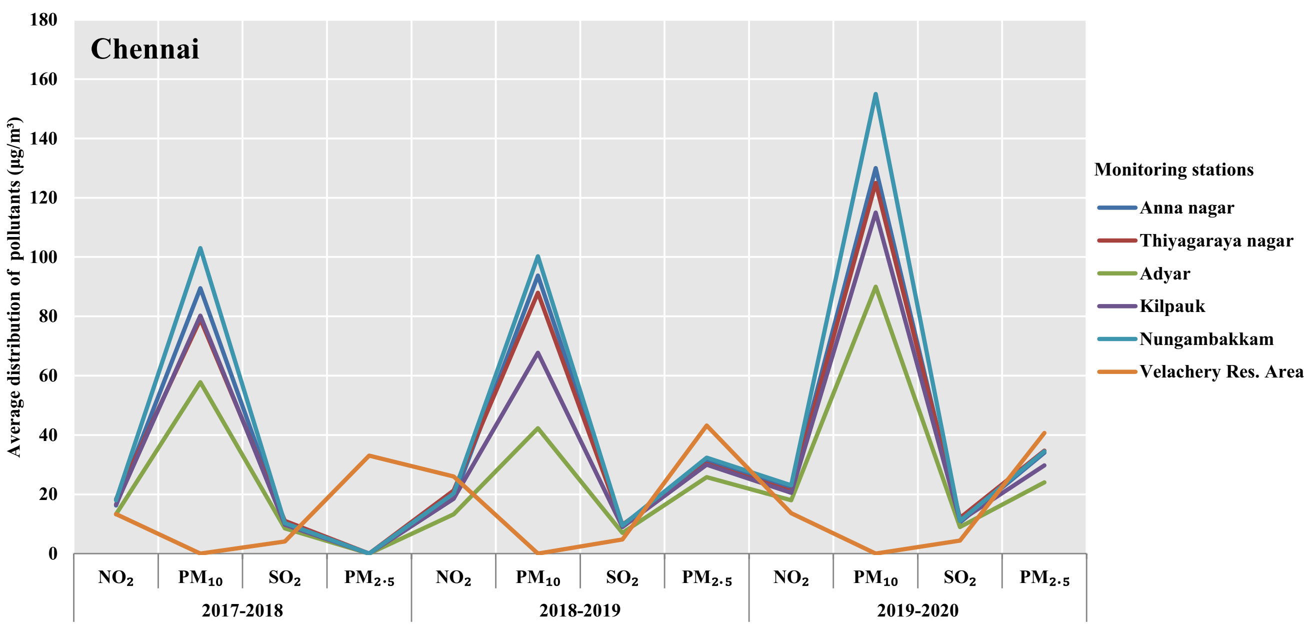


Fig. 4 Average distribution of pollutants (NO_2, PM_{10}, SO_2 and $PM_{2.5}$) in various monitoring stations of Chennai during 2017–2018, 2018–2019 and 2019–2020. (*Data Source*: CPCB)

concentration is found at 33.6 μg/m^3 in Velachery. Adyar and Velachery, being residential areas, receive fewer concentrations of the above three pollutants, whereas Thiyagaraya Nagar and Nungambakkam fall under the mixed zones and commercial zones, thus the level of pollutants is higher than the standard limit of NAAQS, particularly in the case of PM_{10}. The annual average concentration of the pollutants NO_2 and SO_2 in the stations of Chennai ranges between

15–20 and 5–10 µg/m^3, respectively, where the highest NO_2 and SO_2 concentrations are found at Thiyagaraya Nagar (20.3 µg/m^3) and Nungambakkam (10 µg/m^3); whereas, lowest NO_2 and SO_2 concentrations are found at Adyar (15.3 µg/m^3) and Velachery (4.8 µg/m^3). The highest concentration of PM_{10} is noticed at Nungambakkam (126 µg/m^3) and lowest in Adyar (65.5 µg/m^3). $PM_{2.5}$ is observed highest at Velachery (38.3 µg/m^3) and lowest at Adyar (26.2 µg/m^3). In the Station Adyar, the concentration of the three pollutants is indicating the lowest values, i.e. 16, 92, and 24 µg/m^3 in case of NO_2, PM_{10}, and $PM_{2.5}$, respectively. But in the case of SO_2, the lowest value (4.6 µg/m^3) is found at the station Velachery. While, the highest values of NO_2, SO_2, PM_{10}, and $PM_{2.5}$ are found in Nungambakkam and Thiyagaraya Nagar (21.3 µg/m^3), Thiyagaraya Nagar (12.5 µg/m^3), Kilpauk (121 µg/m^3) and Velachery (35 µg/m^3).

3.2 Seasonal Variation of Pollutants

The distribution of air pollutants in the city is greatly influenced by the seasonal variation of the climate (Olise et al. 2020). Despite having a wide range of climatic characteristics from east to west and north to south in India, four distinct seasons are followed by IMD (Indian Meteorological Department) as per international standard: winter, summer, monsoon, and post-monsoon (Pareek et al. 2019). In the present study, 1 year is categorized into three distinct seasons: Summer (March to June), Monsoon (July to October), and Winter (November to February) for all three megacities. Generally, due to low temperatures in winter, air molecules are less vibrant and impose consolidation and stability in the weather condition, which results in less spreading of air pollutants. Thus, the concentration of pollutants gets high in all the cities. Whereas in summer, the air molecules become more convective, unstable, which induces the diffusion of air parcels, resulting in the dissemination of pollutants (Song et al. 2019).

3.2.1 Seasonal Distribution of Pollutants in Kolkata

In the case of Kolkata, the concentration of pollutants is found lowest in the season of monsoon because of proper circulation of winds, which makes the condition favorable for spreading the air pollutants (Shannigrahi et al. 2003; Pareek et al. 2019). In all the 3 years, from 2017 to 2020, the distribution of pollutants did not vary on a large scale, where NO_2 ranges between 32 and 39 µg/m^3 in Summer and Monsoon, while it rises to 53 µg/m^3 in Winter. The values of SO_2 have been shown around 4–7 µg/m^3 in Summer and Monsoon and reaches up to 11.7 µg/m^3 in winter. In the same way, PM_{10} has also claimed its concentration from 66 to 93 µg/m^3 in Summer and Monsoon but shows a remarkable increase in winter i.e. 160–222 µg/m^3. $PM_{2.5}$ values range between 30 and 50 µg/m^3 in monsoon and summer and show the highest values in winter (73–130 µg/m^3). It is interesting to observe that the average amount of SO_2, $PM_{2.5}$, and PM_{10} has increased two times during winter than in the monsoon (Figs. 5, 6 and 7). Apart from the meteorological factors, the use of enormous amounts of heating fuels can also be an influencing factor in case of increasing concentration of pollutants during winter (Chattopadhyay et al. 2010; Spiroska et al. 2011; Jayamurugan et al. 2013).

3.2.2 Seasonal Distribution of Pollutants in Delhi

Given that air pollution may change dramatically from month to month, the present study has analyzed the temporal change of air pollutants on a seasonal basis. Figures 5, 6 and 7 display the seasonal distribution of pollutants in the different monitoring stations in Delhi from

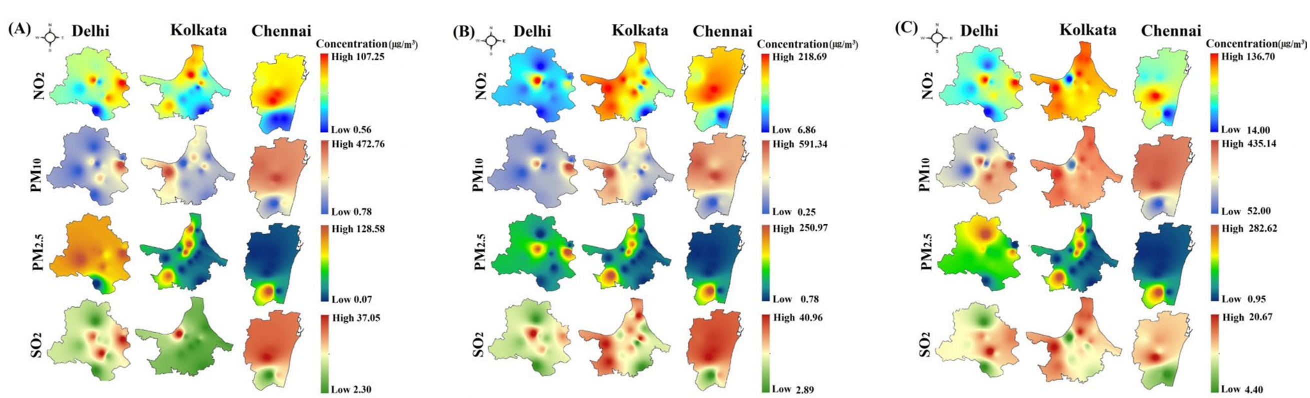


Fig. 5 Spatial concentration of NO_2, PM_{10}, $PM_{2.5}$, and SO_2 during **a** Summer **b** Monsoon, and **c** Winter season in 2017–2018

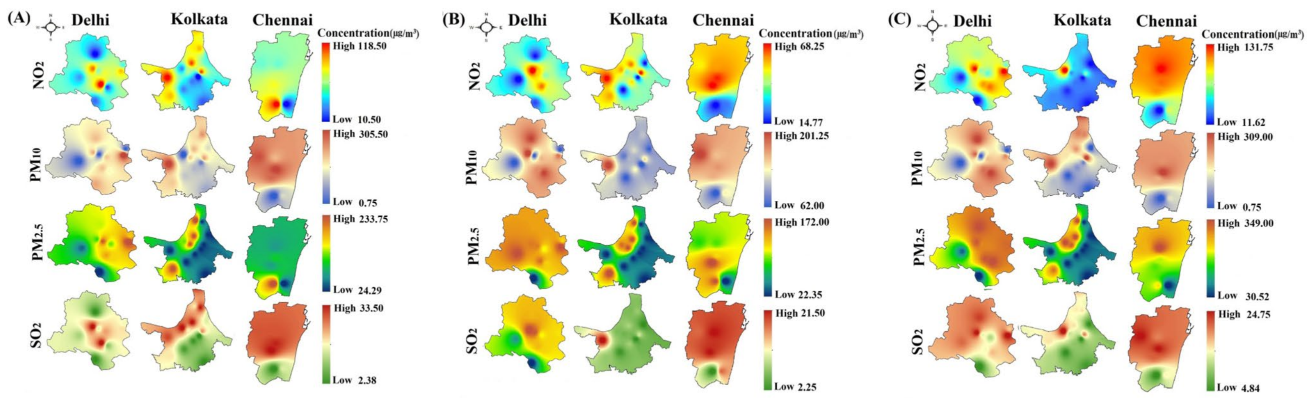


Fig. 6 Spatial concentration of NO_2, PM_{10}, $PM_{2.5}$, and SO_2 during **a** Summer **b** Monsoon, and **c** Winter season in 2018–2019

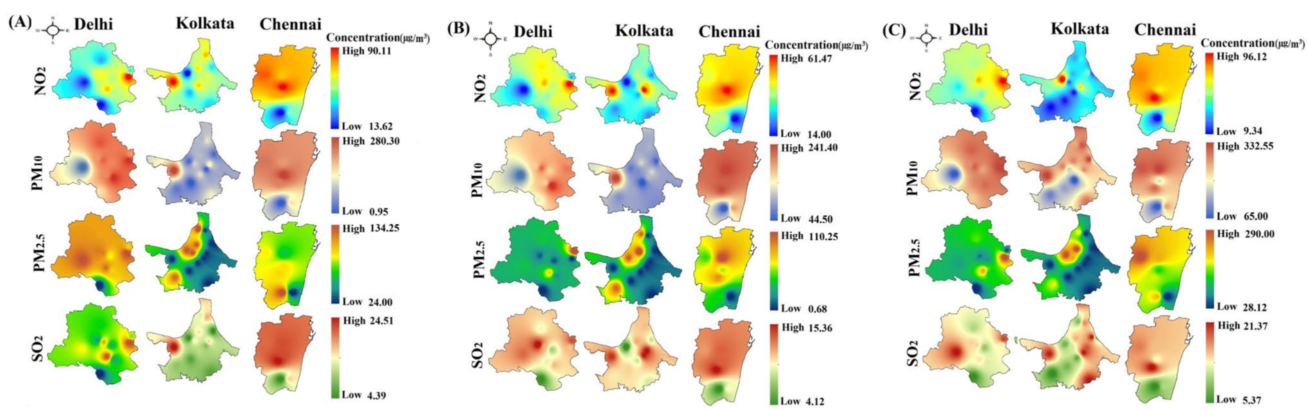


Fig. 7 Spatial concentration of NO2, PM_{10}, $PM_{2.5}$, and SO_2 during **a** Summer **b** Monsoon, and **c** Winter season in 2019–2020

the year 2017 to 2020. In each case, the winter season is showing the highest concentration of air pollutants. In 2017–2018, PM_{10} indicates the value of 329 μg/m^3 in winter, which has decreased to 263 μg/m^3 and 280 μg/m^3 in the next 2 years. The concentrations of $PM_{2.5}$ range between 100 and 160 μg/m^3 in monsoon and summer for the year 2017–2018 and 2018–2019, but have decreased in the year 2019–2020 by 70–100 μg/m^3. The highest concentration of $PM_{2.5}$ is recorded in the winter of 2018–2019 (292 μg/m^3). High PM_{10} levels in Delhi during the post-monsoon season were mainly attributed to the crop residue burning activities in the agricultural fields, firework display during Diwali festival and along with meteorological conditions like high relative humidity, low wind speed, and low boundary layer height resulted in accumulation of Particulate Matter (Jain et al. 2020). NO_2 concentrations are found in between 49 and 55 μg/m^3 in summer, 43 and 60 μg/m^3 in monsoon and 54 and 71 μg/m^3 in winter from 2017 to 2020. Furthermore, the levels of SO_2 are recorded between 14 and 20 μg/m^3 in monsoon and summer in the year of 2017–2019 but it is reduced in the year 2019–2020, having the value of 9–14 μg/m^3.

3.2.3 Seasonal Distribution of Pollutants in Chennai

Air pollutants of Chennai show an apparent seasonal variation in Figs. 5, 6 and 7. On average, the values are in the order of winter > summer > monsoon. In the 3 years (from 2017 to 2020), the value of NO_2 ranges between 16 μg/m^3 and 20 μg/m^3, SO_2 lies from 8 to 10 μg/m^3, PM_{10} has the range of 62–123 μg/m^3 and $PM_{2.5}$ is in between 23 and 45 μg/m^3. For all the four pollutants, it is noticed that the amount of concentration is increased in the year 2019–2020, than the previous 2 years: except $PM_{2.5}$. In all the cases, most of the higher concentrations are found in winter, and the lowest concentrations are observed in the monsoon season. The reason behind the high concentration of pollutants in winter lies mostly in the local weather phenomena

(Kanawade et al. 2020). But due to its geographical location, Chennai does not report much higher values in terms of AQI. The sea breezes have a great influence in controlling the movements of pollutants in the air (CPCB 2011). Along with that, the concentrations of NO_2, SO_2, and $PM_{2.5}$ are under the permissible limit of NAAQS. But in the year 2019–2020, the concentrations of PM_{10} have exceeded the limit. As per CPCB guidelines, the standards are set by 80 μg/m^3, 80 μg/m^3 and 60 μg/m^3 and 100 μg/m^3 for NO_2, SO_2, $PM_{2.5}$, and PM_{10}, respectively.

3.3 Major Sources of Air Pollutants in the Cities

A major contributor to the pollution of Delhi is combustion from vehicles, which contributes nearly 67% of the total air pollution, followed by coal-based thermal power plants (Biswas et al. 2011). The number of personalized vehicles has increased in the city due to increasing economic activities (Dholakia et al. 2013). Delhi has the highest cluster of small-scale industries in India that lead to 12% of air pollutants along with industrial units (Kayes et al. 2019). Due to the continuous growth of population, the Delhi authority has taken the initiative to mitigate the concentration of air pollutants, using CNG in public transport, introducing metros, relocation industries, etc. Despite this, air quality continues to deteriorate (Guttikunda et al. 2014; Amann et al. 2017). Emission in Delhi is complex like the other developing megacities in India, due to contributions from different sources, such as traffic, small industrial sources, biomass burning for cooking and heating, etc. (Mohan and Kandya 2007; Kanawade et al. 2020). In the case of Kolkata, the transport sector has a prime contribution to air pollution (Ghosh et al. 2005). Automobile exhausts contribute to about 70% of the total pollution, followed by industries. Furthermore, small-scale industries, thermal power plants which are in operation in and around Kolkata, have major effects in determining the air quality (Chattopadhyay et al. 2010). Additionally, an increasing number of private motor vehicles mostly two-wheelers, four-wheelers, petrol-driven three-wheelers are causing congestion, pollution, accidents as well as release a huge amount of hydrocarbons besides carbon monoxide and particulate matter. Street hawkers, pavement dwellers, along illegal car-parking are occupying the space of busy traffic intersections in highways, which results in reducing road space and, therefore, increasing huge traffic congestion in the city. As a result, unplanned traffic, huge congestion, narrow road space restrict the normal movement of vehicles, which tends to increase the consumption of fuel, as well as exhaust emission (Das et al. 2006). Similarly, the contributions of road transport, industries, and open waste burning are the main reasons for air pollution in Chennai (Arulprakasajothi et al. 2020; Dinda et al. 2020). Having large commercial ports, the movement of freights in the city roads is very high, which leads to increase emissions from the unregistered vehicles of the city or state (Rajamanickam and Nagan 2018). More than 700 new vehicles run on Chennai roads every day, which is another biggest contributor in terms of increasing SO_2 emissions. Because of these issues, Chennai has experienced a high level of SO_2 concentration (Sharma et al. 2020). The fringe areas of the city are mostly covered with industries which are also another reason for the increase in pollution (Senthilnathan 2008).

3.4 Spatio-Temporal Distribution of Air-Quality Index (AQI)

The Air Quality Index is an index for reporting the air quality of a region daily. The purpose of AQI is to help people to know about how their local air quality impacts their health status (Kyrkilis et al. 2007). As the million plus cities have an overcrowded population and uses of automobiles are increasing day by day, they are experiencing pollution at an extreme level. To bring light to those areas, the present study focuses on the AQI of Indian megacities to explain their air pollution scenario.

In Kolkata, the AQI value ranges between 60–134 and 58–116 in Summer and Monsoon and rises to 275 in Winter (the year 2017–2018). In the case of seasonal distribution, the AQI represents the highest values in winter and lowest in monsoon. And the average annual values are showing a decreasing trend over the years from 2017 to 2020. For example, in 2019–2020, the winter AQI has reached 205, which was near about 275 in 2017–2018 (Fig. 8). The reason behind the reduction of air quality values due to various measures taken by local administrative bodies; and even introduction of improved vehicular technology in the form of electric vehicles, use of CNG fuel in place of diesel and petroleum, improved traffic management, banning of old vehicles, etc. may result into the decreasing trend (Ghose et al. 2004; Gurjar et al. 2016). The AQI values of Delhi are showing the highest AQI values among the three cities, which indicate its severity on public health. It varies from 200 to 500 in the last 3 years and in the winter of 2017, the value exceeds 500. If the station-wise distribution of AQI values is taken into account, it will show the overall decreasing trend over the years from 2017 to 2020, but if the annual average AQI values are considered, they are presenting an odd–even trend, which is increased in 2018–2019 than 2017–2018 and again reduced in 2019–2020 (Gulia et al. 2018). For instance, in the case of winter AQI, the values increased in the year 2018–2019 from 347 (in 2017–2018)

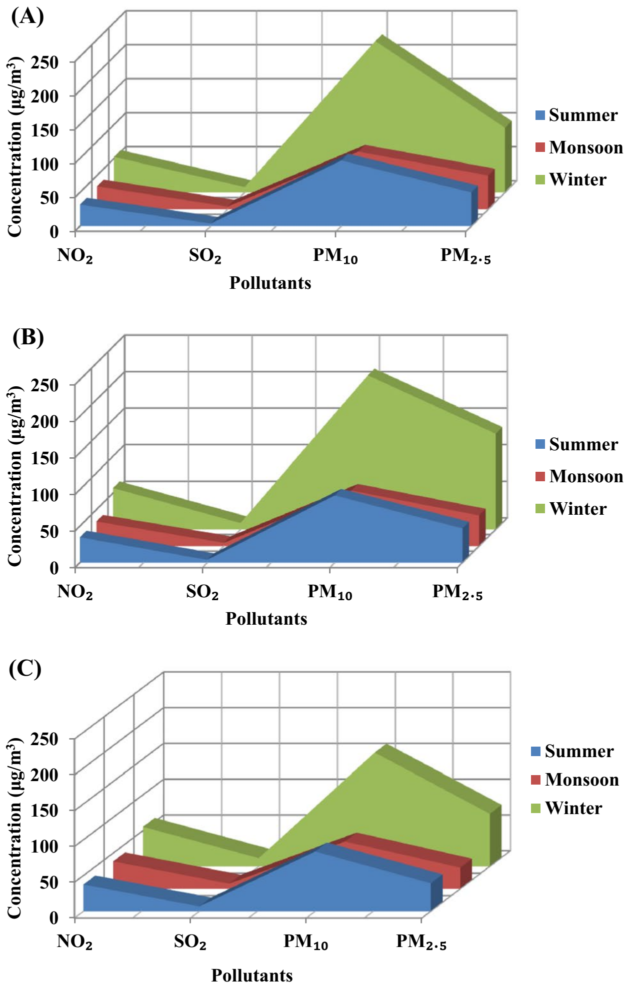


Fig. 8 Seasonal distribution of pollutants (NO_2, SO_2, PM_{10} and $PM_{2.5}$) in Kolkata during **a** 2017–2018, **b** 2018–2019 and **c** 2019–2020

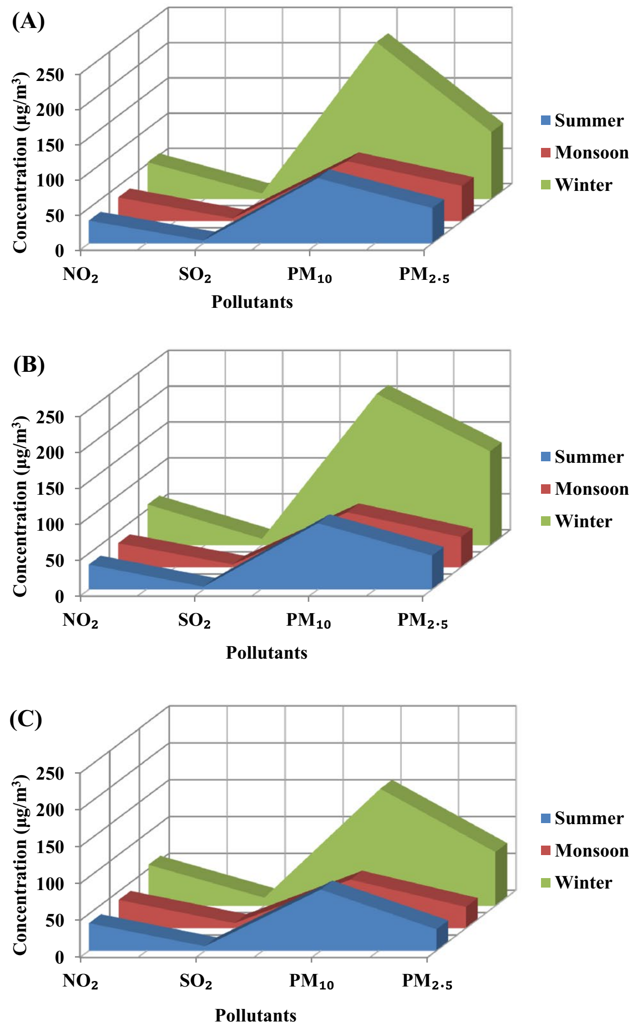


Fig. 9 Seasonal distribution of pollutants (NO_2, SO_2, PM_{10} and $PM_{2.5}$) in Delhi NCR during **a** 2017–2018, **b** 2018–2019 and **c** 2019–2020

to 490 and again reduced in 2019–2020 i.e. 302 (Fig. 9). For Chennai, most of the AQI values lie in between satisfactory and moderate levels as per the NAAQS guideline, ranging from 50 to 160. The ambient air quality in the studied areas of Chennai city is better than the other metropolitan cities, such as Delhi and Kolkata. Still, in the case of summer and winter AQI, it is representing an increasing trend from 2017 to 2020 but the Monsoon AQI values are showing a stochastic trend, which is satisfactory level in 2017–2018, moves to a moderate level in 2018-19 and again returned to a satisfactory level in 2019–2020 (Fig. 10). The AQI data have deteriorated from 2017 to 2018 and not indicted any significant autocorrelation among the AQI values for Chennai, whereas Delhi and Kolkata have shown significant correlation for AQI values as also mentioned by Gurjar et al. (2016), Pareek et al. (2019), and Mahajan and Juneja (2020). In Fig. 11, the spatial, temporal, and seasonal changes of AQI are shown among the cities of Kolkata, Delhi, and Chennai. For all the cases, the pollutant PM_{10} is responsible for the higher AQI value. The important sources of particulate matter are road dust, vehicle emissions, and construction activities.

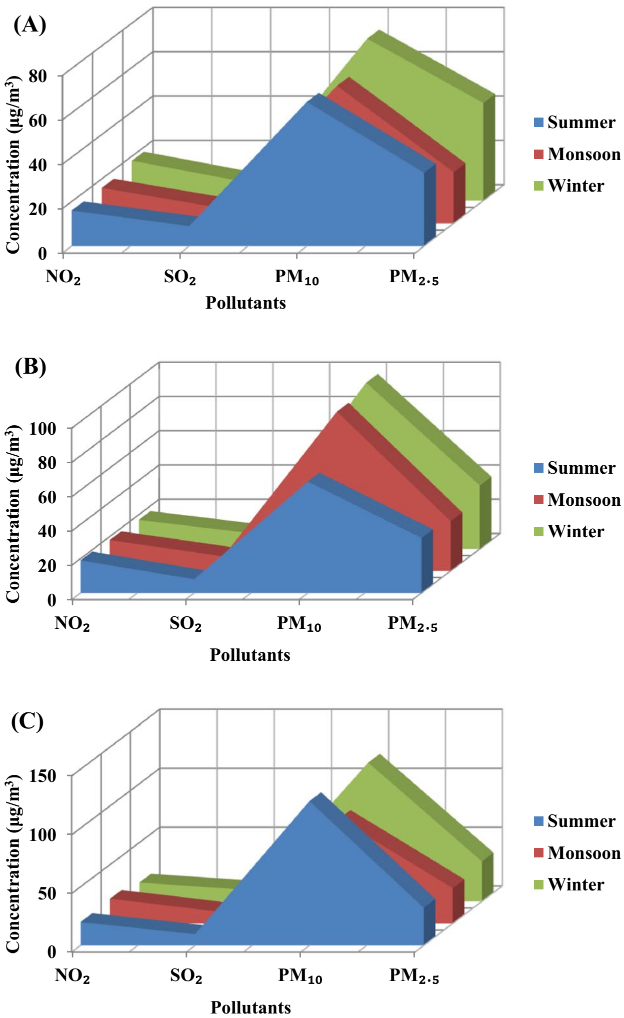


Fig. 10 Seasonal distribution of pollutants (NO_2, SO_2, PM_{10} and $PM_{2.5}$) in Chennai during **a** 2017–2018, **b** 2018–2019 and **c** 2019–2020

3.5 Correlation Between AQI and Different Air Pollutants

To explain the relationship between two or more two variables, correlation is used. In the present study, based on 3 years' daily mean concentrations during 2017–2020, the correlations between AQI and air pollutants are explained by Pearson's correlation coefficients (*r*). For Kolkata, Table 3 shows that AQI, PM_{10}, SO_2, NO_2, and $PM_{2.5}$ exhibit significant positive correlations in pairs. Among them, the optimal correlation is observed among AQI and PM_{10}, with a correlation coefficient of 0.99; followed by NO_2 and SO_2 ($r=0.83$ and 0.62, respectively). It suggests that the higher the amount of PM_{10}, the higher will be the value of AQI. In other words, among all the pollutants, PM_{10} has a significant contribution in extending the value of AQI towards higher digits. On the other hand, NO_2 exhibits optimal correlation with SO_2 having the value (r) of 0.85. For Delhi, a significant positive correlation exists between AQI and $PM_{2.5}$ ($r=0.94$). The reason behind such kind of relation can be found from different studies, which have stated that $PM_{2.5}$ consists of finer particles than the other pollutants. $PM_{2.5}$ is originated due to primary and secondary anthropogenic combustion produced from traffic and energy consumption, road dust, emission from traffic. Along with this, increasing fuel consumption for industrial and domestic units is responsible for heating in winter, leads to an increase of fine particle emissions (Xu et al. 2016; Steeneveld et al. 2018; Sorte et al. 2019). Another significant positive correlation is seen between AQI and NO_2 ($r=0.63$) between SO_2 and NO_2 ($r=0.68$). For Chennai, AQI and PM_{10} are showing the highest positive correlation among the other pollutants ($r=0.89$). Significantly, the correlation between PM_{10} and SO_2 is also noticeable which is 0.85. On the other hand, the relationship between PM_{10} and $PM_{2.5}$ is showing a negative

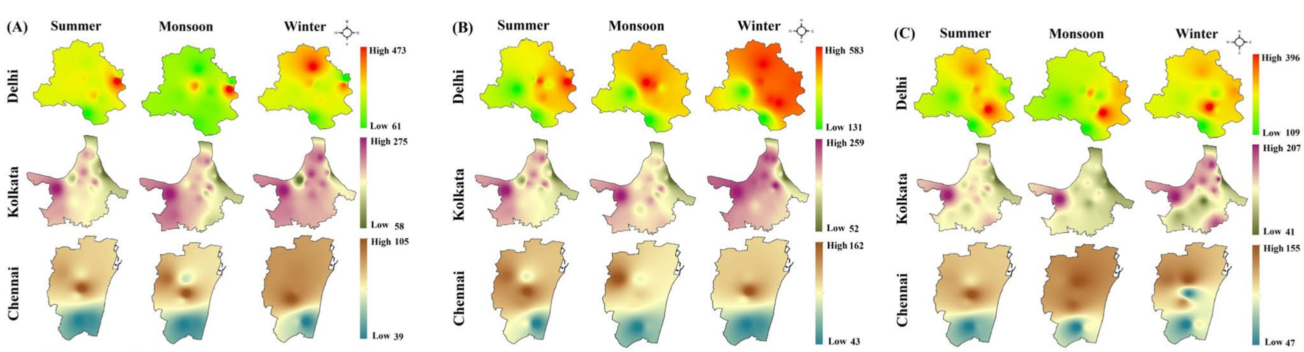


Fig. 11 Status of Air quality index in three mega cities during the period of **a** 2017–2018, **b** 2018–2019 and **c** 2019–2020

Table 3 Correlation coefficient of AQI with each air pollutant in three selected cities in the period of 2017–2020

Kolkata						Delhi						Chennai					
	AQI	NO_2	PM_{10}	SO_2	$PM_{2.5}$		AQI	NO_2	PM_{10}	SO_2	$PM_{2.5}$		AQI	NO_2	PM_{10}	SO_2	$PM_{2.5}$
AQI	1					AQI	1					AQI	1				
NO_2	0.826	1.000				NO_2	0.631	1.000				NO_2	0.568	1.000			
SO_2	0.999***	0.821	1.000			SO_2	0.377	0.675	1.000			SO_2	0.706	0.565	1.000		
PM_{10}	0.622	0.845***	0.619	1.000		PM_{10}	0.481	0.614	0.348	1.000		PM_{10}	0.892***	0.513	0.846***	1.000	
$PM_{2.5}$	0.353	0.414	0.357	0.259	1.000	$PM_{2.5}$	0.942***	0.564	0.291	0.311	1	$PM_{2.5}$	0.271	0.292	0.041	−0.007	1

***Significance level $= p < 0.01$

correlation having a value of -0.007. Though it is very small in number, it cannot be ignored.

Collectively, if we consider the three cities together to generalize the facts, it will be found that more or less similar causes are responsible for the correlations between air pollutants. If pollutants exhibit good correlations, then they have similar sources, the change patterns in air pollution are similar, and they possibly follow the same migration and transformation patterns. For example, $PM_{2.5}$, PM_{10}, SO_2, and NO_2 showed significant correlations in pairs, indicating that the pollution sources affecting mass concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 have strong correlations. Vehicles are the main source for the release of $PM_{2.5}$, SO_2, and NO_2. Besides, the contribution of road dust to PM_{10} generated by motor vehicles cannot be ignored (Guo et al. 2019). Another significant source contributing to mass concentrations of PM_{10}, $PM_{2.5}$, and SO_2 is fossil fuel combustion from industries (Guttikunda et al. 2014). Moreover, NO_2 and SO_2 are positively correlated with $PM_{2.5}$ and PM_{10}, respectively. A strong correlation is found because a higher amount of NO_2 and SO_2 leads to the reduction of particulate matter by transforming the gaseous phase into acidic aerosols in reaction with ammonia, i.e. transformation of NO_2 into HNO_3 in the atmosphere (Xu et al. 2016). These are converted into sulfate and nitrate particles, which are important components of $PM_{2.5}$ and PM_{10} (Mouli et al. 2004; Song et al. 2019).

3.6 Correlation Between AQI and Meteorological Parameters

Based on the meteorological data of Kolkata, Delhi, and Chennai for the last 3 years from 2017–2018 to 2019–2020, the correlation coefficient between the AQIs and the meteorological factors is analyzed in Table 4. It is evident from the table that the largest correlation is found in all three cases with average temperature. AQI is negatively correlated with average temperature showing the values of −0.89, −0.82, and −0.75 for Chennai, Kolkata, and Delhi, respectively. The negative correlation is the indicator of the inverse relationship between AQI and temperature. The higher the temperature, the stronger the convection, resulting in stratification, instability, and easy diffusion of pollutants, and the tendency of pollutants to concentrate reduces (Spiroska et al. 2011; Sharma et al. 2020). On the other hand, lower temperature results in atmospheric stability, which presents favorable conditions for more concentration of pollutants, as the diffusion and dilution process does not transpire (Song et al. 2019). In the case of Chennai, it has shown the strongest negative correlation between AQI and average temperature i.e. when the temperature gets high, the values of AQI or concentration of pollutants (NO_2, SO_2, PM_{10}, $PM_{2.5}$) get less. Because during summer and monsoon, the temperature ranges 27–30 °C and vertical mixing of air, mixing height gets increased; land breeze and sea breezes

Table 4 Correlation Coefficient of AQI with meteorological parameters in Kolkata, Delhi and Chennai during the period 2017–2020

City		Average temperature	Average rainfall	Average wind speed	Average relative humidity
Kolkata	AQI	−0.820***	−0.647	0.225	−0.808***
Delhi		−0.754	−0.634	−0.148	0.220
Chennai		−0.895***	0.157	−0.547	−0.540

***Significance level $p<0.01$

help to control the concentration of pollutants. Whereas during winter, the lower temperature reduces the vertical mixing and the mixing height, thus contributes to the higher value of AQI (Senthilnathan 2008; Jayamurugan et al. 2013). Followed by temperature, the averag-e rainfall is also showing a negative correlation with AQI in Kolkata ($r=-0.65$) and Delhi ($r=-0.63$) except Chennai, indicating a slight positive correlation ($r=0.16$). Precipitation also has a great impact on the change in air quality. In particular, the amount of inhalable particulate matters can be reduced effectively due to precipitation (Song et al. 2019). There is a significant negative correlation between relative humidity and AQI because, during the monsoon when relative humidity goes high, the AQI values show relatively lower values; whereas in summer and winter, as the relative humidity goes down, the AQI value goes up; and represents the inverse relationship. The wind speed has a lag phenomenon to the air purification, especially when the turning weather occurs. When the wind speed is more, AQI gets less on the next day (Amann et al. 2017). In the coastal areas, the local maritime breeze system has significant roles in the dispersion of pollutants and the rate of dispersion of pollutants during daytime and night time is influenced by the differences in atmospheric stability and wind speed (Sorte et al. 2019). As Chennai is situated near the coast, it is presenting a moderate negative correction ($r=-0.55$) than the other two cities. They are not so significantly correlated with AQI, which may be related to the different effects of the different wind directions on air quality.

3.7 Exceedance Factor Analysis

Exceedance factor helps to find out how much polluted a city is and what level of pollution exists there at a specific period. To find out the level of pollution in Delhi, Kolkata, and Chennai, the EF during the period 2017–2020 is measured, which could provide a significant basis for the public and policymakers to take necessary measures to protect public health (Table 5). In the case of NO_2 concentrations, the pollution level of Delhi is critical in the year 2018–2019, but it has shown a decreasing trend in the year 2019–2020. As the NO_2 concentrations of Delhi are much higher than the standard limit prescribed by NAAQS, the pollution level reaches the highest. Kolkata is showing a medium and high level of pollution while Chennai has the pollution level containing the lowest values. For SO_2 concentrations, no city has crossed the limit ascribed by NAAQS (annual standard is 40 µg/m^3). As PM_{10} concentrations are highest among all the pollutants, the exceedance factor has shown a critical level of pollution in all the cases except Chennai (2017–2018). It is also an indicator for the policymakers to pay attention to the sources of PM_{10} and to think about its reduction in concentration to the air because it affects the human health for containing the finer particles (Sharma et al. 2019). Concentrations of $PM_{2.5}$ are also showing the pollution level at a critical stage, except Chennai.

4 Discussion and Conclusion

Indian megacities are often placed within the lists of most polluted cities in the world (Singh et al. 2007; Sharma et al. 2019). From this analysis, it was found that, among the three megacities, Delhi is experiencing severe air pollution and Chennai is in the permissible condition in terms of pollutants' concentrations. A study comparing the air quality among the metropolitan cities of India represents that a higher level of pollution is found in Kolkata in relation to Chennai, and is nearer to Delhi (Ravindra et al. 2016). In all the cases, PM_{10} is the responsible contributor for affecting the air quality. During the study period, from 2017 to 2020, some monitoring stations of Kolkata, such as Moulali, Hyde road, Victoria, are showing a continuous high concentration of pollutants, such as NO_2, SO_2, PM_{10}, and $PM_{2.5}$, for being under industrial and commercial zones (Das et al. 2006; Ghosh et al. 2019; Dinda et al. 2020). The Punjabi Bagh and Anand Vihar are the most polluted places in Delhi as per this study. As Punjabi Bagh has a mixed land-use (commercial, residential and industrial) and Anand Vihar being a commercial area, they have shown the highest concentrations for all the pollutants in the subsequent years. In the case of Chennai, Thiyagaraya Nagar and Nungambakkam are considered as most polluted areas. For being a mixed zone and commercial zones, they have the highest vehicle concentrations, which make them the polluted ones (Amann et al. 2017). Along with anthropogenic activities, meteorological parameters

Table 5 Exceedence factor (EF) and air pollution level of NO_2 for three megacities during 2017–2020

Pollutants	Period	Delhi			Kolkata			Chennai		
		Concentration of pollutants in μg/m^3	EF	Pollution Level	Concentration of pollutants in μg/m^3	EF	Pollution Level	Concentration of pollutants in μg/m^3	EF	Pollution Level
NO_2	2017–2018	60.1	1.502	CP	39.58	0.989	MP	16.65	0.416	LP
	2018–2019	60.79	1.519	CP	41.77	1.044	HP	18.16	0.453	LP
	2019–2020	49.01	1.225	HP	38.84	0.96	MP	16.19	0.422	LP
SO_2	2017–2018	19.5	0.487	LP	5.31	0.132	LP	8.01	0.2	LP
	2018–2019	16.57	0.414	LP	10.66	0.266	LP	9.52	0.238	LP
	2019–2020	11.63	0.29	LP	8.61	0.215	LP	9.12	0.227	LP
PM_{10}	2017–2018	279.58	5.591	CP	133.67	2.673	CP	67.88	1.357	HP
	2018–2019	223.59	4.471	CP	126.6	2.532	CP	110.27	2.205	CP
	2019–2020	202.22	4.044	CP	103.02	2.06	CP	90.22	1.804	CP
$PM_{2.5}$	2017–2018	137.76	4.592	CP	65.25	2.175	CP	33.58	1.119	HP
	2018–2019	195.61	6.52	CP	73.333	2.444	CP	32.92	1.097	HP
	2019–2020	116.26	3.875	CP	47.53	1.584	CP	32.45	1.081	HP

or climatic conditions of an area play a significant role in determining air quality. Moreover, the seasonal distribution of pollutants has shown a significant dimension. A significant reduction in the concentration of PM_{10} has found in Kolkata from the year 2017–2018 to 2019–2020. Delhi is also showing a negative trend in the concentration of SO_2 and PM_{10} for the subsequent years. Chennai has shown an increasing trend in the concentration of PM_{10}, especially in winter. In terms of AQI, Kolkata is showing a decreasing trend, Chennai is showing an increasing trend and Delhi has a trend of increasing at first and then decreasing over the year 2017 to 2020. A strong correlation is found between AQI and PM_{10} and $PM_{2.5}$. In the correlation between AQI and meteorological parameters, temperature and relative humidity have shown the strongest relationship among all (Fig. 12).

Among all the pollutants, SO_2 is the only pollutant that accomplishes the NAAQ standard. But the things are different with other pollutants, such as NO_2, PM_{10}, and $PM_{2.5}$. Their emissions from combustion processes are much above the standard NAAQS regardless of the improvements in fuel quality and technology (Singh et al. 2007; CPCB 2011). The present study is not an exception to that. As the megacities are so much susceptible to air pollution, they should pay more attention to deal with these problems. Many ways of mitigation were suggested by researches, including control rapid urbanization (Dinda et al. 2019a; Li et al. 2020), sustainable land use planning (Gorai et al. 2017; Ghosh et al. 2019), green beld development (Shannigrahi et al. 2003), strictly implementation of regulations (Guo et al. 2019), and improvement of transportation system (Gurjar et al. 2016; Dinda et al. 2019b).

Therefore, with the results obtained from the present study, some management options can be summed up, which could help the regulatory agencies and policy makers to improve the present scenario, including: (a) arrangement of settlements patterns should be improved, (b) proper land use planning should be introduced through the separation of residential and industrial areas, (c) reduction of population density around industrial zones could help to reduce the direct exposure of people to industrial pollutants, (d) green belt should be development, (e) government should promote more access to LPG and PNG and should impose laws on using fossil fuels above a certain limit, (f) regulation for power plants, especially coal-fired power plants should be limited by the government with strict rules and regulations to control the emissions of various air pollutants, (h) giving preference to public transport system and citizens has to motivate to change their preferences from using private to public transport, (i) moreover, public-awareness should be increase among the people about the pollution and necessary measures at individual levels to combat the situation.

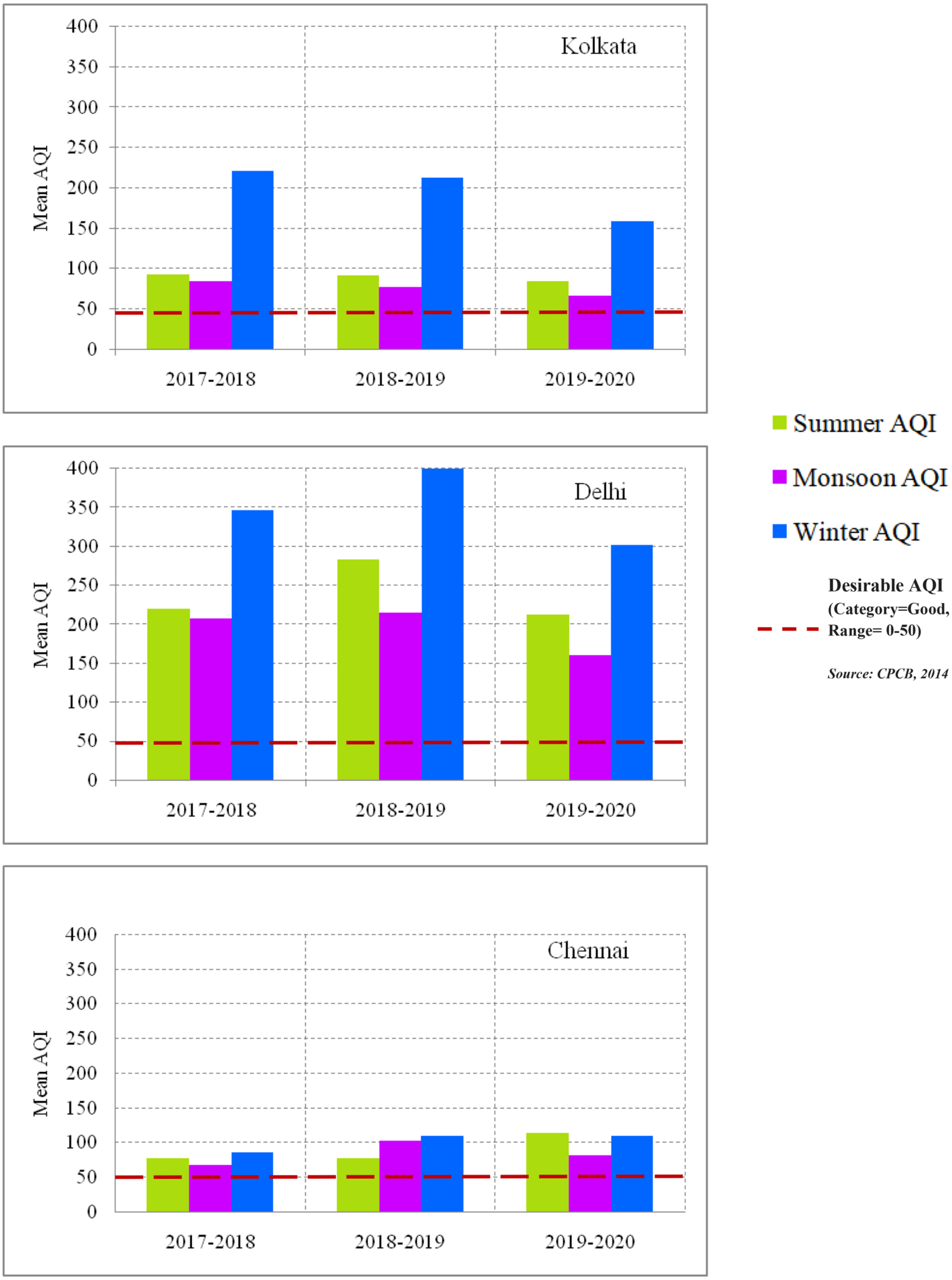


Fig. 12 Annual mean AQI values of three selected cities during the period of 2017–2020

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References

Amann M, Purohit P, Bhanarkar AD, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Kiesewetter G, Klimont Z, Liu J, Majumdar D (2017) Managing future air quality in megacities: a case study for Delhi. Atmos Environ 161:99–111

Arulprakasajothi M, Chandrasekhar U, Yuvarajan D, Teja MB (2020) An analysis of the implications of air pollutants in Chennai. Int J Ambient Energy 41(2):209–213

Biswas J, Upadhyay E, Nayak M, Yadav AK (2011) An analysis of ambient air quality conditions over Delhi, India from 2004 to 2009. Atmos Clim Sci 1(04):214

Census (2011) Census of India 2011. Government of India. http://censusindia.gov.in/DigitalLibrary/Archive_home.aspx. Accessed 17 July 2020

Chattopadhyay S, Gupta S, Saha RN (2010) Spatial and temporal variation of urban air quality: a GIS approach. J Environ Prot 1(03):264

Chiarini B, D'Agostino A, Marzano E, Regoli A (2020) Air quality in urban areas: comparing objective and subjective indicators in European countries. Ecol Indic 121:107144. https://doi.org/10.1016/j.ecolind.2020.107144

CPCB (2011) Air quality monitoring, emission inventory and source apportionment study for Indian cities: national summary report. Central Pollution Control Board (CPCB), New Delhi

Das M, Maiti SK, Mukhopadhyay U (2006) Distribution of PM 2.5 and PM 10-2.5 in PM 10 fraction in ambient air due to vehicular pollution in Kolkata megacity. Environ Monitor Assess 122(1–3):111–123

Debone D, Leirião LFL, Miraglia SGEK (2020) Air quality and health impact assessment of a truckers' strike in Sao Paulo state, Brazil: a case study. Urban Climate 34:100687

Dholakia HH, Purohit P, Rao S, Garg A (2013) Impact of current policies on future airquality and health outcomes in Delhi, India. Atmos Environ 75:241–248

Dinda S, Das K, Chatterjee ND, Ghosh S (2019a) Integration of GIS and statistical approach in mapping of urban sprawl and predicting future growth in Midnapore town, India. Model Earth Syst Environ 5(1):331–352

Dinda S, Ghosh S, Chatterjee ND (2019b) An analysis of transport suitability, modal choice and trip pattern using accessibility and network approach: a study of Jamshedpur city, India. Spatial Inf Res 27(2):169–186

Dinda S, Chatterjee ND, Ghosh S (2020) An integrated simulation approach to the assessment of urban growth pattern and loss in urban green space in Kolkata, India: a GIS-based analysis. Ecol Ind 121:107178

Ghose MK, Paul R, Banerjee SK (2004) Assessment of the impacts of vehicular emissions on urban air quality and its management in Indian context: the case of Kolkata (Calcutta). Environ Sci Policy 7(4):345–351

Ghosh MK, Paul R, Banerjee RK (2005) Assessment of the status of urban air pollution and its impact on human health in the city of Kolkata. Environ Monit Assess 108(1–3):151–167

Ghosh S, Chatterjee ND, Dinda S (2019) Relation between urban biophysical composition and dynamics of land surface temperature in the Kolkata metropolitan area: a GIS and statistical based analysis for sustainable planning. Model Earth Syst Environ 5(1):307–329

Gorai AK, Tchounwou PB, Mitra G (2017) Spatial variation of ground level ozone concentrations and its health impacts in an urban area in India. Aerosol Air Qual Res 17(4):951

Gulia S, Mittal A, Khare M (2018) Quantitative evaluation of source interventions for urban air quality improvement—a case study of Delhi city. Atmos Pollut Res 9(3):577–583

Guo H, Gu X, Ma G, Shi S, Wang W, Zuo X, Zhang X (2019) Spatial and temporal variations of air quality and six air pollutants in China during 2015–2017. Sci Rep 9(1):1–11

Gurjar BR, Ravindra K, Nagpure AS (2016) Air pollution trends over Indian megacities and their local-to-global implications. Atmos Environ 142:475–495

Guttikunda SK, Goel R, Pant P (2014) Nature of air pollution, emission sources, and management in the Indian cities. Atmos Environ 95:501–510

Halim NDA, Latif MT, Mohamed AF, Maulud KNA, Idrus S, Azhari A, Othman M, Sofwan NM (2020) Spatial assessment of land use impact on air quality in mega urban regions, Malaysia. Sustain Cities Soc 63:102436

Haque M, Singh RB (2017) Air pollution and human health in Kolkata, India: a case study. Climate 5(4):77

Jain S, Sharma SK, Vijayan N, Mandal TK (2020) Seasonal characteristics of aerosols (PM2.5 and PM10) and their source apportionment using PMF: a four year study over Delhi, India. Environ Pollut 262:114337. https://doi.org/10.1016/j.envpol.2020.114337

Jayamurugan R, Kumaravel B, Palanivelraja S, Chockalingam MP (2013) Influence of temperature, relative humidity and seasonal variability on ambient air quality in a coastal urban area. Int J Atmos Sci 2013:264046. https://doi.org/10.1155/2013/264046

Kanawade VP, Srivastava AK, Ram K, Asmi E, Vakkari V, Soni VK, Varaprasad V, Sarangi C (2020) What caused severe air pollution episode of November 2016 in New Delhi? Atmos Environ 222:117125

Kayes I, Shahriar SA, Hasan K, Akhter M, Kabir MM, Salam MA (2019) The relationships between meteorological parameters and air pollutants in an urban environment. Global J Environ Sci Manag 5(3):265–278

Kyrkilis G, Chaloulakou A, Kassomenos PA (2007) Development of an aggregate Air Quality Index for an urban Mediterranean agglomeration: relation to potential health effects. Environ Int 33(5):670–676

Li F, Zhou T, Lan F (2020) Relationships between urban form and air quality at different spatial scales: a case study from northern China. Ecol Ind 121:107029

Mahajan H, Juneja K (2020) Air pollution problem in Delhi. J Crit Rev 7(10):723–727

Mohan M, Kandya A (2007) An analysis of the annual and seasonal trends of air qualityindex of Delhi. Environ Monit Assess 131(1–3):267–277

Mouli PC, Kumar MP, Reddy SJ, Mohan SV (2004) Monitoring of air pollution in Indian metropolitan cities: modelling and quality indexing. Int J Environ Pollut 21(4):365–382

Olise FS, Ogundele LT, Olajire MA, Owoade OK (2020) Seasonal Variation, pollution indices and trajectory modeling of bio-monitored airborne particulate around two smelting factories in Osun State, Nigeria. Aerosol Sci Eng 4:260–270. https://doi.org/10.1007/s41810-020-00070-6

Pareek N, Sarmah P, Choudhury A (2019) Comparative analysis of weekly AQI data among selected cities of India. J Basic Appl Eng Res 6(7):396–401

Rajamanickam R, Nagan S (2018) Assessment of comprehensive environmental pollution index of Kurichi Industrial Cluster, Coimbatore District, Tamil Nadu, India—a case study. J Ecol Eng 19(1):191–199

Ravindra K, Sidhu MK, Mor S, John S, Pyne S (2016) Air pollution in India: bridging the gap between science and policy. J Hazard Toxic Radioact Waste 20(4):A4015003

Rumana HS, Sharma RC, Beniwal V, Sharma AK (2014) A retrospective approach to assess human health risks associated with growing air pollution in urbanized area of Thar Desert, western Rajasthan, India. J Environ Health Sci Eng 12(1):23

Senthilnathan T (2008) Measurements of urban ambient air quality of Chennai City. Indian J Air Pollut Control 8(1):35–47

Shannigrahi AS, Sharma R, Fukushima T (2003) Air pollution control by optimal green belt development around the Victoria Memorial monument, Kolkata (India). Int J Environ Stud 60(3):241–249

Sharma R, Kumar R, Sharma DK, Priyadarshini I, Pham BT, Bui DT, Rai S (2019) Inferring air pollution from air quality index by different geographical areas: case study in India. Air Qual Atmos Health 12(11):1347–1357

Sharma R, Kumar R, Singh PK, Raboaca MS, Felseghi RA (2020) A systematic study on the analysis of the emission of CO, CO_2 and HC for four-wheelers and its impact on the sustainable ecosystem. Sustainability 12(17):6707

Singh AK, Gupta HK, Gupta K, Singh P, Gupta VB, Sharma RC (2007) A comparative study of air pollution in Indian cities. Bull Environ Contam Toxicol 78(5):411–416

Song R, Yang L, Liu M, Li C, Yang Y (2019) Spatiotemporal distribution of air pollution characteristics in Jiangsu Province, China. Adv Meteorol 2019:1–14. https://doi.org/10.1155/2019/5907673

Sorte S, Arunachalam S, Naess B, Seppanen C, Rodrigues V, Valencia A, Borrego C, Monteiro A (2019) Assessment of source contribution to air quality in an urban area close to a harbor: case-study in Porto, Portugal. Sci Total Environ 662:347–360

Spiroska J, Rahman A, Pal S (2011) Air pollution in Kolkata: an analysis of current status and interrelation between different factors. SEEU Rev 8(1):182–214

Steeneveld GJ, Klompmaker JO, Groen RJ, Holtslag AA (2018) An urban climate assessment and management tool for combined heat and air quality judgements at neighbourhood scales. Resour Conserv Recycl 132:204–217

Xu G, Jiao L, Zhang B, Zhao S, Yuan M, Gu Y, Liu J, Tang X (2016) Spatial and temporal variability of the PM2.5/PM10 ratio in Wuhan, Central China. Aerosol Air Qual Res 17(3):741–751

Yadav R, Bhatti MS, Kansal SK, Das L, Gilhotra V, Sugha A, Hingmire D, Yadav S, Tandon A, Bhatti R, Goel A (2020) Comparison of ambient air pollution levels of Amritsar during foggy conditions with that of five major north Indian cities: multivariate analysis and air mass back trajectories. SN Appl Sci 2(11):1–11

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