



Spatio-temporal assessment of ambient air quality, their health effects and improvement during COVID-19 lockdown in one of the most polluted cities of India

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Abstract

The present work aims to investigate seasonal variations in air pollution levels in Lucknow and assess the ambient air quality of the city together with highlighting the health impacts of major pollutants like PM₁₀, PM_{2.5}, SO₂, NO₂, Pb, Ni and aerosols from 2010 to 2019. The maximum and minimum values of PM₁₀, PM_{2.5}, SO₂, NO₂, Pb and Ni were found to be 270.75 and 122.45 µg/m³, 124.95 and 95.52 µg/m³, 25.60 and 8.05 µg/m³, 75.65 and 23.85 µg/m³, 0.66 and 0.03 µg/m³ and 0.07 and 0.01 ng/m³, respectively. Health impact of particulate matter has also been assessed with AirQ+, and it was estimated that long-term exposure of PM₁₀ was attributed to between 37 and 48% for post-neonatal (age 1–12 months) mortality rate due to all causes, whereas long-term attributable proportions in mortality due to exposure of PM_{2.5} were to about 19 to 28% from all causes. Further, an attempt has also been made to evaluate the impact of lockdown amid COVID-19 on the ambient air quality of Lucknow. During the lockdown, PM_{2.5} levels reduced by 65% (at Gomti Nagar), 23% (at central school), 79% (at Lalbagh) and 35% (at Talkatora), due to which, air quality index of Gomti Nagar came down to 43, well below 50 which falls in the healthy range. NO₂ levels also came down. However, levels of SO₂ did not show significant reduction. Correlating the data between aerosol optical depth and Angstrom exponent by Pearson correlation analysis revealed a significant positive correlation ($r = 0.65$, $P < 0.001$).

Keywords Air pollution · Aerosol · AirQ+ · Lockdown · AQI · Health effect

Highlights

- Spatio-temporal assessment of various pollutants like PM₁₀, PM_{2.5}, SO₂, NO₂, Pb, Ni and atmospheric aerosols from 2010 to 2019 was performed.
- AQI score for most of the studied locations was found in the poor category.
- During the lockdown, AQI scores decreased to well below 50, in the healthy range.
- High AE value was observed in October to November because of stubble burning during the harvest season in Northern India.
- The health impact of air pollutants was estimated using AirQ+ software.
- Long-term exposure to PM_{2.5} to ambient air increased the risk of stroke by 20%.

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Introduction

Infamous for being one of the most polluted cities in the world, Lucknow, the capital city of Uttar Pradesh, has witnessed unprecedentedly high levels of air pollution over the past few years. Clean air should be an unlimited free natural resource and the basic need of all living beings. Against a daily requirement of 2 kg of food and 3 L of water, an adult inhales and exhales about 8 L of air every single minute. But when this life-sustaining air gets polluted, it can have dire effects not only on humans but also on plants, animals and all living organisms (Ghorani-Azam et al. 2016). Today, the air we breathe is being polluted by various natural and anthropogenic sources like accelerated industrialization, haphazard urbanization, rapid increase in human population and ever-burgeoning number of automobiles on the roads (Satterthwaite et al. 2010). Natural processes absorb these pollutants to a certain extent and air quality is restored, but when the limits are exceeded, pollutants accumulate in the environment and air quality deteriorates. As per WHO data of 2006, more than 80% of urban dwellers are exposed to air quality levels that exceed WHO guideline limits (WHO 2006). However, as per recent 2016 data of WHO, it has now been observed in 90% of total world population (WHO 2016). Over the past few decades, human involvement has drastically modified Earth's chemistry and climate. The emissions from automobiles, prolific burning of fossil fuels, industrial activities and intensification of agricultural practices have escalated the ambient concentration levels of harmful gases like SO₂, NO₂ and CO and of O₃ and particulate matter (PM) to worrying levels (Gurjar et al. 2016; Wu et al. 2020). Effect of SO₂ on ecosystem and human health is well known. Short-term exposure harms the respiratory system, particularly in children and elderly people (Pandey et al. 2011, 2013). It reacts with other gaseous particles in the air to form haze and thereby reduces visibility. Longer exposures to elevated concentrations of SO₂ can aggravate existing heart and lung diseases. Epidemiological studies associate NO₂ and CO with increased cardiovascular mortality, cerebrovascular diseases and ischaemic heart diseases (Atkinson et al. 2018). High concentration of CO in air reduces oxygen supply to critical organs like heart and brain, causing dizziness, unconsciousness and even death. As per the Indian Nitrogen Assessment report 2018, between 1991 and 2001, NO_x emissions grew at 52% and at 69% from 2001 to 2011 (Pathak and Bhatia 2018). The sources of heavy metals in urban air include vehicular exhaust, untreated industrial effluents, street dust and other anthropogenic activities. Elevated concentrations of all the metals are harmful to living organisms. Though there are various routes by which these metals can enter inside the body, inhalation of particles ($\leq 10 \mu\text{m}$) is the commonest (Winkler et al. 2018; Zhang and Batterman 2013). The inorganic components constitute only a small portion by mass of the

particulates; however, they contain some toxic elements which are potential carcinogens even in trace amounts (Shukla et al. 2008).

There is not an iota of doubt in the fact that deteriorating environment with worsening air quality, damaged landscapes and degraded towns would cost us dearly not only in economic terms but also in terms of our physical health and quality of life (Seinfeld and Pandis 1998). Lucknow, the state capital of Uttar Pradesh, was ranked as the ninth most polluted city in the world, as per the report published in March 2019. Within a very short period of time, the city could face serious problems if sincere efforts are not made to regulate and control pollution. There is, therefore, an urgent need to undertake proper carrying capacity studies and planned development of the city.

The use of clean fuel with low sulphur content is considered an effective measure to arrest the rising level of pollution in urban areas (Markandeya et al. 2016a, b). Prompted by the deteriorating air quality in Indian cities like Lucknow, the government has launched several flagship initiatives including implementation of stringent emission norms, strict pollution control measures, improved technology for combustion engines and phasing out of polluting 2-stroke engines. The government has also introduced compressed natural gas (CNG) in public transport system, which is 50% cleaner than coal on carbon emissions and significantly cleaner on SO_x and NO_x and has virtually non-existent PM_{2.5}. Despite these efforts, vehicular pollution continues to remain the primary source of increasing air pollution in Lucknow City (Barman et al. 2008; assessment report CSIR-IITR 2010–2019), leading to generation of a vast amount of PM, noxious gases and heavy metals that push the pollution in the city to *unbearable* levels.

Atmospheric aerosols consist of solid or liquid particles suspended in the atmosphere and include a wide range of phenomena such as dust, smoke, haze, fume, smog, fog and mist (Seinfeld and Pandis 1998; Markandeya et al. 2017). PM refers just to the suspended solid or liquid matter, whereas an aerosol is a collection of suspended particles and the surrounding gases. Aerosols are produced from a variety of anthropogenic and natural sources with a typical size ranging from 0.001 to 10 μm . Natural aerosol particle includes sulphate aerosols from volcanic eruption, sea salt particle from ocean surface, mineral dust aerosols and wind borne dust (Shen et al. 2019; You et al. 2020). Aerosol loading or the amount of aerosols in the atmosphere is usually quantified by mass concentration or by an optical measure, i.e. aerosol optical depth (AOD). Thus, AOD is the qualitative measure of extinction of solar radiation by aerosol scattering and absorption between the points of observation and top of the atmosphere (Kumar et al. 2019; Tiwari et al. 2014, 2015). Angstrom exponent (AE) is a qualitative indicator of aerosol particle size. Higher AE values are a reflection of the fact that fine-mode aerosols are dominating, while lower AE values indicate dominance of coarse-mode aerosols (Das and Jayaraman 2011). Due to

coagulation, the size of fine-mode particles is altered, resulting in increasing aerosol loading under suitable atmospheric condition, thereby leading to an increase of the concentration of coarse-mode particles (Das et al. 2015). The Moderate Resolution Imaging Spectroradiometer onboard two Earth Observing System (EOS) Terra and Aqua satellites at an altitude of 705 km measures reflected solar radiance and terrestrial emission in 36 bands ranging from 0.4 to 14.4 μm wavelength with the different spatial resolutions of 0.25 and 1 km (Gupta et al. 2013). All the above-mentioned facts necessitate the assessment of ambient air quality with respect to respirable suspended particulate matter (PM_{10} and $\text{PM}_{2.5}$), SO_2 , NO_2 , metals (lead (Pb) and Ni) and aerosols in Lucknow City area. In this study, we observed long-term temporal and spatial variations of different ambient air pollutants and health impacts of particulate matters by using AirQ+ software. The study also investigates the impact of lockdown on the air quality of Lucknow City.

Materials and methods

Monitoring location

A total of nine air quality monitoring locations in different areas, i.e. four in residential (Aliganj, Indira Nagar, Vikas Nagar, Gomti Nagar), four in commercial cum traffic (Charbagh, Aminabad, Alambagh, Chowk) and one industrial area (Amausi) were selected for this study (Fig. 1).

Data collection

Air quality data

Particulate matters (PM_{10} and $\text{PM}_{2.5}$) were measured using a gravimetric method, sulphur dioxide (SO_2) was measured using the improved West-Gaeke method, nitrogen dioxide (NO_2) was measured using the modified Jacobs-Hochheiser (Na-arsenite) method and trace metals (Pb and Ni) were measured using an AAS method after sampling on EPM 2000. Air quality data was obtained from our past Institute CSIR-IITR, Lucknow, which has the responsibility to assess the ambient air quality of Lucknow City in two phases: pre-monsoon (November to May, report released on June 5) and post-monsoon (June to October, report released on November 5). The sampling frequency was 24 hourly, twice in a month. Ten-year data from 2010 to 2019 was used in this study.

Data during lockdown

For assessment of day-to-day real-time air quality, a total number of four Continuous Ambient Air Quality Monitoring Stations (CAAQMS) have been installed in Lucknow. Out of these four

stations, two CAAQMS are installed in residential areas, i.e. Gomti Nagar and Aliganj (central school). The remaining two have been installed in commercial and industrial areas, i.e. Lalbagh and Talkatora. To assess the impact of lockdown on the air quality, fortnight data before lockdown (February 21, 2020, to March 21, 2020) and during lockdown (March 22, 2020, to April 20, 2020) have been taken into consideration.

AOD and AE data

The remote sensing instrument called Moderate Resolution Imaging Spectroradiometer (MODIS) permits the scientist to monitor various characteristics of the Earth's terrestrial and oceanic surfaces with a single instrument, also facilitating the analysis of aerosols from the space with maximum accuracy. AE and AOD datasets used in this study were retrieved from both MODIS Terra and Aqua satellites and downloaded from NASA Giovanni website (<https://giovanni.gsfc.nasa.gov/giovanni/>) of level 3 Collection 6.1, which is globally available with $1^\circ \times 1^\circ$ resolution, and averaged values of the daily mean of area were employed in the range of latitude from 26.35° to 27.35° N and longitude of 80.45° – 81.45° E, centralized at Lucknow (26.85° N, 80.95° E) for the period January 2010 to March 2020. In the present study, AOD data at a wavelength of 550 nm and AE at 412 nm/470 nm over land are used as they are associated with major radiative effects and are close to the peak of solar spectrum.

Data analyses

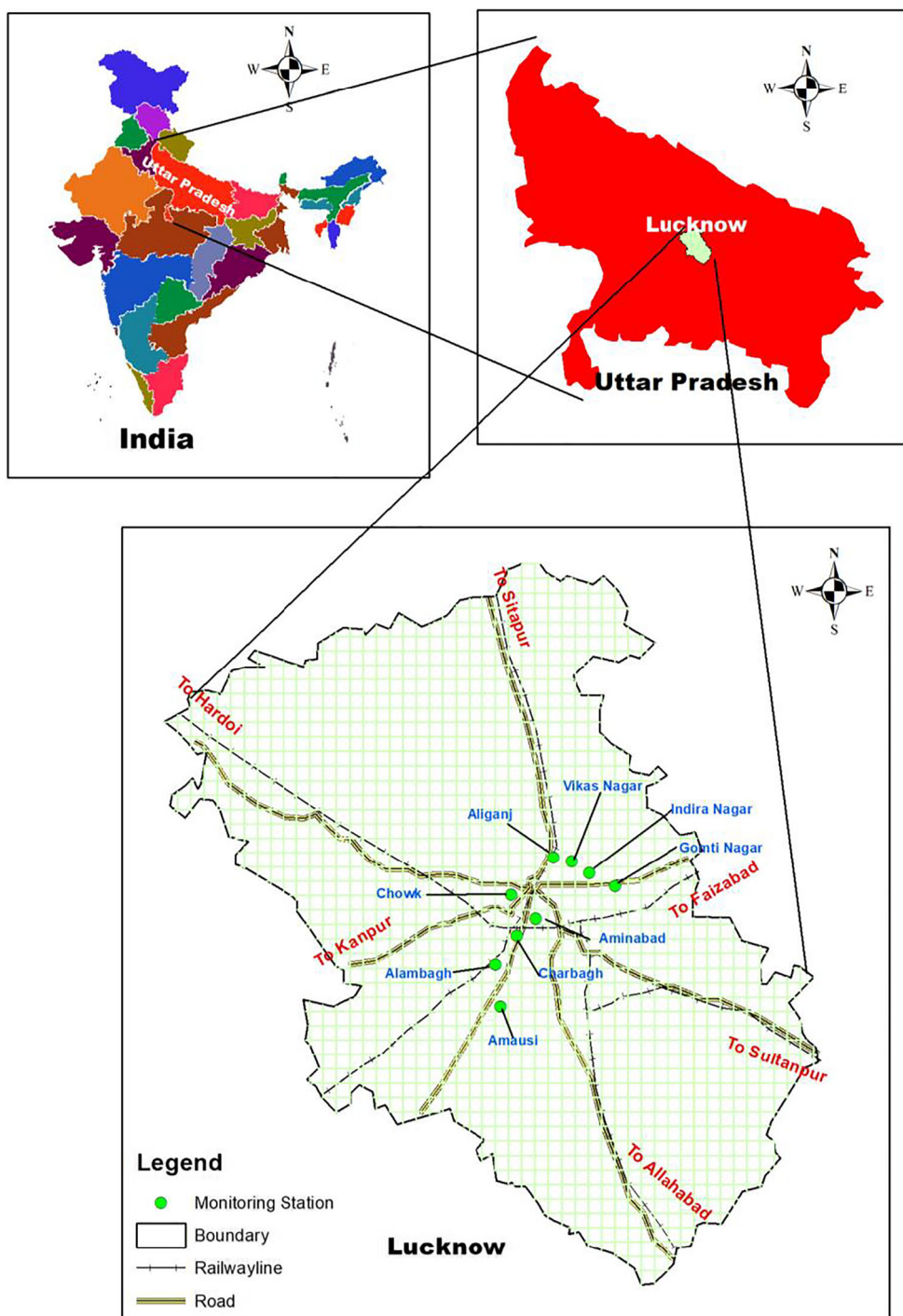
Air quality data

Data was divided into three segments: first was residential area (Aliganj, Indira Nagar, Vikas Nagar and Gomti Nagar), second was commercial area (Charbagh, Aminabad, Alambagh and Chowk) and third was industrial area (Amausi). The data is collected from CSIR-Indian Institute of Toxicology Research as our Institute covers whole-year data, and published in the form of report as pre-monsoon (November to May) and post-monsoon (June to October). It is the whole-year data. The sampling frequency was twice in a month for 24 hourly. Data was summarized as average, minimum and maximum of the pre-monsoon and post-monsoon average data.

Lockdown data

A map of Lucknow has been digitized, and different layers, i.e. continuous air monitoring stations, major roads and railway lines, have been generated. Three criteria of pollutants ($\text{PM}_{2.5}$, SO_2 and NO_2) have been selected, and their fortnight data before and during lockdown has been collected from the CAAQMS real-time data bank of Central Pollution Control

Fig. 1 Monitoring location of the study area in Lucknow City



Board (CPCB). Average values of all three pollutants have been calculated for before and during lockdown period. For air quality index (AQI), the methodology adopted by CPCB, the sub-index against each pollutant and the resultant AQI will be the maximum of these sub-indexes (AQI-CPCB 2020). The sub-index (I_p) is calculated for individual pollutants (C_p) based on ‘linear segment principle’ by using the following equation (Eq. (1)):

$$I_p = \left[\frac{I_{HI} - I_{LO}}{B_{HI} - B_{LO}} \times C_p - B_{LO} \right] + I_{LO} \tag{1}$$

where B_{HI} is the breakpoint concentration greater or equal to the given concentration, B_{LO} is the breakpoint concentration smaller or equal to the given concentration, I_{HI} is the AQI value corresponding to B_{HI} and I_{LO} is the AQI value corresponding to B_{LO} ; subtract one

from I_{LO} , if I_{LO} is greater than 50, and finally, AQI is the max (I_p) (where p is 1, 2, ..., n ; n denotes pollutants).

In the present study, during AQI calculation at all 4 locations, it has been observed that every time the sub-index of $PM_{2.5}$ was maximum compared to SO_2 and NO_2 . Average pollutant data along with AQI values before and during lockdown were mapped to monitoring stations' database, and spatial maps were generated in ArcGIS, version 10.7.1.

Data analysis between AOD and AE

Aerosol data was summarized as mean \pm SD. AOD and AE groups were compared by one-way analysis of variance (ANOVA). Pearson correlation analysis was done to assess the association between AOD and AE datasets. The statistical software Origin (version 9.1) was used for the analysis of data (Markandeya et al. 2015).

Health effects

The AIRQ+ software developed by WHO, updated in 2018, was used for the estimation of health impact assessment of PM_{10} and $PM_{2.5}$ in this study. Relative rise (RR) is the estimation of the magnitude of an association between exposure and disease. It indicates the probability of developing the disease in the exposed group relative to those who are not exposed. Probability is the ratio of developing the disease in the exposed group to that in the non-exposed group. It also indicates the probability of developing the disease in the exposed area at the given time period. Here, we assumed RR to be equal to 1.04 (95% CI = 1.02 to 1.07) for the neonatal age group at baseline PM_{10} ($50 \mu\text{g}/\text{m}^3$). On the other hand, the RR taken for $PM_{2.5}$ was 1.07 (95% CI = 1.05 to 1.09) for all causes of mortality at baseline $PM_{2.5}$ ($40 \mu\text{g}/\text{m}^3$).

RR is usually modelled with a log-linear function as given in Eq. (2)

$$RR = \frac{\exp(\alpha + \beta X_i)}{\exp(\alpha + \beta X_0)} = \exp[\beta(X - X_0)] \quad (2)$$

where X_i is the pollutant concentration ($\mu\text{g}/\text{m}^3$) and X_0 is the cut-off or counterfactual ($\mu\text{g}/\text{m}^3$). In the log-linear model, β is the change in the RR for a 1-unit change in the concentration X_i .

Results and discussion

Analysis of air quality data

The maximum average values for PM_{10} and $PM_{2.5}$ were 271 and $125 \mu\text{g}/\text{m}^3$, respectively, and the yearly average values of

both these pollutants for the stated period (2010 to 2019) were 199 and $96 \mu\text{g}/\text{m}^3$, respectively (Fig. 2a, b). These are much higher than those prescribed by the National Ambient Air Quality Standards (NAAQS) ($60 \mu\text{g}/\text{m}^3$ for PM_{10} and $40 \mu\text{g}/\text{m}^3$ for $PM_{2.5}$). Area-wise, almost all the considered areas reported high particulate pollution, but two commercially important areas, namely Charbagh and Chowk, were worst affected. Charbagh had the highest values for both PM_{10} and $PM_{2.5}$, where the average level was always higher than $199.33 \mu\text{g}/\text{m}^3$ for PM_{10} and $95.52 \mu\text{g}/\text{m}^3$ for $PM_{2.5}$, much above the permissible limits.

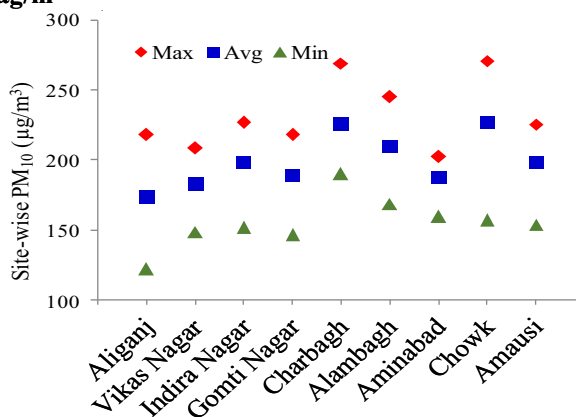
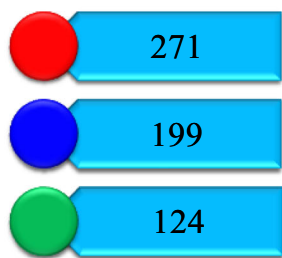
Since particulate matter is the dominant pollutant in most areas of the city, AQI values are directly linked to the level of particulate matter in the air. AQI values from 150 to 200 fall in the unhealthy category (CPCB 2006–2007). At such level of pollution, everyone may begin to experience health effects; especially, members of sensitive groups may experience more serious health problems, and active children and adults and people with a respiratory disease, such as asthma, should avoid prolonged outdoor exertion. Such high particulate pollution in Lucknow is in line with the findings of the IQ Air report (2019) which highlights that, on average, most Indian cities exceed the WHO guidelines for the amount of $PM_{2.5}$ in the atmosphere by nearly 500% (IQAir report 2019).

Pollutants settle down on the ground with the raindrops. As a result, their level in the air decreases drastically during the monsoon season. From Table 1, it can be observed that post-monsoon PM_{10} levels were less than pre-monsoon levels for all the years from 2010 to 2019, with 2015 being the only exception. This may be due to the reason that 2015 was a strong El Nino year due to which there was much less rainfall during the south-west monsoon season. Less rain results in less scavenging of the pollutants from the atmosphere (Shukla et al. 2008).

In contrast to all other considered pollutants, the levels of SO_2 in commercial areas were not much different from those observed in residential and industrial areas. The commercial area of Alambagh reported higher average SO_2 levels than Charbagh, Chowk and Amausi (Fig. 2c). Though the concentrations of SO_2 reported from all the sampling stations are well below the prescribed NAAQS level ($80 \mu\text{g}/\text{m}^3$), consistently high levels in the early post monsoon could be attributed to the stable meteorological conditions. Ghosh et al. (2018) also found that the concentration of SO_2 was higher in post monsoon, which is similar to the present study.

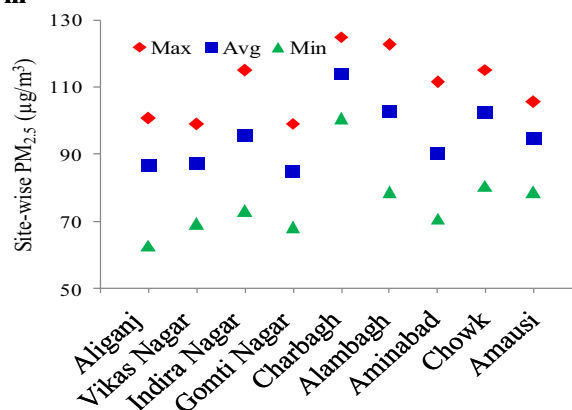
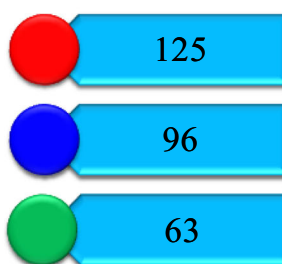
Just like SO_2 , NO_2 concentrations peaked during November to January and were minimum during July to August (Fig. 2c, d), possibly due to a large number of factors like low solar intensity resulting in decreased photochemical loss, anthropogenic emissions, boundary layer processes and local surface wind pattern. Similar observations have been reported from other urban locations like Ahmedabad and Pune, in India (Beig et al. 2013). For almost all the considered

All Site (Max., Avg. and Min.) $\mu\text{g}/\text{m}^3$



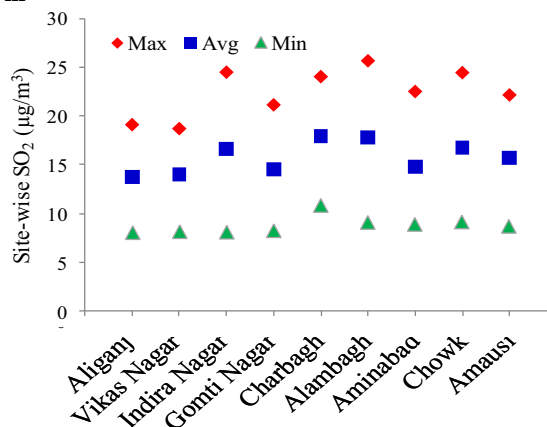
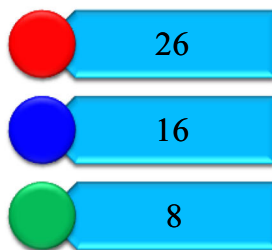
(a)

All Site (Max., Avg. and Min.) $\mu\text{g}/\text{m}^3$



(b)

All Site (Max., Avg. and Min.) $\mu\text{g}/\text{m}^3$



(c)

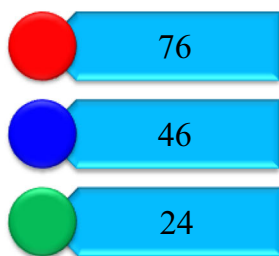
Fig. 2 Variations of the concentration of pollutants (a PM_{10} , b $\text{PM}_{2.5}$, c SO_2 , d NO_2 , e Pb and f Ni) in air quality at different areas of Lucknow City

areas, the levels of NO_2 were higher than $40 \mu\text{g}/\text{m}^3$ (NAAQS 2009). The silver lining is that the NO_2 concentrations at Lucknow were still comparatively lower than those observed at other urban regions of the country.

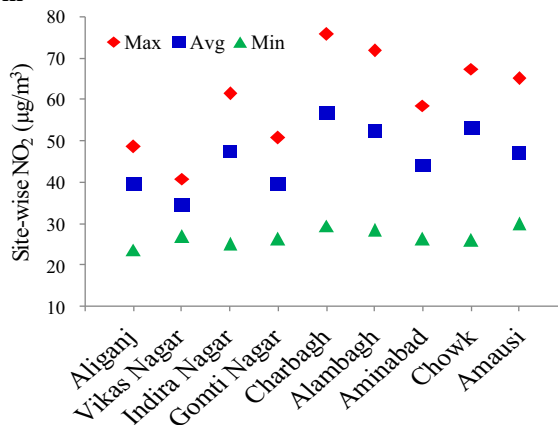
Pollution levels in most regions of North India during the onset of winters reach unbearable levels, engulfing huge areas in thick smog, Lucknow being no exception. This is due to a

combination of factors like increased biomass burning, festive season that culminates with the bursting of firecrackers on the night of Deepawali and a weather pattern which according to experts brings dust-bearing winds from West Asian countries like Iraq, Saudi Arabia and Kuwait. These winds collide with the moisture-bearing wind system coming from the east. Moisture locks in the dust and becomes a cloud. At the same

All Site (Max., Avg. and Min.) $\mu\text{g}/\text{m}^3$



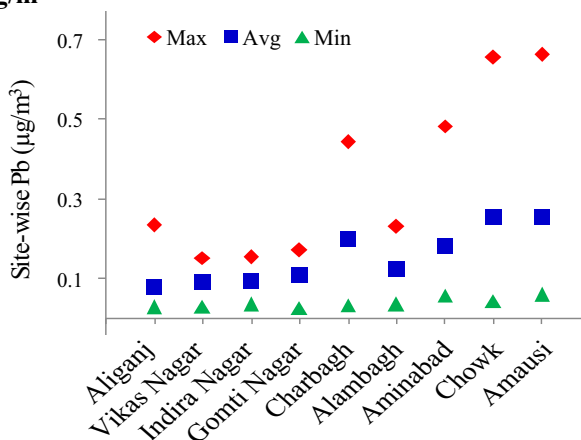
(d)



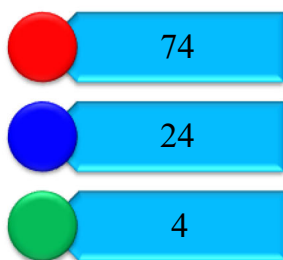
All Site (Max., Avg. and Min.) $\mu\text{g}/\text{m}^3$



(e)



All Site (Max., Avg. and Min.) ng/m^3



(f)

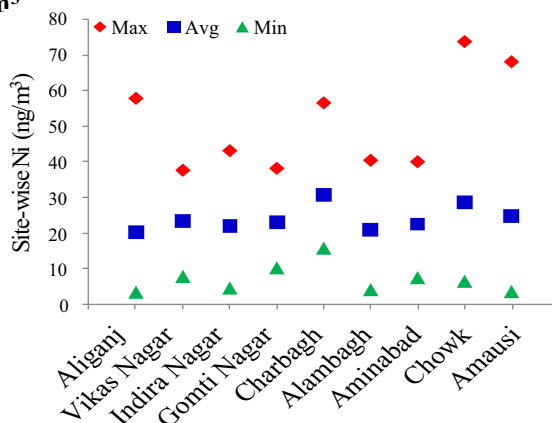


Fig. 2 (continued)

time, there is no wind at the ground level. This creates suffocating conditions (Havens et al. 2018).

As a result of EPA’s regulatory efforts including the removal of Pb from motor vehicle gasoline, levels of Pb in the air decreased by 98% between 1980 and 2014 (Hai et al. 2018). Still high level of Pb pollution is an important issue

in Lucknow. From Fig. 2e, it can be observed that the level of aerial Pb in commercial and industrial areas is almost double that of residential areas. Chowk and Amausi are the two main areas grappling with Pb pollution, where the recorded levels were as high as $0.664 \mu\text{g}/\text{m}^3$. These are higher than the NAAQS-prescribed limit of $0.5 \mu\text{g}/\text{m}^3$. The average value is

Table 1 Seasonal concentration of air pollutants

Parameter	Location	2010		2011		2012		2013		2014		2015		2016		2017		2018		2019	
		Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M	Pre-M	Post-M
PM ₁₀ (µg/m ³)	Average of 4 residential locations	155.9	129.1	181.7	167.2	216.3	167.1	205.8	178.2	209.1	192.4	182.5	195.3	201.4	180.9	223.6	192.0	201.9	208.2	180.1	154.0
PM _{2.5} (µg/m ³)		68.0	68.9	69.6	94.8	88.3	83.5	90.0	97.1	88.4	83.5	90.0	97.1	100.8	91.0	107.5	96.1	93.7	103.2	85.2	79.3
SO ₂ (µg/m ³)		12.4	16.0	14.9	26.2	15.5	20.3	19.2	14.0	18.0	16.0	13.2	18.3	12.0	17.0	11.1	13.1	8.7	10.6	7.0	9.3
NO ₂ (µg/m ³)		27.6	23.9	27.0	38.5	32.8	48.4	41.9	49.7	36.4	48.0	43.3	55.4	39.5	54.1	46.9	46.8	37.8	44.2	34.0	32.2
Pb (µg/m ³)		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1
Ni (ng/m ³)		14.8	16.0	21.9	8.6	13.9	45.8	14.9	10.2	43.3	31.5	17.1	17.5	37.3	47.9	41.1	15.3	8.8	13.9	3.1	19.4
PM ₁₀ (µg/m ³)	Average of 4 commercial locations	206.5	180.4	225.3	193.2	248.9	230.9	235.3	223.9	219.7	217.5	212.4	243.9	230.1	211.1	231.7	199.6	196.3	209.8	174.3	165.4
PM _{2.5} (µg/m ³)		82.5	133.6	83.9	103.5	90.5	107.3	104.8	120.9	90.7	107.3	104.8	120.9	110.2	97.5	114.5	108.7	96.9	104.7	84.7	80.9
SO ₂ (µg/m ³)		14.0	19.3	16.8	31.4	19.6	22.6	21.1	17.4	20.3	18.5	14.6	21.9	13.4	21.3	11.8	14.3	10.3	10.8	8.1	11.0
NO ₂ (µg/m ³)		31.1	24.0	34.1	61.9	39.4	67.0	51.4	60.4	54.4	66.8	62.4	72.4	44.1	66.4	54.6	56.6	51.6	57.1	42.8	35.0
Pb (µg/m ³)		0.5	0.1	0.4	0.1	0.1	0.1	0.2	0.2	0.1	0.4	0.2	0.2	0.2	0.3	0.2	0.3	0.1	0.1	0.1	0.1
Ni (ng/m ³)		17.5	26.5	21.0	11.8	14.6	41.3	19.1	14.7	38.8	37.8	33.1	20.4	42.4	60.0	45.9	21.8	10.5	17.8	6.4	12.2
PM ₁₀ (µg/m ³)	Average of industrial location: Amausi	160.9	156.5	163.0	145.0	227.2	217.9	224.3	226.9	217.3	186.6	199.4	214.2	238.3	212.9	210.1	203.1	196.9	223.3	189.2	153.7
PM _{2.5} (µg/m ³)		66.0	136.0	67.6	90.0	87.0	85.2	96.9	114.3	87.1	85.2	96.9	114.3	111.3	99.6	106.3	94.4	89.4	107.7	79.8	80.1
SO ₂ (µg/m ³)		9.6	15.8	14.3	25.7	17.1	27.2	22.8	18.0	23.5	17.3	10.2	20.6	11.9	17.2	12.2	14.7	7.9	9.5	7.8	10.7
NO ₂ (µg/m ³)		37.6	22.4	29.0	48.8	46.8	48.3	55.9	49.9	39.6	70.6	54.4	75.5	45.3	55.6	47.6	41.3	41.7	50.5	29.8	49.7
Pb (µg/m ³)		1.0	0.1	0.4	0.1	0.1	0.2	0.8	0.5	0.2	0.1	0.1	0.2	0.1	0.2	0.5	0.1	0.1	0.2	0.1	0.1
Ni (ng/m ³)		7.4	10.9	15.7	4.9	12.1	41.0	23.7	14.8	41.0	20.0	17.8	18.3	36.9	98.9	46.8	52.3	9.5	16.8	2.4	4.7

Pre-M pre monsoon, *Post-M* post monsoon

0.16 $\mu\text{g}/\text{m}^3$, but since Pb as a pollutant has no known safe threshold (there is no known sufficiently small amount of Pb that does not cause harm).

Environmental Ni levels depend particularly on natural sources, pollution from nickel-manufacturing industries and airborne particles from combustion of fossil fuels (US EPA 1999). There was a huge variation observed between the highest and lowest average values of Ni, the former being as high as 74 ng/m^3 and the latter 4 ng/m^3 (Fig. 2f). The average value of 24 ng/m^3 for the stated period of the study was higher than the permissible limit of 20 ng/m^3 (NAAQS). Chowk and Amausi were the worst affected areas.

Data analysis before and during lockdown

Lockdown brought everything to a grinding halt, advocating blanket ban on all types of construction activities and restricting non-essential travels. As a result, vehicle density on the roads reduced drastically, ensuring a substantial drop in air pollution levels. Table 2 shows the comparison of the ambient air quality of Lucknow City before and after lockdown.

Based on Eq. (1), AQI has been calculated for all the four locations before and during lockdown. The details of AQI values are given in Table 2.

In the present study during AQI calculation at all 4 locations, it has been observed that every time the sub-index of $\text{PM}_{2.5}$ was maximum compared to SO_2 and NO_2 . Average pollutant data along with AQI values before and during lockdown were mapped to monitoring stations' database, and spatial maps were generated.

Figure 3a shows that, during lockdown, a gradual uniform reduction of $\text{PM}_{2.5}$ has been observed at all locations, whereas from Fig. 3b, it can be observed that no such significant variation has been observed in values of SO_2 before and during lockdown. Before lockdown, the values of NO_2 were higher in residential areas compared to industrial areas (Fig. 3c). But during lockdown, NO_2 values in residential areas were less than those in industrial areas. It may be due to the fact that, in residential areas, the major and prime source of NO_2 is

vehicular pollution. In high-traffic density areas, NO_2 concentration was higher at all residential locations before lockdown, but during lockdown, all vehicular movements got suspended due to which a sharp decline was observed in the values of NO_2 . But in industrial area, the activity continued with little reduction of the man power. From Fig. 3d, it can be observed that, before lockdown, the major areas of Lucknow were severely and moderately polluted, whereas during lockdown, major areas of Lucknow had satisfactory air quality index.

Relationship between AOD and AE values

The spectral characteristics of AOD suggest about potential aerosol particles (course and fine) and their size distribution. The annual mean distribution of AOD and AE for the period of 2010 to 2019 over Lucknow City is presented in Fig. 4. The highest value of AOD was observed in 2016 while lowest was observed in 2010 with a range of 0.76 ± 0.34 to 0.56 ± 0.25 . Tiwari et al. (2018) also reported nearly similar AOD value (0.64) over Kanpur City.

Srivastava et al. (2012) value was 0.63 ± 0.21 , and the current study (with a value of 0.64) presented nearly similar results for annual average. Larger value of AOD in November, December and January may be due to high burning of biomass/agriculture residue and atmospheric condition, while in June and July, it may be due to less data availability of AOD due to cloud interference and water-absorbing type of aerosols. Analysis showed that the highest monthly mean value of AOD was found in the month of November (0.95 ± 0.11) and December (0.95 ± 0.23) followed by January (0.95 ± 0.19), while the lowest monthly mean value of AOD was observed in March (0.39 ± 0.05). Observation further showed that the decadal mean of AOD value during the study period is 0.65 ± 0.27 , which is nearly similar to the decadal AOD value of Varanasi (0.67 ± 0.28), Patna (0.65 ± 0.30) and Kolkata (0.5 ± 0.21) (Kumar et al. 2018). AOD during monsoon season (0.80 ± 0.18) is high as compared to that during summer season (0.54 ± 0.19), possibly due to the hygroscopic growth of water-soluble aerosols.

The annual mean value of AE ranging from 1.47 ± 0.32 to 1.06 ± 0.53 was observed over Lucknow during 2010 to 2019, suggesting the presence of mostly fine-mode particles (emitted from anthropogenic sources, e.g. vehicular, industrial and biomass burning). Further, analysis showed the highest value of monthly mean AE in January (1.66 ± 0.09), but the lowest value in May (0.60 ± 0.11), with a wide range due to daily variations in weather condition and diverse emission sources. Figure 5 shows the monthly mean relation between AOD and AE during 2010 to 2019. Analysis showed that AOD and AE followed the same trend, except August, September and October that are opposite. Tiwari et al. (2018) observed that AE values 1.16 ± 0.11 and 1.2 ± 0.09

Table 2 AQI before and during lockdown

Locations	Before lockdown			During lockdown				
	Sub-index			AQI	Sub-index			AQI
	$\text{PM}_{2.5}$	SO_2	NO_2		$\text{PM}_{2.5}$	SO_2	NO_2	
Gomti Nagar	71	18	35	71	43	14	11	43
Central School	79	10	35	79	64	9	8	64
Lalbagh	213	5	30	213	119	5	20	119
Talkatora	174	4	35	174	129	4	15	129

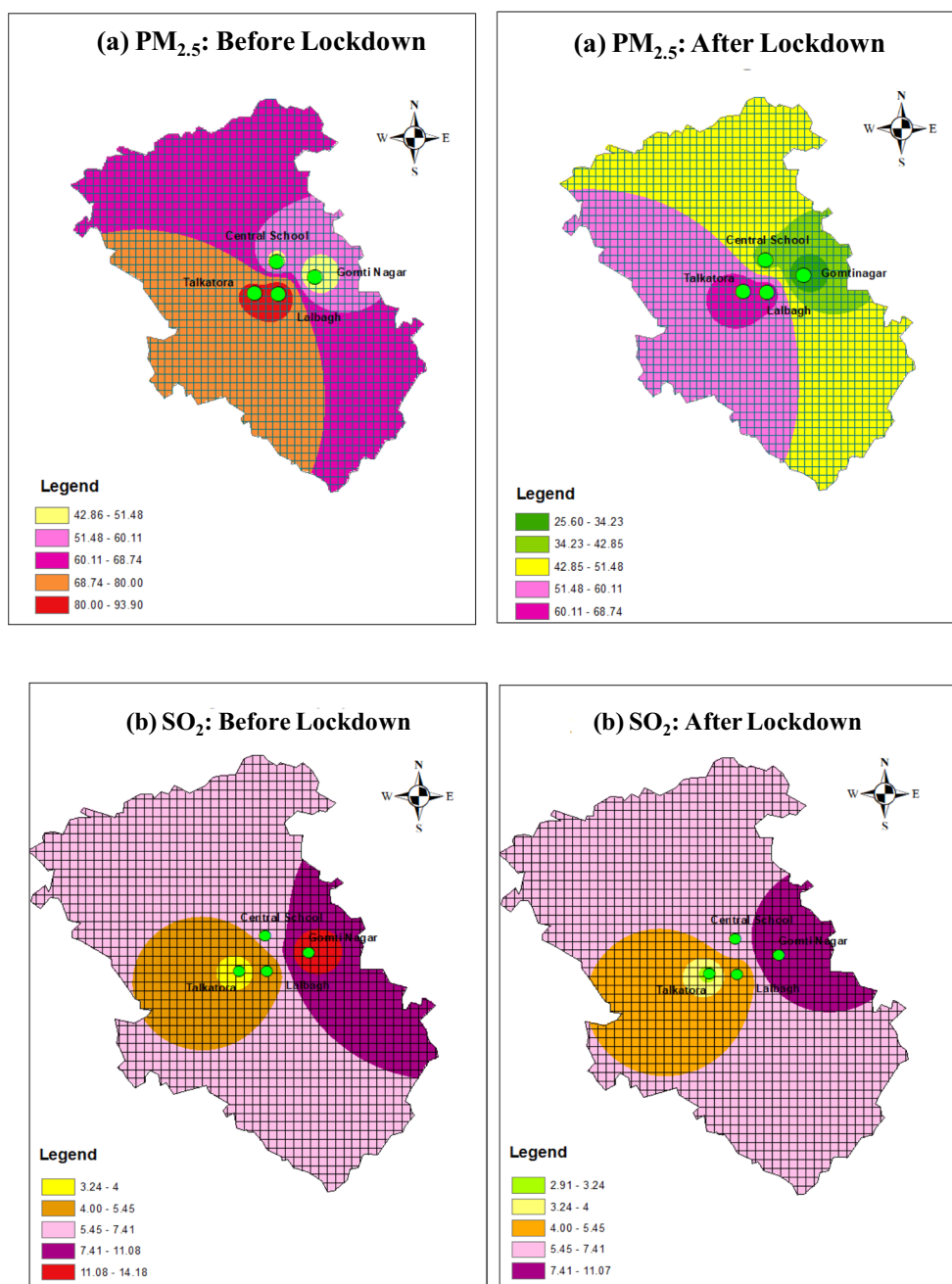


Fig. 3 Variations in PM_{2.5} (a), SO₂ (b), NO₂ (c) and AQI (d) in air quality before and during lockdown at different areas of Lucknow City

for type I and type II, respectively, indicates the dominance of fine-mode aerosol due to anthropogenic activity.

Figure 6 represents the seasonal annual correlation between AOD and AE, pre monsoon (Fig. 6a) and post monsoon (Fig. 6b). AE is the size indicator: small for coarse-mode aerosol particles and large for fine-mode aerosol particles. From Fig. 6, it is clear that AOD correlated with AE in both seasons and in summer due to high dust loading, in which AOD increases but AE decreases because of the larger size of dust particles (course), while in post monsoon/winter, it was due to burning of biomass and bursting of crackers in Diwali festival which increase fine-mode aerosol particles that show a

positive correlation. Correlating the data between AOD and AE by Pearson correlation analysis revealed a significant positive correlation ($r = 0.65, P < 0.001$). High AE value is observed in October to November because of stubble burning during the harvest season in Northern India. Also, bursting of crackers during the festival of Deepawali increases the fine-mode aerosol loading in the atmosphere.

Health effects

Air pollution now represents a considerable global pandemic and is one of the largest environmental health threats

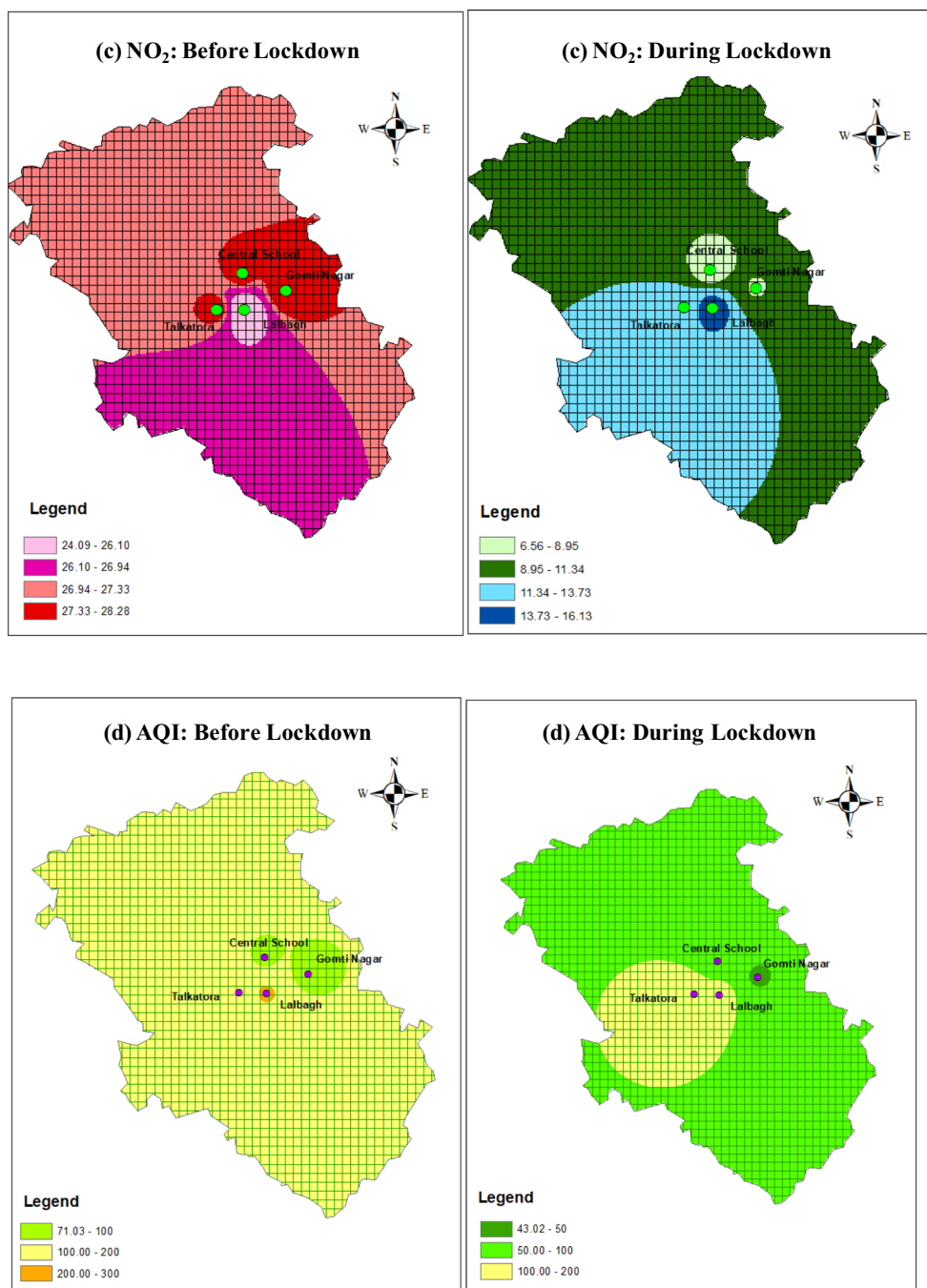
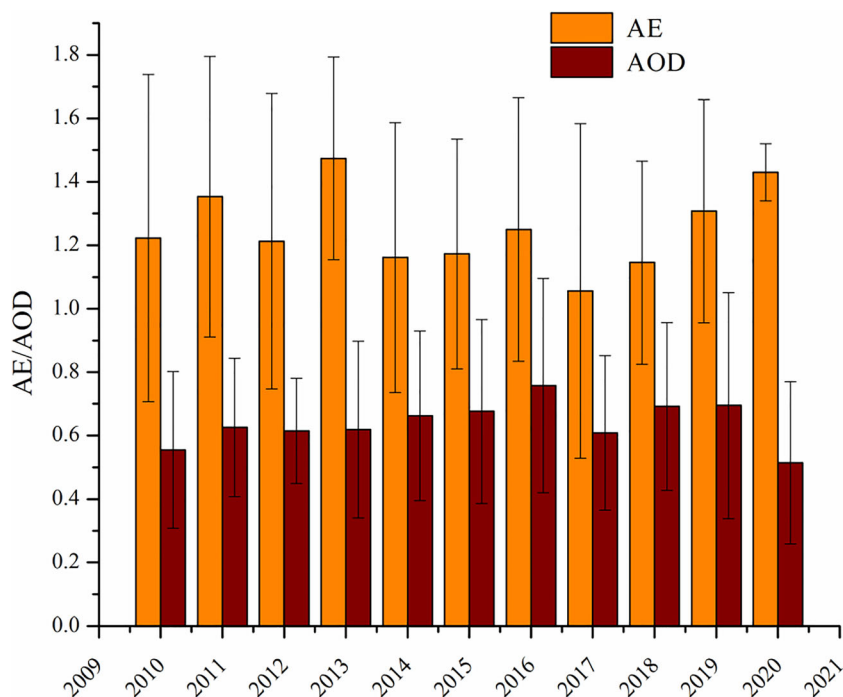


Fig. 3 (continued)

humanity faces. Though ambient air pollution affects developed and developing countries alike, low- and middle-income countries like India bear the maximum brunt. This silent killer is responsible for about 8 million premature deaths every year, mainly due to increasing incidents of cardiac arrests, compromised lung function, chronic obstructive pulmonary disease, asthma attacks and acute respiratory infections. The crux is that this devil called air pollution has created a total global panic and India as a developing country remains highly vulnerable.

PM is the most critical pollutant among all others from the health perspective. According to Global Burden of Disease Study 2015, exposure to fine particulate (PM_{2.5}) is the 5th leading cause of death globally, causing 4.2 million deaths and 103.1 million disability-adjusted life-years in 2015. Reinmuth-Selzle et al. (2017) also observed that PM was responsible for various types of allergies. Fourteen percent of all new cases of diabetes reported in 2016 were linked to air pollution, especially PM_{2.5}, which enters the bloodstream through lungs and reduces insulin production and triggers

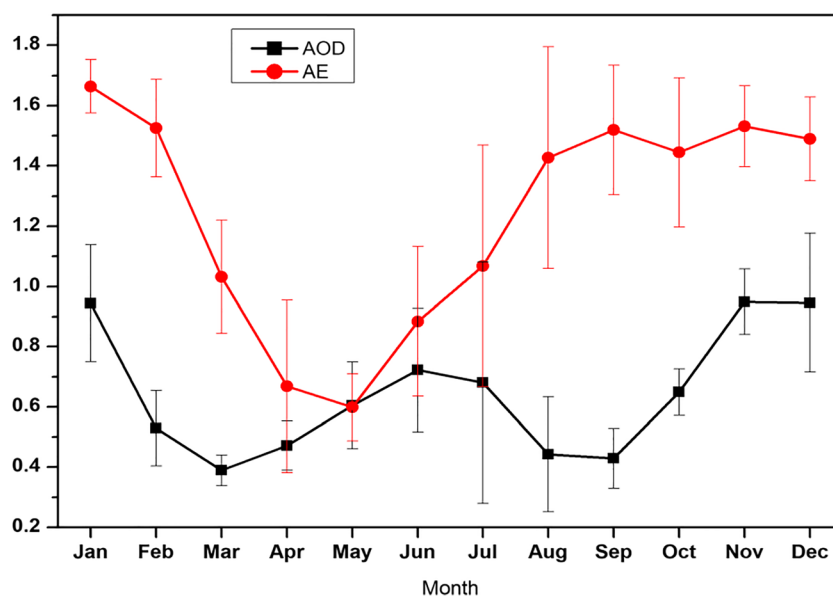
Fig. 4 Annual variations of AOD_{550 nm} and AE_{412–470 nm} (annual mean AOD and AE are calculated by averaging all AOD and AE values for the same month during 2010 to 2019)



inflammation. Small-sized particles ranging from 0.001 to 0.1 μm act as the carrier of pathogenic bacteria and viruses which may cause various types of lung infections including pneumonia. Moreover, these particles increase the rate of blood flow, damage the endothelial cell walls and may even cause cancer. They are also associated with elevated clotting activity, constriction of the airways and fever initiation. Ultrafine particles may cause imbalance between oxygen and carbon dioxide in the lungs. They also inhibit the function of alveolar ducts which basically assist the alveoli to collect the air that has been inhaled, and help in dispersing it to the alveolar sac.

It has been observed (Fig. 7) that the annual mean values of PM₁₀ are more than three times the prescribed standard on PM₁₀, i.e. 60 $\mu\text{g}/\text{m}^3$ except 2019. Health impact of PM₁₀ on post-neonatal mortality has been determined, and it has been observed that out of the total post-neonatal deaths, more than 1/4 is due to exposure of PM₁₀. This study also investigates the impact of PM_{2.5} which is more than twice of prescribed standards. It has been observed that the higher value of PM_{2.5} is responsible for 32% of deaths over the study period (2010–2019). On average, the attributable death rate per lakh population has been observed to be 202 which is much higher than

Fig. 5 Time series plot of AOD_{550 nm} and AE_{412–470 nm} with standard deviation over Lucknow for the period 2010 to 2019



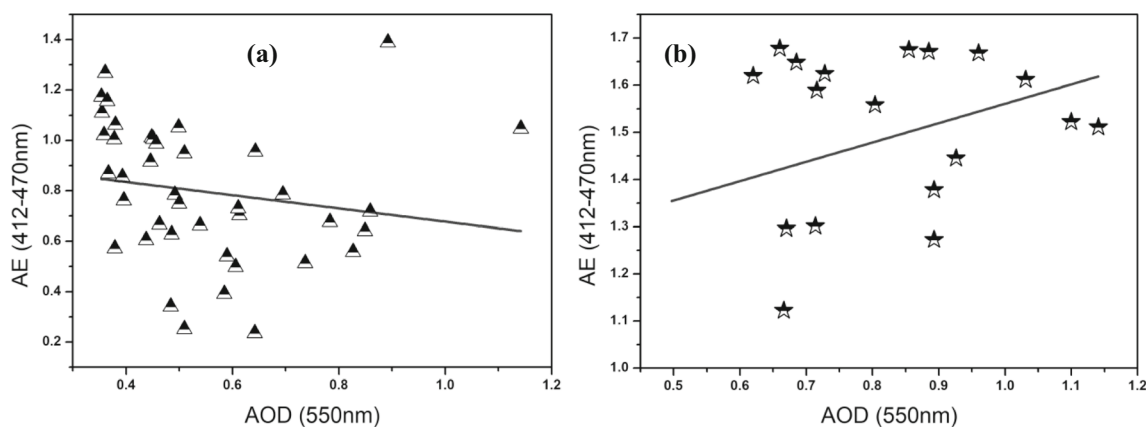


Fig. 6 Correlation between AOD_{550 nm} and AE_{412-470 nm} over Lucknow for the period 2010 to 2019

the nation’s and state’s attributable death rates, i.e. 89.9 and 111.1, respectively (Weiss et al. 2019).

SO₂ is a highly reactive gas and is soluble in water so when inhaled via nose or mouth during breathing, it is mostly absorbed by mucosa and causes various types of allergies. It also causes coughing, wheezing, asthma and a tight feeling around the chest. Concentrations greater than 100 µg/m³ cause inflammation and irritation on the skin. Sometimes, the gas also reacts with other carcinogenic chemicals present in the atmosphere and changes into smaller-sized particles capable of penetrating deep into the lungs and inhibiting the process of gaseous exchange (Pool et al. 1988).

NO₂ exposure may lead to increased asthma attacks and aggravated respiratory illnesses. Lesions in tissues connecting airways with the region of gaseous exchange may be formed with continuous exposure. There is inadequate evidence regarding NO₂ as a potential carcinogen. However, it is considered that NO₂ could produce nitrates and nitrites by reacting with amines forming nitrosamines which are carcinogenic agents (Song et al. 2015).

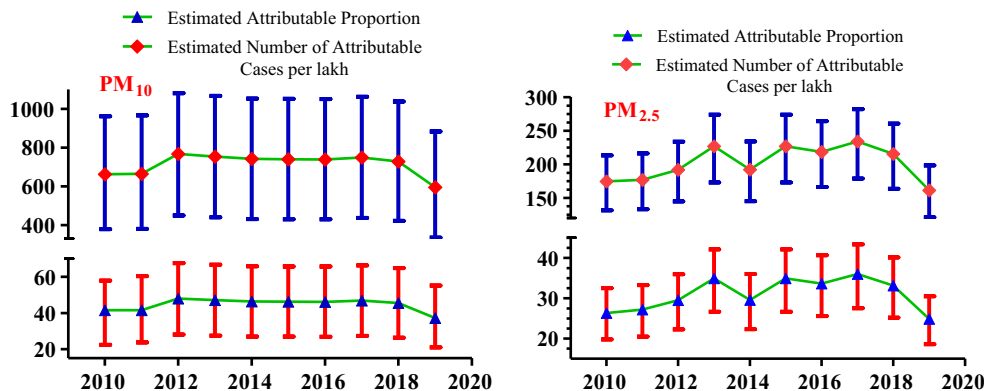
Pb poisoning is called as plumbism, colica pictorial or painter’s colic. It is one such pollutant which, when enters the human body, is hard to flush out. Pb interferes with many body processes and affects almost all organ systems. It damages the central nervous system and is therefore particularly

toxic to children who absorb the pollutant at a faster rate than adults. It binds with the sulphhydryl group present on many enzymes and mimics other metals which act as cofactors in enzymatic reactions. It also interferes in heme synthesis leading to anaemia. In the brain, it is able to pass the blood-brain barrier by substituting the calcium ions causing a neuromuscular disease called as Pb palsy. Pb tends to accumulate in the environment and enters the food chain.

Ni is particularly toxic to human beings and is a known carcinogen. Incidences of lung, kidney and prostate cancers have been reported in workers exposed to high concentrations of Ni. Ni in combination with carbon group forms a highly poisonous gas (Ni(CO)₄). Sensitive people may develop allergy to nickel which affects their skin (US EPA 1999). This condition is known as contact dermatitis. Ni may also impair the development of embryo, leading to congenital defects.

Aerosols have an enormous effect on the Earth’s climate system and air quality, which significantly affects human health. Various epidemiological studies associate aerosols with dire health effects like increased mortality, respiratory illness and cardiovascular diseases. Ultrafine particle (dp < 100 nm) are particularly hazardous to humans as these are small enough to pass through the membranes of the respiratory tract and enter the bloodstream. They can also be transported along olfactory nerves into the brain. Bio-

Fig. 7 Health impacts attributable to long-term exposure to PM₁₀ (post-neonatal infant mortality) and PM_{2.5} (mortality from all causes). The confidence intervals (lower and upper) for the number of excess cases are indicated using bars



aerosols are segment of atmospheric particulate matter that are released from terrestrial and marine ecosystems into the atmospheres. These include a wide variety of living and dead components like bacteria, viruses, fungi, dispersal units like pollen grains and fungal spores and also cellular material from animals and plants. Fröhlich-Nowoisky et al. (2016) also suggested that aerosols work as a carrier of various living and dead components. There is still a dearth of evidence to establish a clear correlation between the physical and chemical properties of ultrafine and large aerosols that actually have adverse health effects on human beings. Bio-aerosols may be allergenic and infectious to living organisms, which influence human health and agriculture on regional and global levels (Reinmuth-Selzle et al. 2017). The health effect of aerosols can be broadly classified into two categories, namely short-term and acute effects like asthmatic attacks and bronchitis and long-term chronic effects like infectious diseases, respiratory allergies and cancer.

Conclusions

The present research concluded that the level of atmospheric particulate matter in all considered locations remained much above the standard prescribed limits, all throughout the stated period. The maximum average concentration of PM₁₀ and PM_{2.5} were 226.55 and 115.0 µg/m³, 270.75 and 111.55 µg/m³ and 225.60 and 124.95 µg/m³ for residential, commercial and industrial areas, respectively. Charbagh and Chowk had the highest particulate pollution possibly due to excessive vehicular movement, increased construction activities, open garbage burning, commercial and industrial activities, etc. Saving SO₂, the observed values of all the other pollutants were higher than the NAAQS standards and this is what has fast transformed the city into an air pollution epicenter, grappling with diseases like ischaemic heart disease, stroke, lung cancer, COPD and acute respiratory infections. On an average, the attributable death rate per lakh population has been observed as 202 in the case of PM_{2.5} for all causes and 714 in the case of PM₁₀ for post-neonatal death which is much higher than the nation's and state's attributable death rates. Amid the consequences of the coronavirus lockdown, the ambient air quality of the city improved considerably, bringing the AQI score into the safe and healthy category. The maximum impact was seen in the PM values of the areas in which high PM levels were reported earlier, historically. Since this is a temporary relief, the need of the hour is to implement long-term measures like strengthening the public transport system, discouraging the use of private vehicles by imposing healthy congestion charges, checking dieselization, offering scrappage schemes for most polluting vehicles, providing for compulsory tarpaulin or protective canvas around construction sites and blanket ban on burning of waste to keep the health hazards at bay.

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Authors' contributions The main investigator was Markandeya, who designed the manuscript. The technical drafting of the manuscript was done by NKS, while VM and PKV helped in the writing and data collection, respectively. Moreover, SPS and DM were advisors of the present research. All the authors have read and approved the manuscript.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval and consent to participate Not applicable

Consent for publication Not applicable

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