Substantial changes in Gaseous pollutants and health effects during COVID-19 in Delhi, India

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ABSTRACT

Background. Coronavirus disease has affected the entire population worldwide in terms of physical and environmental consequences. Therefore, the current study demonstrates the changes in the concentration of gaseous pollutants and their health effects during the COVID-19 pandemic in Delhi, the national capital city of India.

Methodology. In the present study, secondary data on gaseous pollutants such as nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), ammonia (NH_3), and ozone (O_3) were collected from the Central Pollution Control Board (CPCB) on a daily basis. Data were collected from January 1, 2020, to September 30, 2020, to determine the relative changes (%) in gaseous pollutants for pre-lockdown, lockdown, and unlockdown stages of COVID-19.

Results. The current findings for gaseous pollutants reveal that concentration declined in the range of 51%–83% (NO), 40%–69% (NOx), 31%–60% (NO_2), and 25%–40% (NH_3) during the lockdown compared to pre-lockdown period, respectively. The drastic decrease in gaseous pollutants was observed due to restricted measures during lockdown periods. The level of ozone was observed to be higher during the lockdown periods as compared to the pre-lockdown period. These gaseous pollutants are linked between the health risk assessment and hazard identification for non-carcinogenic. However, in infants (0–1 yr), Health Quotient (HQ) for daily and annual groups was found to be higher than the rest of the exposed group (toddlers, children, and adults) in all the periods.

Conclusion. The air quality values for pre-lockdown were calculated to be "poor category to "very poor" category in all zones of Delhi, whereas, during the lockdown period, the air quality levels for all zones were calculated as "satisfactory," except for Northeast Delhi, which displayed the "moderate" category. The computed HQ for daily chronic exposure for each pollutant across the child and adult groups was more than 1 (HQ > 1), which indicated a high probability to induce adverse health outcomes.

INTRODUCTION

The Coronavirus disease 2019 (COVID-19) pandemic has affected the entire population worldwide in terms of physical and mental health, the economy, and the environment. Although the effects of COVID-19 are global, the impact has been severe among low-income group strata of society. This has particularly been the case in India, where mass migration of domestic and industrial laborers and agricultural field workers from metropolitan cities to their native villages was observed; despite the government's restrictions during the countrywide lockdown. This has also resulted in the spread of COVID-19 to the country's most remote corners.

The COVID-19 pandemic has led to severe impacts on the health conditions of people across the globe. Reports from the World Health Organization and other agencies, as of September 25, 2022, indicate that COVID-19 has infected more than 620 million people, and more than 6.5 million people have died across countries (including India) (*Worldometers, 2022*). India was the second most affected country globally, following the United States of America (USA), as of September 25, 2022, with more than 44 million infected cases and more than 0.52 million deaths (*Worldometers, 2022*). Although many patients are asymptomatic, some symptoms include severe interstitial pneumonia with acute respiratory distress syndrome (ARDS) (*Ciceri et al., 2020*) and atopic dermatitis (*Patruno et al., 2020*). Further, the authors also reported a decrease in mortality in patients admitted in hospitals with COVID-19 pneumonia. The transmission is generally person-to-person, and the most likely pathway seems to be airborne (*Faridi et al., 2020*).

Various studies have reported a decrease in pollutant levels across the world during lockdown periods (*Chu et al., 2021*; *Kumari & Toshniwal, 2020*; *Sarkis et al., 2020*; *Zowalaty, Young & Järhult, 2020*; *Sahoo et al., 2020*). *Chu et al. (2021)* reported a decrease of PM_{10} by 53%, 50%, and 30% in Wuhan city, Hubei Province (Wuhan excluded), and China (Hubei excluded), respectively, while SO_2 and CO concentrations were found to be marginally reduced. *Sahoo et al. (2020)* have also reported the reduction of $PM_{2.5}$ and PM_{10} levels (up to -52 and -53.5%, respectively) during lockdown 1.0 as compared to pre-lockdown; but their level rose during the last phase of lockdown and unlock-down phases, possibly due to increased traffic return on the roads. In addition, *Kumari & Toshniwal (2020)* reported the concentration of PM_{10}, $PM_{2.5}$, NO_2 and SO_2 reduced by 55%, 49%, 60% and 19%, and 44%, 37%, 78% and 39% for Delhi and Mumbai, respectively, during post-lockdown phase. Several recent studies and their findings on air pollutants have been reported worldwide during the lockdown period (*Sarkis et al., 2020*; *Zowalaty, Young & Järhult, 2020*) (Table S1).

However, in the later stages of the lockdown, traffic increased when relaxation was provided for various activities, increasing the air pollution levels. Air pollution is associated with higher mortality of COVID-19 patients, with varying effects on severe acute respiratory

and cardiovascular diseases (*Domingo & Rovira, 2020*). Further, older people are among the most sensitive groups (*Lee, Son & Cho, 2007*; *Kotaki et al., 2019*). It is believed that PM forms condensation nuclei for viral attachment (*Lee et al., 2014*). A significant positive correlation was found between COVID-19 incidence and AQI ($PM_{2.5}$ and NO_2) in Wuhan and Xiao Gan. *Abdullah et al. (2020)* reported that $PM_{2.5}$ concentrations dominated the Air Pollutant Index (API) in Malaysia, and reductions in $PM_{2.5}$ concentrations during Malaysia Movement Control Order (MCO) were observed.

To prevent the spread of novel coronavirus (SARS-CoV2), a large number of human populations were confined to their homes during the lockdown period. This has been known as the 'Global Human Confinement Experiment', where humans' positive and adverse impacts on natural ecosystems have been evaluated (*Bate et al., 2020*). They were of the opinion that the confinement experiment could lead to a reduction in CO_2 emissions, pollution, and conservation of biological diversity. However, there are bound to be certain limitations and gaps in data series due to a lack of field monitoring.

Several studies reported in Indian cities that a significant relationship between air pollutants and health risk assessment in urban areas (*Kumar et al., 2014*; *Kumar et al., 2014a*; *Singh et al., 2014*; *Singh et al., 2016*; *Singh, Kumar & Jain, 2021a*; *Singh, Kumar & Jain, 2021b*). A study conducted in Delhi reported that anthropogenic VOC contribution varied between 60–70% in traffic intersection sites (*Kashyap et al., 2019*). A similar study claimed that workplace cancer risks were reported highest at traffic intersections, followed by industrial sites (*Kumar et al., 2020*; *Singh et al., 2022b*). Although various studies have been reported for early phases of lockdown in countries such as China, Italy, USA (*Dutheil, Baker & Navel, 2020*; *Tobías et al., 2020*; *Xu et al., 2020*); and a few studies on metropolitan cities of India such as Delhi and Mumbai (*Jain & Sharma, 2020*; *Mahato, Pal & Ghosh, 2020*; *Sharma et al., 2020*; *Sahoo et al., 2020*; *Singh et al., 2021c*); however, a detailed analysis involving various phases of lockdown and unlockdown is essential. Apart from this, understating the relationship between the gaseous pollutant's concentration and the non-cancer risks of short exposure to these pollutants in different age groups has become a significant research area. Hence, the objective of the present study is to evaluate the levels of gaseous pollutants in different stages of lockdown and unlockdown, thus, studying the air quality status of Delhi during these phases and estimating the air quality index (AQI). Further, during these phases, the health risk exposure (chronic, acute, and hazard quotient) is estimated for different age groups in Delhi.

MATERIALS AND METHODS

Data and sources

In the present study, secondary data on gaseous pollutants such as nitrogen dioxide (NO_2), Nitrogen oxide (NO), oxide of Nitrogen (NOx), sulfur dioxide (SO_2), ammonia (NH_3), and ozone (O_3) were collected from the Central Pollution Control Board (CPCB) on a daily basis. To determine the relative changes (%) in gaseous pollutants for pre-, lockdown, and unlockdown stages, data from January 1, 2020, to September 30, 2020, was collected from CPCB (https://app.cpcbccr.com/ccr#/caaqm-dashboard-all/caaqm-landing) as previously described in *Singh et al. (2022)*; *Singh et al. (2022a)*; *Singh et al. (2022b)*.

In the present study, the hourly and daily data pertaining to the concentration of gaseous pollutants were obtained from the Central Pollution Control Board (CPCB). While procuring continuous data on these gaseous pollutants, a few of the hourly and daily data were found missing. As a result, mean substitution was used, where average values were used to replace those missing values. Further, the daily average of measurements was calculated at every station. The technical specifications of the measurements and instruments used can be found on the CPCB website (https://cpcb.nic.in/archivereport.php). The CPCB database establishes a meticulous approach for sampling, analysis, and calibration; thus, furnishing data quality assurance (QA) or quality control (QC) programs (*Gurjar, Ravindra & Nagpure, 2016*; *Singh, Kumar & Jain, 2021b*).

AQI India provided air pollution data with real-time AQI for various air pollutants. The National Air quality standard (NAAQS) revised its criteria according to eight parameters, namely, PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, O_3, NH_3, and Pb, for the short-term (up to 24 h on average) periods (CPCB, 2016). The AQI was used to retrieve information on air quality in terms of pollution levels because it is directly associated with public health safety. A total of six AQI categories, namely, Good, Satisfactory, Moderate, Poor, Very Poor, and Severe, have been defined as associated with health risks.

Measures

The pandemic situation was classified into three periods: before lockdown, during the lockdown, and after unlockdown. The time before lockdown (between January 1, 2020, and March 24, 2020) was termed the 'pre-lockdown' period, whereas the time between March 25 and May 31, 2020, was termed the 'during lockdown period.' As a result, lockdown was extended four times until May 30, 2020, with the first, second, third, and fourth phases ending on April 14, 2020 (lockdown I), 3rd May 2020 (lockdown II), 17th May 2020 (lockdown III), May 30 (lockdown IV), respectively. After this, the government started relaxing the lockdown and started opening up avenues in a restricted manner during various phases of unlockdown starting from 1st to June 30, 2020 (unlockdown I), for the period of 1st to July 31, 2020 (unlockdown II), 1st to August 31, 2020 (unlockdown III), and 1st to September 30, 2020 (unlockdown IV). The continuous reduction in the levels of gaseous pollutants except ozone was observed in subsequent months during the complete lockdown caused by the complete closure of markets and industrial activities.

All 21 air quality monitoring stations in Delhi were selected in this study and classified into different districts (https://ceodelhi.gov.in/OnlineErms/Reports/PS_LocationListOn15thOctDistrictwise.aspx; Table S2). These include Ashok Vihar, Jawaharlal Nehru Stadium (JLN Stadium), Arya Nagar, Karni Singh, Delhi Technical University (DTU), Income Tax Office (ITO), Jahangirpuri, Lodhi Road, Najafgarh, Narela, North Campus University, Ramakrishna Puram (RK Puram), Rohini, Vivek Vihar, Siri Fort, Okhla, Patparganj, Bawana, Sri Aurobindo Marg, Alipur and Wazirpur.

Human health risk assessment

Human Health Risk Assessment (HHRA) is a process by which the potential impact of the toxin on humans due to exposure is characterized. *Morakinyo, Mukhola & Mokgobu*

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(2020) assessed the possible health risks from exposure to gases such as SO_2, NO_2, CO, and O_3 using the US Environmental Protection Agency's (EPA) human health risk assessment framework. The HHRA is a tool used by regulatory agencies to assist in the formulation of policies that protect public health against the harmful effects of air pollution (*Organisation for Economic Cooperation and Development , 2008*).

Hazard identification

Hazard identification is a procedure to identify the pollutant in an ambient environment that is likely to induce harmful effects on human health (*Saliba et al., 2016*). The identification of gaseous pollutants such as SO_2, NO_2, CO, and O_3 that pose a risk to human health was performed through a review of existing literature (*United States Environmental Protection Agency, 2009*; *Gilbert et al., 2019*; *Kim, Kang & Kim, 2018*; *Odekanle et al., 2020*).

Exposure assessment

The exposure assessment calculates the population exposed to the pollutant, the magnitude, and the duration of exposure. In the present study, the inhalation route is the major route of exposure to the identified pollutants. We estimated the daily and annual readings for normal and acute exposure periods for different age groups, namely infants (birth to a year), toddlers (2–5 years), children (6–12 years), and adults (19–75 years). The classification of age groups has been carried out according to Morakinyo et al. (2017, 2020).

For exposure to non-carcinogenic pollutants (SO_2, NO_2, and O_3), the acute exposure rate equation is mentioned as:

$$AHD = C \times IR/BW \tag{1}$$

where AHD is the average hourly dose for inhalation ($\mu g/kg/hour$), C is the concentration of the pollutant ($\mu g/m^3$), IR is the inhalation rate (m^3/h), and BW is the body weight (kg) (*World Health Organization, 1999*). For exposure to non-carcinogenic pollutants (NO_2, SO_2, O_3), the chronic exposure equation used for the inhalation exposure route is:

$$ADD = (C \times IR \times ED)/(BW \times AT) \tag{2}$$

where, ADD is the average daily dose of the pollutant ($\mu g/kg/day$), ED is the exposure duration (days), and AT is the averaging time (days) (USEPA, 1997).

$$ED \text{ (exposure duration)} = ET \times EF \times DE \tag{3}$$

where, ET is the exposure time (hour/day), EF is the exposure frequency (days/year), and DE is the duration of exposure (year). The recommended values in equations of the daily exposure dose of NO_2, SO_2, and O_3 are presented in Table 1.

Risk characterization

Risk characterization is an estimation of risk to human health due to exposure to a pollutant. In this study, the health risk estimate of possible non-carcinogenic exposure to the pollutant was determined using the hazard quotient (HQ) method (*Muller et al., 2003*; *Saliba et al., 2016*).

Table 1 The recommended values in equations of the daily exposure dose of NO_2, SO_2, O_3.

Parameter	Definition	Values for age categories				Reference
		Infant (0–1 yr.)	Toddler (2–5 yrs.)	Child (6–12 yrs.)	Adult (19–75 yrs.)	
EF	Exposure frequency (days/year)	350	350	350	350	*Morakinyo et al. (2017)*
ED	Exposure frequency (days/year)	1	6	12	30	*USEPA (1992)*
AT	Averaging time (days); AT = ED X 365 days	365	2190	4380	10950	*Matooane & Diab (2003)*
BW	Body weight (kg)	11.3	22.6	45.3	71.8	*Morakinyo et al. (2017)*
InhR	Inhalation rate (m3/day)	9.2	16.74	21.02	21.4	*Morakinyo et al. (2017)*

The risk to health due to exposure to CO, NO_2, SO_2, and O_3 through the inhalation route was estimated using Eqs. (4) and (5)

$$\text{ADD } inh = \frac{C \times \text{InhR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \tag{4}$$

$$\text{HQ} = \frac{\text{ADD}}{\text{REF}}$$

or

$$\text{HQ} = x = \frac{\text{AHD}}{\text{REF}} \text{ (acute exposure)} \tag{5}$$

REF is the reference exposure level for an exposed pollutant that has significant adverse health effects that are likely to occur in exposed groups compared to the unexposed group. Therefore, the RELs for the different pollutants are prescribed by NAAQS. For NO2 and SO2, these are 188 μg/m^3 and 125 μg/m^3 for daily and 40 μg/m^3, 50 μg/m^3 for annual exposure besides 120 μg/m^3 O_3 of 8 h duration (*Morakinyo, Mukhola & Mokgobu, 2020*).

Statistical analysis and procedure

The present study evaluated the variability in air quality parameter concentrations and associated health assessment for 21 monitoring stations in Delhi for pre-lockdown, during the lockdown, and unlockdown periods. The time series plotting technique for particulate and gaseous pollutants was used to determine variable changes during the pre-lockdown, during lockdown, and unlockdown periods. In the present study, SPSS version 26.0 with the significant level "$p < .05$" was employed to carry out the statistical analyses. Further, the correlation was computed to Pearson correlation analysis was performed to find out closely associated variables. ArcGIS 10.4.1 was used to identify the changes in variables and generate an AQI map during the lockdown period as compared to the pre-lockdown and post-lockdown periods.

RESULTS AND DISCUSSION

Concentration of gaseous pollutants in the Pre-lockdown, during the lockdown, and unlockdown periods

In the present study, emphasis was laid on determining changes in the concentrations of gaseous air pollutants comprising NO, NO_2, NOx, O_3, NH_3, and SO_2, in Delhi during the
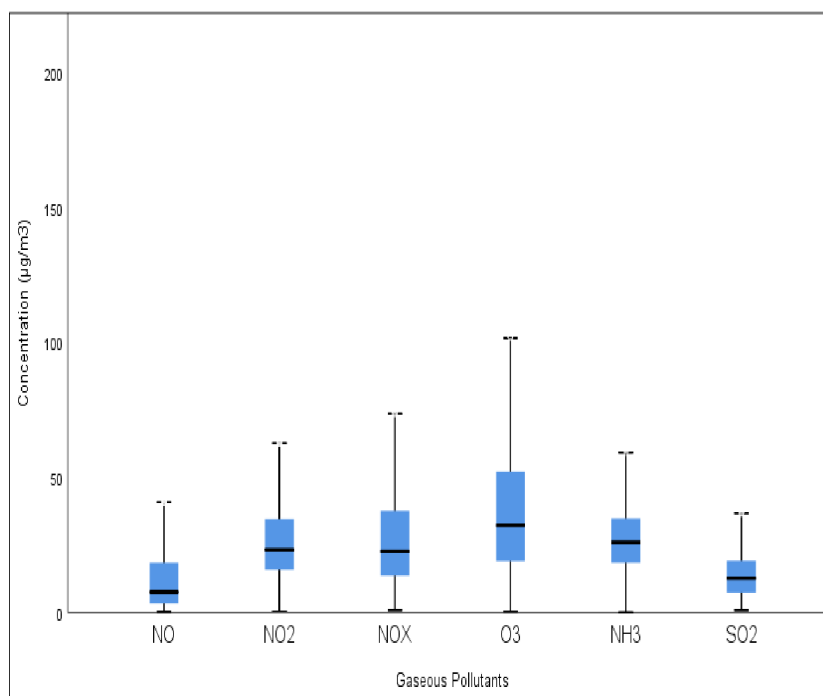
Figure 1 Box plot for all pollutants at Delhi during a pandemic situation.

Full-size 🖼 DOI: 10.7717/peerj.14489/fig-1

pandemic. It was observed that there was a decrease in the concentration of all gaseous pollutants except O_3 from January 2020 to September 2020. Further, in subsequent months, a continuous decline in the concentration of these gaseous pollutants was observed as a result of the complete lockdown. It is believed that as more and more people were forced to spend time in their homes, the COVID-19 pandemic changed the dynamics of anthropogenic emissions from various activities (*Gautam et al., 2020*). The average concentrations across all stations were found to be 16.99, 27.68, 31.25, 38.55, 27.98, and 17.10 $\mu g/m^3$ for NO, NO_2, NOx, O_3, NH_3, and SO_2, during the pandemic period, respectively (Fig. 1). The average values for gaseous pollutants was found to be 38.09, 21.07, 22.41, 24.33, 27.07, 24.15, 23.46, 24.22, and 29.49 $\mu g/m^3$ for NO_2, 48.77, 15.53, 23.52, 23.02, 23.97, 20.88, 19.32, 23.73, and 32.70 $\mu g/m^3$ for NOx, 31.93, 48.64, 55.55, 65.41, 54.50, 41.29, 34.53, 26.49, and 33.54 $\mu g/m^3$ for O_3, 32.66, 23.42, 30.22, 26.48, 24.56, 27.82, 26.85, 23.53, and 24.71 $\mu g/m^3$ whereas for NH_3 15.99, 21.12, 21.61, 2.87, 24.93, 17.93, 17.93, 14.27, 13.09, and 14.33 $\mu g/m^3$ during the pre-lockdown, lockdown I, lockdown II, lockdown IV, unlockdown I, unlockdown II, unlockdown III, and unlockdown IV, respectively.

During the pandemic situation, the time-series graph for NO, NO2, NOx, O3, NH3, and SO2 has been presented in Fig. 2 for pre-lockdown, lockdown I, lockdown II, lockdown III, lockdown IV, unlockdown I, unlockdown II, unlockdown III, and unlockdown IV. During the lockdown period, the decline in nitrogen oxide (NOx = NO + NO2) witnessed a sharp reduction in emissions from both public and private transport (*Kroll et al., 2020*). The values of NO_2, NOx, and NH_3 were reduced by 38%, 56%, and 20%, whereas the value
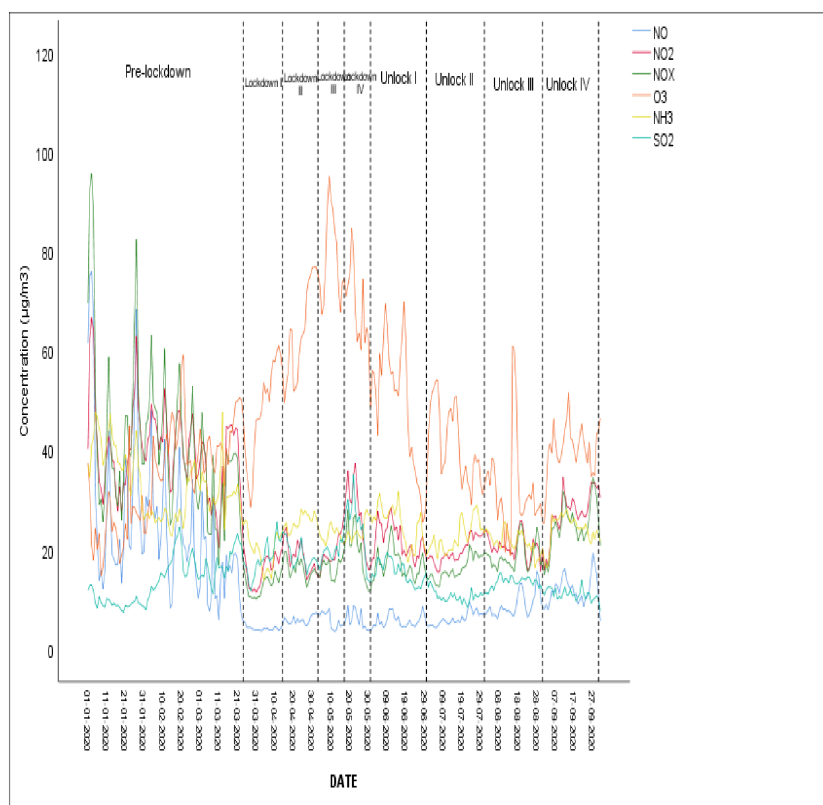
of O_3 was increased by 75% during the lockdown period as compared to the pre-lockdown period. 20% reported similar results in China for 30–50 days (*Li et al., 2020a*; *Li et al., 2020b*; *Zinke, 2020*). The maximum values for NO, NO2, NOx, O3, NH_3, and SO_2 were found at Lodhi Road, North Campus University, Siri Fort, and Najafgarh sites during the pandemic situation. The ozone level during the lockdown period was observed to increase in concentration. Nitrogen oxides (NO, NO_2) and VOCs in the presence of sunlight in the atmosphere are responsible for ozone formation (*Zheng et al., 2021*). The ozone concentration was observed to be higher as compared to other pollutants during the lockdown period because of the absence of NO formation from transport emissions which could not dissociate into O_2 and O. The high level of ozone is usual during the spring and summer sessions due to higher solar radiation, which promotes the photocatalysis of NO_2 (*Collivignarelli et al., 2020*). A slight increase in the concentration of SO_2 was observed during the lockdown period compared to the unlock-down period. This could be due to the restricted supply of power plants in northern India compared to using coal-powered plant energy—an essential commodity during the lockdown.

Zone-wise level of gaseous pollutants
New Delhi (ND)
The monitoring station of RK Puram is represented as the New Delhi zone. The average concentration of RK Puram station was 18.91, 34.79, 34.03, 31.09, and 22.61 $\mu g/m^3$ for NO, NO_2, NOx, O_3, and NH_3, respectively (Fig. 3A). The average concentrations for NO, NO_2, NOx, O_3, and NH_3 were calculated to be 42.62, 46.06, 59.08, 24.59, and 17.10 $\mu g/m^3$ for pre-lockdown whereas they were 3.58, 18.71, 12.85, 55.53 and 19.99 $\mu g/m^3$ for lockdown I, 3.56, 22.15, 14.64, and 28.16 $\mu g/m^3$ for lockdown II, 2.11, 20.92, 12.85, 58.05 and 31.28 $\mu g/m^3$ for lockdown III, whereas 4.78, 38.52, 24.39, 66.39, and 19.24 $\mu g/m^3$ for lockdown IV, respectively. The average concentrations for unlockdown I, unlockdown II, unlockdown III, and unlockdown IV were observed to be 4.42, 7.36, 10.86, 21.06 $\mu g/m^3$ for NO, 28.70, 32.89, 30.40, 38.99 $\mu g/m^3$ for NO2, 18.94, 23.43, 30.40, 38.99 $\mu g/m^3$ for NOx, whereas, 24.75, 35.18, 20.24, 21.60 $\mu g/m^3$ for NH3, respectively. The average values of ozone were found to be 19.35, 10.79, 28.25, and 31.38 $\mu g/m^3$, respectively. The level of gaseous pollutants witnessed a sharp decline during the first two of the four phases of lockdown corresponding to the last year, except for the ozone level. Further, the role of meteorological parameters, especially rainfall, has been considered a significant factor in reducing the concentration and washing out of various atmospheric pollutants (*Elperin et al., 2011*; *Guo et al., 2016*; *Bedi et al., 2020*)

South Delhi (SD)
Karni Singh Marg, Jawaharlal Nehru Stadium, Lodhi Road, and Sri Aurobindo Marg were four monitoring stations under the South Delhi zone. The average concentrations were found to be 20.59 $\mu g/m^3$ (NO), 27.47 $\mu g/m^3$ (NO2), 34.49 $\mu g/m^3$ (NOx), 46.79 $\mu g/m^3$ (O_3), 27.45 $\mu g/m^3$ ($NH3$), and 12.22 $\mu g/m^3$ (SO_2), respectively (Fig. 3B). The average concentrations for NO, NO_2, NOx, O_3, NH_3, and SO_2 were calculated to be 10.48, 28.27, 23.57, 62.46, 23.57, and 11.29 $\mu g/m^3$ for Karni Singh Marg, respectively. The average concentrations for NO, NO_2, NO_x, O_3, NH_3, and SO_2 were found to be 24.70, 37.74, 41.04, 28.33, and 18.01 $\mu g/m^3$ for Jawaharlal Nehru Stadium, respectively, whereas for Lodhi road, it was 41.25, 18.54, 56.93, and 30.53 $\mu g/m^3$ for NO, NO_2, NOx, and O_3 respectively. The average trend for all South Delhi zone monitoring stations was observed in Lodhi road > JLN Stadium > Karni Singh Marg > Sri Aurobindo Marg for NO, NO_2, and NO_x during the pandemic situation, respectively. In the case of ozone, the trend was shown as Karni Singh Marg > JLN Stadium > Lodhi road > Sri Aurobindo Marg during the lockdown period, respectively. The average ozone level trend was observed to increase with subsequent lockdowns: lockdown I > lockdown II > lockdown III > lockdown IV, respectively. In contrast with the absence of dissociation factors (NO and NO2) in the ambient atmosphere, ozone levels at all stations showed a slightly increasing trend during the lockdown period, similar to those during the pre-lockdown period (*Dhaka et al., 2020*). The ozone level was higher at Karni Singh Marg than at other stations in South Delhi, possibly due to more restrictions on transport activities on these premises.
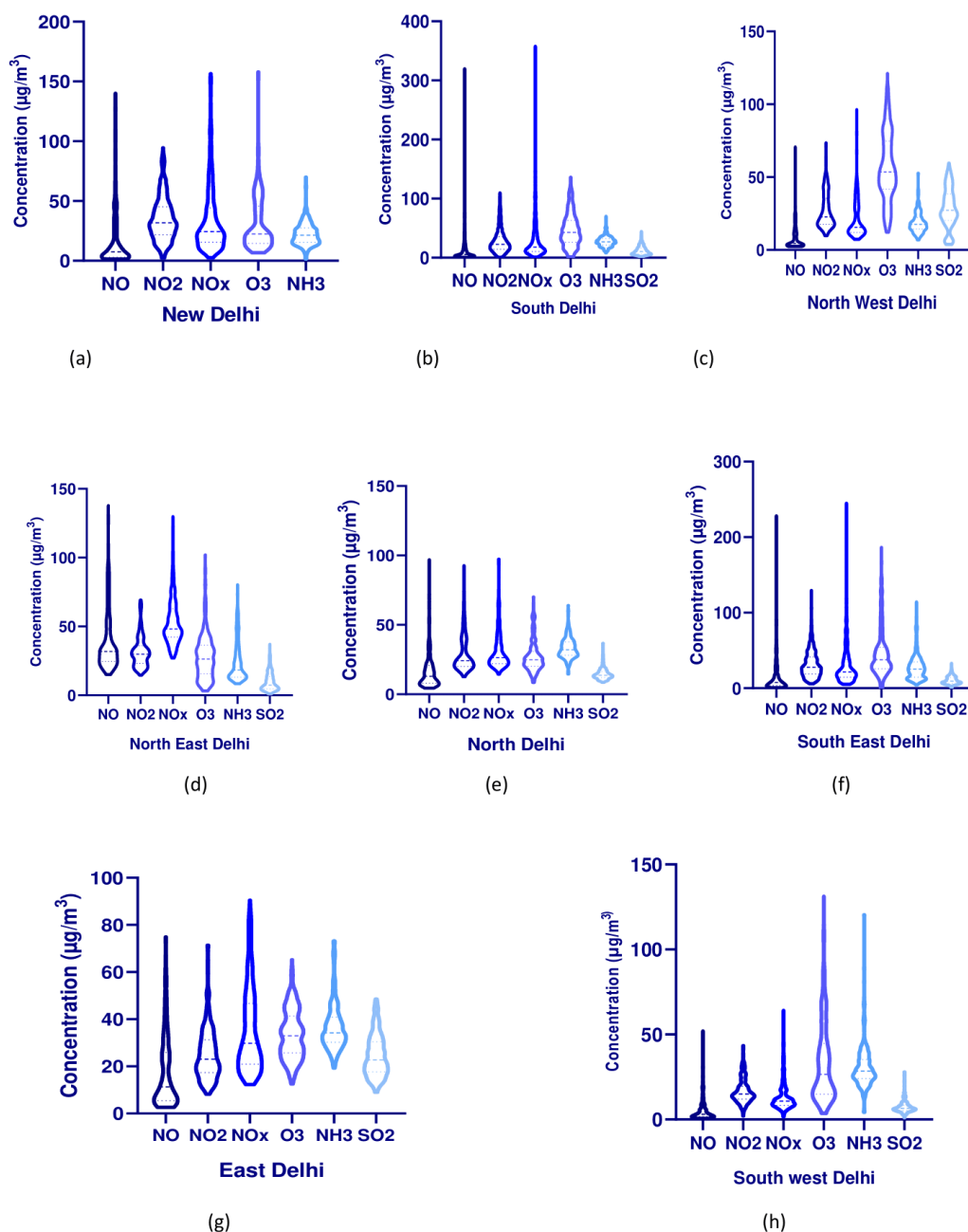
Figure 3 (A–H) Violin plots for all pollutants zone-wise in Delhi during a pandemic situation.
Full-size 🖼 DOI: 10.7717/peerj.14489/fig-3

Northwest Delhi (NWD)

The monitoring stations such as Rohini, Ashok Vihar, and DTU were considered under the North-west Delhi. The average values for Rohini, Ashok Vihar, and DTU were 9.11 μg/m³ (NO), 27.06 μg/m³ (NO₂), 21.60 μg/m³ (NOx), 56.86 μg/m³ (O₃), 18.98 μg/m³ (NH₃), and 28.69 μg/m³ (SO₂) respectively, a similar result was reported in Delhi (*Dutta & Jinsart, 2020*) (Fig. 3C). The average trend of gaseous pollutants was found to be Rohini

> DTU > Ashok Vihar, respectively. The average trend for gaseous pollutants at Rohini declined during the lockdown period and again increased continuously in the unlock-down period, except for O_3. The average concentration of O_3 was continuously increased with values 38.57, 80.75, 98.19, 110.88 $\mu g/m^3$ during the pre-lockdown period, lockdown I, lockdown II, lockdown III, and lockdown IV, respectively. The trend of mean values of gaseous pollutants for Rohini was found to be $O_3 > NO_2 > NH_3 > NO_x > SO_2 > NO$. A similar trend was observed for DTU and Ashok Vihar, respectively. North-west Delhi zone is considered as the industrial zone where the decrease in NO_2 concentration could be attributed to the substantial reduction in emissions, mainly from transport sectors and industrial processes.

Northeast Delhi (NWD)

The monitoring station of ITO has been represented under the Northeast Delhi zone. The average concentrations of gaseous pollutants were calculated to be 39.53, 31.38, 53.52, 28.12, 24.75, and 9.78 $\mu g/m^3$ for NO, NO_2, NO_x, O_3, NH_3, and SO_2, respectively (Fig. 3D). The average trend of gaseous pollutants for ITO observed a sharp decline in lockdown I > lockdown II > l lockdown III > lockdown IV during the lockdown period. In contrast, the unlockdown period showed an increasing trend in the order of unlockdown I > unlockdown II > unlockdown III > unlockdown IV, respectively, except O_3. Ozone levels during the lockdown period witnessed an increase as a result of lowering the concentration of NOx, which may result in ozone intensification levels in urban areas (*Mahato, Pal & Ghosh, 2020*). In addition, a natural increase in insolation and temperature from March to August in the northern hemisphere might lead to a rise in the value of ozone when the maximum ozone concentration is usually recorded (*Gorai, Tchounwou & Mitra, 2017*).

North Delhi zone (NoD)

The monitoring stations such as Alipur, Narela, Bawana, Wazirpur, and North Campus were considered under the North Delhi zone. The average concentrations for gaseous pollutants were calculated to be 15.51, 28.43, 29.44, 27.83, 30.91, and 14.53 $\mu g/m^3$ for NO, NO_2, NO_x, O_3, NH_3, and SO_2, for the North Delhi zone, respectively (Fig. 3E). The average values for NO, NO_2, NO_x, O_3, and NH_3 for Alipur were observed to be 3.26, 23.44, 15.13, 52.65, and 20.51 $\mu g/m^3$ during the lockdown period, whereas 5.05, 14.09, 11.37, 17.34, 26.66 $\mu g/m^3$ during the unlockdown period. The level of pollutants slightly increased during the unlockdown phase, except for ozone; *Dutta & Jinsart (2020)* noticed a similar result in Delhi. The average values for NO, NO_2, NO_x, O_3, and NH_3 for Narela were observed to be 4.17, 31.13, 19.39, 70.73, 34.99, and 15.86 $\mu g/m^3$ during the lockdown period, whereas 8.35, 27.73, 21.55, 21.06, 17.06, and 5.86 $\mu g/m^3$ during the unlockdown period. The average concentrations for NO, NO_2, NO_x, O_3, NH_3, and SO_2 for Wazirpur were found to be 8.21, 33.32, 24.33, 32.31, 30.01, and 15.72 $\mu g/m^3$, whereas 21.52, 32.16, 22.85, 13.43, 35.67, 19.80 $\mu g/m^3$ during the unlockdown period, respectively. The average concentrations for NO, NO_2, NO_x, O_3, and SO_2 for Bawana were 1.04, 22.2, 12.7, 76, and 22.5 $\mu g/m^3$, whereas 2.69, 22.5, 14.2, 34.1, 7.87 $\mu g/m^3$ during the unlockdown period, respectively. The average concentrations for NO, NO_2, NO_x, and O_3, for North Campus University were reported as 10.69, 17.22, 27.91, and 18.81 $\mu g/m^3$ during the lockdown period and 17.88,

16.73, 33.13, and 32.82 $\mu g/m^3$ during the unlockdown period, respectively. The results for gaseous pollutants witnessed a sharp decline during the lockdown period, whereas it slightly increased during the unlockdown period. A similar study conducted in China reported a 6.76 and 24.67 percent reduction in SO_2 and NO_2 (*Dantas et al., 2020*).

Southeast Delhi (SED)

The monitoring stations of Okhla and Siri Fort have been represented under the South Delhi zone. The average concentrations for Vivek Vihar were observed as 11.02, 27.08, 33.93, 36.87, 28.09, 24.60 $\mu g/m^3$ whereas, for Siri Fort, it was 13.34, 31.16, 28.32, 65.30, 19.56, 8.23 $\mu g/m^3$ for NO, NO_2, NOx, O_3, NH_3, and SO_2 during the pandemic situation respectively (Fig. 3F). The decline in NO, NO_2, and NOx could be mainly attributed to restrictions imposed on transport (public and private vehicular movement) during the lockdown. The mean trend for NO, NO_2, NOx, O_3, NH_3, and SO_2 was found to be lockdown III > lockdown IV > lockdown I > lockdown II>during the lockdown period, whereas for the unlock-down period, it showed an increasing trend in the order of unlockdown IV > unlockdown II > unlockdown III > unlockdown I respectively except for O_3.

East Delhi (ED)

The monitoring stations of Arya Nagar, Vivek Vihar, Patparganj, and Anand Vihar have been represented in East Delhi. The average concentrations of East Delhi were found to be 13.24, 22.43, 30.19, 37.99, 37.99, 36.21, and 26.21 $\mu g/m^3$ for NO, NO_2, NOx, O_3, NH_3, andSO_2 during the pandemic period, respectively (Fig. 3G). The mean trend for NO, NO_2, NOx, O_3, NH_3, and SO_2 was found to be lockdown IV > lockdown III > lockdown II > lockdown I during the lockdown period, whereas, for the unlockdown period, it observed an increasing trend in the order of unlockdown IV > unlockdown II > unlockdown III > unlockdown I respectively. Anand Vihar has been considered one of the inter bus terminals of NCR, which found massive traffic congestion and slow movement. During the unlock-down period, the state government has announced relief measures for migrants, and arrangements for buses for migrants to return to their native place increased the level of pollution at Anand Vihar station (*Singh & Kumar, 2021*).

Southwest Delhi (SWD)

Two monitoring stations of Najafgarh and Sri Aurobindo Marg have been represented in Southwest Delhi. The average concentrations were found to be 2.40, 9.04, 12.47, 12.08, 33.57, 19.24 $\mu g/m^3$ for NO, NO_2, NOx, O_3, NH_3, and SO_2 during the pandemic period, respectively (Fig. 3H). The mean trend for NO, NO_2, NOx, O_3, NH_3, and SO_2 was found to be lockdown I > lockdown II > lockdown II > lockdown IV during the lockdown period, whereas for the unlockdown period, it observed an increasing trend in the order of unlockdown IV > unlockdown III > unlockdown II > unlockdown I respectively. The lowest concentrations for all gaseous pollutants were observed at Sri Aurobindo Marg due to more greenery and complete restriction of anthropogenic activities such as transportation, traveling, and industrial activities, which are the primary source of such pollutants (*Sharma et al., 2020*). Other studies conducted in different cities of India indicated that, on average, NO_x concentrations declined by 60%, further suggesting that the impact of lockdown

on air quality was not homogenous across the country due to fluctuating background contributions (*Kumari & Toshniwal, 2020*; *Gulia et al., 2021*).

Non-carcinogenic health risks of NO$_2$, SO$_2$, and O$_3$ via inhalation route

The present study calculated health risk assessment and hazard identification for non-carcinogenic risks from exposure to ADD of NO$_2$, O$_3$, and SO$_2$ via the inhalation route, where we estimated that the inhalation route is the prime pathway for exposure to any pollutants. The health quotient (HQ) was calculated for each pollutant across the exposed groups (infant, toddler, child, and adult) for pre-, during, and unlock-down periods in Delhi. The calculated HQ for daily and annual exposure for each pollutant across the exposed groups was less than 1 (HQ<1) for pre, during, and unlock-down periods. This indicates that the level of pollutants (NO$_2$. O$_3$, and SO$_2$) recorded for Delhi was unlikely to pose any adverse risk to public health (infants, toddlers, children, and adults). However, in infants (0–1 year), HQ for daily and annual groups was calculated higher than the rest of the exposed group (toddler, children, and adult) in all the periods (Table 2). Thus, for all pollutants, daily and annual exposure induces more significant non-carcinogenic effects during the pre-lockdown period than during the lockdown and unlockdown period. The order of HQ for all exposed pollutants was pre-lockdown > unlockdown > lockdown for both daily and annual exposure groups except O$_3$.

Furthermore, daily and annual chronic exposure to exposed pollutants has been calculated for different exposed groups for pre-lockdown, during the lockdown, and unlockdown periods. The calculated HQ for daily chronic exposure to each pollutant across the infant group was found to be less than 1 (HQ< 1), which varies from 0.04 to 0.08 (NO$_2$), 0.09 to 0.17 (O$_3$), and 0.03 to 0.05 (SO$_2$) respectively and which indicates unlikely induced adverse health outcomes. However, the calculated HQ for daily chronic exposure for each pollutant across the child and adult groups was found to be more than 1 (HQ> 1), which varies from 2.99 to 5.54 (NO$_2$), 6.51 to 12.24 (O$_3$), and 2.51 to 3.70 (SO$_2$) for child and 2.36 to 4.37 (NO$_2$), 5.13 to 9.66 (O$_3$), and 2.51 to 2.92 (SO$_2$) for adult respectively and indicated likely to induce adverse health outcomes (Table 3). The order of HQ for exposed pollutants was pre-lockdown > unlockdown > lockdown for both daily and annual exposure groups except O$_3$; a similar observation was also noticed in Delhi (*Dutta & Jinsart, 2020*) and Kolkata (*Bera et al., 2020*). A similar trend for annual chronic exposure was observed for all exposed groups for pre-lockdown, during the lockdown, and unlockdown periods (Fig. 4).

The present study shows that the health risk occurring from exposure to the concentration of gaseous pollutants that were below the prescribed limit by the regulatory agencies (*Katsouyanni et al., 1997*). Several studies reported that human exposure to a low concentration of NO$_2$ might be responsible for respiratory infections and acute and obstructive lung diseases (*Chen et al., 2012*; *Santus et al., 2012*). Many research scholars reported a significant relationship between exposure to a slight concentration of NO$_2$ and the occurrence of acute ischaemic stroke (*Vidale et al., 2010*; *Anderson et al., 2012*). Exposure to O$_3$ could induce various health risks such as coughing, breathlessness, chest

Table 2 Hazard quotients of NO_2, O_3, and SO_2 for daily and annual exposure groups.

	Pre-lockdown				Lockdown				Unlockdown			
	Infant (0–1 yrs)	Toddler (2–5 yrs)	Child (6–12 yrs)	Adult (19–75 yrs)	Infant (0–1 yrs)	Toddler (2–5 yrs)	Child (6–12 yrs)	Adult (19–75 yrs)	Infant (0–1 yrs)	Toddler (2–5 yrs)	Child (6–12 yrs)	Adult (19–75 yrs)
	Daily exposure group											
NO_2	0.16	0.15	0.09	0.06	0.09	0.08	0.05	0.03	0.10	0.09	0.05	0.03
O_3	0.19	0.17	0.11	0.07	0.36	0.33	0.20	0.13	0.22	0.20	0.12	0.08
SO_2	0.09	0.02	0.05	0.03	0.11	0.02	0.06	0.04	0.07	0.01	0.04	0.03
	Annual exposure group											
NO_2	0.76	0.69	0.43	0.27	0.41	0.37	0.23	0.15	0.45	0.41	0.26	0.16
O_3	0.19	0.17	0.11	0.07	0.36	0.33	0.20	0.13	0.22	0.20	0.12	0.08
SO_2	0.23	0.04	0.13	0.08	0.27	0.05	0.15	0.10	0.18	0.03	0.10	0.07

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Table 3 Hazard quotients of NO_2, O_3, and SO_2 for daily and annual chronic exposure groups.

	Pre-Lockdown			Lockdown			Unlockdown		
	Infant (0–1 yr)	Child (6–12 yrs.)	Adult (19–75 yrs.)	Infant (0–1 yr.)	Child (6–12 yrs.)	Adult (19–75 yrs.)	Infant (0–1 yr)	Child (6–12 yrs.)	Adult (19–75 yrs.)
				Daily Chronic Exposure					
NO_2	0.08	5.54	4.37	0.04	2.99	2.36	0.05	3.29	2.60
O_3	0.09	6.51	5.13	0.17	12.24	9.66	0.10	7.49	5.90
SO_2	0.04	3.15	2.49	0.05	3.70	2.92	0.03	2.51	1.98
				Annual Chronic Exposure					
NO_2	0.36	26.05	20.55	0.20	14.08	11.10	0.22	15.47	12.20
O_3	0.09	6.51	5.13	0.17	12.24	9.66	0.10	7.49	5.90
SO_2	0.11	7.88	6.21	0.13	9.26	7.30	0.09	6.27	4.95
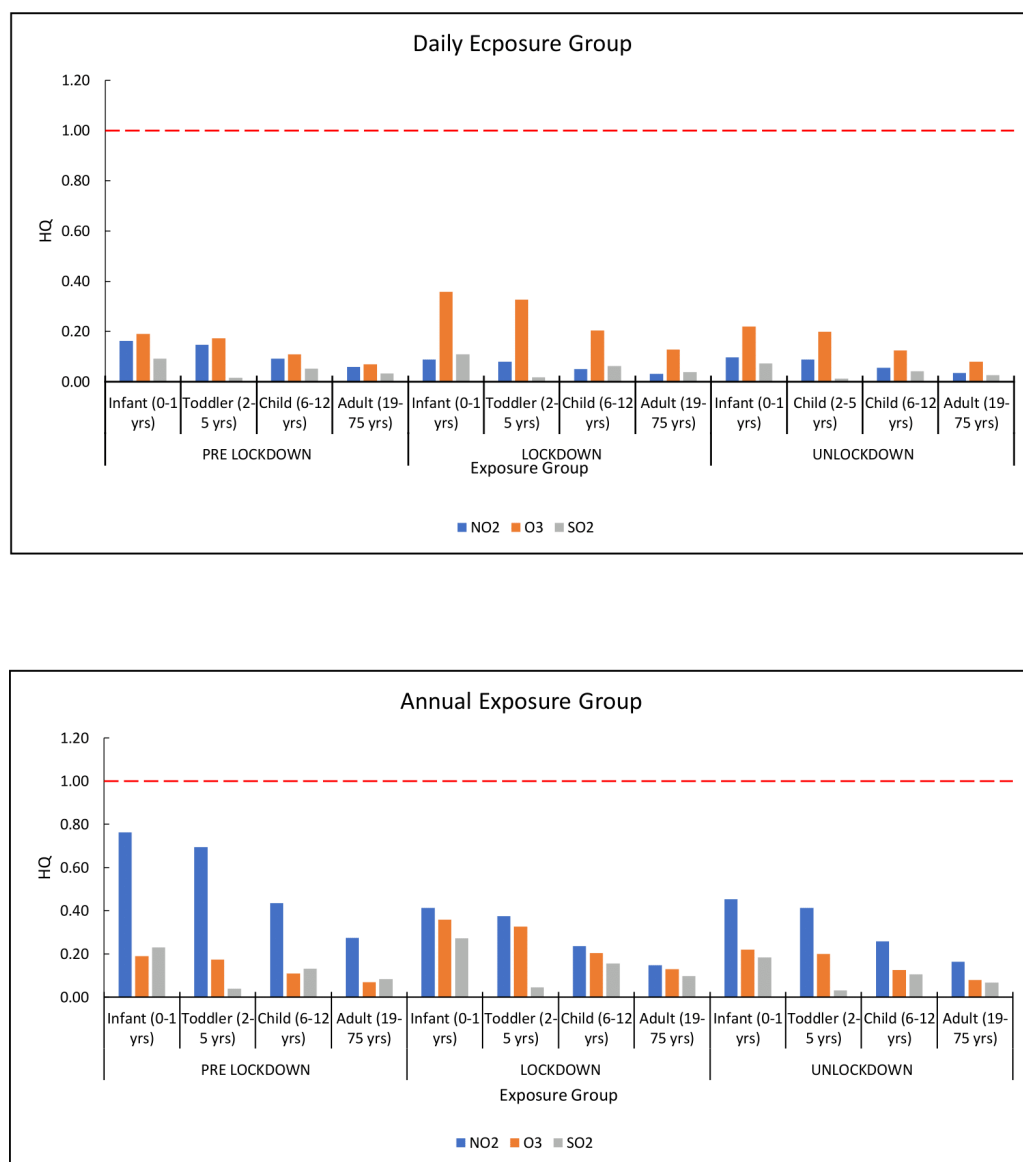
Figure 4 Carcinogenic risks of NO$_2$, SO$_2$, and O$_3$ for daily and annual exposure group.
Full-size ☑ DOI: 10.7717/peerj.14489/fig-4

pain, and impaired lung tissues (*Kim, Jahan & Kabir, 2013*). The health quotient for different pollutants has been presented for all other zones of Delhi in the (Table S3).

Air quality index (AQI)

An Air Quality Index (AQI) provides information about air pollutants, thus, indicating the air quality of a place. As a result, AQI is directly associated with the public health of society since AQI is directly proportional to the public health risk. India's ambient air quality standard is prescribed by National Ambient Air Quality Standards (NAAQS) and computed on the basis of concentration levels of eight pollutants for every 24 h. The air pollution levels have been classified into six AQI groups, namely, "Good," "Satisfactory,"

"Moderate," "Poor," "Very Poor," and "Severe. Several studies reported a significant reduction in air pollutants across 91 Indian cities during the month of March 2020, which were leading to in 'satisfactory' to 'good' category (*Dumka et al., 2020*, *Jain & Sharma, 2020*; *Navinya, Patidar & Phuleria, 2020*; *Metya et al., 2020a*; *Metya et al., 2020b*; *Manisha & Kulshrestha, 2021*). This drastic improvement in AQI was observed across the Indian sub-continent; AQI was improved in Karachi, Islamabad, and Lahore (Khurshied, 2020; *Ali et al., 2020*), Kathmandu (*Pant et al., 2020*; *Shrestha & Shrestha, 2005*), and Bangladesh (*Pavel et al., 2020*; *Islam et al., 2021*).

The air quality level had improved significantly due to reduced air pollutant levels during the lockdown period. The range of air quality levels for all zones was calculated 210 (New Delhi) and 306 (North Delhi), respectively, during the pre-lockdown period, which can be categorized as "poor-to-very-poor." The air quality values for pre-lockdown were found to be "poor category for ED, ND, SD, and SWD to the "very poor" category for NoD, NED, NWD, and SED. The air quality levels for all zones were calculated as "satisfactory" (62–96), except for NED which displayed "moderate" category (163) during the lockdown period (Fig. 5). This result indicates a drastic improvement in air quality during the lockdown period. The values for air quality levels were increased by 71% (ED), 68% (ND), 69% (NoD), 46% (NED), 70% (NWD), 75% (SD), 76% (SED), and 67% (SWD).

Correlation

In the present study, an attempt was made to correlate the concentration of various gases with the monitoring stations of Delhi. Table S4 describes the correlation of NO with various sites in Delhi. It can be seen that NO at Alipur is strongly correlated with Bawana (0.79), DTU (0.67), JLN (0.81), Karni Singh (0.71), Patparganj (0.80), RK Puram (0.74), Rohini (0.71), while Ashok Vihar with DTU (0.62), Bawana with DTU (0.77), JLN with Karni Singh (0.81), Patparganj (0.86), RK Puram (0.81) and Rohini (0.81) reported a similar trend.

Correlation of NO_2 and NO_x at various sites in Delhi (Tables S5, S6) reveals a strong positive correlation between Bawana and JLN, Karni Singh, Najafgarh, Okhla, Patparganj, R K Puram, Rohini, and Siri Fort; Okhla-DTU; Okhla-JLN, JLN-Najafgarh, Rohini-Karni Singh, Najafgarh with Vivek Vihar and Wazirpur, Najafgarh with Okhla and Siri Fort; Okhla with Patparganj, R K Puram, Rohini, and Siri Fort; Wazirpur and Siri Fort, Wazirpur and Vivek Vihar; Rohini and Karni Singh. Similarly, a positive correlation has been observed for Ozone (Table S7) between Bawana and JLN, Karni Singh; DTU and JLN, Karni Singh; Karni Singh and Patparganj, Vivek Vihar; Najafgarh and Sri Aurobindo Marg; Patparganj and Vivek Vihar; Rohini and Vivek Vihar. Correlation analysis of ammonia (Table S8) reveals poor correlation at all sites except Bawana-Vivek Vihar and Wazirpur; and JLN-Vivek Vihar. However, if we analyze the correlation behavior among various gaseous pollutants (Table S9), NO and NO_2 showed a strong positive correlation with NO_x, indicating a common source of origin. However, these three gases revealed a slightly negative relationship with ozone gas. In contrast, lower NO_2 levels showed a significant negative correlation with new COVID-19 cases in Delhi by *Dutta & Jinsart (2020)*.
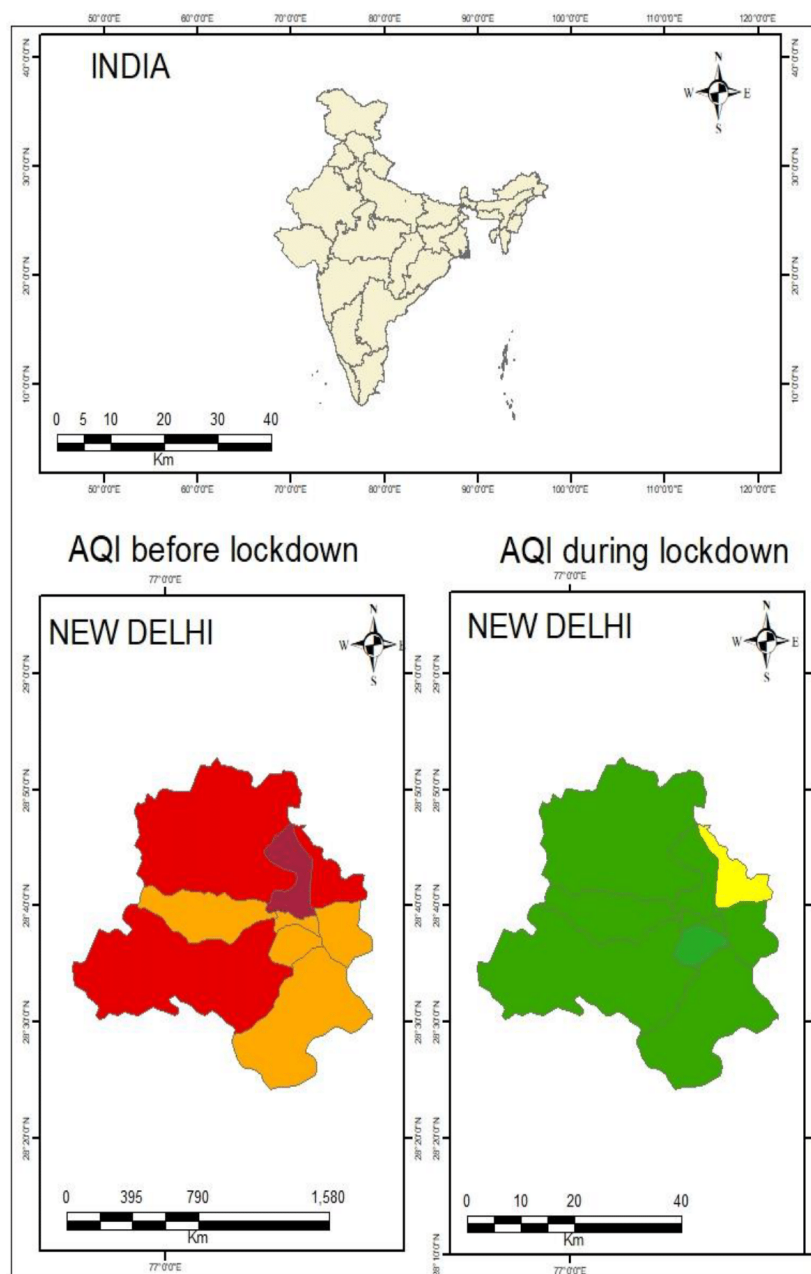
Figure 5   Air quality before and during the pandemic in Delhi.

Full-size 🖼 DOI: 10.7717/peerj.14489/fig-5

CONCLUSIONS

The results revealed a drastic improvement in air quality due to a partial lockdown measure of the National Capital of India. The main restrictions were applied from March 24 to May 30, 2020. The data for air pollutants for 21 monitoring stations was obtained from the Central Pollution Control Board (CPBC). The concentration of gaseous pollutants was significantly reduced except ozone by restricted measures in the use of private vehicles and

suspension of non-essential transportation, construction, and industrial activities during the pandemic situation. The ozone concentration was observed to be higher as compared to other pollutants during the lockdown period because of the absence of NO formation from transport emissions which could not dissociate into O_2 and O. The average concentrations across all stations were found to be 16.99, 27.68, 31.25, 38.55, 27.98, and 17.10 $\mu g/m^3$ for NO, NO_2, NOx, O_3, NH_3, and SO_2, respectively. The trend of gaseous pollutants zone-wise in Delhi was observed in order as NED > SWD > SD > SED > ED > ND > NoD for lockdown I and II and III whereas SED > NED > ED > SD > NoD > ND > SWD for unlockdown I and II. A dissimilar trend was observed in order as NED > ED > ND > SED > NoD > SD > SWD for unlockdown III and IV during the pandemic situation. The air quality values for pre-lockdown were found to be the "poor category for ED, NoD, SD, and SWD to "very poor" category for NoD, NED, NWD, and SED.

The health quotient (HQ) was calculated for each pollutant across the exposed groups (infant, toddler, children, and adults) for pre-lockdown, during the lockdown, and unlockdown periods in Delhi. The calculated HQ for daily and annual exposure for each pollutant across the exposed groups was less than 1 (HQ < 1) for pre-lockdown, during the lockdown, and unlockdown periods. The order of HQ for all exposed pollutants was: pre-lockdown > unlockdown > lockdown for both daily and annual exposure groups except O_3. The calculated HQ for daily chronic exposure for each pollutant across the infant groups was less than 1 (HQ < 1), indicating unlikely induced adverse health outcomes. However, the calculated HQ for daily chronic exposure for each pollutant across the child and adult groups was found to be more than 1 (HQ > 1), which indicated the likeliness to induce adverse health outcomes. The order of HQ for exposed pollutants was pre-lockdown > unlockdown > lockdown for both daily and annual exposure groups except O_3. A similar trend for annual chronic exposure was observed for all exposed groups during pre-lockdown and unlockdown periods.

The air quality levels for all zones were calculated as "Satisfactory," except for Northeast Delhi, which displayed a "moderate" category during the lockdown period. The maximum improvement in air quality was observed in Southeast Delhi (76%), and the lowest was in Northeast Delhi (46%). A correlation behavior was performed among various gaseous pollutants: NO, and NO_2 showed a strong positive correlation with NO_x, indicating a common source of origin. However, these three gases revealed a slightly negative relationship with ozone gas. On the other hand, NO_2 and NO_x indicated a strong positive relationship with CO. The present study would serve as baseline data for future studies and also the impact of anthropogenic activities on the air quality of a region.

Limitations

- Further, increasing the scientific rigor of research in this area, some of the current manuscript's limitations require access to meteorological parameters, including rainfall, relative humidity, solar radiation, and wind speed.
- Furthermore, future studies can examine large sample sizes with different factors to draw exciting results.
- Health assessment studies for a longer time window can be calculated in future studies.

Strength

- The strength of the current manuscript was witnessed to determine changes in gaseous pollutants for pre-lockdown, during the lockdown, and unlockdown periods.
- This is the first study in Delhi, India, to estimate the health risk of human exposure to gaseous pollutants using the US Environmental Protection Agency assessment model.
- These substantial changes have been linked with human health assessment in different age groups.

In the present study, the prediction of long-term and short-term health effects in infants, children, and adults resulting from the inhalation of pollutants was possible.

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Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Bhupendra Singh conceived and designed the experiments, analyzed the data, prepared figures and/or tables, and approved the final draft.
- Puneeta Pandey conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Saikh Mohammad Wabaidur performed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Ram Avtar performed the experiments, prepared figures and/or tables, and approved the final draft.
- Pramod Kumar conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.

- Shakilur Rahman analyzed the data, authored or reviewed drafts of the article, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The raw data, such as gaseous pollutants (NO, NO2, NOx, SO2, and O3) for all the selected monitoring stations of Delhi for 24 h, is available in the Supplementary Files. They are available from the CPCB:

https://app.cpcbccr.com/ccr#/caaqm-dashboard-all/caaqm-landing/data.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.14489#supplemental-information.

REFERENCES

Abdullah S, Mansor AA, Ahmed AN, Napi NNLM, Mansor WNW, Ismail M, Ramly ZTA. 2020. Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic. *Science of The Total Environment* **729**:139022 DOI 10.1016/j.scitotenv.2020.139022.

Ali SM, Malik F, Anjum MS, Siddiqui GF, Anwar MN, Lam SS, Nizami AS, Khokhar MF. 2020. Exploring the linkage between PM2.5 levels and COVID-19 spread and its implications for socio-economic circles. *Environment International* **193**:110421 DOI 10.1016/j.envres.2020.110421.

Anderson ZJ, Kristiansen LC, Anderson KK, Olsen TS, Hvidberg M, Jensen SS, Ketzel M, Loft S, Sorensen M, Tjonneland A. 2012. Stroke and long-term exposure to outdoor air pollution from nitrogen dioxide: a cohort study. *Stroke* **43**:320–325 DOI 10.1161/STROKEAHA.111.629246.

Bate AE, Primack RB, Moraga P, Duarte CM. 2020. COVID-19 pandemic and associated lockdown as a global human confinement experiment to investigate biodiversity conservation. *Biological Conservation* **248**:108665 DOI 10.1016/j.biocon.2020.108665.

Bedi JS, Dhaka P, Vijay D, Aulakh RS, Paul J, Gill S. 2020. Assessment of air quality changes in the four metropolitan cities of India during COVID-19 pandemic lockdown. *Aerosol and Air Quality Research* **0209(Vi)**:2062–2070 DOI 10.4209/aaqr.2020.05.0209.

Bera B, Bhattacharjee S, Shit PK, Sengupta N, Saha S. 2020. Significant impacts of COVID-19 lockdown on urban air pollution in Kolkata (India) and amelioration of environmental health. *Environment, Development and Sustainability* **23**:6913–6940 DOI 10.1007/s10668-020-00898-5.

Chen R, Samoli E, Wong CM, Huang W, Wang Z, Chen B, Kan H. 2012. Associations between short-term exposure to nitrogen dioxide and mortality in 17 Chinese cities: the China Air Pollution and Health Effects Study (CAPES). *Environment International* **45**:32–38 DOI 10.1016/j.envint.2012.04.008.

Chu B, Zhang S, Liu J, Ma Q, He H. 2021. Significant concurrent decrease in $PM_{2.5}$ and NO_2 concentrations in China during COVID-19 epidemic. *Journal of Environmental Sciences* **99**:346–353 DOI 10.1016/j.jes.2020.06.031.

Ciceri F, Ruggeri A, Lembo R, Puglisi R, Landoni G, Zangrillo A, On behalf of the COVID-BioB Study Group. 2020. Decreased inhospital mortality in patients with COVID-19 pneumonia. *Pathogens and Global Health* **114(6)**:281–282 DOI 10.1080/20477724.2020.1785782.

Collivignarelli MC, Abbà A, Bertanza G, Pedrazzani R, Ricciardi P, Miino MC. 2020. Environment Lockdown for CoViD-2019 in Milan. *Science of The Total Environment* **732**:1–9 DOI 10.1016/j.scitotenv.2020.139280.

Dantas G, Siciliano B, França BB, Da Silva CM, Arbilla G. 2020. The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro Brazil. *Science of the Total Environment* **729**:139085 DOI 10.1016/j.scitotenv.2020.139085.

Dhaka SK, Kumar V, Panwar V, Dimri AP, Singh N. 2020. OPEN $PM_{2.5}$diminution and haze events over Delhi during the COVID-19 lockdown period: an interplay between the baseline pollution and meteorology. *Scientific Reports* **10**:1–8 DOI 10.1038/s41598-020-70179-8.

Domingo JL, Rovira J. 2020. Effects of air pollutants on the transmission and severity of respiratory viral infections. *Environmental Research* **187**:109650 DOI 10.1016/j.envres.2020.109650.

Dumka UC, Kaskaoutis DG, Verma S, Ningombam SS, Kumar S, Ghosh S. 2020. Silver linings in the dark clouds of COVID-19: Improvement of air quality over India and Delhi metropolitan area from measurements and WRF-CHIMERE model simulations. *Atmospheric Pollution Research* **12**:225–242 DOI 10.1016/j.apr.2020.11.005.

Dutheil F, Baker SJ, Navel V. 2020. COVID-19 as a factor influencing air pollution? *Environmental Pollution* **263**:114466 DOI 10.1016/j.envpol.2020.114466.

Dutta A, Jinsart W. 2020. Air quality, atmospheric variables and spread of COVID-19 in Delhi (India): an snalysis. *Aerosol and Air Quality Research* **21**:3 DOI 10.4209/aaqr.2020.07.0417.

Elperin T, Fominykh A, Krasovitov B, Vikhansky A. 2011. Effect of rain scavenging on altitudinal distribution of soluble gaseous pollutants in the atmosphere. *Atmospheric Environment* **45**:2427–2433 DOI 10.1016/j.atmosenv.2011.02.008.

Faridi S, Niazi S, Sadeghi K, Naddafi KY, Shamsipour M, Momeniha F, Sadeghniiat K, Nabizadeh R, Yunesian M, Mokamel A, Hassanvand MS, Azad TM. 2020. A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran. *Science of The Total Environment* **725**:138401 DOI 10.1016/j.scitotenv.2020.138401.

Gautam AS, Dilwaliya NK, Srivastava A, Kumar S, Bauddh K, Siingh D, Shah MA, Singh K, Gautam S. 2020. Temporary reduction in air pollution due to anthropogenic activity switch-off during COVID-19 lockdown in northern parts of India. *Environment, Development and Sustainability* **23**:8774–8797 DOI 10.1007/s10668-020-00994-6.

Gilbert F, Serge N, John NL, Samuel L. 2019. Air quality and human health risk assessment in the residential areas at the proximity of the Nkolfoulou landfill in Yaound e Metropolis, Cameroon. *Journal of Chemistry* **9**:3021894.

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 and Air Quality Research* **17(4)**:951–964 DOI 10.4209/aaqr.2016.08.0374.

Gulia S, Goyal N, Mendiratta S, Biswas T, Goyal SK, Kumar R. 2021. COVID 19 lockdown - air quality reflections in indian cities. *Aerosol and Air Quality Research* **5**:200308 DOI 10.4209/aaqr.200308.

Guo LC, Zhang Y, Lin H, Zeng W, Liu T, Xiao J, Rutherford S, You J, Ma W. 2016. The washout effects of rainfall on atmospheric particulate pollution in two Chinese cities. *Environmental Pollution* **215**:195–202 DOI 10.1016/j.envpol.2016.05.003.

Gurjar BR, Ravindra K, Nagpure AS. 2016. Air pollution trends over Indian megacities and their local-to-global implications. *Atmospheric Environment* **142**:475 DOI 10.1016/j.atmosenv.2016.06.030.

Islam MS, Tusher TR, Roy S, Rahman M. 2021. Impacts of nationwide lockdown due to COVID-19 outbreak on air quality in Bangladesh: a spatiotemporal analysis. *Air Quality, Atmosphere and Health-* **14**:351–363 DOI 10.1007/s11869-020-00940-5.

Jain S, Sharma T. 2020. Social and Travel Lockdown Impact Considering Coronavirus Disease (Covid-19) on Air Quality in Megacities of India: Present Benefits, Future Challenges and Way Forward. *Aerosol and Air Quality Research* **20(6)**:1222–1236 DOI 10.4209/aaqr.2020.04.0171.

Kashyap P, Kumar A, Kumar RP, Kumar K. 2019. Biogenic and anthropogenic isoprene emissions in the subtropical urban atmosphere of Delhi. *Atmospheric Pollution Research* **10(5)**:1691–1698 DOI 10.1016/j.apr.2019.07.004.

Katsouyanni K, Touloumi G, Spix C, Schwartz J, Balducci F, Medina S, Rossi G, Wojtyniak B, Sunyer J, Bacharova L. 1997. Short-term effects of ambient sulphur dioxide and particulate matter on mortality in 12 European cities: results from time series data from the APHEA project. Air pollution and health: a European approach. *BMJ* **314**:1658–1663 DOI 10.1136/bmj.314.7095.1658.

Kim KH, Jahan SA, Kabir E. 2013. A review on human health perspective of air pollution with respect to allergies and asthma. *Environment International* **59**:41–52 DOI 10.1016/j.envint.2013.05.007.

Kim H, Kang K, Kim T. 2018. Measurement of particulate matter (PM2.5) and health risk assessment of cooking-generated particles in the kitchen and living rooms of apartment houses. *Sustainability* **10**:1–13 DOI 10.3390/su10030843.

Kotaki K, Ikeda H, Fukuda T, Yuhei K, Yuki F, Kawasaki M, Wakamatsu K, Sugahara K. 2019. Trends in the prevalence of COPD in elderly individuals in an air polluted city in Japan: a cross-sectional study. *International Journal of Chronic Obstructive Pulmonary Disease* **14**:791–798 DOI 10.2147/COPD.S189372.

Kroll JH, Heald CL, Cappa CD, Farmer DK, Fry JL, Murphy JG, Steiner AL. 2020. The complex chemical effects of COVID-19. *Nature Chemistry* **12(2)**:777–779 DOI 10.1038/s41557-020-0535-z.

Kumar A, Singh BP, Punia M, Singh D, Kumar K, Jain VK. 2014a. Determination of volatile organic compounds and associated health risk assessment in residential homes and hostels within an academic institute, New Delhi. *Indoor Air* **24(5)**:474–483 DOI 10.1111/ina.12096.

Kumar A, Singh BP, Punia M, Singh D, Kumar K, Jain VK. 2014. Assessment of indoor air concentrations of VOCs and their associated health risks in the library of Jawaharlal Nehru University, New Delhi. *Environmental Science and Pollution Research* **21(3)**:2240–2248 DOI 10.1007/s11356-013-2150-7.

Kumar RP, Kashyap P, Kumar R, Pandey AK, Kumar A, Kumar K. 2020. Cancer and non-cancer health risk assessment associated with exposure to non-methane hydrocarbons among roadside vendors in Delhi, India. *Human and Ecological Risk Assessment* **26(5)**:1285–1299 DOI 10.1080/10807039.2019.1570077.

Kumari P, Toshniwal D. 2020. Impact of lockdown measures during COVID-19 on air quality–a case study of India. *International Journal of Environmental Health Research* DOI 10.1080/09603123.2020.1778646.

Lee G, Saravia J, You D, Shrestha B, Jaligama S, Hebert V. 2014. Exposure to combustion generated environmentally persistent free radicals enhances severity of influenza virus infection. *Particle and Fibre Toxicology* **11**:57 DOI 10.1186/s12989-014-0057-1.

Lee JT, Son JY, Cho YS. 2007. The adverse effects of fine particle air pollution on respiratory function in the elderly. *Science of The Total Environment* **385**:28–36 DOI 10.1016/j.scitotenv.2007.07.005.

Li H, Xu X-L, Dai D-W, Huang Z-Y, Ma Z, Guan Y-J. 2020a. Air pollution and temperature are associated with increased COVID-19 incidence: a time series study. *International Journal of Infectious Diseases* **97**:278–282 DOI 10.1016/j.ijid.2020.05.076.

Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J, Liu Z, Li H, Shi L, Li R, Azari M, Wang Y, Zhang X, Liu Z, Zhu Y, Zhang K, Xue S, Chel M, Ooi G, Chan A. 2020b. Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. *Science of The Total Environment* **732**:139282 DOI 10.1016/j.scitotenv.2020.139282.

Mahato S, Pal S, Ghosh KG. 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. *Science of The Total Environment* **730**:139086 DOI 10.1016/j.scitotenv.2020.139086.

Manisha M, Kulshrestha UC. 2021. A brief review on changes in air pollution scenario over South Asia during COVID-19 lockdown. *Aerosol and Air Quality Research* **21**:200541 DOI 10.4209/aaqr.200541.

Matooane M, Diab R. 2003. Health risk assessment for sulfur dioxide pollution in South Durban, South Africa. *Archive of Environmental Health* **58**:763–770 DOI 10.3200/AEOH.58.12.763-770.

Metya A, Dagupta P, Halder S, Chakraborty S, Tiwari YK. 2020a. COVID-19 lockdowns improve air quality in the south-east Asian Regions, as seen by the remote sensing satellites. *Aerosol and Air Quality Research* **20**:1772–1782 DOI 10.4209/aaqr.2020.05.0240.

Metya A, Dagupta P, Halder S, Chakraborty S, Tiwari YK. 2020b. COVID-19 lockdowns improve air quality in the south-east Asian Regions, as seen by the remote sensing satellites. *Aerosol and Air Quality Research* **20**:1772–1782 DOI 10.4209/aaqr.2020.05.0240.

Morakinyo OM, Adebowale AS, Mokgobu MI, Mukhola MS. 2017. Health risk of inhalation exposure to sub-10 μm particulate matter and gaseous pollutants in an urban-industrial area in South Africa: An ecological study. *BMJ Open* **7**:e03941 DOI 10.1136/bmjopen-2016-013941.

Morakinyo OM, Mukhola MS, Mokgobu MI. 2020. Ambient gaseous pollutants in an urban area in South Africa: levels and potential human health risk. *Atmosphere* **11(7)**:751 DOI 10.3390/atmos11070751.

Muller E, Diab RD, Binedell M. 2003. Health risk assessment of Kerosene usage in an informal settlement in Durban, South Africa. *Atmospheric Environment* **37**:2015–2022 DOI 10.1016/S1352-2310(03)00125-0.

Navinya C, Patidar G, Phuleria HC. 2020. Examining effects of the COVID-19 national lockdown on ambient air quality across urban India. *Air Quality, Atmosphere & Health* **20**:1759–1771 DOI 10.4209/aaqr.2020.05.0256.

Odekanle EL, Sonibare OO, Odejobi OJ, Fakinle BS, Akeredolu FA. 2020. Air emissions and health risk assessment around abattoir facility. *Heliyon* **6(7)**:E04365 DOI 10.1016/j.heliyon.2020.e04365.

Organisation for Economic Cooperation and Development (OECD). 2008. *OECD environmental outlook to 2030.* Paris: OECD. *Available at* https://www.oecd.org/env/indicators-modelling-outlooks/40200582.pdf .

Pant BP, Mishra A, Shakya S, Poudyal KN. 2020. Impact of COVID-19 lockdown on Particulate Matter (PM2.5) concentration in Kathmandu, Nepal.

Patruno C, Nisticò SP, Napolitano M, Fabbrocini G. 2020. COVID-19, quarantine, and atopic dermatitis. Letter to Editors. *Medical Hypotheses* **143**:109852 DOI 10.1016/j.mehy.2020.109852.

Pavel RS, Salam A, Yesmin M, Ahsan N, Zaman SU, Jeba F. 2020. Impact and correlation of air quality and climate variables with COVID-19 morbidity and mortality in Dhaka, Bangladesh. *medRxiv.* DOI 10.1101/2020.09.12.20193086.

Sahoo PK, Mangla S, Pathak AK, Salomão G, Chudhury PD. 2020. Pre-to-post lockdown impact on air quality and the role of environmental factors in spreading the COVID-19 cases—a study from a worst-hit state of India. *International Journal of Biometeorology* **65**:1–48 DOI 10.1007/s00484-020-02019-3.

Saliba NA., Nassar J, Hussein F, El Kfoury DEL, Nicolas DJ, El Tal T, Baalbaki R. 2016. Airborne toxic pollutants: levels, health effects, and suggested policy implementation framework in developing countries. *Advances in Molecular Toxicology* **10**:187–233 DOI 10.1016/B978-0-12-804700-2.00005-2.

Santus P, Russo A, Madonini E, Allegra L, Blasi F, Centanni S, Miadonna A, Schiraldi G, Amaducci S. 2012. How air pollution influences clinical management of respiratory diseases. A case-crossover study in Milan. *Respiratory Research* **13**:95 DOI 10.1186/1465-9921-13-95.

Sarkis J, Cohen MJ, Dewick P, Schröder P. 2020. A brave new world: Lessons from the COVID- 19 pandemic for transitioning to sustainable supply and production. *Resources, Conservation and Recycling* **159**:104894 DOI 10.1016/j.resconrec.2020.104894.

Sharma S, Zhang M, Anshika GJ, Zhang H, Kota SH. 2020. Effect of restricted emissions during COVID-19 on air quality in India. *Science of The Total Environment* **728**:138878 DOI 10.1016/j.scitotenv.2020.138878.

Shrestha IL, Shrestha SL. 2005. Indoor air pollution from biomass fuels and respiratory health of the exposed population in Nepalese households. *International Journal of Occupational and Environmental Health* **11**:150–160 DOI 10.1179/oeh.2005.11.2.150.

Singh BP, Eldesoky GE, Chandra P, Kumar P, Islam MA, Rahman S. 2022a. A comparative study of particulate matter between New Delhi, India and Riyadh, Saudi Arabia during the COVID-19 lockdown period. *Frontiers in Environmental Science* **9**:784959 DOI 10.3389/fenvs.2021.784959.

Singh BP, Kumar A, Singh D, Punia M, Kumar K, Jain VK. 2014. An assessment of ozone levels, UV radiation and their occupational health hazard estimation during photocopying operation. *Journal of Hazardous Materials* **275**:55–62 DOI 10.1016/j.jhazmat.2014.04.049.

Singh BP, Kumar K, Jain VK. 2021a. Distribution of ring PAHs in particulate/gaseous phase in the urban city of Delhi, India: seasonal variation and cancer risk assessment. *Urban Climate* **40**:101010 DOI 10.1016/j.uclim.2021.101010.

Singh BP, Kumar K, Jain VK. 2021b. Source identification and health risk assessment associated with particulate- and gaseous-phase PAHs at residential sites in Delhi, India. *Air Quality, Atmosphere and Health* **14(10)**:1505–1521 DOI 10.1007/s11869-021-01035-5.

Singh BP, Kumar P. 2021. Spatio-temporal variation in fine particulate matter and effect on air quality during the COVID-19 in New Delhi, India. *Urban Climate* **40**:101013 DOI 10.1016/j.uclim.2021.101013.

Singh BP, Kumari S, Nair A, Kumari S, Wabaidur SM, Avtar R, Rahman S. 2022b. Temporary reduction in VOCs associated with health risk during and after COVID-19 in Maharashtra, India. *Journal of Atmospheric Chemistry* DOI 10.1007/s10874-022-09440-5.

Singh BP, Rana P, Mittal N, Kumar S, Athar M, Abduljaleel Z, Rahman S. 2022. Variations in the Yamuna River water quality during the COVID-19 lockdowns. *Frontiers in Environmental Science* **10**:940640 DOI 10.3389/fenvs.2022.940640.

Singh BP, Singh D, Kumar K, Jain VK. 2021c. Study of seasonal variation of PM2.5 concentration associated with meteorological parameters at residential sites in Delhi, India. *Journal of Atmospheric Chemistry* **78(3)**:161–176 Springer Science and Business Media B.V DOI 10.1007/s10874-021-09419-8.

Singh D, Kumar A, Kumar K, Singh B, Mina U, Singh BB, Jain VK. 2016. Statistical modeling of O3, NOx, CO, PM2.5, VOCs and noise levels in commercial complex and associated health risk assessment in an academic institution. *Science of the Total Environment* **572**:586–594 DOI 10.1016/j.scitotenv.2016.08.086.

Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón MC. 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Science of The Total Environment* **726**:138540 DOI 10.1016/j.scitotenv.2020.138540.

Vidale S, Bonanomi A, Guidotti M, Arnaboldi M, Sterzi R. 2010. Air pollution positively correlates with daily stroke admission and in hospital mortality: a study in the urban area of Como, Italy. *Neurological Sciences* **31**:179–182.

United States Environmental Protection Agency USEPA. 2009. *Risk assessment guidance for superfund Volume 1: human health evaluation manual (Part F, supplemental guidance for inhalation risk assessment).* Washington, D.C.: EPAEPA-540-R-070-002. US EPA, 2011. Air Quality.

United States Environmental Protection Agency (USUSEPA). 1992. Guidelines for exposure assessment. In: *Federal Register.* Washington, D.C., USA: Risk Assessment Forum, U.S. Environmental Protection Agency.

World Health Organization. 1999. Principles for the assessment of risks to human health from exposure to chemicals. In: *Environmental Health Criteria 210.* Geneva, Switzerland.

Worldometers. 2022. *Available at https://www.worldometers.info/coronavirus/* (accessed on 22 September 2022).

Xu K, Cui K, Young LH, Hsieh YK, Wang YF, Zhang J. 2020. Impact of the COVID-19 event on air quality in central China. *Aerosol and Air Quality Research* **20**:915–929 DOI 10.4209/aaqr.2020.04.0150.

Zinke L. 2020. Air quality during COVID-19. *Nature Reviews Earth & Environment* 43017 DOI 10.1038/s43017-020-0087-1.

Zheng H, Kong S, Chen N, Zhenzhen Z, Ying J, Shuning Y, Qi S. 2021. Source apportionment of volatile organic compounds: Implications to reactivity, ozone formation, and secondary organic aerosol potential. *Atmospheric Research* **249**:105344 DOI 10.1016/j.atmosres.2020.105344.

Zowalaty MEE, Young SG, Järhult JD. 2020. Environmental impact of the COVID-19 pandemic—a lesson for the future. *Infection Ecology & Epidemiology* **10(1768)**:1023 DOI 10.1080/20008686.2020.1768023.