COVID-19-associated 2020 lockdown: a study on atmospheric black carbon fall impact on human health

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Abstract The mean mass concentrations of black carbon (BC), biomass burning (BC)bb, and fossil fuel combustion (BC)ff have been estimated during March–May 2020 (during the COVID-19 outbreak) and March–May 2019 at a semiarid region of Agra over the Indo-Gangetic basin region. The daily mean mass concentration of BC in 2020 and 2019 was 3.9 and 6.9 µg m⁻³, respectively. The high monthly mean mass concentration of BC was found to be 4.7, 3.4 and 3.3 µg m⁻³ in Mar-2020, Apr-2020, and May-2020, respectively, whereas in Mar-2019, Apr-2019, and May-2019 was 7.7, 7.5 and 5.4 µg m⁻³, respectively. The absorption coefficient (b_abs) and absorption angstrom exponent (AAE) of black carbon were calculated. The highest mean AAE was 1.6 in the year 2020 (Mar–May 2020) indicating the dominance of biomass burning. The mean mass concentration of fossil fuel (BC)ff and biomass burning (BC)bb is 3.4 and 0.51 µg m⁻³, respectively, in 2020 whereas 6.4 and 0.73 µg m⁻³, respectively, in 2019. The mean fraction contribution of BC with fossil fuel (BC)ff was 82.1 ± 13.5% and biomass burning (BC)bb was 17.9 ± 4.3% in 2020, while in 2019, fossil fuel (BC)ff was 86.7 ± 13.5% and biomass burning (BC)bb was 13.3 ± 6.7%. The population-weighted mean concentration of BC, fossil fuel (BC)ff, and biomass burning (BC)bb has been calculated. The health risk assessment of BC has been analyzed in the form of attributable relative risk factors and attributed relative risk during the COVID-19 outbreak using AirQ+ v.2.0 model. The attributable relative risk factors of BC were 20.6% in 2020 and 29.4% in 2019. The mean attributed relative risk per 10,000,000 populations at 95% confidence interval (CI) due to BC was 184.06 (142.6–225.2) in 2020 and 609.06 (418.3–714.6) in 2019. The low attributed factor and attributed relative risk in 2020 may be attributed to improvements in air quality and a fall in the emission of BC. In 2020, due to the COVID-19 pandemic, the whole country faced the biggest lockdown, ban of the transportation of private vehicles, trains, aircraft, and construction activities, and shut down of the industry leading to a fall in the impact of BC on human health. Overall, this was like a blessing in disguise. This study will help in future planning of mitigation and emission control of air pollutants in large and BC in particular. It only needs a multipronged approach. This study may be like torch bearing to set path for mitigation of impacts of air pollution and improvement of air quality.

Keywords Black carbon · Source apportionment · Air Q+ model · Health risk analysis
Introduction

The ambient air in most cities in Asia is severely polluted and has a tremendous impact not only on the ecosystem but also on public health. They have significant impacts with varying chemical composition, emission mechanisms, and their presence in the air. Various air pollutants of serious concern are particulate matter (PM), organic matter (OC), elemental carbon (EC), black carbon (BC), etc. Black carbon (BC) is produced from the incomplete/partial combustion of fossil fuels and biofuel (Kant et al. 2019; Liu et al. 2014; Srivastava et al. 2012). BC emission has increased rapidly with rapid industrialization, uncontrolled use of coal, diesel emission, waste burning, and vehicular emissions (Dumka et al. 2019; Vaishya et al. 2017). The major part of BC emissions is made by southeast Asia, Eastern China, and the Indo-Gangetic basin (IGB) of India along with equatorial Africa, the USA, Mexico, and the Northern Latin America (Ramnathan and Carmichael, 2008; Myhre, 2014). Indiscriminate burning of forests and grasslands in addition to combustion of solid fuels burned for domestic purposes coupled with vehicular emissions is its largest sources in these regions (Paliwal et al. 2016; Prasad et al. 2018; Sharma et al. 2010). The majority of black carbon emission is due to biofuel cooking (cow dung cake, coal, wood) in South Asia, while the sources of black carbon emission are coal combustion for residential and industrial purposes in East Asia (Venkataraman et al. 2005). The Indo-Gangetic basin is one of the biggest river basins in the world and a global hot spot for aerosols (Mhawish et al. 2017; Singh et al. 2017). The major source of BC is the emissions from fossil fuels, biofuels, wood, and old transport vehicles (Banerjee et al. 2015; Janssen et al. 2011). Regional meteorology also plays role in the transport of the emitted pollutants to a longer distance (Murari et al. 2016). Agra is situated in the region of the Indo-Gangetic basin where man-made anthropogenic sources are in abundance. These anthropogenic sources generate aerosol black carbon over this region. Several earlier studies of mass concentration of BC have been recorded over northern India (Gadhavi et al., 2015; Gupta et al. 2017, 2019; Kumar et al. 2007; Latha et al. 2016; Safai et al. 2007). The high concentration of BC over the IGB region is mainly due to the excessive increase in the burning of fossil fuels, crop burning/harvesting, automobile emission, use of diesel generating sets, and small industries in and around the region (Safai et al. 2007; Tiwari et al. 2013). The high concentration of BC has posed a severe threat to human health than fine particles (Kinney et al. 2000; Katsouyann et al. 2001; Janssen et al. 2011; Lia et al., 2016; Gupta et al. 2019).

The COVID-19 pandemic spread all over the world claimed thousands of lives and made millions of people affected (Maa et al. 2020; Singh et al. 2020). Globally, 5,934,936 confirmed cases and 367,166 confirmed deaths due to COVID-19 have been reported in May 2020 (WHO, 2020). The symptoms of disease due to the coronavirus (COVID-19) are similar to airborne diseases like sneezing, coughing, short breathing, and lung impairment and are associated with excess morbidity and mortality. During the COVID-19 pandemic, the lockdown has been practiced all over the world to contain the spread of diseases. This has led to improvements in air quality in various countries but it is far too early to speak of long-term change. India has also observed a lockdown in 2020 and later on unlock after being under the biggest lockdown. On March 22, 2020, India observed 14 h of voluntary public curfew (Janta curfew). It was followed by a mandatory nationwide lockdown for 21 days March 25–April 14 (1st lockdown) which was further extended till May 3, 2020 (2nd lockdown) and so on with nearly 1.3 billion people staying home during this pandemic situation. This has minimized the use of private vehicles, other non-essential transportation, construction activity, etc. During this period, the crop residue burning has been recorded as very low because of the migration of laborers who used to work in large-scale farms (rice paddies) in northwestern India and returned to their farms (Wei et al. 2022). The entire country has been put under a lockdown as a measure to curb the spread of the coronavirus and experienced an unexpected decrease in the concentration of pollutants compared to previous years. The effects of black carbon are always challenging due to climate variability. COVID-19 lockdown gave the unseen scenario for the Indian climate. Recently, various studies have been reported around the world related to the ambient concentration of particulate matter and various other air pollutants (Granier et al. 2019; CPCB, 2020; Forster et al. 2020; Doumbia et al. 2021) but no studies have been reported on changes of black carbon...
concentration and their source identification during the COVID-19 outbreak. Therefore, the goal of the present investigation is to study black carbon mass concentration and its equivalent fractions of biomass and fossil burning and health risk assessment in the Agra region over the IGB during the pandemic.

Materials and methods

Site characteristics

The present study has been carried out in Agra a semiarid region situated over the Indo-Gangetic basin (Fig. 1). It is surrounded by the Thar Desert of Rajasthan on its southeast, west, and northwest peripheries. Agra is famous for its ‘Taj-Mahal’ and cultural heritage. Agra has always been the center of attraction for tourists. As per the census of 2011, the population of Agra is 15, 85,704 and the floating population is about 23,000 tourists per day. The major source of air pollution in Agra is the urban population, emissions from automobiles, and the use of cow dung cake and waste for cooking and heating purposes. The small domestically operated industries (Petha and glass manufacturing) in Agra and nearby regions significantly use coal, cow dung, wood, and agro-waste as primary fuels. The commercial and personal vehicles in Agra have increased from 4 to 6.4 Lakhs from 2003 to 2011 (Gupta et al. 2019). The major contributor of air pollutants in Agra is truck, auto, bus, and two-wheeler.

Black carbon measurement and analysis

Black carbon concentration was monitored at Agra over the IGB in India from March 1 to May 3, 2020 during the COVID-19 pandemic and from March 1 to May 3, 2019. AE-33 seven channels Aethalometer (Magee Scientific USA) instrument was used for the measurement of real-time black carbon mass concentrations. It is a self-contained optical transmission-based automatic instrument. It was run at a flow rate of 2 L/min and data were collected at an interval of one minute. The mass concentration of BC is estimated by the attenuation of the aerosol particle deposited on the filter at 880 nm (Drinovec et al. 2015; Helina et al. 2018). The entire datasets of black carbon during lockdown have been measured for 60 days (pre-lockdown (March 1–21,}

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**Fig. 1** Location map of the study area
2020), Janta curfew (March 22, 2020), 1st lockdown (March 25–April 14, 2020), 2nd lockdown (April 16–May 3, 2020)) and used similar days interval for 2019 also. AE-33 provides absorption coefficient ($b_{abs}$) and concentration of BC which has been compensated and changed in optical attenuation at any selected time duration (Drinovec et al. 2015).

\[
b_{abs} = b_{ATN} \frac{1}{C \cdot R(ATN)}
\]  

(1)

where $C$ and $R$ are two effects of the changing optical properties of the filter. This leads to an enhancement of the optical path and thus to enhanced light absorption of the deposited particle. The absorption coefficients ($b_{abs}$) for the study period are obtained from Eq. (1). The absorption coefficients ($b_{abs}$) values are further used to analyze the absorption wavelength exponents ($\alpha_{abs}$) at 370–950 nm.

\[
b_{abs}(\lambda) = K \cdot \lambda^{-\alpha}
\]  

(2)

where $b_{abs}$ is the spectrally dependent mass absorption efficiency, $K$ is a constant, $\lambda$ is the light wavelength, and $\alpha$ is the absorption angstrom exponent (AAE). The values of $\alpha$ represent the emission sources of BC concentration at a different wavelength (i.e., the absorption coefficient of BC is close to 1 represents the automobile emission (fossil fuel) and more than 2 or 2.5 represent the emission from biomass burning) (Kirchstetter et al. 2004).

In this study, the contribution of biomass burning and fossil fuel to the BC has been calculated (Magee Scientific, 2016; Helina et al. 2018). The contribution of $\beta_{absbb}$ (biomass) and $\beta_{absff}$ (fossil fuel) has been calculated at two different wavelengths ($\lambda_1$, $\lambda_2$), based on the absorption dependency of different particles:

For fossil fuel (ff) :

\[
\frac{b_{abs}(\lambda_1)_{ff}}{b_{abs}(\lambda_2)_{ff}} = \left( \frac{\lambda_1}{\lambda_2} \right)^{-\alpha_{ff}}
\]  

(3)

For biomass burning (bb) :

\[
\frac{b_{abs}(\lambda_1)_{bb}}{b_{abs}(\lambda_2)_{bb}} = \left( \frac{\lambda_1}{\lambda_2} \right)^{-\alpha_{bb}}
\]  

(4)

The determination of fractionation of $\beta_{absbb}$ (biomass) at 880 nm and $\beta_{absff}$ (fossil fuel) at 370 nm has been calculated by using the following equation

\[
b_{abs}(\lambda) = b_{abs}(\lambda)_{ff} + b_{abs}(\lambda)_{bb}
\]  

(5)

where $\beta_{absff}$ is the spectrally dependent mass absorption efficiency at 880 nm and $\beta_{absbb}$ is the spectrally dependent mass absorption efficiency at 370 nm.

\[
BB(\%) = \frac{b_{abs}(\lambda_2)_{bb}}{b_{abs}(\lambda_2)}
\]  

(6)

\[
BC_{bb} = BB \times BC
\]  

(7)

\[
BC_{ff} = (1 - BB) \times BC
\]  

(8)

Exposure contributions of BC, BC_{ff}, and BC_{bb} toward the population and health impact assessment

The exposure contribution of BC, BC_{ff}, and BC_{bb} of the population has been calculated in terms of population-weighted mean concentration (the risk of pollutants on exposed populations in the particular area) by the following equation:

Population weighted mean concentration = \( \frac{\sum(P_i \times C_i)}{P_{tot}} \)

where $i$ is designated for the cell in the domain, $P_i$ is given cell location population, $C_i$ is the particulate concentration in the same cell location, and $P_{tot}$ is the total population in air basin-wide (Mahmud et al. 2012). For calculation of population-weighted mean concentration, the total population for the computational cell was taken to be 1,585,704. The total population of the given cell locations of Agra has been categorized into Zone I (498,801), Zone II (299,853), Zone III (398,393), and Zone IV (388,609).

The estimation of health risk assessment due to pollution has been performed using the AirQ + v.2.0 model given by World Health Organization. AirQ + v.2.0 model is designed to analyze the mortality and morbidity due to air pollutant concentrations. This software adopts the risk of death and the attributable factor of BC with the impacts of long-term exposure on human health. AirQ + v.2.0 provides the incidence rate in the population exposed (per 100,000 population/year) with the incidence rate in the counterfactual population in which known relative risks (RR) of exposure (Fattore et al. 2011).
In the calculation of RR in ambient air pollution, the whole population is assumed to be exposed; the population attributable fraction (PAF) estimates the proportion of cases that are prevented if the exposure was zero, in case the whole population is exposed.

\[
\text{PAF} = \frac{\text{RR} - 1}{\text{RR}}
\]

If the level of exposure was reduced in a population to a (counterfactual) level where RR is equal to one, PAF would be zero. If only a fraction \( p \) of a population is exposed, the formula is generalized to

\[
\text{PAF} = \frac{p(\text{RR} - 1)}{p(\text{RR} - 1)}, 0 < p \leq 1
\]

The required data to run the Air Q+ v.2.0 model include daily averages and the 98 percentile of the population. The RR has low, high, and median values (i.e., 95% confidence interval) and is considered for the health risk assessment. The relative risk (RR) of black carbon (per 1 µg m\(^{-3}\)) with a 95% confidence interval has been taken as 1.061 (1.049–1.073) for this study (Hoek et al. 2013).

**Result and discussion**

**Mean mass concentration of BC**

The mean mass concentration of BC has been analyzed from March to May 2020 (during COVID-19 outbreaks) and March–May 2019 at Agra situated over the IGB (Fig. 2a). The daily mean mass concentration of BC is 3.9 µg m\(^{-3}\) in and 6.9 µg m\(^{-3}\) in 2020.
and 2019, respectively. There is a 43% fall in the mean concentration of BC during COVID-19-associated lockdown. The monthly mean mass concentration of BC in Mar-2020, Apr-2020, and May-2020 was 4.7, 3.4, and 3.3 µg m⁻³, whereas in Mar-2019, Apr-2019, and May-2019 was 7.7, 7.5, and 5.4 µg m⁻³, respectively. The high concentration in 2019 may be due to uncontrolled emissions from biomass/fossil fuel burning while the low concentration in 2020 may be due to a massive lockdown 2020 to contain the spread of the COVID-19 pandemic. Various past studies have shown that the measured high BC concentration was associated with contribution from the local and regional distant locations (Dumka et al. 2010; Tiwari et al. 2013; Gupta et al. 2017; Singh et al. 2017). The lockdown due to the COVID-19 pandemic in 2020 led to a restriction on the movement of vehicles, close of construction activities as well as a partial industrial shutdown which may have resulted in a decrease in fuel combustion and a fall in the concentration of BC.

Wavelength dependence for identification of dominant sources of black carbon

The absorption coefficient (\(b_{abs}\)) and absorption angstrom exponent (AAE) of black carbon were calculated for the study period (Fig. 2). A lower absorption coefficient has been found in the year 2020 than in 2019 (Fig. 2a). It may be due to the emission of BC being more confined near to the shorter wavelength (UV region) than the longer wavelength (IR region). The highest mean AAE was 1.6 in the year 2020 (Mar–May 2020) indicating the dominance of biomass burning (Fig. 2b). The use of biofuel for residential purposes (mainly cooking) and waste burning increases the biomass burning in 2020 due to the COVID-19 lockdown. The lowest mean AAE was 0.98 in the year 2019 (Mar–May 2019) indicating the dominance of fossil fuels. It is mainly due to automobile exhaust and long-range transport as well as prevailing meteorological conditions (Gupta et al. 2017). Heavy duty (buses, trucks, buses, etc.) diesel vehicles can contribute an average of 42% BC (Reddy and Venkataraman, 2002a). During pre-lockdown (Mar 1–21, 2020) and Janta curfew (Mar 22, 2020), the mean AAE was 0.88 and 0.94, respectively. The mean AAE in pre-lockdown and Janta curfew shows the dominance of fossil fuel emissions which mainly get generated from the automobile emission. In the 1st lockdown (Mar 25–Apr 15, 2020) and 2nd lockdown (Apr 16–May 3, 2020), the mean AAE was 2.3 and 2.1, respectively, which indicates the dominance of biomass burning. It may be due to the ban on movement of vehicles, partial shutdown of industries, increase in the use of biofuel (as a large number of people were staying in their homes during the lockdown period which had increased the household activity), and waste burning. Various studies have previously confirmed that biomass burning, fuel-wood, and crop waste burning were primary contributors to BC in north India (Gupta et al. 2019; Safai et al. 2007).

Determination and fractionation of fossil fuel (BC)\(_{ff}\) and biomass burning (BC)\(_{bb}\)

The daily mean mass concentration of BC\(_{ff}\) and BC\(_{bb}\) is determined and presented in Fig. 3. The mean mass concentration of BC\(_{ff}\) and BC\(_{bb}\) was found to be 6.4 and 0.73 µg m⁻³, respectively, in 2019 whereas 3.4 and 0.51 µg m⁻³, respectively, in 2020. The ratio of (BC)\(_{bb}\)/(BC)\(_{ff}\) is also shown in Fig. 3. The ratio of (BC)\(_{bb}\)/(BC)\(_{ff}\) varied from 0.11 to 0.88 with a mean value of 0.21 in 2019, whereas the ratio of (BC)\(_{bb}\)/(BC)\(_{ff}\) varied from 0.09 to 0.35 with a mean value of 0.19 in 2020. Monthly mean mass concentration of BC\(_{ff}\) and BC\(_{bb}\) was found to be 3.9 and 0.43 µg m⁻³ in Mar-2020, 3.6 and 0.55 µg m⁻³ in Apr-2020, 3.8 and 0.56 µg m⁻³ in May-2020, 6.5 and 0.54 µg m⁻³ in Mar-2019, 5.7 and 0.84 µg m⁻³ in Apr-2019, and 6.9 and 0.81 µg m⁻³ in May-2019. The drop-down concentration of BC\(_{ff}\) and BC\(_{bb}\) in 2020 than 2019 is mainly due to the complete ban on outside movement during the lockdown. This sharp decrease in air pollution was like a blessing in disguise amid the corona pandemic. The hourly variation in concentration of BC\(_{ff}\) and BC\(_{bb}\) has been analyzed during pre-lockdown, Janta curfew, 1st lockdown, and 2nd lockdown (Fig. 4). During pre-lockdown (March 1–21, 2020), the hourly mean mass concentration of BC\(_{ff}\) and BC\(_{bb}\) was 3.2 µg m⁻³ (2.6–4.2 µg m⁻³) and 0.61 µg m⁻³ (0.31–1.0 µg m⁻³), respectively (Fig. 4a). BC\(_{ff}\) mass concentration fall is about 20% which is mainly due to the confinement of the public at home and banned on the movement of vehicles. The concentration of BC\(_{ff}\) ranges from 1.3 to 4.9 µg m⁻³ and BC\(_{bb}\) ranges from 0.28 to 1.3 µg m⁻³ on Janata curfew (March 22, 2020) (Fig. 4b) shows the significant variation during
early morning hours around 07:00–13:00 h (IST) and a sharp peak in the evening around 17:00–20:00 h (IST). During the 1st lockdown (Mar 25–Apr 15, 2020), the temporal variation in concentration of fossil fuel (BC)$_{ff}$ ranges from 2.7 to 4.3 µg m$^{-3}$, and biomass burning (BC)$_{bb}$ ranges from 0.46 to 1.5 µg m$^{-3}$ (Fig. 4c). The continuous increase in the concentration of BC$_{ff}$ has been from 21:00 to 04:00 h (IST). This may be probably due to the permission of restricted movement of vehicles for transportation of goods and essential items at the night time. More or less similar trends have been observed during the 2nd lockdown; however, the value was different (Fig. 4d). The mean mass fraction contribution of BC with fossil fuel (BC)$_{ff}$ was 86.7 ± 13.5% and biomass burning (BC)$_{bb}$ was 13.3 ± 6.7% in 2019, whereas in 2020, the fraction contribution of BC with fossil fuel (BC)$_{ff}$ was 82.1 ± 13.5% and biomass burning (BC)$_{bb}$ was 17.9 ± 4.3% (Fig. 5). There was a decrease in BC$_{ff}$ in 2020 in comparison with the same period of 2019 which can be attributed to the impact of lockdown. The percentage fractionation trends of BC$_{ff}$ and (BC)$_{bb}$ show similar trends during 2019 and 2020. Various recent studies have shown the similar trends of BC$_{ff}$ and BC$_{bb}$ in Ahmedabad (80% and 20%), Gorakhpur (74% and 26%), Dehradun (66% and 34%), and Delhi (94% and 6%), (Dumka et al. 2019; Kant et al. 2019; Rajesh & Ramachandran, 2017; Vaishya et al., 2017). In Agra, the results of BC$_{ff}$ were higher than in other sites in 2019 and 2020 except in Delhi. It may be due to the high anthropogenic source strength (high vehicular and industrial emission) of BC in Delhi. In comparison with other places, the study site was also influenced by the same source as Delhi. The BC$_{bb}$ in Agra was lower than other sites while higher than in Delhi in 2019 and 2020. The large fraction of
biomass in Agra than Delhi may be due to the local emission from uses of biofuels (like woods and cow dung cake for cooking purposes).

Health risk assessment of BC, fossil fuel (BC)_{ff}, and biomass burning (BC)_{bb} during COVID-19 pandemic

Fine particulate matter has been considered an indicator and has been attributed to most deaths, while BC also puts weight on health risks. The population-weighted mean concentration of BC, BC_{ff}, and BC_{bb} is calculated for four major zones and presented in Table 1. The mean population-weighted concentration of BC, BC_{ff}, and BC_{bb} in Zone I was 1.1, 0.99, and 0.22 µg m^{-3}, respectively, in 2020 and 2.1, 1.2 and 0.34 µg m^{-3}, respectively, in 2019. In zone II, mean population-weighted concentration was 0.71, 0.54, and 0.15 µg m^{-3}, respectively, in 2020, and 1.5, 0.64, and 0.42 µg m^{-3}, respectively, in 2019. In Zone III, the mean population-weighted concentration was 1.2, 0.85, and 0.19 µg m^{-3}, respectively, in 2020, and 1.9, 0.86, and 0.12 µg m^{-3}, respectively, in 2019. The mean population-weighted concentration of BC, BC_{ff}, and BC_{bb} in zone IV was 0.94, 0.82, and 0.18 µg m^{-3} in 2020 and 1.8, 0.84 and 0.13 µg m^{-3} in 2020. It has been seen that the population-weighted mean concentration is lower in 2020 in comparison with 2019.

The low population-weighted mean in 2020 may be resultant of the impact of lockdown associated with the COVID-19 pandemic. The lockdown has reduced health risks and enhanced life expectancy. The high mean population-weighted concentration of BC was found in Zone III and the lowest in Zone II. The high mean population-weighted concentration of BC_{ff} and BC_{bb} in pre-lockdown was found in Zone I followed by Zone III, Zone IV, and Zone II. During the Janta curfew (Mar 22, 2020), the high mean population-weighted concentration of BC and BC_{ff} has been found in the zone I followed by Zone III, Zone IV, and Zone II, while the high mean population-weighted concentration of BC_{bb} is found in Zone II followed by Zone I, Zone III and Zone IV. In 1st lockdown (Mar 25–Apr 15, 2020) and 2nd lockdown (Apr 16–May 3, 2020), high mean population-weighted concentrations of BC, BC_{ff}, and BC_{bb} have been found in Zone I followed by Zone III, Zone IV, and Zone II. The high mean population-weighted concentration of BC_{bb} in lockdown revealed that the use of biofuel for household activity has increased. Various short-term studies on health effects have shown the associations with BC are more robust than with particulate matter (Segersson et al. 2017; Villeneuve and Goldberg, 2020; Rathod & Beig, 2021; Evangelou et al. 2021), which causes the cardiovascular mortality.
and cardiopulmonary hospital admissions (Zanobetti & Schwartz, 2006; Brauer et al. 2007; Li and Ariya, 2021; Ambade et al. 2021; Sigh and Gokhale, 2022).

The health risk assessment of BC has been analyzed as attributable relative risk factors and attributed relative risk during March–May 2020 (during COVID-19 outbreaks), March–May 2019 and pre-lockdown, Janta curfew, 1st lockdown, and 2nd lockdown in 2020 due to COVID-19 outbreak using Air Q+ model and is presented in Tables 2 and 3. Agra is under acute risk due to inhabitants being prone to severe diseases. The attributable risk factors of BC were 20.6% in 2020 and 29.4% in 2019. The attributable risk factors of BC in Mar-2020, Apr-2020 and May-2020 were 24.2, 13.2, and 12.7%, respectively, whereas in the month of Mar-2019, Apr-2019, and May-2019 were 32.7, 31.2, and 22.9%, respectively. The mean attributed relative risk per 10,000,000 populations at 95% CI due to BC was 184.06 (142.6–225.2) in 2020 and 609.06 (418.3–714.6) in 2019. The high-risk factor in 2019 was mainly due to the strong local emission sources, biomass combustion, waste burning, vehicular emission, as well as long-range transport, which caused more premature deaths in 2019 while low in 2020 may be attributed to improving air quality and fall in the emission of BC due to lockdown. Monthly high attributed relative risk was observed in March and the lowest in May for both years (2020 and 2019). During the days of the COVID-19 pandemic, the high attributed relative risk was found during pre-lockdown and Janta curfew, whereas the lowest risk was found in the 1st and 2nd lockdown (Table 3). In 2020, due to the COVID-19 pandemic, the whole country faced the biggest lockdown, banned the transportation of private vehicles, trains, aircraft, and construction activities, and shut

Fig. 5 Percentage contribution (%) of fossil fuel (BC)$_{ff}$ and biomass burning (BC)$_{bb}$ during the study period

![Graph showing percentage contribution of fossil fuel (BC)$_{ff}$ and biomass burning (BC)$_{bb}$]

- For 2019:
  - BC$_{ff}$: [Graph showing contribution]
  - BC$_{bb}$: [Graph showing contribution]
- For 2020:
  - BC$_{ff}$: [Graph showing contribution]
  - BC$_{bb}$: [Graph showing contribution]
Table 1  Population-weighted mean concentrations of the different fractions of BC from different source categories

| BC fraction | 2019 | 2020 | Pre-lockdown (March 1–21, 2020) | Janta curfew (Mar 22, 2020) | 1st lockdown (Mar 25–Apr 15, 2020) | 2nd lockdown (Apr 16–May 3, 2020) |
|-------------|------|------|-------------------------------|-----------------------------|-----------------------------------|-------------------------------|
| Zone I      |      |      |                               |                             |                                   |                               |
| BC          | 2.1  | 1.1  | 1.4                          | 1.7                         | 0.99                             | 0.85                          |
| BC_{ff}     | 1.2  | 0.99 | 0.91                         | 0.72                        | 0.67                             | 0.75                          |
| BC_{bb}     | 0.34 | 0.22 | 0.28                         | 0.15                        | 0.19                             | 0.21                          |
| Zone II     |      |      |                               |                             |                                   |                               |
| BC          | 1.5  | 0.71 | 0.97                         | 1.2                         | 0.65                             | 0.53                          |
| BC_{ff}     | 0.64 | 0.54 | 0.59                         | 0.49                        | 0.44                             | 0.49                          |
| BC_{bb}     | 0.42 | 0.15 | 0.12                         | 0.19                        | 0.11                             | 0.13                          |
| Zone III    |      |      |                               |                             |                                   |                               |
| BC          | 1.9  | 1.2  | 1.5                          | 1.6                         | 0.86                             | 0.71                          |
| BC_{ff}     | 0.86 | 0.85 | 0.78                         | 0.63                        | 0.58                             | 0.66                          |
| BC_{bb}     | 0.12 | 0.19 | 0.16                         | 0.13                        | 0.16                             | 0.20                          |
| Zone IV     |      |      |                               |                             |                                   |                               |
| BC          | 1.8  | 0.94 | 1.3                          | 1.5                         | 0.84                             | 0.69                          |
| BC_{ff}     | 0.84 | 0.82 | 0.76                         | 0.62                        | 0.57                             | 0.64                          |
| BC_{bb}     | 0.13 | 0.18 | 0.15                         | 0.12                        | 0.14                             | 0.19                          |

Table 2  Attributable risk factor and attributed relative risk due to BC in 2019 and 2020

|          | Attributable factor (%) | Attributed relative risk (per 100,000 population) due to BC |
|----------|-------------------------|------------------------------------------------------------|
|          | 2019  | 2020  | RR-1.061 | RR-1.049 | RR-1.073 | RR-1.061 | RR-1.049 | RR-1.073 |
| Mean     | 29.4  | 20.6  | 609.06   | 418.3    | 714.6     | 184.06   | 142.6    | 225.2     |
| March    | 32.7  | 24.2  | 188.9    | 155.8    | 225.0     | 188.9    | 155.8    | 225.0     |
| April    | 31.9  | 13.2  | 181.7    | 131.2    | 226.4     | 181.7    | 131.2    | 226.4     |
| May      | 22.9  | 12.7  | 144.4    | 109.2    | 211.4     | 144.4    | 109.2    | 211.4     |

Table 3  Attributable risk factor and attributed relative risk due to BC in COVID-19 pandemic days

|                        | Attributable factor (%) | Attributed relative risk (per 100,000 population) factor due to BC in lockdown |
|------------------------|-------------------------|---------------------------------------------------------------------------------|
| Pre-lockdown (Mar 1–21, 2020) | 21.5 | 237.4 | 186.2 | 272.2 |
| Janta Curfew (Mar 22, 2020)       | 12.2 | 243.9 | 198.3 | 265.8 |
| 1st lockdown (Mar 25–Apr 15, 2020) | 13.7 | 246.01 | 196.2 | 280.8 |
| 2nd lockdown (Apr 16–May 3, 2020)  | 10.6 | 169.9 | 123.2 | 213.5 |
down the industries; this leads to a fall in the impact of BC on human health. Lockdown in 2020 decreased the effects of air pollutants on human health (Qu et al. 2020; Singh et al. 2020; WHO, 2020; Alvarado et al. 2022). The ill effects of the pandemic and consecutive impositions of lockdown have numerous impacts on human life and the economy around the world but it has been a blessing in disguise for the environment and related pollution. Ambient air pollutant has long been attributed to be the primary cause of many chronic diseases, viz. heart attack, lung infections, pneumonia, etc. These diseases have been attributed to mortality and morbidity.

**Conclusion**

The mean BC mass concentration has been analyzed from March–May 2020 (during COVID-19 outbreaks) and March–May 2019 at Agra. The daily mean mass concentration of BC in 2020 and 2019 is 3.9 and 6.9 µg m\(^{-3}\), respectively. A lower BC mass concentration has been found in the year 2020 than in 2019. This fall in mass concentration may be due to a lockdown in 2020 to contain the spread of the COVID-19 pandemic. Temporal variation in concentration of fossil fuel (BC\(_{ff}\)) and biomass burning (BC\(_{bb}\)) has been also analyzed during pre-lockdown, Janta curfew, 1st lockdown, and 2nd lockdown. The mean percentage contribution of BC with BC\(_{ff}\) and BC\(_{bb}\) has been also observed in 2020 and 2019. The percentage fractionation trends of BC\(_{ff}\) and BC\(_{bb}\) have shown similar trends during the study period. It is mainly due to the complete ban and restricted permission of vehicles of government agencies to provide essential commodities and medical facilities. The population-weighted mean concentration of BC, fossil fuel (BC\(_{ff}\)), and biomass burning (BC\(_{bb}\)) has been calculated to assess the risk on exposed populations of the four major zones of particular area. The low population-weighted mean concentration of BC, BC\(_{ff}\), and BC\(_{bb}\) in 2020 than 2022 may be due to the low source strength of emission of black carbon from automobiles, biomass, and fossil fuel burning, crop burning/harvesting because of lockdown. The attributable relative risk factors of BC were 20.6% in 2020 and 29.4% in 2019. The mean attributed relative risk per 1000, 0000 populations at 95% CI due to BC was 184.06 (142.6–225.2) in 2020 and 609.06 (418.3–714.6) in 2019. The low attributed factor and attributed relative risk in 2020 may be attributed to improvements in air quality and a fall in the emission of BC due to lockdown. In 2020, due to the COVID-19 pandemic, the whole country faced the biggest lockdown, banned transportation of private vehicles, trains, aircraft, and construction activities, and shut down of the industry leading to a fall in the impact of BC on human health.

**Implications**

The lockdown in 2020 has realized that air quality can be improved if certain strict control measures are taken. The improvement of air quality due to lockdown has exercised the authorities and environmental researchers to re-assess their strategies. There is a hope to for clean air India. There is a need to come out-of-the-box methods to tackle and tighten norms of air pollution. The pandemic-related lockdown measure gave us a narrow but welcoming glimpse of clean air. Although lockdown in 2020 was forced to contain the spread of COVID-19 pandemic, now it can be made voluntarily. This has also set to reset our target to bring down the pollution load and improve air quality at a certain interval of time. Overall, it was like a blessing in disguise. Standard for metrics of quality measurement can be set down to a new low level and it can be achieved. This study will help in future planning of mitigation and emission control of air pollutants in large and BC in particular. It only needs a multipronged approach. This study may be like torch bearing to set path for mitigation of impacts of air pollution and improvement of air quality.

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Data availability  All the generated and analyzed data are included in this article.

Declarations

Conflict of interest  There are no financial interests to authors and institutions. We do not have any conflict of interest. We do not have even any non-financial interests and conflicts.

Human or animal rights  Authors declare no animal research involvement in this study.

Consent to participate  We are responsible for the contents of the articles.

Consent to publish  Author and co-authors confirm that the research work has not been published fully or partially elsewhere and has not been shared. We all give our consent to publish in your well-reputed journal.

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