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Review

COVID-19 pandemic: What can we learn for better air quality and human health?

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ABSTRACT

The COVID-19 lockdown resulted in improved air quality in many cities across the world. With the objective of what could be the new learning from the COVID-19 pandemic and subsequent lockdowns for better air quality and human health, a critical synthesis of the available evidence concerning air pollution reduction, the population at risk and natural versus anthropogenic emissions was conducted. Can the new societal norms adopted during pandemics, such as the use of face cover, awareness regarding respiratory hand hygiene, and physical distancing, help in reducing disease burden in the future? The use of masks will be more socially acceptable during the high air pollution episodes in lower and middle-income countries, which could help to reduce air pollution exposure. Although post-pandemic, some air pollution reduction strategies may be affected, such as car-pooling and the use of mass transit systems for commuting to avoid exposure to airborne infections like coronavirus. However, promoting non-motorized modes of transportation such as cycling and walking within cities as currently being enabled in Europe and other countries could overshadow such losses. This demand focus on increasing walkability in a town for all ages and populations, including for a differently-abled community. The study highlighted that for better health and sustainability there. is also a need to promote other measures such as work-from-home, technological infrastructure, the extension of smart cities, and the use of information technology.

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Introduction

COVID-19 pandemic is one of the biggest global public health emergencies in recent centuries [1,2]. The threat of COVID-19 spread caused global health emergencies, resulting in governments' unprecedented decisions, including the lockdown of cities, specific states, or whole countries. The lockdown forces people to stay where they are, and only essential services are being allowed. Restricted vehicles' movement, closure of industries, and other activities resulted in a significant reduction in anthropogenic emissions of air pollutants. This led to an improvement in the air quality of many cities worldwide [3], which was far possible to achieve despite several measures. With the halt of all major anthropogenic activities that are prominent sources of air pollution, air quality improved globally [4–9]. However, the emissions from natural sources, household sources, and other essential services still contribute to air pollution in many regions [10,11]. It was also observed that meteorology and secondary air pollutants played a significant role in degrading the overall impact of air pollution reduction from anthropogenic sources [8,12,13].

In the wake of the COVID-19 pandemic, this ecological experiment offers the potential to examine air pollution and explore the knowledge to build evidence-based future policies and planning. This paper discusses the emerging studies on COVID-19 and air pollution reduction, the population at risk, natural versus anthropogenic emissions for better scientific understanding. The study also addresses the following question: how the new knowledge about air pollution reduction during COVID-19 lockdown can be explored to plan future air pollution mitigation strategies and policy recommendations, especially in lower and middle-income countries, which are known for having the global hotspot of air pollution. Further, the study discussed how the new societal norms taught us during the COVID-19 pandemic could help in human behavioral change to minimize air pollution exposure after the pandemic is over and how the new learning could be explored to strengthen pollution and infectious diseases control strategies.

COVID-19 pandemic: route of transmission and impact of meteorology

The transmission mechanism of the COVID-19 pathogen is of great concern. The experimental studies onSARS-CoV-2 show that environmental spread is possible as the pathogen remains contagious in aerosols (<5 μm) for hours and up to days on the fomite and surfaces [14]. Morawska and Cao [15] highlighted that the virus-containing fine air droplets from an infected person could travel tens of meters in the air, which can be a significant path of transmission in microenvironments [16] and needed to be examined further to address the increasing threat of COVID-19. A similar study by Liu et al. [4,5] found concentrations of SARS-CoV-2 RNA in aerosols of some areas of hospitals in Wuhan having COVID-19 patients and reported that it has the potential to be transmitted via aerosols.

On the contrary, an initial study by Faridi et al. [17] in an Iranian hospital reported airborne samples collected between 2–5 m distance from the patients' beds did not confirm any COVID-19 virus in the sampled air. The research base is evolving rapidly to provide insights into the airborne transmission, which is likely to become even more important under the eased movement restrictions in the future [18].

According to the Indian Council of Medical Research [19], one COVID-19 infected person in India can transmit the virus to 406 people in 30 days if no precaution is taken. Also, the role of meteorological factors can be of great interest in understanding the spread of coronavirus. Qi et al. [20] recently studied that when relative humidity is between 67% and 85.5% in mainland China, increasing every 1 °C average ambient temperature can reduce daily confirmed cases by 36–57%. Similarly, when the average ambient temperature is between 5.04 °C and 8.2 °C, every 1% relative humidity increase can reduce confirmed cases daily by 11%–22%. Rendana et al. [21] in Indonesia found a significant correlation between meteorological factors and the COVID-19 epidemic spread rate. However, it has to be noted that these are initial findings, and more evidence-based studies are required to understand better how the novel coronavirus behaves under different geographical and meteorological conditions.

COVID-19 pandemic: air pollution and population at risk

Apart from all medical and public health measures to control the COVID-19 pandemic, it is also imperative to identify and study environmental factors such as air pollution (indoor and ambient), airborne pollens, which could enhance the severity of COVID-19 [22,23]. A study conducted by Wu et al. [24,25] reported that the population above 59 years of age is at a 5.1-times higher risk of death in China if infected with COVID-19 disease. Among COVID-19 affected people, a fatality risk of 1.4% was estimated in China's Wuhan province, from where this outbreak started [24,25]. Further, the study highlights that there is an 8% increase in the COVID-19 mortality rate with every 1 μ gm^{-3} increase in $PM_{2.5}$ in the population that has long-term exposure to $PM_{2.5}$. However, in India, Saini and Sharma [26] reported that though the risk of $PM_{2.5}$ related premature deaths in the older population is higher than the population of the age group between 25–50 years, but percentage share is higher relatively higher in this age group. Hence, this age group could be at higher mortality risk from exposure to fine $PM_{2.5}$ particles. The detailed analysis of studies linking air pollution with COVID-19 is presented in Table 1.

However, our understanding is developing fast each day as new scientific evidence is evolving. A statistically significant association between COVID-19 and short-term exposure to several air quality parameters, including $PM_{2.5,}$ was reported by Yongjian et al. [27] in China and observed that 10 μg m^{-3} increase in $PM_{2.5}$ could be associated with a 2.24% increase in COVID-19 cases with a lag period of 0–14 days. Long-term exposure to NO_2 may be one of the major contributing risk factors to casualty due to COVID-19 in European countries, as studied by Ogen [28]. A nationwide study in China by Wang et al. [6,7] indicated that COVID-19 risk likely increased by enhanced particulate pollution. Similarly, Conticini et al. [29] also mentioned that people with severe underlying health conditions, especially respiratory and circulatory, are at higher risk of being affected by COVID-19.

Table 1
Studies linking air pollution and impact of COVID-19.

Country	Study observation	Reference
United States	As per the study's findings, an elevation of 1 $\mu g/m^3$ in $PM_{2.5}$ was correlated with a surge of 8% in the death rate of COVID-19 (95 percent confidence interval [CI]: 2 percent, 15 percent). Results were statistically robust and very crucial for secondary and sensitivity analyses.	[83]
United States	The following research concluded that the unusual optimistic effect of COVID-19 decreases the burden on the environs, while the vulnerability of COVID-19 cases raises due to higher environmental pollution.	[68]
France	By Utilizing Artificial Neural Networks (ANNs) the levels of $PM_{2.5}$ and PM_{10} correlated with COVID-19-related deaths have been calculated. The underlying theory is that COVID-19 will activate due to a pre-determined concentration of particulate matter and as a result, the respiratory system is more vulnerable to this infection.	[67]
Netherlands	The analysis reveals that per one $\mu g/m^3$ increment in PM2.5 could be associated with 9.4 more COVID-19 cases, three times additional hospital admissions, and 2.3 more preterm deaths.	[76]
Northern Italy	The following research correlated a one-unit rise in PM2.5 (μg/m3) concentration with an increase of 9% in COVID-19-related mortality (95% CI: 6–12%).	[61]
Germany	Elevated air pollution levels (PM_{10} and Ozone) by one standard deviation 3 to 12 days after emergence of symptoms increase deaths by 30% (males) and 35% (females) of the mean. Furthermore, air pollution increases the number of reported cases of COVID-19.	[66]
Italy	In this study, the PM_{10} and $PM_{2.5}$ displayed a stronger non-linear association than NO_2 with lethality, mortality and incidence rates of COVID-19. In particular, while considering the incidence rate and mortality, $PM_{2.5}$ and PM_{10} concentrations showed an excellent correlation with NO_2 in Italy.	[56]
Italy	Prolonged exposure to air pollutants (i.e., $PM_{2.5}$) was linked with alveolar ACE-2 receptor overexpression, which resulted in a severe infection of COVID-19. High ambient NO_2 can be responsible for severe lung damage correlated with a worse outcome in COVID-19 pneumonia.	[37]
Italy	They infer that the regular new admissions of COVID-19 could be positively linked to the PM and Air Quality Index. They also found out that short exposure to $PM_{2.5}$ and PM_{10} with potential exposure to viruses may have a significant adverse effect on the immune system in humans.	[30]
Asia	A robust association between atmospheric pollutants and COVID-19 was observed, suggesting that air pollution could have some association in raising the global COVID-19 deaths. Past exposures to a high $PM_{2.5}$ level over a long time have been positively associated with COVID-19 mortality per unit recorded ($p < 0{,}05$) relative to PM_{10}, with a poor correlation having $p = 0.118$.	[65]
China	They observed that quality of air has a positive association with newly reported cases, and COVID-19 spreads by 5–7% as the AQI rises by ten units.	[77]
China	They observed significant positive associations with newly COVID-19 confirmed cases and the levels of $PM_{2.5}$, PM_{10}, NO_2 and O_3 over last few weeks.	[27]
Chin<a	After relative humidity and temperature change, R_0 (basic reproductive number) was positively correlated with the NO_2 concentration levels at 63 cities in China. Interaction between R_0 and ambient NO_2 suggested that NO_2 could increase the inherent risk of infection in the COVID-19 transmission process.	[76]
Japan	Research indicates that exposure to fine atmospheric particles can affect respiratory infections triggered by the severe acute respiratory syndrome of COVID-19.	[57]
India	This study in six Indian megacities found a positive correlation between $PM_{2.5}$ levels and COVID-19 mortality having a strong correlation.	[58]
Systematic Review	The study highlights the considerable contribution of prolonged exposure to air pollution and the lethality and spread of COVID-19. In particular, $PM_{2.5}$ and NO_2 tend to be more strongly associated with COVID-19 than PM_{10}.	[62]

Conticini et al. [29] reported that populations residing and exposed to high air pollution are more prone to develop chronic respiratory ailments and highly vulnerable to getting infection by a biological agent. The increased air pollution levels weaken the first line of defense of the upper respiratory system and make the subject more prone to attack by agents like COVID-19 [29]. Zoran et al. [30] reported a positive correlation between ground-level ozone with confirmed total COVID-19 infections and total death cases in Milan. During the shutdown, most of the population stays indoors. This minimized the exposure to ambient air pollutants, which helped decrease morbidity and mortality due to air pollution [31] and restricted the transmission of COVID-19.

Globally, 7 million premature deaths are linked with air pollution (WHO, 2016). As per some initial studies, there is an improvement in air quality during COVID-19 lockdown in different parts of the world [12,13,80,81,82]. This allows scientific communities to understand how they can have the competence to enhance the quality of air levels in the lockdown period or better than these levels through policy change. He et al. [32,33] estimated that with improved air quality, such as during lockdown, up to 36,000 premature deaths can be prevented per month in China. Liu et al. [34,35] estimated that the improvements in air quality during lockdown had been expected to avert around 99,270−146,649 premature deaths across 597 major cities in 76 countries. However, these estimates are based on short-term gains. In contrast, air pollution-related premature deaths were mainly reported due to long-term chronic exposure and hence need to be investigated further following regress scientific methodologies.

As per the WHO, 92% of the world population lives in poor air quality areas and mostly in developing countries. Frontera et al. [36,37] suggested that the air pollutants, along with meteorological parameters, can act as a carrier to COVID-19 viruses, leading to indirect infection diffusion [38]. The lockdown during the COVID-19 pandemic could reduce cardiovascular morbidity and mortality as air pollution and traffic noise are major risk factors for them [79]. However, contrary to societal loneliness, depression and mental health issues could arise during and after the lockdown [39]. However, detailed epidemiological studies are required to better understand the associated health benefits and emerging risks by having a holistic approach. This will help to plan the human risk reduction strategies effectively and minimize the direct and indirect impact of the COVID-19 pandemic.

COVID-19 pandemic: air pollution exposure and human behavioural change

The pandemic has sensitized observation of measures to prevent exposure such as wearing of face cover or masks in lower and middle-income countries of Asia and Africa continents, where it was not a common practice except in a few countries like China, Japan, and Singapore [40,41]. However, the question here is 'Can wearing face masks reduce the risk of air pollution exposure?

Several recent studies have provided background on the efficacy of anti-pollution masks (e.g., [17,42,43]). They found facemasks are useful not only to reduce particulate matter exposure but also to minimize associated health risks. The use of masks reduces exposure to fine particles, but the cost of facemasks increases with the effectiveness of filtering the fine particles. In contrast, some studies discuss that overused or contaminated masks could increase health risks. Hence, it is suggested that everyone should not wear a mask except for the occupational setting where it is a must, such as health care workers/hospital staff/doctors/caregiver workers [44].

However, the use of facemasks and their effectiveness depends on the environmental conditions, social practices, customs, and individual behavioral factors along with knowledge and availability usage of the type of masks, duration of use, masks fitting, care of hygiene and willingness and capability to pay. The behavioral change observed at present may be temporary or may not be strictly followed. Still, it appears that the use of face cover or masks will be more acceptable now during the high pollution days in the lower and middle-income countries. However, the population should be adequately trained to effectively use face cover as the false sense of security in high air pollution settings may increase the risk of air pollution exposure. It is important to note that masks may not be required at locations where air pollution remains low, including open areas or where public density is low. However, it might be a helpful tool to reduce air pollution exposure in countries like India and China, where high air pollution episodes are frequent.

This pandemic has resulted in the general population's sensitization towards respiratory wellness, observation of respiratory hygiene, keeping a physical distance from suspects, and seeking medical care in case of symptoms. The surveillance for the active and passive search for probable cases with respiratory illnesses, use of technology, electronic record maintenance and linking medical records with strict health follow-ups will help in identifying the vulnerable population and making the illness-specific policies. Using an epidemiological-economic model, Newbold et al. [45] highlighted that physical distancing measures could be a good preventive measure for public health and significantly impact the economy and the environment. The work from home, reduction in travel, online school and colleges and business meeting implicitly reduce the air pollution emission from various sources. Even before the COVID-19, infections related to hand hygiene and healthcare infections significantly impact the patients (7–10%) in different geographical regions [46].

In contrast, various strategies to reduce air pollution such as car-pooling and uses of mass transits could be negatively impacted as people will be afraid to share their car or traveling in a crowded mode of transport. This can increase personal vehicles' use for commuting to the office and other purposes, especially in developing countries like India, where clean air zones or pollution taxes do not exist, such as in many European countries. Hence, in countries where work-from-home is not common, specifically in the government sector, e.g., India, there is an opportunity to promote the work-from-home, including the private sectors such as Information Technology (IT) industry. However, the use of IT is an integral part of 'Smart Cities', which is an urban renewal and retrofitting program.

Information and communication technologies (ICT) and the internet of things (IoT) offer the potential to meet the communities' emerging needs, especially in lower and middle-income countries. For example, online classes can be encouraged to avoid large gatherings in the classroom. As a first step, the government needs to provide a safe environment and focus on population health. However, the population also learns to live with emerging diseases such as COVID-19 over a period of time. The practices followed by the public to minimize the exposure of COVID-19 and the learning of individual and community behavior offers new dimensions to strengthen the efforts to reduce air pollution and its vulnerability (Fig. 1). The best practices adopted during the pandemic should be promoted to minimize the health risks and to expropriate the environmental measures.

During and after the COVID-19 pandemic, there should be a concern for environmental protection and preservation. The clean air and water news created a wave in social media, which could help to engage the new generation for ecological protection. There could be an increased population movement for environmental actions such as a ban on wildlife trade, deforestation, clean air, and noise pollution. Similar observations were also made by Chakraborty and Maity [47]. Furthermore, Zambrano-Monserrate et al. [48] also linked COVID 19 pandemic with positive impact (clean beaches, reduction in noise pollution) and negative aspects (e.g., increase in household waste, reduced recycling).

Based on the emerging evidence, it is apparent that there will be a significant impact of COVID-19 on the physical, social, and behavioral aspects of health, as depicted in Fig. 2. The figure also highlights emerging norms, which brings focus on social determinants to promote health and equity. The COVID-19 pandemic has brought much societal influence in lower and middle-income countries and could help to align development with sustainable development goals (SDGs). The policymakers can tap on these opportunities, especially in lower and middle-income countries, to educate and make use of population perception into action for sustainability.

COVID-19 lockdown and natural versus anthropogenic emission

During the lockdown, all the major activities like transportation and small-scale industries were closed. However, the emissions from natural sources (i.e., wind-blown dust, pollens), households and other essential services that were still there can have a significant portion of emissions. Also, there were some severe air pollution episodes in China during the COVID-19 lockdown due to the formation of secondary air pollutants. Further, this reflects that meteorology plays a vital role in building air pollutants [6,7]. In China, despite the reduction in primary air pollutant sources during the lockdown, some haze events were reported due to local emissions and adverse meteorological conditions [49]. It was observed that meteorology and secondary air pollutants played a significant role in these high air pollution episodes due to the availability of precursors, indicating the role of atmospheric reactivity [10,11].

In a megacity like Delhi, which is considered one of the world's most polluted cities [50]. Mahato et al. [51] reported a ~53% reduction in NO_2 during the initial lockdown period. The apparent decline in NOx due to the closure of transportation activities there was increased O_3 and also night-time NO_3 radical. The reduction in NO emissions may also likely increase O_3 concentrations as the conversion reaction of NO and O_3 to form NO_2 is reduced due to the low presence of NO in ambient air [9].

However, the primary emissions of air pollutants reduced substantially, i.e., $PM_{2.5}$ by 43% [52], during the lockdown and also across the cities of the world reported by Chauhan and Singh [53]. This provides an opportunity to examine the new baseline of pollution from anthropogenic emissions and better understand the natural sources and atmospheric reactivity. The detailed analysis of studies' reporting changes in air quality during COVID-19 lockdown is presented in Table 2. The concentration of other pollutants such as SO_2 was also reported to be increased in some regions during the lockdown period and majorly attributed to the combustion of coal in thermal power plants and an increase in usage in households for cooking and heating purposes [8,9]. A sharp decline of 8.8% in global CO_2 emissions was also seen in the period of COVID-19 lock-

Table 2
Studies reported change in air pollution during COVID lockdown.

Study region	Highlights of the study	Reference
Bangladesh (Chittagong)	• During the lockdown, a reduction of 40%, 32%, and 13% was observed for Particulate Matter ($PM_{2.5}$, PM_{10}) and NO_2 when compared to the mean concentrations of these pollutants for the period 2012-2019.	[84]
Brazil (Sao Paulo)	• Up to 77.3%, 54.3%, and 64.8% reduction in NO, NO_2, and CO were reported to be connected with the lockdown when the data was compared to the five-year monthly mean. • Up to 30% increase in O_3 concentration was observed.	[85]
Brazil (Sao Paulo)	• A significant reduction of 34-68% was observed for 13 stations when compared against the BAU period of March 2020. • Similar reductions in NOx were observed for the National truck drivers' strike in the year 2018.	[86]
Brazil	• NO_2 (24.1-32.9%: based on median values) and CO (37.0-43.6%: based on median values) showed significant reduction compared with the previous year	[87]
Canada (Ontario)	• O_3 concentrations were lower at 12 monitoring stations when compared with previous data. • NO_2 and NO reduction were observed across Ontario.	[88]
China (Northern China)	• A reduction of 5.93%, 13.66, 6.76, 24.67, 4.58 percent was observed in $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, respectively. • Reduction of Particulate Matter ($PM_{2.5}$), and CO were partially influenced by the individual movement, whereas $PM_{10,}$ NO_2, and SO_2 were completely influenced.	[89]
China (Yangtze river delta region)	• WRF-Chem and CAMx based simulation showed a reduction in $PM_{2.5}$ (27-46%), SO_2 (16-26%), NOx (29-47%), and VOCs (37-57%), and no reduction in O_3 levels. • The study highlighted the additional contribution of residual pollution, residential sources and long-range transport.	[90]
China	• A large majority of the cities showed a decline in AQI, with a reduction in Particulate Matter ($PM_{2.5}$, PM_{10}), CO, NO_2, and $SO_{2,}$ whereas an increase in O_3. • Despite the restrictions imposed on motor vehicles and secondary industries, the higher air pollution in northern China was attributed to emissions from the residential sector.	[103]
China	• NO_2 concentration increased across China. • Particulate Matter ($PM_{2.5}$) kept steady or even increased in some areas due to COVID-19 lockdown. • In major cities, HCHO concentration was steady.	[91]
China	• The heavy haze was observed during the lockdown in eastern China due to secondary pollution. • A significant decrease in NO_x led to increased O_3 and night-time NO_3.	[92]
China	• Over East China, the Tropospheric NO_2 decreased, which was driven by COVID-19 lockdowns.	[49]
China	• Many of the cities showed a reduction in $PM_{2.5}$ • The reduction ratios of Particulate Matter ($PM_{2.5}$) concentration were found to be lower than the reduction ratios of precursor pollutants, somewhat attributed to unfavorable meteorology.	[104]
China (Shanghai)	• Nitrate concentration decreased by ~60%, which can reduce the NOx concentration. • Ammonium concentration decreased by ~45%. • It was observed that Particulate Matter ($PM_{2.5}$) could be mainly attributed to decreasing concentrations of nitrate and primary aerosols	[93]
China (Wuhan)	• Pollutants CO, NO_2, PM_{10}, $PM_{2.5}$ and SO_2 showed a reduction, whereas O_3 showed enhancement. • Mean mass concentration of nitrate, ammonium, sulfate, OC, EC and chloride decreased in 2020 compared with 2019. • The lockdown period observe an enhancement in the secondary formation of $PM_{2.5}$	[94]
China (Wuhan)	• Satellite data of TROPOMI showed a significant decline in NO_2 (up to 70% in populated areas)	[95]
China and Europe	• Substantial reduction in NOx (~56%) in all cities and increase in Ozone (17% in Europe and 36% in Wuhan) • Reduction in PM was higher in Wuhan than in European cities	[96]
China	• A positive association between Particulate Matter ($PM_{2.5}$ & PM_{10}), NO_2, CO, O_3 and a negative association between SO_2 with COVID-19 confirmed cases.	[124]
China	• A significant reduction in NO_2 (~30%) was observed. This might have decreased the total deaths due to air pollution.	[31]
China	• A total of 8911 NO_2-related deaths and 3214 $PM_{2.5}$ related deaths were averted in China due to improved air quality during the lockdown. • The study supported climate mitigation-related traffic restrictions and the transition to electric vehicles for human health benefits.	[97]

Table 2 (*Continued*)

Study region	Highlights of the study	Reference
China	• In urban areas, a reduction of ambient air pollutants was observed. • People were exposed to indoor air pollutants as lockdown forced them to remain indoors.	[63]
China	• In comparison with the previous year, Air Quality Index in cities dipped to 6.34 points as $PM_{2.5}$ concentration decreased by 7.05 μgm^{-3}.	[32]
China	• A higher mortality rate was observed in regions with poor air quality.	[98]
China	• Low Planetary Boundary Layer (PBL), which had reduced by 45%, coincided with a severe air pollution episode over northern China, triggering strong aerosol-PBL interactions.	[72]
China (Hubei)	• During COVID-19 lockdown (January 24–February 29, 2020), AOD and Angstrom's exponent decreased and increased. • The AOD values decreased by 39.2% & 29.4% and Angstrom's exponent values increased 31.0% & 45.3% in Hubei and Wuhan, respectively, because of the strict lockdown and restrictions.	[70]
China	• During COVID-19 lockdown in Hangzhou, China, NO_x decreased by 77%, which led to a significant O_3 increase. • Increased NO_3^- and SO_4^{2-} formation was observed during the COVID-19 lockdown due to increased secondary aerosol formation. • $PM_{2.5}$ decline (50%) was only partially compensated due to increasing aerosol formation.	[34]
Europe	• Over the whole continent, the NO_2 concentration decreased consistently. The reductions range from 5% to 55% compared to the same period in 2015–2019 for 80% of the sites considered.	[99]
India (Delhi NCR Region)	• In the Delhi NCR region, the Air Quality improved by 58%. • Particulate Matter ($PM_{2.5}$ & PM_{10}) levels decreased by 55-65%. • Maximum reduction was observed in the case of NO and NO_x (~ 50-78%). • Reduction observed in SO_2, CO, NH_3 and C_6H_6 were consistent and significant.	[64]
India (Delhi, Mumbai, Kolkata, Bangalore, Chennai)	• Among the five megacities of India, Delhi showed the highest reduction in $PM_{2.5}$ (41%) and PM_{10} (52%), Mumbai showed the highest reduction in NO_2 (75%), and CO (46%), and Kolkata showed the highest reduction in O_3 (17%) for before and during lockdown period of 2020. • When compared with the preceding year, Delhi showed the highest reduction in PM_{10} (52%) and CO (41%), Bangalore showed the maximum decrease in $PM_{2.5}$ (47%), and Kolkata showed the highest reduction in NO_2 (66%). • An increase in O_3 was observed in all five cities except Bangalore, where it showed an 11% decline for the comparison of before and during the lockdown period of 2020. However, for comparison of the lockdown period of the current and previous year, Delhi (14%) and Bangalore (21%) both showed a decline in O_3.	[100]
India (Dwarka region)	• The pre-lockdown PM_{10} levels of 189-278 $\mu g/m^3$ in the stone quarrying and crushing region of Dwarka river basin, reduced to 50-60 $\mu g/m^3$.	[105]
India (Delhi)	• Reduction of ~57% and 33% Particulate Matter (PM_{10} and $PM_{2.5}$) was observed in comparison to the previous data.	[51]
India	• The study in 22 cities of India observed a reduction of 43, 31, 18, and 10% in $PM_{2.5}$, PM_{10}, NO_2, and CO. • There was a 17% increase in O_3 and a minor change in SO_2.	[52]
India (Lucknow and Delhi)	• The concentration of Particulate Matter ($PM_{2.5}$) declined sharply on the 1st week of lockdown in both cities. However, on the last day of 1st phase of lockdown. • The levels of SO_2 did not show a significant change in both the cities	[106]
India	• 42-60% reduction in Particulate Matter ($PM_{2.5}$) and 46-61% in NO_2 according to Surface and satellite data. • An improvement of 21-56% in AQI provided the opportunity for future air quality policy-related changes.	[69]
India (Delhi & Mumbai)	• 40-50% reduction was observed in NO_2 levels against the previous year in Delhi and Mumbai.	[107]
India (17 cities)	• A decline in Particulate Matter (PM_{10} & $PM_{2.5}$), CO and NO_2, for the 17 cities of India was highest for Ahmedabad (67%), followed by Delhi (70%) and Bangalore (86%). • The pollutant reduction was higher for larger cities whereas lower for smaller towns. • Over a day, the highest decline was observed in the time period of 7:00-10:00 hrs and 19:00-22:00 hrs.	[108]
India (Gujarat)	• AQI of the state observed a reduction between 34-75%. • A most significant decline was observed for NO_2 (30-84%), which was linked with industrial activities and traffic.	[109]

Table 2 (*Continued*)

Study region	Highlights of the study	Reference
India	• During the lockdown, Particulate Matter (PM_{10} & $PM_{2.5}$) and NO_2 decreased in 134 sites across India. • A reduction of ~40–60% in PM_{10} & $PM_{2.5}$; ~20–40% in CO, ~30–70% in NO_2; and significant changes in O_3 and SO_2.	[71]
India (Delhi, Mumbai, and Singrauli)	• Reduction in Particulate Matter (PM_{10} & $PM_{2.5}$), NO_2, and SO_2 for Delhi were 55, 49, 60, and 19%, respectively. Whereas for Mumbai, the reduction was 44, 37, 78, and 39%, respectively. • For a small city Singrauli, the positive impact of lockdown on air quality was less and the only pollutant that showed a reduction in the case of Singrauli was NO_2 (12.5%)	[110]
India	• NO_2 (45%) and AOD (60%) reduced sharply during the lockdown. • The study also reports a reduction in $PM_{2.5}$ and NO_2 in six megacities.	[111]
India (Chennai)	• Particulate Matter ($PM_{2.5}$) concentration decreased during the lockdown (ranging from ~32 – 187%) • O_3 and SO_2 values increased during lockdown for two sites: Teynampet (~48% in O_3 and ~40% in SO_2) and Velachery (and ~5% in O_3 and~42% in SO_2), whereas decreased for Alandur (~50% in O_3 and ~30% in SO_2) and Manali (~247% in SO_2). • NO_x and CO showed a significant dip during the lockdown (~47–125%) for the studied locations.	[71]
India	• During the lockdown, the AOD values over eastern, central, and western India were high. • Emission sources of NO_2 and SO_2 were strong from Eastern India which were related to coal-fired power plants and coal mining.	[75]
Italy	• The study tested the hypothesis that atmospheric pollution of a region influenced the COVID-19 outbreak in Italy. • Northern Italy, which showed the highest level of contamination.	[112]
Italy	• A positive association between COVID-19 cases and levels of NO_2 was observed.	[113]
Italy (Milan)	• The city showed a significant reduction in vehicular pollutant CO. • SO_2 also showed a reduction in Milan, but not in the adjacent cities, which were related to the closure of workplaces in Milan. • Benzene in Milan was one of the reasons for increased O_3 concentrations besides the cause of minor NO concentration.	[114]
Kazakhstan (Almaty)	• Particulate Matter ($PM_{2.5}$) reduced by 21% compared to the previous two years. • More than 66% of the days of lockdown period, $PM_{2.5}$ exceeded the WHO daily limits, thus underlining the contribution of non-traffic sources. • CO and NO_2 also showed a significant reduction.	[115]
Malaysia	• Reduction in Particulate Matter ($PM_{2.5}$) observed over 50% of the monitoring stations during lockdown • An increment in $PM_{2.5}$ levels during lockdown at the background station was attributed to meteorology and other anthropogenic activities	[116]
Morocco (Sale)	• A reduction of 96, 75, 49% was observed for NO_2, PM_{10}, SO_2, respectively, and during the lockdown in comparison with historical data. • Long-range transport during lockdown impacted the reduction in PM_{10} adversely.	[117]
Spain (Barcelona)	• NO_2 and BC (45-51%) showed a significant reduction. • A lower reduction was observed for PM_{10} (28-31%).	[118]
Spain (multi-city)	• A significant reduction in NO_2 was observed during the lockdown in most of the cities but CO, SO_2, and PM_{10} in some cities increased, whereas the O_3 level increased.	[59]
Western Europe	• The study showed that lockdown decreased NO_2 followed by $PM_{2.5}$ but reported an alleviated effect on O_3 due to atmospheric reactivity.	[119]
USA (California)	• The study followed a statistical approach to observe a correlation between COVID-19 cases and air pollutants. • A significant correlation was observed for Particulate Matter ($PM_{2.5}$ & PM_{10}), NO_2, SO_2, and CO.	[120]
USA	• Historical pollution and current pollution concentrations were compared all around the country. • A significant decline in NO_2 concentrations was observed during the COVID-19 period (25.5% reduction with a decrease of 4.8 ppb) • A decrease in $PM_{2.5}$ concentration was observed during the COVID-19 period, which is significant in statistical terms in urban and rural counties.	[121]
Southeast Asia	• Reduction in Himawari-8 AOD. • Considerable reduction in NO_2 over urban areas.	[122]

Table 2 (*Continued*)

Study region	Highlights of the study	Reference
Multi-country study	• A substantial reduction was observed in NO_2 and AOD in several countries. • Although meteorological conditions cannot be directly related to positive cases, countries with a temperature between $4^{o}C \pm 2^{\circ}C$ to $\sim 19^{o}C \pm 2^{\circ}C$ and Absolute humidity of 4-9 gm^3 are at higher risk of COVID-19 outbreaks.	[123]
Multi-country study	• The concentration of particulate matter (PM2.5) in Beijing, Delhi, Dubai, Los Angeles, Mumbai, New York, Rome, Shanghai and Zaragoza, declined considerably.	[53]
Multi-country study	• Notable association between air quality improvement and contingency measures. • A negative aspect of lockdown involves a reduction in recycling, and the increase in waste, thus indirectly increasing air pollution besides water and land.	[48]
Multi-country study	• The highest $PM_{2.5}$ reduction (57%) was in Bogotá, Colombia. • The second-highest reduction of $PM_{2.5}$ (42%) was in Kuwait City. • The capitals of America, Africa and Asia saw the greatest $PM_{2.5}$ reductions.	[102]
China, Spain, France, Italy, USA	• A reduction of up to 30% was observed in NO_2 using OMI and TROPOMI. • For the US, the reduction was observed to be up to 30%.	[101]

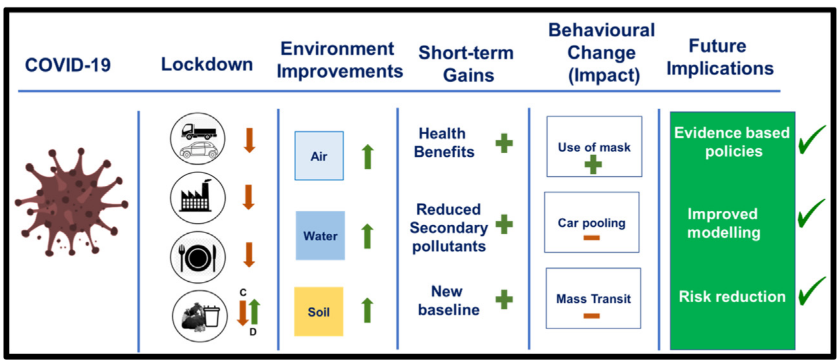

Fig. 1. Impact of COVID-19 lockdown on environment and its future implications for better air quality.

down, but with the unlocking phases, this effect diminished [4,5]. The forest fires are commonly observed in summer and emissions from forest fires and their transboundary movement degrade the air quality locally and in the regions. The air pollution emissions during harvesting and after the burning of crop residue in agricultural fields results typically in poor air quality in many regions across the world, including the Indian region [10,11]. However, the emission from the crop residue burning can be minimized using an integrated approach of technology, policy, and behavioral factors [10].

Apart from crop residue burning, the natural emission due to dust storms during the summers will also increase the atmospheric load of particulate matter. These sporadic peaks of high air pollution increase the risk for the vulnerable population and could further add to the disease burden due to respiratory and circulatory diseases. Extended lockdown, specifically in India and nearby countries, provided an opportunity to better understand air pollutants' natural and anthropogenic contributions. However, while making these estimates, the natural and meteorological variability should be considered as the contributions vary season-to-season and year-to-year.

Air pollution reduction during COVID-19 lockdown: learning for air pollution control strategies

The unprecedented steps of lockdown provided ecological design to study the reduction in air pollution in the absence of significant sources. The decrease in anthropogenic emissions resulted in a new season-specific baseline of air pollution. This can be computed in air pollution modeling and weather forecasting to improve air quality predictions, enabling timely measures, as also highlighted by Gurjar et al. [54] and Ravindra et al. [55]. Further, this will also allow authorities to understand and learn how, in the future, how the reduction in air pollution can also help to minimize the risk of emerging threats such as coronavirus and develop public health risk reduction strategies.

As a matter of fact, 'lockdown' cannot be a permanent or long-term solution for reducing air pollution levels in any geographical area. To bring back the economy, the various sectors would resume their activities sooner or later. Taking an example of India, post-Lockdown, considering the weather conditions, agricultural and industrial practices, festivals, and expected increase in human activities as well as reduced car-pooling or use of public/mass transport system, the present Air Quality Index may reach to alarmingly high levels. Hence, the national health programs on air pollution such as National Programme on Climate Change and Human Health (NPCCHH) and National Clean Air Programme (NCAP) could be tuned to adapt strategies learned during COVID-19 lockdown to promote social and behavioral factors that would protect the population from hazards of air pollution and promote better population health.

Considering the factual situation, policy interventions are needed to mitigate air pollution sources and promote alternative measures to reduce emissions and carbon footprint. The suggested actions may be a coordinated approach of related sectors, including adopting policies and technologies for source reduction of air pollution, increase in green cover, use of green technologies, and use of renewable resources such as solar power. Further, the cities should also focus on developing pedestrian/ cyclist-friendly infrastructure, promoting the non-motorized mode of transportation in

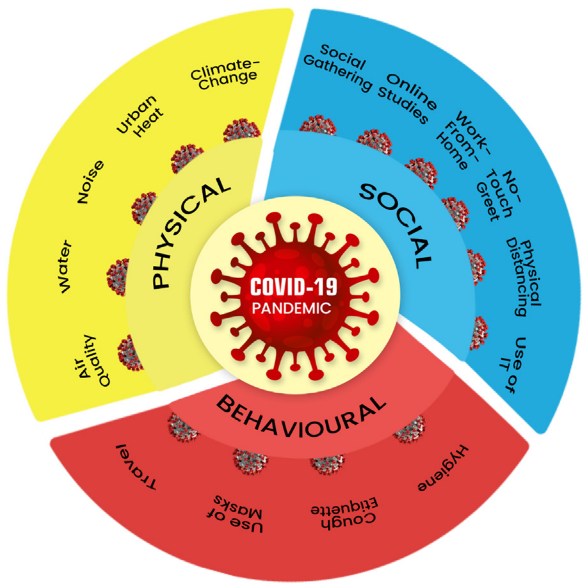

Fig. 2. Physical, social, and behavioral aspects of COVID-19 pandemic, including new norms.

a town for all ages and populations, including the differently-abled community. The policies related to other measures such as work-from-home, online classes, virtual conferences, telemedicine, and digital banking may be strengthened.

The worsening of the Air Quality Index is being envisaged to raise the number of cases suffering from respiratory as well as cardiovascular illnesses, especially in those who are co-morbid. The policy intervention shall be needed then to build the capacity of healthcare personnel to manage diseases due to air pollution. The healthcare infrastructure may further be strengthened by providing appropriate equipment and technology to manage cardio-respiratory illnesses. The surveillance system needs to be supported in terms of triangulation of health data with pollution level and meteorological parameters and issue of health warning alert in cases of rising Air Quality Index level.

Further, The contribution and role of primary air pollutants in the formation of secondary air pollution can be examined, including the atmospheric reactivity of certain pollutants. The contribution of non-exhaust emission [12,13] to the total road emissions can also be better estimated utilizing the lockdown air quality data. The lockdown also provides an opportunity to understand the contribution of natural emissions such as pollen, wind-blown dust, and dust storms to atmospheric pollution. The use of long-term lockdown air pollution data along with meteorology, health, and other parameters offers to explore new knowledge for evidence-based policies, which could help to better plan and minimize the risk of air pollution exposure in the global hotspots.

Conclusions

The spread of the COVID-19 disease caused a global health emergency and led to strict measures such as a lockdown. The route of COVID-19 is considered to be the spread of infectious aerosol and brought many new societal influences, such as the use of face cover or masks. After the pandemic, the use of masks could be more societally acceptable, especially in lower and middle-income countries. Accepting face masks and their extended usages will reduce air pollution exposure, resulting in reduced associated health risks, specifically during high pollution episodes. However, communities need to be educated about best practices as the inappropriate use of masks in high air pollution settings might give a false impression of security. Further, various social and behavioral factors needed to be addressed to help the early adoption of new norms and reduce the chances of contracting the infection. The pandemic also reiterates on social determinants and SDGs for better population health, well-being, and sustainability. The lockdown of cities and towns resulted in a decrease in emissions. It hence provided a unique opportunity to examine the contribution of various natural and anthropogenic sources of air pollution, including atmospheric chemistry and their reactivity. This offers potential for local and regional authorities to better understand the atmospheric emission sources to plan evidence-based short- and long-term mitigation strategies for air quality improvement and to minimize the associated burden of disease and disabilities.

Ethical approval

Not required.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

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Competing interests

None declared.

Availability of data and materials

Not applicable.

CRediT authorship contribution statement

Khaiwal Ravindra: Conceptualization, Methodology, Formal analysis, Validation, Writing – review & editing. **Tanbir Singh:** Methodology, Formal analysis, Validation, Writing – review & editing. **Shikha Vardhan:** Validation, Writing – review & editing. **Aakash Shrivastava:** Writing – review & editing. **Sujeet Singh:** Writing – review & editing. **Prashant Kumar:** Validation, Writing – review & editing. **Suman Mor:** Methodology, Formal analysis, Validation, Writing – review & editing.

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