

## Critical Review

# Exposure to air pollution and COVID-19 severity: A review of current insights, management, and challenges

Nurshad Ali,<sup>1</sup> Khandaker A. Fariha,<sup>1</sup> Farjana Islam,<sup>1</sup> Moshiul A. Mishu,<sup>1</sup> Nayan C. Mohanto,<sup>1</sup> Mohammad J. Hosen,<sup>2</sup> and Khaled Hossain<sup>3</sup>

<sup>1</sup>Department of Biochemistry and Molecular Biology, Shahjalal University of Science and Technology, Sylhet, Bangladesh

<sup>2</sup>Department of Genetic Engineering and Biotechnology, Shahjalal University of Science and Technology, Sylhet, Bangladesh

<sup>3</sup>Department of Biochemistry and Molecular Biology, University of Rajshahi, Rajshahi, Bangladesh

### Abstract

Several epidemiological studies have suggested a link between air pollution and respiratory tract infections. The outbreak of coronavirus disease 2019 (COVID-19) poses a great threat to public health worldwide. However, some parts of the globe have been worse affected in terms of prevalence and deaths than others. The causes and conditions of such variations have yet to be explored. Although some studies indicated a possible correlation between air pollution and COVID-19 severity, there is yet insufficient data for a meaningful answer. This review summarizes the impact of air pollution on COVID-19 infections and severity and discusses the possible management strategies and challenges involved. The available literature investigating the correlation between air pollution and COVID-19 infections and mortality are included in the review. The studies reviewed here suggest that exposure to air pollution, particularly to PM<sub>2.5</sub> and NO<sub>2</sub>, is positively correlated with COVID-19 infections and mortality. Some data indicate that air pollution can play an important role in the airborne transmission of SARS-CoV-2. A high percentage of COVID-19 incidences has been reported in the most polluted areas, where patients needed hospital admission. The available data also show that both short-term and long-term air pollution may enhance COVID-19 severity. However, most of the studies that showed a link between air pollution and COVID-19 infections and mortality did not consider potential confounders during the correlation analysis. Therefore, more specific studies need to be performed focusing on some additional confounders such as individual age, population density, and pre-existing comorbidities to determine the impact of air pollution on COVID-19 infections and deaths. *Integr Environ Assess Manag* 2021;00:1–9. © 2021 SETAC

**KEYWORDS:** Air pollution, COVID-19, Incidence, Mortality, Public health

### INTRODUCTION

Coronavirus Disease 2019 (COVID-19) is a great threat to global health (Ali et al., 2021). Healthcare professionals are struggling to treat COVID-19 patients efficiently (Ali, 2020a). First, COVID-19 was determined as a pneumonia outbreak in Wuhan, China, in December 2019, but later it spread around the world. However, many regions have been hit much worse in terms of incidence and mortality than others. The presence of multiple comorbidities and some factors in the environment can contribute to COVID-19 incidence and lethality rates. Some studies suggested that air pollution may be one of the contributors to the spread of COVID-19. However, the exact reasons for this observed variation between and within countries require more investigation.

Air pollution is associated with various diseases and premature deaths around the world (Global Burden of Disease, 2018). It has been reported that air pollution is connected with several respiratory diseases, for example, lung cancer, chronic pulmonary disease, acute respiratory infections and related deaths, and as well as with ischemic heart disease and stroke (Brauer, 2010). A common source of air pollution is attributable to the presence of suspended particulates, certain gases, and volatile organic substances in the atmosphere. These gases include nitrogen oxides (NO<sub>x</sub>), ammonia (NH<sub>3</sub>), ozone (O<sub>3</sub>), sulfur dioxides (SO<sub>2</sub>), and carbon monoxide (CO). The volatile compounds include benzene, toluene, ethylbenzene, and xylenes. Particulate matter (PM) is the sum of all liquid and solid particles suspended in the air, many of which cause adverse health effects. There are several sources of fine particles. Particulate matter is categorized as PM<sub>2.5</sub> and PM<sub>10</sub> (diameter less than 2.5 or 10 μm, respectively), where PM<sub>2.5</sub> is considered one of the important air pollutants and is associated with millions of deaths per year around the globe (Lelieveld et al., 2015). Both PM<sub>2.5</sub> and PM<sub>10</sub> in the atmosphere are mainly

**Correspondence** Nurshad Ali, Department of Biochemistry and Molecular Biology, Shahjalal University of Science and Technology, Sylhet 3114, Bangladesh.

Email: nur\_rubd@yahoo.com and nali-bmb@sust.edu

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associated with respiration-related disorders and prolonged hospital stays for pneumonia and lung disease (Brauer, 2010; Lelieveld et al., 2015). Besides PM, increased concentration of NO<sub>2</sub> in the atmosphere is toxic for respiratory systems in humans (Latzka et al., 2009). Nitrogen dioxide (NO<sub>2</sub>) enters the atmosphere from anthropogenic and natural activities and has harmful effects on the respiratory organ s— prolonged exposure is linked with a number of disorders (Lelieveld et al., 2015).

In a previous study, it has been shown that air pollution may increase mortality rates from severe acute respiratory syndrome coronavirus 2 (SARS-CoV) infections (Cui et al., 2003). Under the experimental circumstances, SARS-CoV-2 can remain viable and infectious in aerosols for hours, suggesting that aerosol and fomite may be a carrier of SARS-CoV-2 transmission (van Doremalen et al., 2020). However, the relationship of air pollution with high rates of COVID-19 infections is still unclear and requires further investigation.

Several studies suggested that outdoor levels of air pollution may be a carrier of the infection and significant risk factors of severity for COVID-19 (Conticini et al., 2020; Pozzer et al., 2020). Of the environmental quality parameters, some other conditions such as humidity, temperature, wind, and sunlight indicated a decreased spread of COVID-19 (Chen et al., 2020; Coccia, 2020a), and air pollution might play a positive role in airborne transmission of SARS-CoV-2 and COVID-19 severity (Domingo et al., 2020). Nevertheless, an interdisciplinary and multidimensional approach needs to be considered to gain an insight into COVID-19's diffusion and to draw a conclusion (Bontempi et al., 2020). Some studies reported a possible link between air pollution and COVID-19 infections and deaths. However, still, there is a lack of data-dependent studies on this topic.

In this review paper, we summarized the potential impact of air pollution on COVID-19 incidence and deaths. We identified the scientific literature available on this topic, which may still be limited; many environmental studies are currently underway and their results will add greatly to what is known at present. Moreover, from this compiled information, we discussed the challenges associated with linking air pollution to both impaired health and mortality from COVID-19 and identified. We also discussed about the preliminarily management strategies for rapid reductions in air pollution in developing countries and urban areas as part of the overall strategy for combating this global pandemic.

## METHODS

We undertook a search of the published scientific literature for peer-reviewed relevant studies describing the relationship between air pollution and the COVID-19 outbreak. We considered the available data to assess knowledge in this area. Inclusion criteria were as follows: (i) we chose studies that fit with the aims of this review, (ii) papers published in peer-reviewed journals between January 1, 2000 and December 31, 2020, and (iii) papers written in the English language. Exclusion criteria were as follows: (i) we excluded letter, as well as opinion-type papers

on this topic, and (ii) we also excluded papers published before January 2000. We relied upon scientific databases PubMed and Medline, Science Direct, Google Scholar, MedRxiv, and arXiv to search and select relevant literature applying the following keywords: SARS-CoV-2 or COVID-19 with air pollution, particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>), NO<sub>2</sub>, SO<sub>2</sub> and O<sub>3</sub>.

## RESULTS

### *Impact of short-term exposure to air pollution on COVID-19*

Short-term exposure has been defined as exposure to air pollution within 2 months. The available studies that reported the short-term effects of air pollution on COVID-19 incidence and deaths are presented in Table 1. A study in the United States reported a correlation between short-term exposure to air pollution and the COVID-19 pandemic (Bashir et al., 2020). In China, a study reported a positive correlation of air quality index (AQI) with the prevalence of COVID-19 in Xiao Gan and Wuhan (Li et al., 2020). Among air pollutants, PM<sub>2.5</sub> and NO<sub>2</sub> showed a strong correlation with COVID-19 incidence. In another study in Wuhan, a positive correlation was also found between PM<sub>2.5</sub> and the number of COVID-19 deaths per day (Jiang & Xu, 2021). Another study in Italy found that an increased AQI by 10 units was responsible for an increase in the spreading of SARS-CoV-2 from 5% to 7% (Zhang et al., 2020). A positive association was also noticed between air pollutants (PM<sub>10</sub>, PM<sub>2.5</sub>, O<sub>3</sub>, and NO<sub>2</sub>) and COVID-19 cases in 120 cities in China (Zhu et al., 2020). In the same country, PM<sub>2.5</sub> and PM<sub>10</sub> showed a positive association with the case fatality rate after adjusting relative humidity, temperature, and other variables (Yao et al., 2020). An increased concentration of ambient CO has been shown as one of the risk factors of rapid SARS-CoV-2 transmission, whereas high temperature, air pressure, and active ventilation were associated with reduced viral transmission (Lin et al., 2020).

A study analyzed the geographical characteristics of COVID-19 infections and made a correlation with different annual satellites and ground AQI in France, Germany, Iran, China, Italy, Spain, the United Kingdom and the United States of America (Pansini & Fornacca, 2020). After adjustment of population size, increased viral infections were found in those areas where increased levels of NO<sub>2</sub> and PM<sub>2.5</sub> were present. Poor air quality also showed a relationship with a higher mortality rate from COVID-19 (Pansini & Fornacca, 2020). In France, a study noted a positive correlation of PM<sub>10</sub> and PM<sub>2.5</sub> with COVID-19 deaths (Magazzino et al., 2020).

In Italy, a study that used data from more than 100 cities reported an association of PM<sub>10</sub> with the spreading of COVID-19 (Setti et al., 2020). In this study, the authors suggested that PM<sub>10</sub> might act as a carrier of droplet nuclei and may influence SARS-CoV-2 transmission (Setti et al., 2020). This finding was supported by further investigation, where a link between air pollution and the extended diffusion of COVID-19 has been observed (Coccia, 2020b).

TABLE 1 List of available studies that determined the effects of air pollution on COVID-19

Reference	Study period	Country (areas)	Major findings
Li et al. (2020)	Jan 26–Feb 29, 2020	China (Wuhan and XiaoGan)	A positive correlation was observed between AQI and COVID-19 incidence in both cities. Among air pollutants, PM <sub>2.5</sub> and NO <sub>2</sub> showed the highest correlation with COVID-19 incidence.
Lin et al. (2020)	Jan 21–April 3, 2020	China (29 provinces)	Increased concentration of CO was the risk factor of rapid spreading of SARS-CoV-2, while increased temperatures, active ventilation and air pressure were associated with reduced viral transmission.
Zhang et al. (2020)	Jan 24–Feb 29, 2020	China (219 prefecture cities)	Air pollution was positively correlated with COVID-19 cases. Increased AQI by 10 units was associated with the spread of SARS-CoV-2 from 5% to 7%.
Zhu et al. (2020)	Jan 23–Feb 29, 2020	China (120 cities)	Air pollutants (PM <sub>2.5</sub> , PM <sub>10</sub> , NO <sub>2</sub> and O <sub>3</sub> ) showed a positive correlation with COVID-19 cases.
Yao et al. (2020)	Jan 19–Mar 15, 2020	China (Wuhan)	PM <sub>2.5</sub> and PM <sub>10</sub> showed a positive association with the case fatality rate (CFR) after adjustment of temperature and relative humidity and other variables.
Jiang and Xu (2021)	Jan 25–April 7, 2020	China (Wuhan)	A positive correlation was found between PM <sub>2.5</sub> and COVID-19 deaths per day.
Pansini and Fornacca (2020)	Not available	China, France, Germany, Iran, Italy, Spain, United Kingdom and the USA	Increased SARS-CoV-2 infections were found in those regions where high levels of PM <sub>2.5</sub> and NO <sub>2</sub> were present. A correlation was observed between air quality levels and COVID-19 transmission and deaths.
Hoang et al. (2020)	Feb 24–Sep 13, 2020	South Korea (Seoul-Gyeonggi and Daegu-Gyeongbuk)	NO <sub>2</sub> concentration showed a positive association with daily confirmed COVID-19 cases. The effect of PM <sub>2.5</sub> , CO, and SO <sub>2</sub> on COVID-19 infection was different between the regions.
Travaglio et al. (2021)	Upto April 10, 2020	England	Poor air quality markers, such as NO and SO <sub>2</sub> were associated with an increased rate of COVID-19 related deaths when population density was adjusted.
Konstantinoudis et al. (2021)	Up to Jun 30, 2020	England	Every 1 µg/m <sup>3</sup> increase in NO <sub>2</sub> and PM <sub>2.5</sub> was associated with an increase of 0.5% and 1.4% in the COVID-19 deaths rate, respectively, after controlling for confounders.
Magazzino et al. (2020)	NA	France (3 cities)	A positive relationship was found between PM <sub>2.5</sub> and PM <sub>10</sub> and COVID-19 deaths.
Ogen (2020)	Jan–Feb 2020	France, Germany, Italy, and Spain	Higher rates of mortality were observed in some regions where NO <sub>2</sub> was present at the highest concentrations combined with downward air pressure.
Mele and Magazzino (2020)	Jan 29–May 18, 2020	India (25 cities)	A direct relationship was noticed between increased levels of PM <sub>2.5</sub> and COVID-19 deaths.
Zoran et al. (2020a)	Jan 1–April 30, 2020	Italy (Milan)	A positive correlation was observed between COVID-19 infections and ground-level O <sub>3</sub> .
Zoran et al. (2020b)	Jan 1–April 30, 2020	Italy (Milan)	PM and AQI were positively correlated with daily new cases of COVID-19.
Fattorini and Regoli (2020)	Up to April 27, 2020	Italy (71 provinces)	A positive correlation was found between long-term air quality data and COVID-19 cases.
Setti et al. (2020)	Feb 24–Mar 13, 2020	Italy (110 provinces)	An association was found between daily PM <sub>10</sub> exceedances and the initial spreading of COVID-19.

(Continued)

TABLE 1 (Continued)

Reference	Study period	Country (areas)	Major findings
			Authors suggested that PM <sub>10</sub> may influence the SARS-CoV-2 transmission.
Coker et al. (2020)	Jan 1–April 30, 2020	Italy (Northern parts)	An association was found between ambient PM <sub>2.5</sub> levels and high mortality rate from COVID-19.
Coccia (2020b)	Mar 17–April, 2020	Italy (Northern parts)	An association was noticed between air pollution and the vast diffusion of COVID-19.
Frontera et al. (2020)	Up to Mar 31, 2020	Italy	Increased rates of COVID-19 infection and deaths were observed in the highly polluted region.
Fiasca et al. (2020)	2016–2020 (Mar–Oct 2020)	Italy	After adjustment of old age index and population density, increased concentrations of PM <sub>2.5</sub> and NO <sub>2</sub> were associated with the incidence of COVID-19.
Filippini et al. (2020)	Feb 23–Apr 22, 2020	Italy (2 regions)	In multivariable negative binomial regression analysis, a positive association was found between NO <sub>2</sub> and COVID-19.
Hutter et al. (2020)	Feb 28–Apr 21, 2020	Vienna, Austria	In Vienna, Austria, PM <sub>10</sub> and NO <sub>2</sub> showed a positive association with the risk of COVID-19 diagnosis after adjusting for population age and other variables (e.g., percentage of foreign nationals, university degree, unemployment status and population density in the regression model).
Vasquez-Apestegui et al. (2020)	Up to Jun 12, 2020	Peru (20 districts in Lima)	Previous long-term PM <sub>2.5</sub> exposure was associated with higher rates of COVID-19 transmission.
López-Feldman et al. (2021)	2018–2020	Mexico city, Mexico	PM <sub>2.5</sub> increased the probability of deaths from COVID-19. The effect was increased with age (40 years or older).
Andree (2020)	Upto Mar 31, 2020	The Netherlands (355 municipalities)	PM <sub>2.5</sub> was an important predictor of COVID-19 incidence and hospital stay. An increased pollutant concentration by 20% was related to almost 100% of COVID-19 incidence.
Hendryx and Luo (2020)	Upto May 31, 2020	USA	COVID-19 incidence and death rates were positively correlated with the larger diesel particulate matter (DPM).
Wu et al. (2020)	Upto April 04, 2020	USA (3000 counties)	An increase of only 1 µg/m <sup>3</sup> in long-term PM <sub>2.5</sub> exposure was associated with an increased deaths rate (8%) from COVID-19.
Bashir et al. (2020)	Mar 4–April 24, 2020	USA (California)	Air pollutants such as PM <sub>10</sub> , PM <sub>2.5</sub> , SO <sub>2</sub> , NO <sub>2</sub> , and CO showed a positive correlation with the COVID-19 pandemic.
Adhikari & Yin (2020)	Mar 1–April 20, 2020	USA (New York)	Short-term exposures to O <sub>3</sub> and other meteorological factors may be related to COVID-19 transmission and disease initiation, but disease progression and deaths may depend on other potential factors.
Liang et al. (2020)	Jan 22–April 29, 2020	USA (nationwide)	County-level average NO <sub>2</sub> concentrations showed a positive association with both COVID-19 case-fatality rate and mortality rate. PM <sub>2.5</sub> showed a marginal association with a 10.8% increase in COVID-19 mortality rate, however long-term exposure to PM <sub>2.5</sub> or O <sub>3</sub> did not show a association with COVID-19 deaths.

(Continued)

TABLE 1 (Continued)

Reference	Study period	Country (areas)	Major findings
Meo et al. (2021)	Mar 19–Sep 22, 2020	10 countries, California, USA	PM <sub>2.5</sub> , CO, and O <sub>3</sub> concentrations showed a temporal association with the increase in the incidence of and mortality due to COVID-19.
Chakrabarty et al. (2020)	Mar 2–Apr 30, 2020	USA	Long-term air pollution renders a population more susceptible to COVID-19.
S. Liu and Li (2020)	2017–2019	USA	In regression analysis ground-level O <sub>3</sub> and NO <sub>2</sub> were positively correlated with county-level mortality rates of COVID-19 after controlling for confounders (household income, hospital beds availability, population density, and days since first confirmed COVID-19 case).
Pozzer et al. (2020)	Year 2019	Global	Particulate air pollution contributed about 15% to COVID-19 mortality worldwide, 27% in East Asia, 19% in Europe, and 17% in North America.

This study also suggested that polluted air increased SARS-CoV-2 transmission to individuals through person-to-person transmission. Increased rates of COVID-19 infection and deaths were also observed in highly polluted regions in Italy (Frontera et al., 2020). Applying the “double-hit hypothesis,” the authors also proposed that prolonged exposure to PM<sub>2.5</sub> leads to overexpression of the alveolar ACE-2 receptor, which may expand the viral load in subjects exposed to air pollutants, in turn reducing ACE-2 and impairing the host defense system. Furthermore, short-term exposure to air pollutants such as O<sub>3</sub> and some meteorological parameters can also be related to the spread of COVID-19 and may lead to its incidence, but the disease progression and death rates may depend on other potential factors (Adhikari & Yin, 2020). In multivariable negative binomial regression models, a positive association was observed between NO<sub>2</sub> and COVID-19 deaths in Italy (Filippini et al., 2020). In a study in Vienna, Austria, PM<sub>10</sub> and NO<sub>2</sub> showed a positive association with the risk of COVID-19 diagnosis after adjusting for population age and other variables (e.g., percentage of foreign nationals, university degree, unemployment status, and population density in regression analysis) (Hutter et al., 2020).

#### **Impact of prolonged exposure to air pollution on COVID-19**

Prolonged exposure has been defined as exposure to air pollution for more than 2 months. Table 1 presents the available studies that indicate the long-term effects of air pollution on COVID-19 incidence and deaths. In the United States of America, a large-scale study reported a relationship between prolonged PM<sub>2.5</sub> exposure and risk of death due to COVID-19 after adjusting for confounding variables (Wu et al., 2020). In that study, the authors also indicated that an increase of 1 µg/m<sup>3</sup> in PM<sub>2.5</sub> exposure was associated with an increased death rate (about 8%) due to COVID-19 (Wu et al., 2020). Another nationwide study in the

United States of America indicated a positive relationship between country-level mean NO<sub>2</sub> concentrations and COVID-19 infection and death rates in different pollutant models (Liang et al., 2020). In that study, PM<sub>2.5</sub> showed a marginal association with 10.8% increases in COVID-19 mortality rate; however, long-term exposure to PM<sub>2.5</sub> or O<sub>3</sub> did not show an association with COVID-19 deaths outcome. In a study in California, USA, PM<sub>2.5</sub>, CO, and O<sub>3</sub> concentrations showed a temporal association with an increase in the incidence of, and mortality due to, COVID-19 (Meo et al., 2021). In a regression analysis, ground-level O<sub>3</sub> and NO<sub>2</sub> showed a positive correlation with county-level COVID-19 death rates in the United States, after controlling confounders such as household income, hospital bed availability, and population density (S. Liu & Li, 2020). In Mexico City, PM<sub>2.5</sub> showed a trend for increasing the probability of deaths from COVID-19 and the effect was greater with age (40 years or older) (López-Feldman et al., 2021). A study in Germany, France, Italy, and Spain showed a correlation of NO<sub>2</sub> exposure with COVID-19 deaths (Ogen, 2020). In this study, adjustment to some covariates such as age distribution and population size was not considered during the analysis of the results.

The evidence for the association of NO<sub>2</sub> exposure to increased mortality is not nearly as strong as for PM<sub>2.5</sub> (Atkinson et al., 2018); therefore, other potential confounders should be considered during the analysis of the correlation between air pollution and increased rates of mortality. A study conducted in Italy showed a positive correlation between a high concentration of air pollutants and COVID-19 mortality (Conticini et al., 2020). Another study, using data from 71 provinces in Italy, indicates a positive correlation of air quality with COVID-19 incidence, giving further evidence that prolonged air pollution could influence viral transmission (Fattorini & Regoli, 2020). A positive correlation has also been found between AQI, PM, and ground-level O<sub>3</sub> and COVID-19 incidence (Zoran et al., 2020a, 2020b). Another study showed

an association of PM<sub>2.5</sub> levels with a high mortality rate from COVID-19 (Coker et al., 2020). In that study, per unit rise in PM<sub>2.5</sub> levels ( $\mu\text{g}/\text{m}^3$ ) caused increased (9%) COVID-19-related mortality (Coker et al., 2020). After adjustment of population density and age, increased concentrations of PM<sub>2.5</sub> and NO<sub>2</sub> were associated with COVID-19 incidence in Italy (Fiasca et al., 2020).

A study on collected data from the US Environmental Protection Agency (EJSCREEN) showed a positive correlation between COVID-19 infections and deaths with higher levels of diesel particulate matter (DPM) (Hendryx & Luo, 2020). In the Netherlands, a study using data from 355 municipalities indicated PM<sub>2.5</sub> as an important indicator of COVID-19 incidence and hospital stay (Andree, 2020). An increased pollutant concentration by 20% was related to almost 100% of COVID-19 incidence (Andree, 2020). In England, a study showed that every  $1 \mu\text{g}/\text{m}^3$  increase in PM<sub>2.5</sub> and NO<sub>2</sub> was associated with increases of 0.5% and 1.4% in the COVID-19 death rate, respectively, after controlling for confounders (Konstantinou et al., 2021). Another study in England provided further evidence on the relationship of air pollution with COVID-19 severity (Travaglio et al., 2021). In that study, a relationship was found between pollutants emitted from fossil fuels and vulnerability to viral infections (Travaglio et al., 2021). The authors showed the association without adjustment for age distribution, population size, and other potential variables (Travaglio et al., 2021). However, this result further indicates that individuals exposed to prolonged air pollution are more vulnerable to SARS-CoV-2 infections.

Furthermore, a study in India reported a relationship of an increased PM<sub>2.5</sub> level with COVID-19 deaths (Mele & Magazzino, 2020). In two clusters of South Korea (Daegu–Gyeongbuk and Seoul–Gyeonggi), NO<sub>2</sub> concentration showed a positive association with the daily rate of confirmed COVID-19 cases (Hoang et al., 2020). The effect of PM<sub>2.5</sub>, CO, and SO<sub>2</sub> on COVID-19 infection varied within regions. In Peru, a higher rate of COVID-19 incidence was associated with prior prolonged exposure to PM<sub>2.5</sub> (Vasquez-Apestegui et al., 2020). A global study reported that particulate air pollution causes about 15% of COVID-19 deaths around the globe, 19% in Europe, 27% in East Asia, and 17% in North America (Pozzer et al., 2020). It has been reported that air pollution can interrupt the body's general defenses versus various airborne microorganisms, which include SARS-CoV-2 (Myllyvirta & Thieriot, 2020).

## DISCUSSION

Existing literature suggests that both short-term and long-term air pollution may increase COVID-19 infections and mortality. A high prevalence of COVID-19 infections and deaths was observed in the highly polluted regions, which may be linked with immune response. Investigational studies performed for other respiratory viruses support the hypothesis that exposure to air pollution may facilitate COVID-19 infections through a weakened immune response. In animal and human studies, it has been

demonstrated that exposure to air pollutants enhances mucosal permeability and oxidative stress, reduces surfactant antimicrobial proteins and antioxidants, as well as hinders macrophage phagocytosis (Cieniewicz & Jaspers, 2007; Frampton et al., 1989). In previous pandemics, a compromised immune defense due to air pollution was noticed in patients with acute pneumonia (Cui et al., 2003; Min et al., 2016). Available data also indicate that increased COVID-19 deaths might be related to cytokine storm syndrome (Mehta et al., 2020).

In addition to air pollutants, reduced temperature, the prevalence of lung cancer, decreased vitamin D levels, UV index, and smoking may influence the spread of COVID-19 infections (Ali, 2020b; Notari & Torrieri, 2020). Pre-existing heart disease, diabetes, liver disease, and other medical conditions may also worsen COVID-19 severity (Ali & Hossain, 2020; Ali, 2020c; Ejaz et al., 2020). It is worthwhile to indicate that industrialized urban areas have increased levels of air pollutants (e.g., NO<sub>2</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>), increased population density, and higher rates of COVID infections and mortality in the initial stages of the pandemic. Therefore, even though the correlation is evident in the referenced studies, such correlation does not indicate a causal association of air pollution with COVID-19 fatalities. Further possible confounding effects should be considered during such correlation analysis.

It has been suggested that some confounders such as male sex, older age, and increased population density may contribute to the higher rates of incidence and mortality from COVID-19 (Contini & Costabile, 2020; Pansini & Fornacca, 2020). Data now available in many countries showed a strong effect of age and pre-existing comorbidities on mortality rates from COVID-19. The level of available medical care and the socioeconomic status of local populations may also be important. Higher air pollution levels are frequently correlated with lower socioeconomic status. A cross-sectional study reported that demographic, climatic (not temperature), and social factors play an important, and hypertension prevalence are associated with COVID-19-related deaths (Rodriguez-Villamizar et al., 2021). Also, social distancing may have a positive impact in reducing COVID-19 transmission. A football match held on February 19, 2020, between Atalanta and Valencia was attended by 40,000 fans in a stadium with no social distancing, followed by a large increase in cases and subsequent mortality in the areas of Italy and Spain with high NO<sub>2</sub> levels.

The weather may also have an impact on COVID-19. It has been suggested that higher temperatures and higher relative humidity may eliminate the viability of the virus (Chan et al., 2011; Şahin, 2020). A nonlinear relationship was found between temperature and SARS-CoV-2 transmission (Zhang et al., 2020). Severe acute respiratory syndrome coronavirus 2 may persist in the air through complex interactions with gases and particles, which may depend on chemical composition, charges of particles, and meteorological factors such as temperature, UV radiation, and relative humidity. Therefore, determining the causal effect and getting an exact

estimate of air pollution effects on COVID-19 incidence and mortality require rigorous and time-consuming research (Heederik et al., 2020).

Although most of the available data suggest a link between air pollution and COVID-19 severity, precautions should be taken in interpreting these study findings, as the infections are still ongoing in many countries. Studies also suggested that short-term exposure to air pollutants (especially  $O_3$ ) and some meteorological factors may influence the spread of COVID-19, but the aggravation of disease and fatality may depend on several parameters (Adhikari & Yin, 2020). Therefore, in addition to possible airborne SARS-CoV-2 transmission, other factors and virus spreading routes in humans should be considered while interpreting the impact of air pollution on COVID-19 severity. Previously, it has also been shown that SARS infections were more likely to be fatal if the infected individuals stayed in the extremely polluted regions for a longer period (Cui et al., 2003).

Long-term  $NO_2$  exposure, which largely emits from traffic, may increase susceptibility to the adverse outcomes of COVID-19, independent of  $O_3$  and  $PM_{2.5}$  exposure (Liang et al., 2020). Therefore, making a greater effort to lower ambient air pollution and traffic emissions may be an effective approach in reducing COVID-19-related mortality. Lockdown strategies may also reduce air pollution as observed in some parts of China and India (Singh & Chauhan, 2020; Wang et al., 2020). A study from China suggests that a longer life expectancy may be gained by reducing the ambient  $PM_{2.5}$  levels (Qi et al., 2020). Restriction of movement of people for certain periods could also reduce viral transmission. A study in China indicated that the movement of people could be one important stimulator of COVID-19 transmission (K. Liu, Ai, et al., 2020). Implementing some policy interventions, such as shelter-in-place could reduce mobility, would result in fewer crowds and less human contact; as a result, the rapid spread of COVID-19 can be prevented.

However, limited treatment and health resources, especially in lower-middle-income countries, may be a barrier in combating COVID-19. Moreover, insufficient treatment facilities for poor people who live in highly polluted industrial or slum areas may influence the incidence of and mortality from COVID-19. Therefore, increased attention needs to be paid to these unprivileged people, who are vulnerable to exposure to high levels of air pollution. Furthermore, exposure to indoor pollution is important, as people spend most of their time indoors. Several indoor sources such as cooking, smoking, candle burning, and badly installed wood-burning units with poor ventilation may pollute the indoor air. Thus, the role of indoor air pollution in COVID-19 should be taken into consideration.

### Conclusions and recommendations

The available data show that both long-term and short-term air pollution may play an important role in the airborne spreading of SARS-CoV-2 and may enhance the severity of

COVID-19. An increased rate of COVID-19 infections and deaths was more frequently observed in highly air polluted areas than elsewhere. Exposure to  $NO_2$  and  $PM_{2.5}$  was more often correlated with COVID-19 infections and mortality than  $PM_{10}$ . However, differences in lockdown strategies, infection stage, geographical location, socioeconomic components, air quality, and meteorological parameters may be associated with the variations in the available study findings.

Besides outdoor air pollution, the role of indoor air pollution in COVID-19 should be examined in future studies. Moreover, our surrounding environment should also be considered, as it may exacerbate COVID-19 infections. The previous studies that determined the relationship between air pollution and COVID-19 severity had several limitations, for example, most of them were ecological, retrospective, and cross-sectional, and did not account for potential confounders in their analysis. A simple correlation analysis will not be effective in determining the impact of air pollution on COVID-19 morbidity and mortality. Therefore, more specific studies are required focusing on potential confounders such as age, population density, and pre-existing comorbidities in exploring the interactions between air pollution and SARS-CoV-2 and their adverse effects on human health. Government and policymakers from environmental and health sectors should consider integrated approaches that can reduce air pollution and related outbreaks in the future. Also, an understanding of the nature of the SARS-CoV-2 may be useful in determining effective strategies for alleviating the disease and fighting against similar pandemics in the future.

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### CONFLICT OF INTEREST

The authors declare that there are no conflict of interests.

### AUTHOR CONTRIBUTION

*Conceptualization:* Nurshad Ali. *Data acquisition and analysis:* Khandaker A. Fariha, Farjana Islam, Moshui A. Mishu, and Nayan C. Mohanto. *Drafting of the manuscript:* Nurshad Ali. *Critical review of the manuscript:* Mohammad J. Hossen and Khaled Hossain. *Supervision:* Nurshad Ali.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the published literature and are also cited in the present manuscript.

### ORCID

Nurshad Ali  <http://orcid.org/0000-0003-1649-0887>

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