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Positive association between outdoor air pollution and the incidence and severity of COVID-19. A review of the recent scientific evidences

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ABSTRACT

In June 2020, we published a review focused on assessing the influence of various air pollutants on the transmission of SARS-CoV-2, and the severity of COVID-19 in patients infected by the coronavirus. The results of most of those reviewed studies suggested that chronic exposure to certain air pollutants might lead to more severe and lethal forms of COVID-19, as well as delays/complications in the recovery of the patients. Since then, a notable number of studies on this topic have been published, including also various reviews. Given the importance of this issue, we have updated the information published since our previous review. Taking together the previous results and those of most investigations now reviewed, we have concluded that there is a significant association between chronic exposure to various outdoor air pollutants: PM_{2.5}, PM₁₀, O₃, NO₂, SO₂ and CO, and the incidence/risk of COVID-19 cases, as well as the severity/mortality of the disease. Unfortunately, studies on the potential influence of other important air pollutants such as VOCs, dioxins and furans, or metals, are not available in the scientific literature. In relation to the influence of outdoor air pollutants on the transmission of SARS-CoV-2, although the scientific evidence is much more limited, some studies point to PM_{2.5} and PM₁₀ as potential airborne transmitters of the virus. Anyhow, it is clear that environmental air pollution plays an important negative role in COVID-19, increasing its incidence and mortality.

1. Introduction

Numerous scientific evidences have linked outdoor air pollution to the occurrence of a number of cardiovascular and respiratory diseases, including chronic obstructive pulmonary disease (COPD), asthma, and some typus of cancer, among others (Bălă et al., 2021; Dominski et al., 2021; Orellano et al., 2020), being also associated with infectious diseases transmission (Domingo and Rovira, 2020). Regarding viruses specifically, air pollution, which is considered a mixture of a number of chemicals such as CO, NO_x, O₃, sulfur SO_x, particular matters (PM), and volatile organic compounds (VOCs), may enhance respiratory infections (Domingo and Rovira, 2020; Rodrigues et al., 2019). It can be due to the prolongation of the aerosol transmission of viruses, and also to enhance the ability of viruses to invade airway epithelial cells. Moreover, air pollution can also aggravate respiratory symptoms by inhibiting the expression of key inflammatory mediators (Cooper and Loxham, 2019).

The airborne transmission of SARS-CoV-2 is evident (Morawska and Cao, 2020). In turn, both air pollution and COVID-19 lead to respiratory health risks and mortality. Although air pollution is directly related with

acute and chronic health effects, including increased risk of respiratory infections, the scientific evidence related to COVID-19 is more limited. In recent months, a number of studies have highlighted the importance of air pollutants in COVID-19 transmissibility, suggesting potential mechanisms that would explain this connection. It has been argued that droplets with virus particles may bind to particulate matter (PM), which might promote the diffusion of virus droplets in the air (Setti et al., 2020a; Morawska and Milton, 2020; Zoran et al., 2020a,b).

In spite of the huge number of studies -more or less directly related with SARS-CoV-2/COVID-19- published in the last 18–20 months, some controversial questions remain still without a clear response. One of the most relevant issues is the lack of sufficient scientific evidence on the origin of SARS-CoV-2 (Domingo, 2021a,b). Another one is the association between exposure to air pollutants with the transmission of SARS-CoV-2 and the severity of the COVID-19. In June 2020, we published a review-paper that summarized the scientific information available at that time on that important issue. The terms “air pollution/pollutants” and “COVID-19/SARS-CoV-2” were used for the search in the databases. The results of most of the studies reviewed

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suggested/concluded that chronic exposure to certain air pollutants might lead to more severe and lethal forms of COVID-19, delaying/-complicating the recovery of patients suffering the disease (Domingo et al., 2020). Since then, the results of a considerable number of new studies have been published. Therefore, to summarize all this new information should be of interest. Consequently, the present review-paper was aimed at assessing again the influence of outdoor air pollution on the transmission of SARS-CoV-2 and its relationship with the morbidity/mortality of COVID-19.

The databases Pubmed (<https://pubmed.ncbi.nlm.nih.gov/>) and Scopus (<https://www.scopus.com/>) were used. The terms for the search were “transmission of SARS-CoV-2 AND air pollution” and “air pollution/air pollutants AND COVID-19”. The period for the search of the scientific literature covered between June 2020 (when our previous review on this topic was published) and August 10, 2021. The reviewed studies are next summarized, being classified by continents, and by countries in each continent. For each country, they are discussed according to the respective dates of publication, from least to most recent.

2. Recent studies by continents and countries

2.1. Asia

2.1.1. China

Li et al. (2020) conducted an exploratory analysis looking for the potential association between environmental conditions and COVID-19 incidence/mortality in Wuhan and XiaoGan. Air quality index (AQI), 4 air pollutants (PM_{2.5}, PM₁₀, NO₂ and CO), as well as 5 meteorological variables were examined. It was found that PM_{2.5} and NO₂ could promote the transmission of COVID-19, while temperature was also associated with an increased incidence of the disease. In turn, Jiang et al. (2020) studied the potential association of air pollutants and meteorological variables with daily COVID-19 incidence, as well as the factors influencing the SARS-CoV-2 pandemic in Wuhan, Xiaogan and Huanggang. The air pollutants included in that study were the following: PM_{2.5}, PM₁₀, SO₂, CO, NO₂ and O₃. It was observed that PM_{2.5} and humidity were associated with an increased risk of COVID-19. In contrast, PM₁₀ and temperature were associated with a decreased risk of COVID-19. Also, in the line of determining the factors significantly contributing to the transmissibility of SARS-CoV-2, Lin et al. (2020) investigated the impact of meteorological factors and air quality in various regions of mainland China. Their study involved meteorological parameters and the concentrations of CO, PM_{2.5}, PM₁₀, NO₂, SO₂, and O₃ between January 21, 2020 and April 3, 2020. The relationship between these factors and the basic reproductive ratio (R₀) of COVID-19 was analyzed. In the provinces with high flow, the results indicated that higher ambient CO concentration was a risk factor for increased transmissibility of SARS-CoV-2, while higher temperature and air pressure, as well as efficient ventilation reduced its transmissibility. The effects of meteorological parameters and other air pollutants varied in different regions, with 24-h average concentration of NO₂ and daily maximum temperature inversely correlated to R₀. On the other hand, Zhang et al. (2021) examined time series data of levels of PM_{2.5}, PM₁₀, NO₂, CO, SO₂ and O₃ and some meteorological variables, for the period between December 1, 2019 and April 6, 2020, in relation to daily COVID-19 confirmed cases. Significant positive associations were observed between short-term exposure to PM_{2.5}, PM₁₀ and NO₂ with daily new confirmed cases, which suggested that there was a significant association between air pollution and the transmission of the coronavirus. Specifically regarding to the ambient NO₂ levels, the association with the spread of COVID-19 was studied in the Hubei Province (Yao et al., 2021). The temporal analysis of the data indicated that all the 11 Hubei cities (excepting Xianning City) showed significant positive correlations between NO₂ concentration and R₀. Since NO₂ is an indicator of traffic-related air pollution, the association between air NO₂ levels and the spread of COVID-19 could suggest that reduced population

movement would have reduced the transmission of the SARS-CoV-2.

Yu et al. (2021) investigated the spatial relationship between COVID-19, population density, and air concentrations of PM_{2.5}, at country basis on a global scale (251 countries, including China). The results from statistical analysis showed that population density was strongly correlated with COVID-19 infection and mortality, as well as with PM_{2.5} concentrations. These authors recommended a strict vehicle emission control, and encouraged the uses of new energies to reduce air pollution, especially in those countries where both PM_{2.5} concentrations and COVID-19 confirmed cases, or deaths, were being particularly high. On the other hand, in a study conducted in 41 Chinese cities (Wuhan was not included), Lu et al. (2021) examined the impact of airborne pollutants on COVID-19 morbidity, controlling for meteorological variables. Time-series values of selected atmospheric and weather variables (during the period January 20, 2020 to February 29, 2020), together with daily COVID-19 confirmed cases, were examined. The results showed that daily COVID-19 confirmed cases were positively correlated with short-term exposure to PM_{2.5}, O₃, SO₂, and NO₂. Thus, a 10 µg/m³ increase in the concentrations of PM_{2.5}, O₃, SO₂ and NO₂ was positively associated with relative risks of 1.050, 1.011, 1.052 and 1.094 of daily new confirmed cases, respectively. Recently, Zhou et al. (2021) reported the results of a study also focused on assessing the interactive effects between meteorological factors and various air pollutants (PM_{2.5}, SO₂, CO and O₃) on the transmission of COVID-19 in 120 Chinese cities, covering the majority of mainland China. In the same line that most of the above studies conducted in China, positive associations were observed between the number of confirmed cases of COVID-19 and the air concentrations of CO, PM_{2.5} and O₃. Nevertheless, this study found negative associations for SO₂.

2.1.2. India and Pakistan

Mehmood et al. (2020) raised the question of whether air pollution could be worsening the death rates due to COVID-19 in India and Pakistan, countries where the concentrations of PM_{2.5} were then 700 and 1000 µg/m³ in New Delhi and Lahore, respectively. These levels were between 28 and 40 times higher than the mean daily concentrations of PM_{2.5}. According to the WHO official COVID-19 data, at that time (June 20, 2020), India was being the 4th worst affected country by COVID-19, with more than 395,048 infected cases and 12,948 deaths, while Pakistan had recorded over 171,666 cases of infection with 3382 deaths. A link between air levels of NO₂ and PM_{2.5}, and COVID-19 infection severity, was also reported by Paital and Agrawal (2020), who examined specific areas of India and other 5 countries (China, Italy, Russia, Chile and Qatar). Since the rate of severity and death was higher in patients of air polluted areas compared to those residing in less polluted zones, it was concluded that air pollution had a positive influence on the rate of propagation and severity of COVID-19 cases. These authors suggested that the mechanism might be attributed to air pollution-mediated co-morbidities and aerosol-induced respiratory disorders, and also to NO₂-induced higher expression of ACE-2 (angiotensin-converting enzyme 2) receptor, which would act as binding ligand for SARS-CoV-2 in human respiratory cells. On the other hand, in the state of Maharashtra (India), Sahoo et al. (2021) evaluated the lockdown and unlock impact on air quality, and explored the association between environmental conditions -including meteorological parameters and air pollutants-demographic factors, and COVID-19 incidence/-mortality. Although population density was found to be an important factor for the rapid spread of SARS-CoV-2, it was also suggested that past exposure to high levels of PM_{2.5} and PM₁₀ could have led to higher risks of COVID-19 mortality. Similarly, Kolluru et al. (2021) examined the influence of lockdown and unlock periods on the PM₁₀, PM_{2.5}, CO and O₃ concentrations in 5 Indian megacities (Bangalore, Chennai, Delhi, Kolkata and Mumbai), as well as the role of pollutant concentrations, air quality index, and meteorological variables on COVID-19 daily confirmed cases and deaths. The results showed a significant correlation of PM_{2.5}, PM₁₀, CO, O₃ concentrations with the confirmed cases and

deaths during the lockdown period. Among these pollutants, O₃ showed the highest variability, up to 34% for COVID-19 confirmed cases and deaths. Recently, [Sahu et al. \(2021\)](#) established a link between emissions of PM_{2.5} and COVID-19 over India, which was based on anthropogenic sources and air quality data. The results demonstrated that COVID-19 and PM_{2.5} emissions, were significantly correlated (0.66) with reported COVID-19 cases, and also with the number of resulting deaths (0.61).

In Pakistan, [Mehmood et al. \(2021\)](#) examined the air quality and COVID-19 distribution during pre-lockdown, lockdown, relaxation period, and smart lockdown in Lahore, Karachi, Peshawar and Islamabad. Data on the levels of PM_{2.5} and NO₂ collected during the different periods were used. All these cities showed a high incidence of COVID-19 cases. Since high concentrations of PM_{2.5} and NO₂ were also observed, it was suggested that air pollution should be significantly reduced in order to diminish the risks of potential cases of COVID-19.

2.1.3. Japan and Republic of Korea

In Japan, [Azuma et al. \(2020\)](#) evaluated the effect of climate and/or air pollution on the spread of COVID-19 in that country. The analyzed data corresponded to the period March 13, 2020–April 6, 2020, just before the Japanese government declared the state of emergency. With respect to air pollutants, the epidemic growth of COVID-19 was not associated with the concentrations of NO, NO₂, O₃, and PM_{2.5}. However, the results also suggested that short-term exposure to suspended particles might influence the respiratory infections caused by SARS-CoV-2. In the Republic of Korea, [Lim et al. \(2021\)](#) investigated the role of environmental factors -such as climate and air pollutants-on the transmission of SARS-CoV-2. For it, the relationship between these variables with the confirmed daily COVID-19 cases in two areas of the country (Seoul metropolitan and Daegu-Gyeongbuk regions) was analyzed. It was observed that O₃ levels were positively correlated with the spread of SARS-CoV-2 in both analyzed regions. The authors hypothesized that O₃ could disrupt the respiratory epithelial barrier, making individuals more susceptible to the SARS-CoV-2 infection. With the exception of O₃, no correlation between SARS-CoV-2 transmission and the rest of analyzed air pollutants was observed. Notwithstanding, in another Korean study, which included data of confirmed cases of COVID-19 between February 24, 2020 and September 12, 2020, results were different. Thus, when [Hoang et al. \(2021\)](#) examined the association between six air pollutants (PM_{2.5}, PM₁₀, O₃, NO₂, CO and SO₂) and COVID-19 infection, NO₂ concentration was positively associated with daily confirmed cases in Seoul-Gyeonggi and Daegu-Gyeongbuk clusters, while the influence of PM_{2.5}, CO and SO₂ on COVID-19 infection was different in the two regions. In relation to O₃, a potential heterogeneity was found for its association with confirmed cases in Seoul-Gyeonggi area, but non-significant associations were noted for this pollutant in Daegu-Gyeongbuk area. Recently, [Lym and Kim \(2021\)](#) investigated the role of PM₁₀, PM_{2.5}, SO₂, CO, NO₂ and O₃, as well as some meteorological variables, on the daily confirmed COVID-19 transmission cases at 25 local districts of Seoul, paying particular attention for the lagged influences of PM_{2.5} and other covariates on COVID-19 infection. The study period was August 1, 2020–December 31, 2020. Interestingly, PM_{2.5} was positively correlated with the number of COVID-19 cases, leading to an elevated risk. In contrast, temperature contributed to lowering the relative risk of the disease.

2.1.4. Iran

[Bigdeli et al. \(2021\)](#) assessed the relationship between the satellite-based concentrations of CO, NO₂, O₃ and SO₂, and the number of COVID-19 cases in 31 provinces of Iran, by combining the tropospheric levels of these air pollutants and the number of confirmed cases between February 19, 2020 and March 22, 2020. The largest mean concentrations of CO, NO₂, O₃ and SO₂ were observed in those provinces having 63%, 58%, 20%, and 55% of all COVID-19 cases. For these authors, this result could be an indicator that even short-term exposure to

high levels of air pollutants might be an important factor to increase the risk of COVID-19 infection. In general, CO had the most significant effect on the density of confirmed cases, whereas unexpectedly, SO₂ showed a decreasing effect on that density. In a subsequent study, which was conducted in Tehran during the spring and summer of 2020, [Khorsandi et al. \(2021\)](#) examined the temporal cross-correlation between daily exposure to PM_{2.5}, PM₁₀ and O₃, meteorological conditions, and the hospital admission/mortality rate associated with COVID-19. It was found that short-term exposure to PM_{2.5}, PM₁₀, and O₃ (and also elevated temperatures) was significantly associated with COVID-19-related hospital admissions and mortality during the summer.

2.1.5. Other Asian countries

In Bangladesh, [Hassan et al. \(2021\)](#) determined the spatial relationships between the incidence of COVID-19 in Dhaka and variables such as air pollution, and geo-meteorological and social parameters. With respect to air pollutants, PM_{2.5}, CO and O₃ were highly and significantly correlated with COVID-19 infection rate. In turn, in Singapore, [Lorenzo et al. \(2021\)](#) studied the potential association between the concentrations of several air pollutants and the number of daily COVID-19 cases, controlling for other meteorological factors. Data on the levels of PM_{2.5}, PM₁₀, O₃, CO, NO₂ and SO₂, as well as meteorological factors (rainfall, humidity, temperature) were collected from January 23, 2020 to April 6, 2020. Significantly positive associations were found between the air concentrations of NO₂ and PM_{2.5} (also temperature) with COVID-19 case numbers, while the air levels of PM₁₀, O₃, SO₂ and CO (also rainfall and humidity) were associated with lower average daily numbers of COVID-19 cases. On the other hand, in the Bangkok Metropolitan Region (Thailand), [Sangkham et al. \(2021\)](#) investigated the relationship between meteorological factors, the air quality index (AQI), and 6 air pollutants (CO, NO₂, SO₂, O₃, PM₁₀, PM_{2.5}), with the daily confirmed cases of COVID-19. Data were collected from January 1, 2020 to March 30, 2020. In contrast to the results of most of the above summarized studies, CO, NO₂, SO₂, O₃, PM₁₀, and PM_{2.5}, (also AQI) were negatively associated with the daily number of confirmed COVID-19 cases. Recently, [Baniasad et al. \(2021\)](#) reported the results of a study whose main purpose was to identify the impact of environmental (air pollution, weather, mobility) and socio-political factors on COVID-19 transmission in eight Asian countries: Iran, Turkey, India, Russia (included because it is a transcontinental country extending from Asia to Europe), Saudi Arabia, the United Arab Emirates, the Philippines, and the Republic of Korea. Regarding air pollution, the authors concluded that a long-term analysis of the levels of air pollutants and COVID-19 incidence in these countries showed a higher risk of mortality for those populations consistently exposed to lower air quality. However, the authors highlighted that an accurate estimate of air pollution's impact on COVID-19 cases required additional information at an individual level. Although "indoor air pollution" is out of scope of the current review, due to its potential interest, we here include the results of a study conducted by [Nor et al. \(2021\)](#) in a hospital of Kuala Lumpur (Malaysia). These authors investigated the PM_{2.5} burden and SARS-CoV-2 from several wards with COVID-19 patients in that hospital. The results showed that PM_{2.5} could act as potential SARS-CoV-2 carrier also in indoor environments.

2.2. America

2.2.1. Canada

[Stieb et al. \(2020\)](#) conducted an ecological study of COVID-19 cases and 17-years average PM_{2.5} concentrations covering 111 Canadian health regions. Data were analyzed using negative binomial regression models, and controlled for province, temperature, health and demographic characteristics, as well as time since peak incidence by health region. Long-term exposure to PM_{2.5} showed a positive -but non-significant- association with COVID-19 incidence. However, the

association was larger in magnitude and significant in the most highly affected health regions, and in those with potentially less exposure measurement error. The context of that study was questioned by Goldberg and Villeneuve (2021), who in a Letter to the Editor textually wrote: “the possible contributions of air pollution on increasing incidence of COVID-19, put in this context, is at best a drop in a very large bucket”, suggesting that studies on air pollution and COVID-19 might detract from the need of implementing public health measures essential to control the spread of COVID-19. In the letter of response to Goldberg and Villeneuve (2021), Stieb et al. (2021) remarked that, in their paper, they did not suggest that air pollution was likely to predominate over other factors mediating the spread of COVID-19. Stieb et al. (2021) stated that “even based on evidence available prior to the COVID-19 pandemic, air pollution is likely to incrementally increase the risk of COVID-19, as it does other respiratory infections”. In another vein, To et al. (2021) examined the association of UV radiation, O₃, and the incidence of COVID-19 in Ontario, from January to June 2020. The influence of UV radiation was examined taking into account that it is a natural environmental antimicrobial, while the effects of O₃ were assessed not for being an air pollutant, but due to its antimicrobial properties. The authors found evidence to support the hypothesis that higher UV was associated with lower transmission of COVID-19. However, some evidence that ground-level O₃ positively influenced COVID-19 transmission was also noticed, which is in line with results of various above studies.

2.2.2. USA

Mendy et al. (2021) reported the results of the first individual-level study on the association between PM_{2.5} exposure and hospitalizations for COVID-19 conducted in USA. It included 1128 COVID-19 patients diagnosed at the University of Cincinnati healthcare system (Ohio) between March 13, 2020 and July 5, 2020. The means PM_{2.5} were 11.34 and 13.83 µg/m³, for the 10-year average exposure, and for the 10-year maximal exposure, respectively. Long-term exposure to PM_{2.5} was associated with higher odds of hospitalization in COVID-19 patients with pre-existing asthma or COPD. This is in agreement with the results of other studies suggesting that PM_{2.5} exposure might exacerbate asthma and COPD, by causing airway inflammation through the release of proinflammatory cytokines and free radicals from activated alveolar macrophages. In turn, Gujral and Sinha (2021) investigated the association between exposure to PM_{2.5}, PM₁₀ and O₃, and the COVID-19 incidence in Los Angeles and Ventura counties, CA. The results showed a significant relationship between airborne pollutants and COVID-19 cases. It was seen that short-term exposure to ground-level O₃ was positively related to daily confirmed cases, while in contrast, exposure to PM_{2.5} and PM₁₀ showed a negative association. This last result was rather surprising taking into account the conclusions of most of the above reviewed papers. However, the authors also noticed that although the empirical results suggested positive associations, considering the paucity of data, it would be early to establish a conclusive statement. In addition, the analysis of county-level emission interactions suggested that increased influence from other counties positively affected the COVID-19 confirmed cases.

Using statistical analysis, Chakrabarty et al. (2021) studied the role of PM_{2.5} concentrations on COVID-19's rapid spread across the USA. Data corresponded to the period March 2, 2020–April 30, 2020. It was found that an increase of 1 µg/m³ in PM_{2.5} levels (below current national ambient air quality standards) was associated with an increase of 0.25 in R₀ (the basic reproduction ratio). Moreover, a 10% increase in secondary inorganic composition (sulfate-nitrate-ammonium) in PM_{2.5} was associated with an increase in R₀ by 0.22. In relation also to the association between air pollutants -more specifically PM_{2.5}- and the incidence of COVID-19 in the USA, Fang et al. (2021) performed a study whose main hypothesis was that long-term PM_{2.5} exposure might lead to chronic respiratory inflammation. This, in turn, would enhance the risk of SARS-CoV-2 infection. It was found that each 1 µg/m³ increase in the annual average concentration of PM_{2.5} was associated with 7.60%

increase in the cumulative COVID-19 risk. This association was observed over two surges of the pandemic, with increases from 5.06% to 8.58% for each 1 µg/m³ increase in PM_{2.5}. The possible relevance of PM_{2.5} in COVID-19 infections was also recently highlighted by Milicevic et al. (2021). These authors estimated the R₀ for USA states. Using non-linear dynamics methods, concluded that PM_{2.5} would be a major predictor of R₀, with corrections from factors such as other air pollutants, prosperity measures, population density, chronic disease levels, and possibly racial composition. Influence of exposure to high levels of PM_{2.5} on the increased risks of hospitalization among COVID-19 infected individuals, was also recently demonstrated by Bowe et al. (2021). A national cohort of 169,102 COVID-19 positive United States Veterans, enrolled between March 2, 2020 and January 31, 2021, and followed them through February 15, 2021, was the basis for that study.

On the other hand, Meo et al. (2021a) investigated the relationship of wildfire allied pollutants, (PM_{2.5}, CO and O₃) with the dynamics of new daily cases and deaths due to SARS-CoV 2 infection in 10 counties of California, which were affected by wildfire. The results demonstrated that -as it might be expected-daily mean PM_{2.5}, CO and O₃ concentrations significantly increased after wildfire. These air pollutants were temporally associated with daily cases and daily deaths due to SARS-CoV-2 infection. Recently, the same research group (Meo et al., 2021b) published the results of another study focused on investigating the relationship between air levels of PM_{2.5}, CO, NO₂ and O₃ with the SARS-CoV-2-related daily new cases, and daily deaths, in five regions of USA: Los Angeles, New Mexico, New York, Ohio, and Florida. The number of cases and deaths increased significantly with the increased levels of PM_{2.5}, CO, NO₂ and O₃. It was found that for each 1 unit increase in the air concentrations of PM_{2.5}, CO, NO₂ and O₃, the number of SARS-CoV-2 infections significantly increased by 0.1%, 14.8%, 1.1%, and 0.1%, respectively. In addition, for each 1 unit increase in the air concentrations of CO, NO₂ and O₃, the number of deaths significantly increased by 4.2%, 3.4%, and 1.5%, respectively. These findings clearly support that exposure to air pollutants may cause more lethal forms of COVID-19.

2.2.3. Central/South America

In order to assess the relationship between the total confirmed cases of COVID-19 in Victoria (Mexico), and the levels of PM_{2.5}, PM₁₀ and CO, as well as meteorological factors (relative humidity, temperature, and absolute humidity), Tello-Leal and Macías-Hernández (2021) carried out a Pearson correlation analysis with air quality data covering from February 16, 2020 to June 6, 2020, and those related to the cases of COVID-19 covered from March 23, 2020 to June 6, 2020. It was found that the cases of COVID-19 were strongly associated with CO concentrations, whereas the levels of PM_{2.5} and PM₁₀ showed also a significant correlation for confirmed cases of COVID-19. In turn, in the municipalities of Sinaloa (Mexico) Páez-Osuna et al. (2021) examined the relationship between the COVID-19 mortality rate and PM_{2.5}. Meteorological and demographic factors were also assessed. The study was focused on the accumulated mortality rate during the first and second wave of the COVID-19 pandemic in Mexico from February 2020 to April 2021. The results indicated that COVID-19 mortality rate in the municipalities of Sinaloa was higher in those places with higher anthropogenic PM_{2.5} emissions and with elevated population density. Interestingly, it was noticed that the link between COVID-19 and PM_{2.5} could involve not only major cities, but also rural and small municipalities, where large emissions of ammonia forms (NH₃) derived from agriculture, are produced, being precursors of PM_{2.5}. Similar results were also found in Peru, where Vasquez-Apestequi et al. (2021) reported higher rates of COVID-19 in Metropolitan Lima, which would be attributable -among other variables-to the increased exposure to PM_{2.5} in previous years. However, a post-hoc analysis of the data did not find an association with the mortality rate. In Arequipa city (also in Peru), Wannaz et al. (2021) observed a positive correlation between PM₁₀ concentrations and the number of individuals infected with COVID-19,

with a delay of 15 days. It was concluded that atmospheric PM₁₀ (but not PM_{2.5}) could be a vehicle for the transmission of SARS-CoV-2. On the other hand, [Dales et al. \(2021\)](#) assessed the associations between daily changes in ambient air pollution and mortality from COVID-19 in Santiago (Chile) (March–August 2020). Data were adjusted for unwanted temporal trends, day of the week, temperature, and humidity. A significant association between acute interquartile range increases in the levels CO, NO₂ and PM_{2.5}, with increases of approximately 6% in the daily COVID-19 related deaths, was found.

2.3. Europe

2.3.1. Italy

Italy was the first country in Europe in being hit hard by the current pandemic. For that reason, probably most studies regarding the relationship between the levels of air pollutants and the diffusion of COVID-19 have been conducted in that country. In a study performed to determine the factors involved in the spread of COVID-19, using data of samples of 55 Italian province capitals, and data of infected individuals at April 7, 2020, [Coccia \(2020\)](#) revealed that the accelerated and vast diffusion of COVID-19 in North Italy showed a high association with air pollution of cities, measured with days exceeding the limits set for PM₁₀ or ozone. With respect to the potential role of PM in the spreading of COVID-19 in Northern Italy, [Setti et al. \(2020a\)](#) analyzed 34 samples of outdoor/airborne PM₁₀ from an industrial site of Bergamo Province, the epicenter of the Italian COVID-19 epidemic from February 21, 2020 to March 11, 2020. The results indicated that SARS-CoV-2 could be present on outdoor PM, suggesting that in conditions of atmospheric stability and high concentrations of PM, the coronavirus could create clusters with outdoor PM₁₀ and enhance its atmospheric persistence. In another study conducted by the same research group ([Setti et al., 2020b](#)), the possibility that air pollution could produce a 'boost effect' of the COVID-19 epidemic, thus representing a kind of an exceptional 'super-spread event', was assessed. That was the first observational study based on initial epidemic diffusion in Italy. A significant association between the geographical distribution of daily PM₁₀ exceedances and the initial spreading of COVID-19 in the 110 Italian provinces was found. On the other hand, in a study conducted in the metropolitan area of Milan, [Zoran et al. \(2020a\)](#) investigated the correlation between the high levels of SARS-CoV-2 infection accelerated transmission and lethality, and surface air pollution. The impact of the most abundant gaseous air pollutants O₃ and NO₂ -and also climate factors-on SARS-CoV-2 spreading, was examined for the period January–April 2020. The results showed positive correlations between air O₃ levels, and negative correlations of NO₂, with confirmed total COVID-19 infections, daily new positive and total deaths cases. It was suggested that the effects of the air pollutants on the transmission and severity of COVID-19 viral infections might be explained due to adverse respiratory symptoms, and also by a decrease of the immunity. These same researchers ([Zoran et al., 2020b](#)) reported a strong influence of atmospheric PM₁₀ and PM_{2.5} on COVID-19 cases outbreak in Milan. Exposure to PM₁₀ and PM_{2.5}, with possible attachment of different viruses or bacteria, would have a significant negative impact of the human immune system. This might be a main reason to explain that influence. Also in the Lombardy region, [Dragone et al. \(2021\)](#) studied the correlation between air pollutants (and also meteorological conditions) with the spread of SARS-CoV-2 infections. Once more, the results showed that the air pollutants -and climate conditions-could promote the spread of active viral particles. In this sense, [Coccia \(2021\)](#) reported that statistical evidence from data in Northern Italian cities, seemed -in general terms-to support the dynamics transmission of the SARS-CoV-2. It, in addition to human-to-human diffusion, might be also explained by a stagnation of atmospheric pollutants and viral agents. This taking into account that low wind speeds could promote a longer permanence of viral particles -including SARS-CoV-2- in polluted air, favoring the spread of COVID-19. However, the diffusion of infectious diseases is due to a

number of factors. Therefore, this conclusion was only tentative ([Coccia, 2021](#)).

[Accarino et al. \(2021\)](#) assessed the correlation between short-term exposure to atmospheric levels of PM_{2.5}, PM₁₀ and NO₂ in the first quarter of 2020, and COVID-19 diffusion variables (incidence and mortality). There was moderate-to-strong correlation between the number of days exceeding the annual regulatory limits of PM₁₀, PM_{2.5} and NO₂, and COVID-19 incidence, mortality and lethality rates. For the incidence and mortality rates in the whole Italian country, PM_{2.5} and PM₁₀ levels exhibited a stronger correlation compared with NO₂. However, in a study conducted in 16 Northern Italy provinces, which were severely hit by the epidemic, [Filippini et al. \(2021\)](#) observed a positive, non-linear association between high NO₂ tropospheric levels and subsequent COVID-19 mortality rates at different time periods. It would suggest an effect of health pollution in increasing the case-fatality ratio of the disease. In turn, [De Angelis et al. \(2021\)](#) studied the impact of long-term exposure to PM_{2.5}, PM₁₀ and NO₂ on COVID-19 incidence and excess in all-cause mortality in Lombardy (March and April 2020) through an ecological approach. Demographic, socioeconomic and meteorological variables were also considered. The results showed an increase of 10 µg/m³ in the mean annual concentrations of PM_{2.5} and PM₁₀ over the previous years, which was associated with 58% and 34% increases in COVID-19 incidence rates, respectively. Moreover, a 10 µg/m³ increase of annual mean PM_{2.5} concentration was associated with a 23% increase in all-cause mortality. In contrast, an inverse association was noticed between the concentrations of NO₂ and COVID-19 (incidence and mortality). In Lombardy, [Stufano et al. \(2021\)](#) analyzed the short-term relationship between air pollution (and also climatic factors) and the susceptibility to SARS-CoV-2 infection. It was concluded that although air pollutants and climate did not seem to be a cause of SARS-CoV-2 spread, short-term exposure to PM₁₀, PM_{2.5} and O₃ in some lags could be related to an increased incidence of COVID-19. It would be probably linked to an increased susceptibility of the host, which in turn, could be due to the dysregulation of the immune system, or also to the worsening of the conditions associated with severe SARS-CoV-2 infections. Recently, [Ho et al. \(2021\)](#) have reported the results of an analysis performed in the Lombardy and Veneto regions, on the contribution of NO₂, PM_{2.5}, PM₁₀, O₃ and SO₂ to the incidence, mortality, and fatality rates of COVID-19, both short- and long-term exposure for 8 years (January 2013–May 2020). The most striking result was the finding of the significant role of exposure to SO₂ in COVID-19 pandemic via inducing systemic and respiratory inflammation. The effects of the remaining pollutants were in line than those reported in other Italian studies. Finally, and related with the potential transmission of SARS-CoV-2 in PM, [Pivato et al. \(2021\)](#) collected in Padua 44 samples of PM_{2.5} and PM₁₀ between February 24, 2020 and March 9, 2020, which were analyzed for SARS-CoV-2. The results did not show the presence of SARS-CoV-2 in outdoor PM. According to these authors ([Pivato et al., 2021](#)), it would indicate a low probability of virus airborne transmission through PM.

2.3.2. Spain

At the beginning of the pandemic, Spain was also another of the most affected European countries by the coronavirus. This would explain the comparatively higher number of studies conducted in this country. [Saez et al. \(2020\)](#) investigated -using a mixed longitudinal ecological study-whether long-term exposure to air pollutants such as PM₁₀ and NO₂, increased the risk of COVID-19 incidence and death in Catalonia. Catalonia, a mainly urban region, has been one of most affected Spanish regions by the COVID-19 pandemic. The study period was between February 25, 2020 and May 16, 2020. It was found that for every 1 µm/m³ above the mean, the risk of a positive test case increased by 2.7% for NO₂ and 3.0% for PM₁₀. Our research group ([Marquès et al., 2021a](#)), determined -also in Catalonia-the association of COVID-19 with PM₁₀, NO₂ and O₃. We assessed the potential differences in the incidence and lethality of COVID-19 in two regions of Tarragona Province during the

period March 8, 2020 and May 10, 2020. The population included in these two regions belonged to either an industrial area, where the largest petrochemical complex of Southern Europe is placed, or in an agricultural area of Southern Catalonia. In spite of the limitations of that study, our preliminary findings indicated that the industrialized/urban areas of Tarragona Province showed a higher incidence and mortality of COVID-19 than the agricultural/rural zones. [Zaldo-Aubanell et al. \(2021\)](#) analyzed, also in Catalonia, the associations between COVID-19 incidence and mortality, and long-term exposure to air NO₂ and PM₁₀, while adjusting for demographic information, socioeconomic status, and general health status. The results of that study were aligned with those of previous investigations showing that the baseline features of the regions in terms of health status and air pollutant concentrations (NO₂ and PM₁₀ in that case), among others, modulated the impact of the COVID-19 at a regional scale. On the other hand, as a possible indicator of COVID-19 diffusion in Madrid and in order to assess the hypothesis of air transmission due to the high number of observed daily cases, [Linillos-Pradillo et al. \(2021\)](#) determined the presence of SARS-CoV-2 in outdoor air samples of PM₁₀, PM_{2.5} and PM₁ collected in May 2020. Although SARS-CoV-2 could not be detected in quartz fiber filters samplers for PM₁₀, PM_{2.5} and PM₁ fractions, the authors indicated that the absence of viral genomes could be due to factors such as the limitations of socio-economic activity in Spain at that time. It resulted in reduced circulation of the SARS-CoV-2 in general, and around the experimental site, in particular.

[Linares et al. \(2021\)](#) analyzed the impact of environmental factors and Sahara dust intrusions on the incidence and severity of COVID-19. The association between incidence rates and daily hospital admissions and average daily concentrations of PM₁₀, NO₂, and O₃ in were examined in 9 Spanish regions between February 1, 2020 to December 31, 2020. To consider the days with Saharan dust advection, a dichotomous variable was calculated: North African intrusions, named NAF, equals 1 on a day with advection, and 0 on a day without it. It was found that air pollutants, especially NO₂, were related to the incidence and severity of COVID-19 in Spain. Moreover, Saharan dust intrusions had an effect beyond that, which could be attributed to air pollution. [Zoran et al. \(2021\)](#) quantified during the period January 1, 2020–February 28, 2021, the impact of climate and air pollution factors seasonality on the incidence and severity of COVID-19 in Madrid metropolitan region. While ground level O₃ showed a significant negative relationship with daily new COVID-19 confirmed cases and deaths, the fast transmission of COVID-19 and daily new confirmed positive cases and deaths were associated with high levels of air pollution, mainly PM₁₀ and NO₂ (also a lower daily average air temperature and wind speed intensity). Recently, we have assessed the underlying effect of long-term exposure to NO₂ and PM₁₀ on the severity and mortality of COVID-19 in Catalonia ([Marquès et al., 2021b](#)). Clinical variables of individuals admitted to various hospitals of the region due to COVID-19 infection were examined together with the clinical histories and the estimated long-term exposure to NO₂ and PM₁₀. PM₁₀ showed the highest effects estimates on COVID-19 severity. Although for mortality, the highest effect estimates corresponded to age, PM₁₀ was just the following factor. We found that an increase of 1 µg/m³ in PM₁₀ concentration caused increases of 3.06% and 2.68% of patients suffering COVID-19 as a severe disease, and deaths, respectively. This result shows that long-term PM₁₀ burdens above WHO guidelines exacerbate COVID-19 outcomes.

2.3.3. Other European countries

[Hutter et al. \(2020\)](#) examined whether in a large city such as Vienna (Austria), with a known variance of air pollution across districts, a relationship with local incidence and mortality of COVID-19 might be established. An association between chronic exposure to increased levels of NO₂ and PM₁₀, and COVID-19 incidence and mortality was observed. The daily hazard was about 40% higher both for incidence and for death from COVID-19, for PM₁₀ levels 20 µg/m³, whereas NO₂ was also significantly associated with deaths due to COVID-19. In turn, [Meo et al.](#)

[\(2021c\)](#) investigated the effects of PM_{2.5}, CO and O₃ on the daily incidence and deaths due to SARS-CoV-2 infection in London, UK. These pollutants showed a positive association with an increased number of COVID-19 daily cases and daily deaths in London. For O₃, for example, with 1-unit increase, the number of cases and deaths were significantly increased by 0.8% and 4.4%, respectively.

2.4. Middle east

In Saudi Arabia, [Ben Maatoug et al. \(2021\)](#) examined the role of some air pollutants (and meteorological parameters) on the transmission of SARS-CoV-2. Exposure to air pollution influenced the daily evolution of infections in most affected cities of Saudi Arabia (Riyadh, Jeddah and Makkah), in which the prevalence of the COVID-19 was relatively high during the summer 2020. Also in Saudi Arabia, [Meo et al. \(2021d\)](#) investigated the effect of 3 weeks before and after the onset of a sandstorm on the levels of PM_{2.5}, CO, O₃ and NO₂, and the day-to-day new cases and deaths due to SARS-CoV-2 in Riyadh. The sandstorm significantly increased the air concentrations of PM_{2.5}, CO and O₃, which were temporally associated with increased SARS-CoV-2 cases. Nevertheless, no significant difference was seen in the levels of NO₂ and the number of deaths after the sandstorm.

On the other hand, [Levi and Barnett-Itzhaki \(2021\)](#) examined the association between population chronic exposure to 5 air pollutants: NO_x, CO, PM₁₀, PM_{2.5} and SO₂ in 2016–2019, and COVID-19 morbidity in Israel. Statistically significant nationwide associations were found between these air pollutants in 279 Israeli cities and towns, and COVID-19 morbidity rates. In Turkey, [Kayalar et al. \(2021\)](#) recently reported the results of a study aimed at investigating the role of ambient PM as potential carriers for SARS-CoV-2. PM samples -within various size-ranges- were collected from 13 locations within 10 cities in western Turkey between May 13, 2020 and June 14, 2020. The highest percentages of detection of the coronavirus on PM samples corresponded to hospital gardens in Tekirdağ, Zonguldak, and Istanbul, especially for PM_{2.5}. It suggests that SARS-CoV-2 may be transported by ambient particles, especially at sites close to the infection hot-spots.

2.5. Multi-country data

[Fernández et al. \(2021\)](#) examined the relationship between biodiversity, environmental and other ecosystem factors, with the COVID-19 spread and mortality at global levels. Data on COVID-19 spread and mortality -and related risk factors-were collected from 218 countries between January 21, 2020 and May 18, 2020. A significant relationship was found between COVID-19 infection spread and mortality, and the loss of biodiversity, high level of air pollutants (particularly PM₁₀, PM_{2.5} and O₃) and decreased air quality. In turn, [Solimini et al. \(2021\)](#) conducted a worldwide ecological analysis focused on evaluating the association between reported COVID-19 cases and long-term exposure to PM at the subnational (i.e., regional) level. A 10 µg/m³ increase of pollution level was associated with 8.1% and 11.5% increases in the number of cases (in a 14 days window), for PM_{2.5} and PM₁₀, respectively. [Barnett-Itzhaki and Levi \(2021\)](#) investigated the associations between exposure to PM_{2.5} and NO_x, the percentages of population exposed to PM_{2.5} concentrations exceeding WHO guideline levels, and the morbidity and mortality over time, following the detection of the first COVID-19 positive case in 36 OECD countries. Significant multi-state associations between the concentrations of the dominant air pollutants PM_{2.5} and NO_x in 36 OECD countries, and the morbidity and mortality from COVID-19, were observed. [Meng et al. \(2021\)](#) estimated the excess all-cause mortality during COVID-19 and examined the potential impact of air pollution and human activity in 16 different countries. Compared with the impact on COVID-19 mortality, in comparison to most of the above studies, the relative risks of weekly NO₂ and PM_{2.5} were lower. Among the world's top 10 infected countries from February 1, 2020 to June 30, 2020, [Sharma et al. \(2021\)](#) investigated the

association between COVID-19 confirmed cases and deaths, and meteorological factors and air levels of PM_{2.5}. Regarding PM_{2.5}, a significant and positive impact on the COVID-19 confirmed cases and deaths was observed across the 10 countries under study.

3. Recent reviews on the topic

Since our previous review on this topic was published (Domingo et al., 2020), a number of authors have been progressively reviewing the scientific information on this important issue. Table 1 summarizes the results of the most relevant review-articles that we have found in the available literature.

4. Conclusions

The number of scientific articles on the association between air pollution and the transmission of SARS-CoV-2, and the incidence/severity of COVID-19, is considerable. The published studies belong to a number of different continents, countries and regions, obviously with significant differences in geographical, meteorological and socioeconomic conditions. In addition, they have been conducted with different methodologies and with different number of individuals involved in the investigations. Therefore, it is not easy to summarize all these results and to draw definitive conclusions. Anyway, in line with the conclusions of our previous review on this topic (Domingo et al., 2020), and also in agreement with the conclusions of most of the reviews published since then (see Table 1), it seems evident that there has been/is a clear association between the air concentrations of certain air pollutants and the incidence and severity/mortality of COVID-19. A limitation of the current review has been the number of air pollutants that were included: PM_{2.5}, PM₁₀, O₃, NO₂, SO₂ and CO. It is due to the fact that, unfortunately, studies on the potential influence of air pollutants such as VOCs, dioxins and furans, or metals, among others, are not available in the scientific literature. Studies including these pollutants could add important information for a better knowledge on the association between air pollution and COVID-19. The influence of pesticides, another group of environmental pollutants of important concern, is another issue requiring attention.

Focusing exclusively on the 6 air pollutants included in the studies here reviewed, we have noticed that there is a clear association between the incidence/risk of COVID-19 cases and the air concentrations of PM, mainly PM_{2.5}, but also PM₁₀. It also concerns mortality, with special risks for PM_{2.5}. A notable number of investigations have also reported a significant association between the levels of O₃, NO₂ and CO, and the number of COVID-19 cases. However, only very few studies have reported a relationship between mortality and O₃ and CO, while only one (Filippini et al., 2021) with NO₂. For SO₂, among the revised studies, only 4 investigations have associated air SO₂ concentrations with the number of COVID-19 cases, but none with mortality. In contrast to the results of most revised studies, Sangkham et al. (2021) did not find any relationship between the air levels of CO, PM_{2.5}, PM₁₀, O₃, NO₂ and SO₂, and the incidence/mortality of COVID-19, while Lorenzo et al. (2021) found a positive association only for PM_{2.5} and NO₂, but negative for PM₁₀, O₃, SO₂ and CO.

Regarding the potential influence of these air pollutants on the transmission of SARS-CoV-2, the scientific evidence is much more limited, among other reasons since it has been much less investigated. However, it has been reported, for example, that PM could aggravate neurological symptoms of SARS-CoV-2 (Borisova and Komisarenko, 2020), as well as respiratory and cardiovascular effects of COVID-19 (Espejo et al., 2020; Tanwar et al., 2021). Air pollution could also mean a possible dangerous synergy with COVID-19 for semen quality and male fertility (Montano et al., 2021a,b). Positive results on the influence of PM on SARS-CoV-2 transmission have been reported by Setti et al. (2020a,b) and Tung et al. (2021) for PM_{2.5} and PM₁₀, and by Kayalar et al. (2021) and Nor et al. (2021) for PM_{2.5}. Nevertheless, there

Table 1

Summary of results of recent reviews on the influence of air pollution of the transmission of SARS-CoV-2 and the incidence and severity of COVID-19.

Topic of the Review	Main results and conclusions	Reference
To highlight the potential role of PMs in the spread of COVID-19 in Italian cities	**Long-term exposure and short-term exposure to high levels of pollutants are correlated to an increase in COVID-19 contagion. ** COVID-19 infection should be investigated in relation to ACE2 expression after PM exposure in order to verify the different susceptibility to infection by PM exposed and non-exposed cells.	Comunian et al. (2020)
Potential link between compromised air quality and transmission of SARS-CoV-2 in affected areas of India	**Polluted environments can enhance the transmission rate of SARS-CoV-2 under moderate-to-high humidity conditions.	Manoj et al. (2020)
Effects of air pollution on COVID-19 infection and mortality	**Exposure to air pollution especially NO ₂ and PM _{2.5} may increase the susceptibility of infection and mortality from COVID-19. **Air pollution can cause adverse effects on the prognosis of patients affected by SARS-CoV-2 infection.	Ali and Islam (2020)
To estimate the fraction of COVID-19 mortality that is attributable to the long-term exposure to ambient fine particulate air pollution	**Air pollution is an important cofactor increasing the risk of mortality from COVID-19.	Pozzer et al. (2020)
The role of air pollution in COVID-19 spread and lethality	**Important contribution of chronic exposure to air pollution on the COVID-19 spread and lethality. ** PM _{2.5} and NO ₂ would be more closely correlated to COVID-19 than PM ₁₀ .	Copat et al. (2020)
Association between the level of ambient air pollution and COVID-19	**PM exposure could weaken and dysregulate immune response, resulting in a failure to defend against virus invasion. **PM exposure could cause ACE2 overexpression to increase viral load during invasion. **Airborne PM could increase transmission distance of SARS-CoV-2.	Wang et al. (2020)
Impact of outdoor air pollution on COVID-19: evidence from <i>in vitro</i> , animal, and human studies	**Both short- and long-term exposures to air pollution may be important aggravating factors for SARS-CoV-2 transmission and COVID-19 severity and lethality through multiple mechanisms.	Bourdrel et al. (2021)
To summarize knowledge on SARS-CoV-2 transmission pathways	**The results suggest the influence of certain underestimated factors on the environmental behavior and survival of the SARS-CoV-2. **Outdoor risk sources such as aerosolized particles emitted during wastewater treatment and particulate matter, both of which may act as virus carriers, should be carefully assessed.	Senatore et al. (2021)
How outdoor pollution exposure could potentially affect the viral life cycle of SARS-CoV-2 and pathogenesis of COVID-19	**Exposure to NO ₂ , O ₃ and particulate matter could predispose exposed populations toward developing COVID-19-associated immunopathology,	Woodby et al. (2021)

(continued on next page)

Table 1 (continued)

Topic of the Review	Main results and conclusions	Reference
Potential impact of air pollution on COVID-19 incidence and deaths.	enhancing virus-induced tissue inflammation and damage. **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. **Exposure to NO ₂ and PM _{2.5} was more often correlated with COVID-19 infections and mortality than PM ₁₀ .	Ali et al. (2021)
Acute and chronic exposure to air pollution in relation with incidence, prevalence, severity and mortality of COVID-19	**Short-term and long-term exposures to PM _{2.5} , and long-term exposure to NO ₂ appear to be most consistently associated with COVID-19. O ₃ only for incident cases. **Studies assessing the effects of acute exposures presented substantial risks of bias.	Katoto et al. (2021)
Role and potential association of air pollution especially particulate matter pollution in the transmission of COVID-19.	**There appears to be a positive role of atmospheric particulate matter (PM) pollution and the spread of COVID-19. **Some studies propose that PM operates as a virus carrier, promoting its transport through the air. **Exposure to ambient PM may reduce the resistance to infection in the population.	Maleki et al. (2021)
Possible transmission routes of COVID-19 and different mutations of the virus via environmental media	** Particulate matter may be a carrier for SARS-CoV-2. **More investigations should be undertaken focusing on the environmental transmission pathways of virus, which could contribute to the prevention and control of the COVID-19 epidemic.	Shao et al. (2021)
To review the role of PMs in the spread of COVID-19, as well as the relationship among COVID-19, PMs, and angiotensin-converting enzyme 2 (ACE2)	**There is scientific evidence on the correlation between PM levels and the spread of SARS-CoV-2. **ACE2 plays a very significant role in COVID-19	Khan et al. (2021)
Influence of air pollution and climate indicators on COVID-19.	**Air pollution and meteorological parameters have critical effects on the rate of propagation and severity of COVID-19 cases. **The mechanisms may include air pollution-mediated comorbidities, airway damage, pulmonary epithelial permeability, inflammatory and immune dysregulation, metabolic pathway and pollution-induced overexpression of ACE-2 receptor.	Zhao et al. (2021)
Potential relationship of PM with several life-limiting human diseases and COVID-19	**PM exposure could be related as a carrier for SARS-CoV-2 transmission and COVID-19 infection. **Oxidative stress and inflammatory responses are considered as the major mechanism involved in the PM induced adverse effects.	Zhu et al. (2021)
To review the cumulative effects of ambient PM _{2.5} -exposure and SARS-CoV-2 transmission on exacerbating cardiopulmonary outcomes	**Exposure to air pollution increases susceptibility to COVID-19 infection, creating a pre-inflammatory state in patients. **Air pollutants affect	Lai et al. (2021)

Table 1 (continued)

Topic of the Review	Main results and conclusions	Reference
To review literature focused on the transmission of SARS-CoV-2 in the spread of COVID-19 and present an environmental perspective on why airborne transmission has not been very conclusive so far	respiratory and cardiovascular health, COVID-19 prognosis and mortality are impacted by the presence of respiratory and cardiovascular comorbidities. **Chronic exposure to air pollution increases inflammation in populations that are thus more susceptible to contracting the coronavirus. **One of the reasons for reduced emphasis on airborne transmission could be that the smaller droplets have a smaller number of viruses as compared to larger droplets. ** Small droplets containing SARS-CoV-2 might also physically combine with or attach to pre-existing PM so that their behavior and fate may be governed by PM composition.	Ram et al. (2021)

is no specific reports on the potential influence of NO₂, SO₂ and CO, while for O₃ only To et al. (2021) have found a positive result. By contrast, a negative association between the transmission of SARS-CoV-2 and air pollution was reported by Linillos-Pradillo et al. (2021) for PM_{2.5} and PM₁₀, and by Pivato et al. (2021) for PM₁₀.

Based on the results of most of the studies here reviewed, which have been published in the last 12–14 months, we can conclude that there is a significant association between chronic exposure to these air pollutants: PM_{2.5}, PM₁₀, O₃, NO₂, SO₂ and CO, and the incidence/risk of COVID-19 cases, and the severity/mortality of the disease. The results are especially evident for PM, and particularly for PM_{2.5}, but the influence of O₃, NO₂, CO, and even SO₂ is not negligible at all.

According to the WHO, approximately 90% of the population are exposed to air pollution concentrations that put them at increased risks for serious cardiorespiratory diseases, including cancer. It is also estimated that 4.2 million of persons die every year as a result of exposure to outdoor ambient air pollution (WHO, 2021). Taking this into mind, among the 206.209.918 global confirmed cases of COVID-19, and the 4.346.368 deaths due to the pandemic registered at August 13, 2021 (JHU, 2021), how many of this tremendous number of infected individuals -and especially how many deaths-have been due to the negative influence/synergy between air pollution and COVID-19? This is a question that must be deeply investigated. Also, if some pollutants such as PM can spread the coronavirus requires. The origin of SARS-CoV-2 is not scientifically well-known yet (Dominski et al., 2021,b). In the current circumstances, unfortunately, nobody can discard that in a few years, months, or even weeks, new pandemics due to respiratory viruses may arise. The world must be prepared for this serious potential threat. For this specifically, but also for all other many reasons, including very especially the current annual number of deaths to the air pollution (WHO, 2021), and also to prevent/avoid/limit the devastating current effects of climate change, a very significant reduction of environmental contamination in general, and air pollution in particular cannot wait any longer.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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