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An updated systematic review on the association between atmospheric particulate matter pollution and prevalence of SARS-CoV-2

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ABSTRACT

On December 31, 2019, the novel human coronavirus (COVID-19) was emerged in Wuhan city, China, which is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). There is a much controversial debate about the major pathways of transmission of the virus including airborne route. The present work is a systematic literature review (SR) aimed to assess the association of air pollution especially particulate matter pollution in the transmission and acceleration of the spread of SARS-CoV-2. The systematic literature search was performed to identify the available studies published through October 31, 2020 concerning the transmission of the disease and particulate matter air pollution in four international electronic databases. From the results of the included studies, there are suggestions that atmospheric particulate matter pollution plays a role in the SARS-CoV-2 spread, but the literature has not confirmed that it enhances the transmission although some studies have proposed that atmospheric particulate matter can operate as a virus carrier, promoting its spread. Therefore, although PM concentration alone cannot be effective in spreading the COVID-19 disease, other meteorological and environmental parameters including size of particles in ambient air, weather conditions, wind speed, relative humidity (RH) and temperature are involved. Therefore, it is necessary to consider all influencing parameters to prevent the spreading of COVID-19 disease. More studies are required to strengthen the scientific evidence and support more definitive conclusions.

1. Introduction

On December 31, 2019, the novel human coronavirus (SARS-CoV-2) was emerged in China (Wuhan city) and called COVID-19 disease by World Health Organization (WHO) (Huang et al., 2020; Zhou et al., 2020). On February 11, 2020, because the rapid spreading of COVID-19 disease in all countries and territories in the world, the WHO declared the pandemic situation of the disease. The pandemic of SARS-CoV-2 was emerged from Southern China and swiftly spread globally, consequently, causes detrimental effects on public health, especially health-care centers, economic situations, and environmental conditions.

In the initial period after the disease had been identified, the WHO and other official authorities declared that the main routes of the transmission of the virus was person-to-person transmission through large droplets. Therefore, hand washing and maintain social distance is critical to avoid disease. However, other routes of transmission were also possible such as close contact of the infected person to others (prolonged and unprotected), large and small droplets emitted from cough, sneeze and even normal speaking of infected subjects, and inhalation of airborne particles containing the virus in the air (Eissenberg, Kanj et al., 2020; Ghinai and McPherson, 2020; Qu, Li et al., 2020).

There has been a controversial debate about the major routes of

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transmission of COVID-19. Previous studies reported that there was a positive relation between air pollution and viral respiratory diseases such as influenza-associated disease, SARS-CoV-1 (Booth, Kournikakis et al., 2005; Li, Huang et al., 2005; Iuliano, Roguski et al., 2018). Therefore, there is a high possibility of airborne transmission of COVID-19 and then, determination of the potential role of air pollution (pollutants) in the spreads of SARS-CoV-2 is of utmost importance.

Air pollution is defined as a mixture of natural or anthropogenic compounds in indoor or ambient air including solid particle (such as particulate matter (PM), bioaerosols), liquid (droplets) and gases (carbon monoxide (CO), nitrogen (NOx) and sulfur (SOx). Among these substances, PM is the most widespread health threat in cities (Singh 1995; Block and Calderón-Garcidueñas 2009; Allen 2015). PM is a heterogeneous mixture of suspended liquid droplets and solid particles with various size, shape, and chemical features, with spatial-temporal variations that are present in the ambient urban air (Potukuchi and Wexler 1995; Pope III, Ezzati et al., 2009; Janssen, Hoek et al., 2011). Ambient PM is categorized into various size fractions; coarse particles with diameter ≥2.5 μm and ≤10 μm (PM_{10}); fine particles with diameter ≤ 2.5 μm ($PM_{2.5}$); PM_{10} that is the sum of the coarse and fine PM, and the ultrafine particles with diameter ≤ 0.1 μm ($PM_{0.1}$) (Block and Calderón-Garcidueñas 2009; Khan, Hamid et al., 2019; Zoran, Savastru et al., 2019). PM contains various substances including metals, elemental and organic carbon, sulfates, and nitrates (Ghio, Carraway et al., 2012; Wooding, Ryu et al., 2019). It has been reported that increasing pollutant concentrations are associated with more daily confirmed COVID-19 positive cases and the related mortality rate increases (Contini and Costabile 2020; Domingo and Rovira 2020; Wu, Nethery et al., 2020). Coccia 2020 has highlighted the key role of the air pollutants in the transmission dynamics of COVID-19 and reported that the quick and global spread of COVID-19 may be associated with days with PM_{10} concentration higher than the EU daily threshold value of 50 μg/m^3 (Coccia 2020). Recently in an experimental study, Setti, Passarini et al., 2020 demonstrated that the RNA of the virus can be present on ambient atmospheric PM in stable atmospheric condition and high levels of $PM_{10.}$ This result suggests that PM concentrations can be used as an indicator for a high potential for infection (Setti et al., 2020). Additionally, Martelletti and Martelletti (2020) reported that areas in northern Italy with high PM_{10} and $PM_{2.5}$ concentrations had the most COVID-19 affected individuals. Therefore, they expressed that the COVID-19 may find appropriate transport vectors among airborne particles.

In general, one of the main issues to prevent and control epidemic situations is to understand the exact routes of disease transmission. Considering the rapid spread of COVID-19, it seems that there are multiple pathways for the transmission of the virus including airborne pathways. The WHO defines airborne route as "the spread of an infectious agent caused by the release of droplet nuclei, which, if suspended in the air, remain infected for long distances and times (WHO, 2014). Based on this definition, it may be that besides human-to-human transmission, other routes especially airborne transmission may be important and involved in the transmission of the COVID-19 (Hadei, Hopke et al., 2020). Additionally, it is reported that SARS-CoV-2 RNA could be found in indoor air samples in hospitals (Kenarkoohi, Noorimotlagh et al., 2020; Liu, Ning et al., 2020; Razzini, Castrica et al., 2020; Wang, Feng et al., 2020) and in crowded government offices and public transport vehicles (e.g., bus or subway) (Hadei, 2021). A systematic review based on the peer-reviewed studies suggested the possibility of airborne transmission of SARS-CoV-2 in the indoor air environment (Noorimotlagh, Jaafarzadeh et al., 2020). Therefore, to better understand and clarify the possibility of airborne transmission, the present study has reviewed the literature to investigate the role and potential association of air pollution especially particulate matter pollution in the transmission of COVID-19.

2. Methods

The objective was to identify all the available articles from the inception of SARS-CoV-2 disease until October 31, 2020 based to investigate the role and potential association of air pollution especially airborne PM for COVID-19 transmission. This review was performed following the recommendations of "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines (Noorimotlagh, Karami et al., 2020; Noorimotlagh, Mirzaee et al., 2020). Two independent researchers (MM, ZN) conducted the literature search for studies published from Nov 1, 2019 to Oct 31, 2020 using Google Scholar, PubMed (MEDLINE), Scopus (Elsevier), and ISI Web of Science. The search terms using Medical Subject Headings (MeSH) were (“Severe Acute Respiratory Syndrome” OR “SARS” OR “coronavirus” OR “CoV” OR “COVID-19” OR “Human Coronaviruses” OR “HCoV” OR “Severe Acute Respiratory Syndrome- Coronaviruses” OR “SARS-CoV” OR “Severe Acute Respiratory Syndrome- Coronaviruses-2” OR “SARS-CoV-2” OR “new coronavirus” OR “Novel Coronaviruses” OR “nCov” OR “2019 Novel Coronavirus” OR “2019-nCoV” OR “Wuhan coronavirus”) **AND** (“Air pollution” OR “Air pollutants” OR “Particulate Matter” OR “PM” OR “PM_{10}” OR “$PM_{2.5}$”).

Articles were selected according to the following inclusion criteria: a) the language of the article should be English; b) an electronic version of studies is available and c) it focuses on COVID-19 transmission via PM. Articles were excluded if they met the following criteria: other languages, review articles, protocols, guidelines, short communication, letters to the editor, conference abstracts, abstract only, and oral presentations. Finally, we systematically extracted information from each original article including the study ID, study location, study design, type of PM and concentration, key finding(s), and meteorology parameters (relative humidity (RH) and temperature).

3. Results

The initial search identified 167 studies from the four databases. Among these studies, 36, 95, 10, and 7 papers were removed due to duplicates, not related to COVID-19 transmission via PM, review articles, and short communication or letters to editors, respectively. Finally, 19 studies were included in the current review following the inclusion and exclusion criteria, and the full text of all 19 articles were completely reviewed (Adhikari and Yin 2020; Bontempi 2020; Cartenì, Di Francesco et al., 2020; Chennakesavulu and Reddy 2020; Chia, Coleman et al., 2020; Coccia 2020; Fattorini and Regoli 2020; Fronza, Lusic et al., 2020; Gupta, Bherwani et al., 2020; Hendryx and Luo 2020; Kumar 2020; Li, Xu et al., 2020; Sasidharan, Singh et al., 2020; Setti, Passarini et al., 2020; Yao, Pan et al., 2020a, 2020b; Yao, Pan et al. 2020a, 2020a, 2020b, 2020b, 2020b, 2020b, 2020b; Zhu, Xie et al., 2020a, 2020b; Zhu, Xie et al. 2020a, 2020a, 2020b, 2020b, 2020b, 2020b; Zoran, Savastru et al., 2020). Table 1 provides the main information of 19 included articles. Four studies are related to PM_{10} in Singapore (n = 1) and Italy (n = 3) (Bontempi 2020; Chia, Coleman et al., 2020; Coccia 2020; Setti, Passarini et al., 2020). Four other studies focused on $PM_{2.5}$ (Adhikari and Yin 2020; Chennakesavulu and Reddy 2020; Hendryx and Luo 2020; Sasidharan, Singh et al., 2020; Zoran, Savastru et al., 2020). These studies were from London (n = 1), tropical and temperate zone countries (n = 1), and the USA (n = 2). Eleven papers were relevant to both PM_{10} and $PM_{2.5}$ (Fattorini and Regoli 2020; Fronza, Lusic et al., 2020; Gupta, Bherwani et al., 2020; Kumar 2020; Li, Xu et al., 2020; Yao, Pan et al., 2020a, 2020b; Yao, Pan et al. 2020a, 2020a, 2020b, 2020b, 2020b, 2020b, 2020b; Zhu, Xie et al., 2020a, 2020b; Zhu, Xie et al. 2020a, 2020a, 2020b, 2020b, 2020b, 2020b). These studies were focused on Asia (n = 1), China (n = 5), Italy (n = 3), India (n = 1), and European nations (France, Germany, Spain, and Italy) (n = 1).

To investigate the hypothesis of COVID-19 transmission via PM, the main data included articles were discussed in the following section.

Table 1
The detail key finding of 19 reviewed studies on the relation between atmospheric particulate matter and SARS-CoV-2 prevalence.

Study ID	The main objective	Study Design	Type of PM (μg/m^3)		Meteorological parameters		Key finding
			PM $_{10}$	$PM_{2.5}$	Tem (°C)	RH (%)	
(Chia, Coleman et al., 2020), Singapore	Hospital air and surface contamination	Experimental	✓		23	53–59	Air samples from two of 3 airborne infection isolation rooms tested positive.
(Kumar 2020), India	meteorological parameters and spread of virus	Experimental	✓	✓	–	30–55	Increase level of $PM_{2.5}$, may increase the incidences and deaths of disease in India.
(Yao, Pan et al. 2020a, 2020b), Chinese	Association of PM and case fatality rate	Experimental	80.2	49.1	–	–	By 10 μg/m^3 increase in concentration of $PM_{2.5}$ and PM_{10}, the case fatality rate enhanced about 0.24–0.26%
(Sasidharan, Singh et al., 2020), London	human-mobility reduction for countering the virus transmission	Experimental	88	–	–	–	A strong correlation between increment in $PM_{2.5}$ levels and an increased risk of virus transmission
(Chennakesavulu and Reddy 2020), tropical and Temperate zone countries	The effect of $PM_{2.5}$ and latitude on spreading of the virus	Experimental	0–150	–	Tropical: 20–45 Temperate zone: 3–13		In temperate zone countries, $PM_{2.5}$ concentration below 20 mg/m^3 increases SARS-CoV-2 spreading rate.
(Cartenì, Di Francesco et al., 2020), Italy	mobility habits on the spread of the virus	case study	PM		–	–	PM pollutant has a direct association with the virus infection.
(Zoran, Savastru et al., 2020), Italy	Surface concentration of PM_{10} and $PM_{2.5}$ and with SARS-CoV-2	Experimental	✓	✓	0–18	23–92	Ambient airborne aerosols might be possible diffusion routes of SARS-CoV-2. Dry weather is favorable for SARS-CoV-2 viral infection spreading, but humid weather has the opposite effect.
(Yao, Pan et al. 2020a, 2020b), China	PM pollution and the disease case fatality rate	Experimental	52.77	41.77	7.18	81.37	A positive association between PM_{10} and $PM_{2.5}$ and the case fatality rate of SARS-CoV-2 in Wuhan
(Hendryx and Luo 2020), USA	SARS-CoV-2 infection and pollution concentrations	Experimental	–	✓	–	–	Higher SARS-CoV-2 prevalence was observed in association with $PM_{2.5}$
(Zhu, Xie et al. 2020a, 2020b), China	air quality and SARS-CoV-2 infection	Experimental	62.97	46.43	2.82	67.25	Limiting the movements could reduce SARS-CoV-2 cases by improving air quality.
(Setti, Passarini et al., 2020), Italy	Finding the virus RNA on PM	Experimental	25.1 to 52.1	–	6.8–8.5	61–69	Detection of the virus RNA on ambient PM
(Fattorini and Regoli 2020), Italy	the Covid-19 outbreak risk and the chronic air pollution levels	–	16.9 to 37.7	5.7 to 31.5	–	–	Long term exposure to atmospheric pollution may act as a favorable route to the spread of Covid-19.
(Coccia 2020), Italy	Determined factors in diffusion of COVID-19	Experimental	✓		Hinterland cities: 9.11 Coastal cities: 10.61	Hinterland cities:68.31 Coastal cities:74.40	Cities with more than 100 days of air pollution have a very high average number of infected individuals
(Li, Xu et al., 2020), China	Association of Air pollution with increased COVID-19 incidence	Experimental	Wuhan: 51.88 XiaoGan: 59.65	Wuhan: 44.16 XiaoGan: 50.39	Wuhan: 7.19 XiaoGan: 7.26		All pollutants on the outdoor air has a positive relationship with daily SARS-CoV-2 incidence ($PM_{2.5}$ exhibited statistical significance). Daily temperature and daily lowest temperatures were predominantly correlated with SARS-CoV-2 incidence (inversely). COVID-19 incidence inversely correlated with the daily sunshine duration and temperature.
(Zhu, Xie et al. 2020a, 2020b), China	short-term exposure to air pollution and SARS-CoV-2	Experimental	62.97	46.43	2.82	67.25	Positive associations of $PM_{2.5}$, PM_{10} with SARS-CoV-2 confirmed cases
(Bontempi 2020), Italy	possible virus airborne transmission due to air PM	Computational	3 to 87	–	–	–	It is not possible to conclude that COVID-19 diffusion mechanism also occurs through the air, by using PM_{10} as a carrier.
(Adhikari and Yin 2020), USA	Short-Term effects of $PM_{2.5}$ on confirmed cases and deaths of COVID-19	Experimental	–	4.733	8	62.90	A one-unit increase in the moving average of $PM_{2.5}$ (μg/m3) was related with a 33.11% decrease in the daily new disease cases.
(Fronza, Lusic et al., 2020), European nations, Spain, Germany, France, and Italy	Effects of spatial-temporal variations in atmospheric factors on COVID-19 outbreak	Computational	40	30	–	–	SARS-CoV-2 infection frequency positively correlates with $PM_{2.5}$
(Gupta, Bherwani et al., 2020), Asian	Air pollution and possible aggravating of COVID-19 lethality	statistical models	59 to 292	45 to 173	–	–	Percentage mortality per reported SARS-CoV-2 cases is correlated significantly with $PM_{2.5}$ than with PM_{10}

4. Discussion

There is a controversial debate about the transmission route of the COVID-19 in this pandemic situation. At the beginning of the disease, all official and authority centers were focused on prevention procedures such as observing social distance, hand washing, avoiding the touch of contaminated surfaces, and disinfection of contaminated hands and surfaces. Subsequently, additional evidence of the other important routes of transmission including airborne pathways were published and became the subject of debate about the effectiveness of airborne pathways in the transmission of COVID-19. According to the WHO (2014), airborne transmission is defined as the spread of an infectious agent caused by the dissemination of droplet nuclei (aerosols) that remain infectious when suspended in air over long distances and time. Therefore, the present study aimed to assess the association of air particulate matter (PM) pollution in the spreading of COVID-19 prevalence.

In addition to serving as a transport vector, exposure to PM may also enhance the susceptibility to viral infections. Interquartile range increases in $PM_{2.5}$ over the previous 7 days were associated with increased excess rates (ERs) of influenza emergency department visits (3.9%; 95% CI, 2.1–5.6%). They also found that although $PM_{2.5}$ concentrations had substantially decreased in recent years (2014–16) relative to the 2005–07 period, the ER had increased in the recent period. They attributed the increase to increased formation of secondary organic aerosol (SOA) due to the increased availability of oxidative species because of the reduction in SO_2 and NOx emissions over this time period. In a follow-up analysis, Croft et al. (2020) found that increased rates of ED visits for influenza were associated with interquartile range increases in concentrations of source specific $PM_{2.5}$ from light-duty gasoline vehicles (excess rate [ER] = 9.2%; 95% CI: 4.3%, 14.3%) and heavy-duty diesel vehicles (ER = 3.9%; 95% CI: 1.1%, 6.8%) for lag days 0–3. They suggested that since the gasoline vehicles were strongly correlated with SOA and diesel PM is known to have substantial oxidative potential (e.g., Cheung et al., 2009), it is the ability of reactive particles to induce oxidative stress and systemic inflammation that enhanced the infectiousness of the virus (Hopke, 2015). Thus, it may be that some of the differences in the effectiveness of PM in transmitting the virus may result from differences in composition among the various locations.

There is evidence demonstrating that the virus can survive in PM for up to 3 h (Santarpia, Rivera et al., 2020; Van Doremalen, Bushmaker et al., 2020). This lifetime suggests that it can spread from the source (infected person) through the air. Based on the growing trend of infections and understanding the basic knowledge of the spread of viral infections, Morawska and Cao (2020) proposed that the virus was likely to spread in the air. SARS-CoV-2 virus is ejected along with liquid or solid materials through coughing (Xie et al., 2009; Lindsey et al., 2012), speaking (Asadi et al., 2019), and sneezing (Bourouiba, 2020). The droplets rapidly evaporate and remain suspended so they can disperse in the air (Santarpia, Rivera et al., 2020; Wang and Du 2020). Various micro-organisms including viruses from the infected persons, both symptomatic and asymptomatic persons, are dissolved in the mucous and become bioaerosols. Initial droplets can range from a few micrometers up to 80 μm or larger (Xie et al., 2009). Due to the smaller size of the bioaerosols, viruses remain suspended in the air and can spread beyond distance from the origin of emission (Santarpia, Rivera et al., 2020; Wang and Du 2020). According to the results of a research, in COVID-19 patients even without any aerosol-generating procedure, SARS-CoV-2 can be thrown in the air via particles sized of 1–4 μm, so can be left in the air and transferred (Chia, Coleman et al., 2020). Wang and Du (2020), reported that airborne transmission by aerosols could play a critical role in the transmission of the virus since they diagnosed new cases of the disease in Inner Mongolia and Wuhan city where the patients had no direct contact with any confirmed cases of SARS-CoV-2. Therefore, they speculated that the virus may directly spread via aerosol and recommended experimental studies to confirm this hypothesis (Wang and Du 2020). In confirmation of this result, Kumar et al. (2020) reported that during the first quarantine period in India (March 25-April 15), the aerosol concentrations decreased and decreased the spread of the virus in the air (Kumar 2020). These data support the hypothesis that atmospheric conditions can produce a significant effect on airborne droplets (including $PM_{2.5}$ concentration) to spread SARS-CoV-2. Therefore, they hypothesized that an enhanced concentration of $PM_{2.5}$ could cause an increase in infectious droplets/aerosols containing SARS-CoV-2 less than 2.5 μm in diameter (Fronza, Lusic et al., 2020). In the presence of atmospheric $PM_{2.5}$, COVID-19 particles could attach to atmospheric particles and form solid/liquid interface ($PM_{2.5}$/the virus SARS-CoV-2). Meteorological parameters including wind speed, temperature, and relative humidity (RH) influence the movement of solid/liquid particles. Therefore, the formed droplets containing the virus can travel up to 10 m at low concentrations less than 20 μg/m^3 of $PM_{2.5}$. The results of this study also support the airborne transfer mechanism (Hext et al., 1999).

The transmission dynamics of COVID-19 were strongly positively correlated with ambient air pollution in the cities concerning high level of PM_{10} concentrations. The high average number of infected people were found in cities that previously had PM_{10} exceedances of the EU limits for more than 100 days, while lower average numbers of infected people were in the cities with less than 100 days of air pollution (Coccia 2020). SARS-CoV-2 may use a type of "highway" composed of atmospheric particles that increases its indirect transport (Setti, Passarini et al., 2020).

Pollutant concentrations in the ambient air especially $PM_{2.5}$ and PM_{10} have been shown to affect the spread of human respiratory obstructive virus in children (Ye, Fu et al., 2016). Similarly, Wu, Nethery et al. (2020) estimated that an increase of 1 μg/m^3 in $PM_{2.5}$ concentration resulted in an 8% enhance in SARS-CoV-2-induced mortality in the USA. In a similar study, Yao, Pan et al. (2020a), 2020b reported a positive correlation between PM_{10} and $PM_{2.5}$ concentrations with the case mortality rate of SARS-CoV-2 in Wuhan, China providing further evidence for the role of air pollution in the spread of SARS-CoV-2. The other authors also found a positive correlation between PM concentrations and COVID-19 mortality rates in cities inside and outside Hubei Province. They reported that a 10 μg/m^3 enhance in PM_{10} and $PM_{2.5}$ concentration increased the SARS-CoV-2 mortality by 0.26% and 0.24%, respectively (Yao, Pan et al. 2020a, 2020b). Similar to previous studies, Yao, Pan et al., (2020a), 2020b show that COVID-19 mortality rates were significantly associated with $PM_{2.5}$ and PM_{10} in 49 Chinese cities (Yao, Pan et al. 2020a, 2020b). Besides, they identified very high cases of COVID-19 in South East Asian cities that had high $PM_{2.5}$ concentrations such as Mumbai, Delhi, again supporting the role of $PM_{2.5}$ in the transmission of COVID-19 cases in South East Asia (Yao, Pan et al. 2020a, 2020b). Alternatively, in temperate countries, when $PM_{2.5}$ concentrations were less than 20 μg/m^3, a higher rate of COVID-19 was detected (Chennakesavulu and Reddy 2020). Other studies have reported associations that suggest that particulate pollution is one of the causes of the rapid spread of COVID-19 (Coccia 2020; Piazzalunga-Expert 2020; Setti, Passarini et al., 2020a).

The experimental evidence reported that under strong atmospheric stability conditions and high levels of PM_{10}, such as those seen in the Po Valley of Italy COVID-19 can be present on ambient atmospheric PM (Setti et al., 2020a). Setti et al. (2020a,b) confirmed the presence of the virus RNA on suspended particles (PM) at the peak of the Italian epidemic, thereby suggesting that it could make coagulate with the ambient PM_{10}, reduce it diffusivity and thus, increase the longevity of SARS-CoV-2 in the atmosphere. Stadnytskyi et al. (2020) reported that the spread of the virus through enough small nuclei that were suspended for a sufficiently long time was a possible method of viral transmission. Therefore, the presence of the virus in ambient atmospheric PM_{10} air samples could potentially be an early indicator for the disease (Setti, Passarini et al., 2020c).

PM could enhance airborne viral transmission as it confirmed that outdoor $PM_{2.5}$ are strongly associated with the risk of influenza-like disease during the cold season in China (Beijing) (Feng, Li et al., 2016). However, the opposite evidence has been published. For example, in Lombardy and Piedmont, the association between PM_{10} concentrations and infections were analyzed to correlate high PM levels and SARS-CoV-2. The cities of Turin and Alessandria, which suffered from high PM_{10} concentrations during the 20 days before the health crisis, were found to have fewer infections (0.01 and 0.03, respectively). However, in Bergamo, where the limit of 50 μg/m^3 for PM_{10} concentrations was only rarely exceeded, the highest number of infections were found even though RNA was found in the ambient PM_{10} (Setti et al., 2020b). Data on PM_{10} concentrations and cases of infection in Lombardy and Piedmont were analyzed and showed that there was no direct association between the presence of high levels of PM_{10} and the spread of the virus. As a result, PM_{10} concentrations in northern Italian cities could not be directly related to COVID-19 contamination (Bontempi 2020). It may be that particle size and/or compositions were not favorable for the viability of the virus on the particles even though RNA was clearly found in the ambient PM (Setti et al., 2020b).

Several articles have provided empirical evidence that airborne transmission of some viral infectious diseases is very important. Initially, the deposition time of a droplet was calculated with a diameter of 10 μm containing 9 mg/ml of salt and 3 mg/ml protein with RH 100%, 90%, and 64% (Vejerano and Marr 2018; Marr, Tang et al., 2019). It was found that the droplet decreases to 2.8 μm and 1.9 μm at 90% and 64% RH, respectively (Vejerano and Marr 2018; Marr, Tang et al., 2019). The deposition time of particles with different diameters is very different. Ten μm droplets with 100% humidity remain suspended for only 8 min in still air, while the 1.9 μm ones in RH less than 64% remains suspended for more than 3 h, creating a much greater opportunity for airborne transmission (Vejerano and Marr 2018; Marr, Tang et al., 2019).

Under certain weather conditions (Bashir et al., 2020), air pollution appears to act as a carrier of the COVID-19 virus, facilitating its transmission and spread, then, enabling it to survive actively at different residence times. Smog and haze were observed on several consecutive days in Milan arising from the accumulation of ground-level air pollutants due to radiation inversions on cold, dry days. During these days, the highest number of COVID-19 patients were reported partially supporting the idea that there is a relationship between rapid spread of COVID-19 and "the degree of air pollution as well the local topography along with climatic conditions" (Zoran et al., 2020).

Due to its relatively smaller size, $PM_{2.5}$ has greater health impacts because it can penetrate more easily into the respiratory tract and reach the alveoli (Tellier 2009). Both size PM, particularly $PM_{2.5}$ concentrations, were consistently higher than the US Environmental Protection Agency (EPA) guidelines in Wuhan and Xiao Gan. Fattorini and Regoli (2020) hypothesize that $PM_{2.5}$ is a substantial factor promoting SARS-CoV-2 transmission. Another study argues that air pollution in the coastal city of Weihai in China was slightly lower than in inland Jinan (Wei, Liu et al., 2020). This study supports the results of another study conducted by Wei et al. (2020) in which Italian coastal cities have less air pollution and COVID-19 virus infection is less prevalent than inland cities with high levels of air pollution (Wei, Liu et al., 2020).

Bashir et al. (2020) used Spearman and Kendall correlation tests to assess the relationship between $PM_{2.5}$ and PM_{10} with COVID-19 cases in New York City. They found that average temperature, minimum temperature, and air quality were significantly associated with the COVID-19 pandemic. Coker et al. (2020) reported an increase of only 1 μg/m^3 in $PM_{2.5}$ concentration was associated with an 9% enhancement in COVID-19-induced mortality in northern Italy In 120 Chinese cities, an association between a 10 μg/m^3 increase in $PM_{2.5}$, PM_{10}, and SARS-CoV-2-induced infection was observed, with a 2.24 and 1.76% increase in the number of daily confirmed cases, respectively (Yongjian, Jingu et al., 2020).

Atmospheric PM was found to carry more germs during polluted periods than clean ones (Wei, Zou et al., 2016). Bioaerosols particles and high microbial concentrations in suspended particles (PM) play a role in viral infection transmission dynamics (Zhang, Li et al., 2019; Morawska and Cao 2020). For example, studies on airborne bacteria in $PM_{2.5}$ from the Beijing-Tianjin-Hebei region in China showed that air pollutants are major factors in shaping the structure of the bacterial community (Gao, Fan et al., 2016; Xie, Fan et al., 2018). However, Liang et al. (2020) reported that in the United States, long-term exposure to NO_2, which largely arises from urban combustion sources such as traffic, may enhance susceptibility to severe COVID-19 outcomes, independent of long-term $PM_{2.5}$ and O_3 exposures.

The high effect of COVID-19 in the regions with high levels of PM ($PM_{2.5}$ and PM_{10}) was hypothesized in different parts of northern Italy (Distante and Piscitelli, 2020; Fattorini and Regoli, 2020; Martelletti and Martelletti 2020; Sciomer et al., 2020; Zoran et al., 2020). In this regard, it has been hypothesized that the presence of air pollutants - along with specific climatic conditions - may mean the long-term persistence of viral particles in the air, which in turn could lead to indirect release of SARS-CoV-2 (Frontera et al., 2020). It has been suggested that the dynamics of COVID-19 transmission could be due to the transmission of air pollution to humans, not direct human-to-human transmission. Another study in Italy, using data from infected people and air pollution from 55 Italian provincial capitals, reported that the rapid and widespread diffusion of COVID-19 in northern Italy was closely linked to the number of days that PM_{10} concentration was higher than the threshold level. It was also emphasized that the polluted cities in the hinterland with low wind speed which influence the atmospheric stability, have a larger number of infected people than the coastal cities (Coccia 2020).

The spread of SARS-CoV-2 by $PM_{2.5}$ and overcrowding is evident in overcrowded cities such as Mumbai, Dhaka, Ahmedabad, Chennai, and Jakarta in India, where large numbers of people are infected with COVID-19. The higher possibility to spread of SARS-CoV-2 confirmed in the areas with higher populations and lower air quality. Besides, data analysis in Italy shows how the regions of the country with the highest PM pollution are in the north of the country where the high level of SARS-CoV-2 lethality has been reported. The opposite is true for areas in the south. Given the effects of air quality on the prevalence of COVID-19, some recent research has shown that people who are exposed to long-term air pollution are more likely to become infected with the SARS-CoV-2 (Conticini, Frediani et al., 2020). It has been determined that SARS-CoV-2 can be transmitted through the release of infectious airborne droplets from coughing or sneezing or through nuclei with small aerodynamic diameters (Kutter, Spronken et al., 2018). In general, droplets larger than 50 μm immediately fall to the ground, while particles with dimensions of 5 μm take more than an hour to reach the ground from a height of 3 m (Tellier 2009). Besides, particles with an aerodynamic diameter of less than 2 μm are suspended in the air for hours or days and are more likely to reach the alveolar regions of the lungs (Wong and Lai 2004). In research done in Wuhan, China, they detected SARS-CoV- 2 in particles with 0.25–1.0 μm diameter and, also another study has detected the virus in 1–4 μm particles (Liu, Ning et al., 2020).

The concentration of the virus in the droplet (viral particles/microliter) increases as the volume (the radius of the droplet) decreases. This relationship suggests that under adverse environmental conditions assessed by the formation of $PM_{2.5}$, the number of persistent droplets with a high viral load indicates a significant increase in hospitalized cases (Fronza et al., 2020). As the size of the particles decreases, their deposition rate also decreases, and then, their spread is increased. This supports the transmission of SARS-CoV-2 that is high in temperate zones. Based on this evidence, it concluded that the concentration of PM (<20 mg/m^3), latitude, temperature (<13 °C), particle size (<$PM_{2.5}$) are suitable environmental conditions for the spreading of SARS-CoV-2 (Chennakesavulu and Reddy 2020).

RH may be an important meteorological parameter that had a positive effect on the transmission of the virus. In a study done in Milan during January–April period, it was concluded that outdoor daily RH was positively correlated with $PM_{2.5}$ (R^2 = 0.59) and PM_{10}

concentrations ($R^2 = 0.64$) (Zoran et al., 2020). Pearson correlation coefficient was positively correlated between the average daily concentration of $PM_{2.5}$ in Milan with the average daily RH ($R^2 = 0.59$) and air quality index (AQI) ($R^2 = 0.60$) (Zoran et al., 2020). The higher humidity levels are associated with atmospheric instability and PM capture by water droplets (Zhu et al., 2018; Wu, Chen et al., 2020). There is also a relationship between transmission and humidity, while viruses in droplets and aerosols survive well at low RH of approximately 50%, as opposed to high humidity levels. Therefore, it can be concluded that the wet particles can carry PM and viruses. However, according to some literature in virology and epidemiology, RH is a key climatic variable in understanding infection and viral transmission, which was negatively associated with the total number of cases of COVID-19 recorded in Milan (Zoran et al., 2020). The formation of small droplets is essential for the transmission of viral infection, while exhaled respiratory droplets settle very rapidly at high humidity levels. At lower levels of rainfall and daily wind speeds, the spread of the virus may be rapid. Statistical analysis shows that Pearson correlation coefficients between the mean daily PM level were inversely proportional to the average daily wind speed, $R^2 = -0.50$, and $R^2 = -0.32$ for PM_{10} and $PM_{2.5}$, respectively. Similar to other findings, the time series of climatic variables studied in the study was done by Zoran et al., (2020) showed that a sudden drop in outdoor temperature may trigger the COVID-19 epidemic in temperate climates and the RH facilitate aerosol expansion in dry air (Wu, Chen et al., 2020).

5. Conclusions

According to the results inferred from included literature, there appears to be a positive role of atmospheric particulate matter (PM) pollution and the spread of COVID-19. Some studies proposed that PM operates as a virus carrier, promoting its transport through the air. Exposure to ambient PM may also reduce the resistance to infection in the population although the degree of influence may depend on the particulate composition.

Therefore, based on the issues raised in the discussion, it can be concluded that PM concentration alone is not the only environmental factor involved in spreading SARS-CoV-2. Various environmental factors such as particle size and composition of the ambient PM, weather conditions including wind speed, RH and temperature are involved. Therefore, if there is a high concentration of $PM_{2.5}$ and wind, we can expect a more rapid spread of the virus. There are important limitations in the available evidence. Therefore, during this continuing COVID-19 pandemic, more studies such as the role of multiple pollutants and detailed chemical characterization of the PM are required to support and strengthen the scientific evidence for the role of air pollution in enhancing viral spread and infection. However, the major consistent results of most studies in the present analysis suggest that the atmospheric particulate matter pollution especially $PM_{2.5}$ had an important contribution to accelerate the spread of SARS-CoV-2.

CRediT author statement

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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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