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Effect of ambient air pollutants PM2.5 and PM10 on COVID-19 incidence and mortality: observational study

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Abstract. – OBJECTIVE: Environmental pollution is a leading global challenge affecting weather conditions and causing severe environmental, social, and public health problems. This study explores the impact of ambient air pollutants, particular matter (PM), PM2.5 and PM10 on morbidity and mortality of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) globally.

MATERIALS AND METHODS: In this study, initially 492 research articles were identified through seven search engines containing Web of Science, Medline, PubMed, EMBASE, Scopus, WHO COVID-19 literature, and Ovid databases by consuming keywords "Environmental pollution, Ambient air pollutants, particulate matter, PM2.5, PM10, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), and COVID-19 pandemic". Finally, 26 original research publications were included for the analysis, and the remaining were excluded. These studies were originated from the United States of America (9), China (5), Italy (3), India (1), worldwide (1), and one study each from England, Spain, Canada, Saudi Arabia, Singapore, Japan, and Iran.

RESULTS: The analysis based on a worldwide dataset assembled the information from the global literature from December 2019 to September 30, 2021. The assessment for the various regions to a global extent was based on air pollutants and COVID-19 cases and deaths. Twenty- six studies met the selection criteria representing almost all over the world. Based on the synthesis of scientific studies, it was identified that PM2.5 and PM10 are associated with 15.08%, 11.44 increased COVID-19 cases, and 9.26% and 0.75% COVID-19 deaths, respectively.

CONCLUSIONS: The evidence indicates that PM2.5 and PM10 can affect COVID-19 epidemiology in various geographical regions. The findings established an association and a possible causal link between increasing ambient air pollutants, particulate matter PM2.5 and PM10 with increased incidence and mortality of COVID-19. The global health authorities must take strict preventive measures to minimize air pollution and combat such challenging and threatening COVID-19 pandemic globally.

Key Words:
Environmental pollutants, PM2.5, PM10, SARS-CoV-2, COVID-19 pandemic.

Introduction

The interaction between humans and their physical surroundings has a significant role in the social, behavioral, neuropsychological developments, and the pattern of health and disease[1]. The swift unplanned urbanization and industrialization disturb normal environmental proportions worldwide[2]. Environmental pollution is a growing international public health issue and causes 4.2 million deaths per annum[3]. Environmental factors play a significant role in health, diseases, surveillance, prevention[4], and climate and weather conditions. One of humanity's challenges is spreading infectious diseases, including the Severe Acute Respiratory Syndrome coronavirus 2 (SARS CoV-2).

Environmental pollution swiftly changes the climate and affects the geographical distribution of various bacterial and viral diseases. The SARS CoV-2, also known as the COVID-19 pandemic, has caused a highly threatening and challenging situation worldwide. It involved every corner of the globe, including urban, rural regions in developing and developed countries. The global prevalence of COVID-19 infection rates is variable; it is higher in the highly populated, large metropolitan cities[5,6]. The SARS-CoV-2 is a respiratory virus transmitted mainly through droplet nuclei in the environment[5].

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The recent literature linked a relationship between weather conditions[7], and air pollutants play a substantial part in the etiopathology of the SARS-CoV-2 disease[8]. The literature highlights that exposure to air pollutants is related to rising rates of COVID-19 occurrence, disease severity, and deaths[9]. In addition, pollutant sources such as wildfires[10], sandstorms[11], and smoking have been linked with more significant risk factors of COVID-19[12]. Although the literature highlights the role of air pollutants, it lacks to establish the linkage between fine and coarse pollutants and SARS-CoV-2 morbidity and mortality. The present study investigates the impact of air pollutants PM2.5 and PM10 on daily SARS-CoV-2 cases and deaths. This study also highlights the possible evidence for a better understanding of mechanisms involved in air pollutants and SARS-CoV-2 cases and deaths.

Materials and Methods

This study employed an observational, descriptive approach to explore the impact of ambient air pollutants particulate matter PM2.5 and PM10 on SARS-CoV-2 morbidity and mortality.

Selection of Studies

In this study, we searched the literature related to "air pollutants, PM2.5, and PM10 and COVID-19" incidence and mortality in global databases: initially, the number of studies available based on the keywords were 492 and they focused on the environmental pollutants and morbidity; moreover, mortality of SARS-CoV-2 was identified from the various databases: PubMed, Medline, EMBASE, Web of Science, Scopus, Google Scholar, WHO COVID-19 literature and Ovid up to September 30, 2021 (Figure 1). The studies that were consistent with the selection criteria were thoroughly examined. The relevant studies were explored through the keywords and search terms, including "Environmental pollution, air pollutants, particulate matter, PM2.5, PM10, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) infection, COVID-19 pandemic". The publications were searched from December 2019 to September 30, 2021, without language restrictions on the search process. Finally, 26 original research articles on PM2.5, PM10, and SARS-CoV-2 cases and deaths were included for the analysis, and the remaining articles were excluded. The data were based on the 26 studies that published the findings on PM2.5 PM10 and SARS-CoV-2 worldwide. These studies were originated from the United States of America (9), China (5), Italy (3), India (1), worldwide (1), and one study each from England, Spain, Canada, Saudi Arabia, Singapore, Japan, and Iran.

Suitability of the Studies

The suitability of articles was scrutinized and analyzed by the title and abstract of the study. Once eligible studies had been shortlisted, relevant characteristics and results were extracted by an investigator and verified by another investigator. The difference of opinion was resolved through the input of the third investigator, and the majority decision was upheld where the third investigator reviewed a publication. Extracted data included sample size, types of pollutants, SARS-CoV-2 cases, deaths, and risk estimates for each exposure category was determined. The articles were carefully analyzed for the SARS-CoV-2 occurrence and fatalities.

A total of 26 original studies were included that explored the impact of "air pollutants, PM2.5, PM10 on COVID-19 morbidity and mortality". Twenty-six articles were analyzed for PM2.5 (Table I), and 11 articles were analyzed for PM10 (Table II). The analysis was based on the perspective, cross-sectional, case-cohort, longitudinal community-based studies and explored all possible relations between air pollutants and the SARS-CoV-2 cases and deaths.

Inclusion and Exclusion Criteria

For this study, the criteria for the selection of the studies were highly standardized. The studies had to be published in peer-reviewed, PubMed, and Web of Science indexed journals; human model; original research; including cross-sectional, case-control, cohort, observational studies that investigate the PM2.5, and PM10 exposure risks with SARS-CoV-2 mobility and mortality. However, the studies published in journals not indexed in PubMed or Web of Science were excluded. Moreover, animal model studies, non-original research, review, editorial, case reports, or meta-analysis were also excluded. Furthermore, preprint papers indexed in Medline (MedRxiv) were excluded as the literature was not peer-reviewed and unpublished. The study title, abstract, and detailed article information were evaluated and included for the analysis. Two investigators made the final selection of the study, and another research team member resolved the disagreement.

Table I. Associations of ambient air pollutants particulate matter PM2.5 with COVID-19 incidence and mortality.

Author and study year	Study/Sample Collection site	Sample size during the study period	Time of study	PM2.5 and COVID-19 outcomes
Meo et al[8]	London, United Kingdom (UK)	December 4, 2020, SARS-CoV-2 cases in London 161,626	February 24 to November 2, 2020	Each unit increase in PM2.5, SARS-CoV-2 cases & deaths increased by 1.1% & 2.3% respectively. PM2.5 has a positive linkage with cases and deaths.
Meo et al[10]	San-Francisco USA	Mean daily cases 58 cumulative cases 3939, deaths 0.45 cumulative deaths 43	March 20, 2020, to September 16, 2020.	Each PM2.5 unit caused an increase in daily cases, cumulative cases, and cumulative deaths of SARS-CoV-2 by 0.5%, 0.9%, and 0.6%, respectively.
Meo et al[11]	Saudi Arabia	Mean cases before sandstorm 120, after sandstorm 161.	Feb 20 to Mar 12; Mar 13 to April 2, 2021.	After the sandstorm, PM2.5: increased by 76.71%, and SARS-CoV-2 cases increased by 33.87%.
Meo et al[13]	LA, New Mexico, NY, Ohio & FL, USA	Median cases 25th-75th 1192(569-3183) deaths 25 (85-54	March 13 to December 31, 2020.	Each unit increase in PM2.5, SARS-CoV-2 infection increased by 0.1%
DeAngelis et al[15]	Lombardy, Italy an industrial city	61,377 19 cases and 40,401 deaths	Feb 20-April 16; March 1 to April 30 2020	Each 10 µg/m3 PM2.5 linked to 58% rise in cases and 23% deaths. 1.28, (CI 1.16-1.40; 1.16 (95 % CI 1.09-1.24
Solimini et al[17]	Worldwide five continents	237,749 SARS-CoV-2 cases	May 30, 2020	Each 10-µg/m^3 $PM_{2.5}$ linked with 8.1% rise in cases (95% CI (5.4-10.5)
Zhu et al[20]	China, 120 cities, four metropolitans	About 58,000 cases	Jan-Feb-2020	Each 10 µg/m3 PM2.5 linked to 2.24% increased cases (95% CI 1.02–3.46)
Bianconi et al[21]	Italy 110 regions	105,792 cases and 12,428 deaths	March 1-31, 2020	PM2.5 related to more COVID 19 cases β 0.71, and mortality β 0.68, p=0.004.
Adhikari & Yin[25]	New York, USA	42023 SARS-CoV-2 cases & 3221 deaths	March-April 2020	I unit rise in PM2.5 µg/m3 linked to 33.11% (95% CI 31.04–35.22) decrease in SARS-CoVv2 cases.
Hadei et al[26]	Tehran, Tabriz & Mashhad, Iran	114,964 cases and 21,549 deaths	Feb 20, 2020 to Jan 4, 2021	PM2.5 showed significant associations for mortality. 1.06 (95% CI: 0.99, 1.13)
Stieb et al[27]	111 Canadian Health counties	73,390 cases	5/13/2020	1-µg/m^3 rise allied to 7% high COVID 19 cases. IRR 1.07 (CI 0.97-1.18 µg/m^3).
Meo et al[31]	10 counties in California USA	Mean cases before wildfire 64.13±2.65 100.62 ± 5.03; deaths: 0.89 ± 0.05 2.21 ± 0.211.	March 19 to August 15, 2020; & August 15 to Sept 22, 2020	PM2.5 AOR=1.068; CI=1.059-1.077, cases, AOR 1.886; CI=1.427-1.997, deaths, AOR= 1.140; 95% CI =1.076-1.209 cases and deaths increased by 56.9%, & 148.21%
Zhou et al[32]	USA	--	March 15 to Dec 16, 2020	COVID-19 cases raised by 11.7%; CI: 8.2-16.0; and deaths 8.4%; CI: 2.1-15.3
Konstantinoudis et al[39]	England	38,573 COVID-19 deaths	up to June 30, 2020	1 µg/m3 rise PM2.5 linked to 1.4% (CI: -2.1%-5.1%) high SARS-CoV-2 deaths.
Sahoo[40]	288 regions in India	21,700 cases	Jan 23-April 23, 2020	10-µg/m^3 increase related to 2.21% cases (95% CI 1.13 to 3.29)
Valdés et al[41]	Chile, South America	4574 cases and 84 deaths per 100,000	2020	PM2.5 µg/m^3 increased 1.3% cases (CI 1.008-1.017. No link with mortality
Yao et al[42]	China 49 cities	82,214 cases	April 12, 2020	PM2.5 µg/m^3 increased case and fatality rate 0.24% (CI 0.01%–0.48%)
Zheng et al[43]	China	81,132 cases	12/31/19 to 3/6/20	10-µg/m^3 $PM_{2.5}$ rise linked to 32.30% upsurge in cases (95% CI 22.5-42.4%)
Azuma et al[44]	28 areas in Japan	6529 cases	March 13 to April 6, 2020	The average number of cases per million people was 132.5 (IQR 67.3-171.1). PM2.5 has no linkage with COVID-19 cases.
Jiang et al[45]	Wuhan, Xiaogan, and Huanggang, China.	Jan 25, Feb 29, 2020	Jan 25 to Feb 29, 2020	PM2.5 has relative risk with COVID-19 incidences in China: "Wuhan 1.036 (95% CI: 1.032-1.039); Xiaogan 1.059 (95% CI: 1.046-1.072); and Huanggang 1.144 (95% CI, 1.12-1.169)".

Table continued

Table I. *(Continued).* Associations of ambient air pollutants particulate matter PM2.5 with COVID-19 incidence and mortality.

Author and study year	Study/Sample Collection site	Sample size during the study period	Time of study	PM2.5 and COVID-19 outcomes
Ma et al[46]	Shanghai, China	337 cases	Jan 21, 2020-Feb 29, 2020 lag days 0-14	10-μg/m^3 rise in PM2.5 significantly increase (7.8%) daily COVID-19 cases. 1.101 (95% CI: 1.034–1.210)
Lorenzo et al[47]	Singapore	1375 cases & 6 deaths during study	Jan 23, 2020-, April 6, 2020.	One-unit 1μg/m3 significantly increase 22.6% cases (95% CI: 12.0%-34.3%).
Bowe et al[48]	USA	25,422 hospitalized cases	March 2 2020 &Feb15,2021.	1.9 μg/m3 PM2.5 was linked to 10% (95% CI: 8%-12%) rise in the risk
Mendy et al[49]	USA	14,783 COVID-19 patients	March 13, 2 to Sept 30, 2020.	PM2.5 related to 18% high hospital rate, 1.18; 95% CI: 1.11-1.26).
Lie et al[50]	554, counties USA	2.1 million cumulative cases	March 1 and June 30, 2020	A 10μg/m3 PM2.5 rise, daily cases increase by 9.41% (CI: 8.77%-10.04%)

Data Extraction

All the selected original articles were carefully examined. The required information was recorded, including the authors' name, publication year, geographical location, pollutants exposure, lag days, study outcomes, incidence, mortality, effect size, the percentage increased, and 95% CI. The findings were recorded, and a third research team member resolved any difference in opinion.

Statistical Analysis and Ethical Approval

The studies and their outcome were gathered from the publicly available studies and did not involve the patients or their medical records directly; hence no ethical approval was obtained. The findings were entered into the computer, and their outcome was recorded and analyzed.

Results

In this study, based on the primary keywords and studies published from December 2019 to September 30, 2021, we have identified 492 articles in the different web engines and finally included 26 original studies (Figure 1). The studies assessed and displayed the impact of air pollutants, PM2.5, PM10, and SARS-CoV-2 cases and deaths in different countries worldwide. The outcome of the included studies is summarized in Tables I-IV. The primary analyses were based on cross-sectional, retrospective cohorts, and time-series studies.

All the 26 studies were original, published the findings on the impact of ambient air pollutants particulate matter PM2.5, and PM10 on SARS-CoV-2 cases and deaths worldwide. Twenty-six studies on PM2.5 and SARS-CoV-2 cases and deaths were originated from the United States of America (9), China (5), Italy (3), India (1), worldwide (1), and one study each from England, Spain, Canada, Saudi Arabia, Singapore, Japan and Iran (Table I).

Out of these studies 26 studies, 24 studies established a substantial relationship between PM2.5 and SARS-CoV-2 cases and deaths. It was also found that increased air pollutants PM2.5 was significantly linked with an increased number of SARS-CoV-2 cases and deaths (Tables I, II, III, Figures 2, 3).

Table II demonstrates the total of 11 studies that show the association between PM10 and SARS-CoV-2 cases and deaths. These studies on PM10 and SARS-CoV-2 originated from China (5), Italy (3), Spain (1), India (1), and one stuy's findings were based on the data five contents (Table II, Figure 3). Out of 11 studies, ten studies found a substantial positive association between PM10 and SARS-CoV-2 cases and deaths (Table II). It was recognized that increased air pollutants PM10 was significantly linked with an increased number of SARS-CoV-2 cases and deaths (Table II). It was also identified that PM2.5 and PM10 were associated with 15.08% and 11.44 increased COVID-19 cases, and 9.26% and 0.75% COVID-19 deaths, respectively.

Discussion

Environmental pollution is a most significant challenge and threat to this highly advanced and most modern world. Air pollution has an impact on climate change, weather conditions, and public health. Initially, the concept of toxic effects of air

Table II. Associations of ambient air pollutants particulate matter PM10 with COVID-19 incidence and mortality.

Author and study year	Study location	Sample size	Time of Study	PM 10 and COVID-19 outcomes
DeAngelis et al[15]	Lombardy, an industrial city, Italy.	61,377 COVID-19 cases and 40,401 deaths	Feb 20-April 16, 2020; Mar 1-April 30,2020	10 μg/m^3 PM10 linked to 34% increased cases; IRR 1.23, (CI 1.13-1.33, SMR 1.22 (95 % CI 1.14-1.32
Solimini et al[17]	5 continents, 730 regions	237,749 SARS-CoV-2 cases	May 30, 2020	10 μg/m^3 PM10 allied with 11.5% rise (CI 7.8-14.9%) cases
Zhu et al[20]	120 cities, 4 municipalities in China	About 58,000 cases	Jan-Feb-2020	PM10 10μg/m3 linked to 1.76% rise in cases (95% CI 0.89 to 2.63%) lag 0-14 days
Bianconi et al[21]	Italy 110 provinces	105,792 cases and 12,428 deaths	March 1, to March 31, 2020	PM10 related to more COVID -19 cases β 0.61, p=0.031 and mortality β 0.61 p=0.029.
Sahoo[40]	288 regions in India	21,700 cases	Jan 23-April 23, 2020	10 μg/m^3 PM10 increase linked to 2.67% bigger cases (95% CI 0.33 to 5.01%) Lag 0-14
Yao et al[42]	China 49 cities	82,214 cases	Up to April 12, 2020	PM10 μg/m3 increase cases and fatality rate 0.26% (CI 0.00%-0.51%)
Zheng et al [43]	China 324 cities	81,132 COVID-19 cases 50,783 cases in mainland, China	Dec 31, 2019-March 6, 2020	Each 10 μg/m^3 PM10 increase linked to 14.2% rise cases (95% CI 7.9 to 20.5%).
Jiang et al[45]	Wuhan, Xiaogan, and Huanggang, China.	Jan 25, Feb 29, 2020	Jan 25 to Feb 29, 2020	PM10 has negative association with COVID-19 incidences 0.915 (95% CI, 0.896-0.934).
Ma et al[46]	Shanghai, China	337 COVID-19 cases	Jan 21, 2020- Feb 29, 2020. lag days 0-7 & 0-14 days	PM,10 10-μg/m3 rise was linked to 13.9% increase in cases (95% CI: 1.005-1.314)
Setti et al[51]	110 Italian provinces	17660 of the 60.4 million inhabitants in Italy	February 24 to March 13	Low polluted regions had a median of 0.03 cases, while in high polluted areas, 0.26 cases over 1000 residents
Saez et al[52]	Catalonia Spain 178 counties	---	February 25 to May 16, 2020.	1 μm/m3 PM10 had positive link with 3.0% (95% ICr: -1.4%,7.44%) Increased cases

pollutants was limited to the respiratory system. However, literature acknowledges that air pollutants are harmful to every cell of the human body. During the present pandemic of COVID-19, the community concerns are significantly increased once the studies highlighted that those environmental pollutants are the primary source for the spread of the SARS-CoV-2 diseases globally[13]. The present study identified that PM2.5 and PM10 positively linked with increased SARS-COV-2 daily cases and deaths.

The particulate matter PM10 particles have an aerodynamic diameter equal to or more than 10 (PM10 μm), and PM2.5 are fine inhalable elements with an aerodynamic diameter of 2.5 μm or less. The fine PM particles are the leading environmental risk factor, as they can penetrate deep into the human body (Figure 2). After the initial outbreak of SARS-CoV-2 in China, SARS-CoV-2 spreaded very fast across the globe. Among various factors, in such geographical differences, a possible role for environmental pollution has been hypothesized. This study provides evidence that PM2.5 and PM10 cause the spread of the SARAS-CoV-2 disease in different regions. The literature supports the hypothesis and offers favorable context between air pollutants and spreading the SARS-CoV-2 illness[14].

De Angelis et al[15] described the relationship of PM2.5 and PM10 pollutants with SARS-CoV-2 incidence and mortality. A 10-μg/m^3 upsurge in PM2.5 caused a 58% amplified risk of COVID oc-

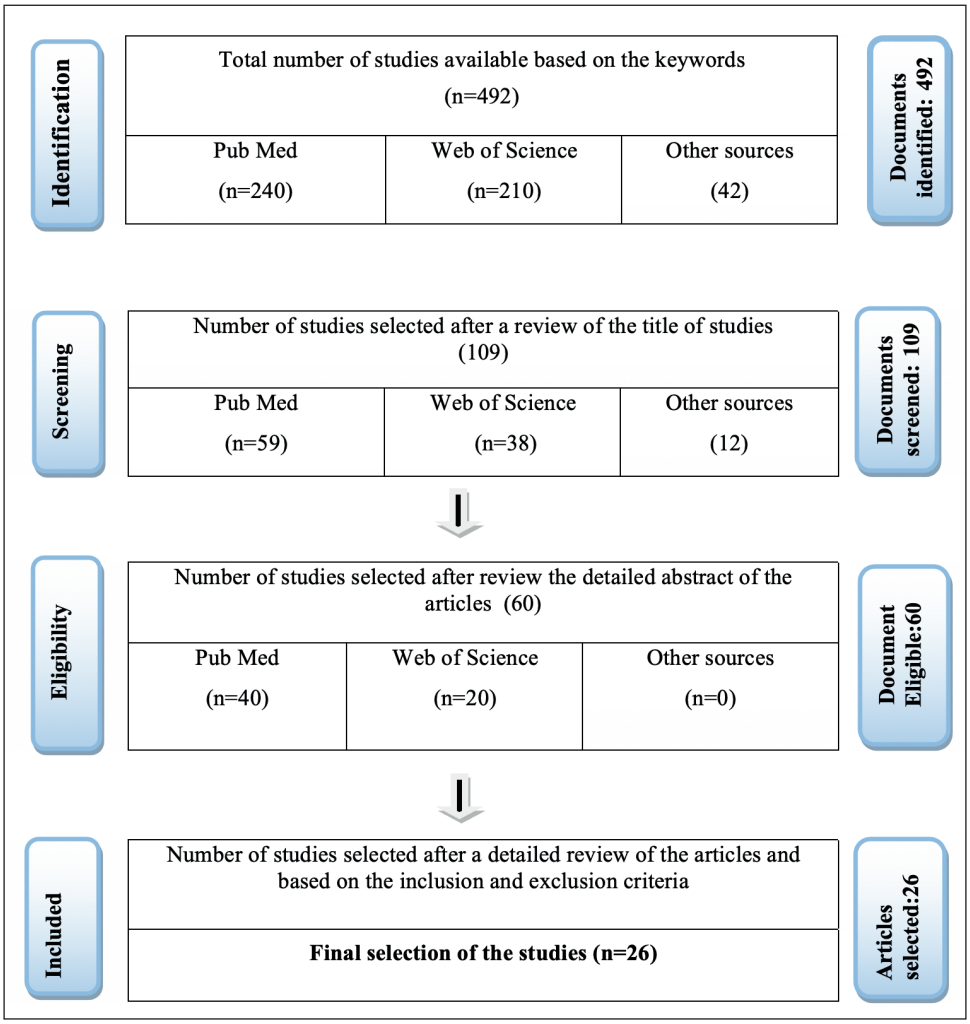

Figure 1. PRISMA Flow diagram for the selection of studies.

currence in Lombardy, Italy[15]. Sharma et al[16] 2021 published a study in 10 nations and found that PM2.5 was allied with the growing amount of SARS-CoV-2 cases and deaths. Similarly, Solomini et al[17] performed a sizeable sample-sized study of 237,749 patients from sixty-three countries in five continents and found a 10-µg/m^3 increase in $PM_{2.5}$ was allied with an 8.1% rise in COVID-19 cases.

While considering the studies from the US, Wu et al[18] performed a sizeable sample-sized study of 3,000 counties and reported that 1 µg/m^3 rise in PM2.5 was correlated to an 8% increase in COVID-19 deaths. Another study from Mexico, USA, demonstrated that one unit rise in µg/m^3 PM2.5 caused a 7.4% high risk of COVID-19 deaths[19]. Similar to these studies, Zhu et al[20] completed a survey in about 120 towns in China. The authors found that 10 µg/m^3 upsurge in PM2.5 caused a 2.24% rise in COVID-19 mortality. A similar association has been established between PM2.5 and increased COVID-19 morbidity and mortality in a couple of Italian studies[21-23].

Another large sample-sized study[24] based on the 107 Italian regions showed that the COVID-19 cases and deaths were higher in areas closest to Lodi, Lombardy, and the impact was most probably due to high ozone levels. In contradiction to all these studies, Adhikari and Yin[25] reported that increased PM2.5 was related to a lower risk of COVID-19 cases and mortality.

Hadei et al[26] demonstrated that PM2.5 has a rising risk for SARS-CoV-2 incidence and mortality in three different cities in Iran. In another study, Stieb et al[27] found that one µg/m^3 growth of PM2.5 has been linked with a 7% increase in COVID-19 cases. Liu et al[28] studied various global nations, including USA, Canada, Korea, China, Japan, Russia,

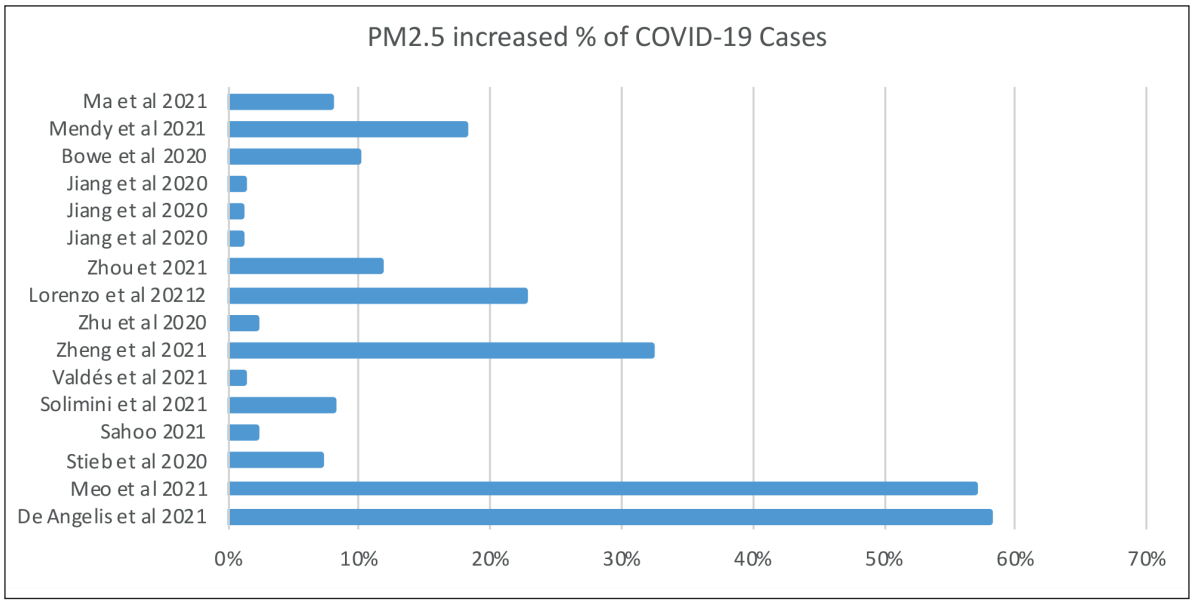

Figure 2. Association of PM2.5 with an increasing percentage of COVID-19 cases.

England, France, and Germany, and found high environmental levels of PM2.5 PM10 related to increased rates of SARS-CoV-2 cases. The authors noticed that the impact of PM2.5 on COVID-19 incidence was more in England, Germany, France, the USA, Canada, and Russia. However, PM10 linkage with COVID-19 occurrence was more in Russia, England, Germany, and France[28].

Kolluru et al[29] performed a study in five metropolitan cities, Delhi, Kolkata, Mumbai, Bangalore, and Chennai, and reported that high PM2.5 and PM10 were related to the significantly increased COVID-19 cases and deaths. Another study[30] based on about 11 million COVID-19 cases from six South Asian countries, including Afghanistan, Bangladesh, India, Nepal, Pakistan, and Sri Lanka demonstrated that PM2.5 was linked with rising rates of COVID-19 cases and death.

Meo et al[8] published a study associated with air pollutants and SARS-CoV-2 cases and deaths in London, England. The study findings suggested that high air pollutants were related to the high number of COVID-19 cases and deaths. Moreover, each 1 μg/m^3 upsurge in PM2.5 increases 2.3% SARS-CoV-2 cases and deaths. Meo et al[31]

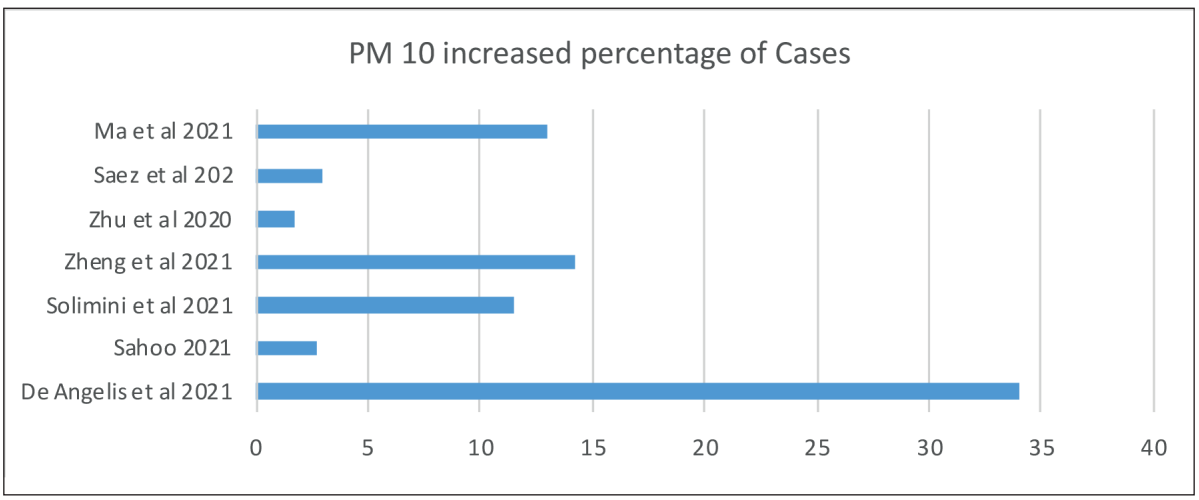

Figure 3. Association of PM10 with an increasing percentage of COVID-19 cases.

Table III. Association of PM2.5 and PM10 with COVID-19 cases.

Author & Study Year	Study Region	Increased percentage of COVID-19 Cases	$PM_{2.5}$ cases and 95% CI		
			Minimum	Maximum	Average
PM2.5 and COVID 19 cases (%)					
Bowe et al [48]	USA	10	8	12	10
De Angelis et al[15]	Lombardy, Italy	58	1.16	1.4	1.28
Jiang et al[45]	Wuhan, China	1.04	1.023	1.039	1.031
Jiang et al[45]	Xiaogan, China	1.06	1.046	1.039	1.042
Jiang et al[45]	Huanggang, China	1.14	1.12	1.69	1.405
Lorenzo et al[47]	Singapore	22.60	12	34.3	23.15
Ma et al[46]	Shanghai, China	7.80	1.034	1.21	1.122
Mendy et al[49]	USA	18.00	1.11	1.26	1.185
Meo et al[31]	California, USA	56.90	1.427	1.997	1.71
Sahoo[40]	India	2.21	1.13	3.29	2.21
Solimini et al[17]	Worldwide	8.10	5.4	10.5	7.95
Stieb et al[27]	Canada	7.00	0.97	1.18	1.075
Valdés et al[41]	Chile	1.30	1.008	1.017	1.012
Zheng et al[43]	China	32.30	22.5	42.4	32.45
Zhou et al [32]	USA	11.70	8.2	16	12.1
Zhu et al [20]	120 Cities, China	2.24	1.02	3.46	2.24
PM10 and COVID-19 cases (%)					
De Angelis et al[15]	Lombardy, Italy	34	1.16	1.4	1.28
Ma et al[46]	Shanghaie, China	13	22.5	42.4	32.45
Saez et al[52]	Spain	3	1.008	1.017	1.0125
Sahoo[40]	India	2.67	1.427	1.997	1.712
Solimini et al[17]	Worldwide	11.5	0.97	1.18	1.075
Zheng et al[43]	China	14.2	1.13	3.29	2.21
Zhu et al[20]	120 Cities, China	1.76	5.4	10.5	7.95

Table IV. Association of PM2.5 with COVID-19 deaths.

Author & Study year	Study Region	PM2.5 link with COVID-19 deaths (%)	PM2.5 Deaths and 95% CI		
			Minimum	Maximum	Average
De Angelis et al[15]	Lombardy, Italy	23	1.09	1.24	1.165
Konstantinoudis et al[39]	England	5.4	2.5	8.4	5.45
Meo et al[31]	California USA	148.21	1.076	1.209	1.1425
Yao et al[42]	China, 49 cities	0.24	0.01	0.48	0.245
Zhou et[32]	USA	8.4	2.1	15.3	8.7

conducted another study in ten counties in California, which were affected by the wildfires. The authors reported that during the wildfire, the PM2.5 levels amplified by 221%; and during the same wildfire period, COVID-19 cases ascended by 57%, the deaths increased by 148%[31]. On the other hand, Meo et al[10] reported that high PM2.5 levels significantly linked to elevated rates of COVID-19 cases in San Francisco during the same wildfire period.

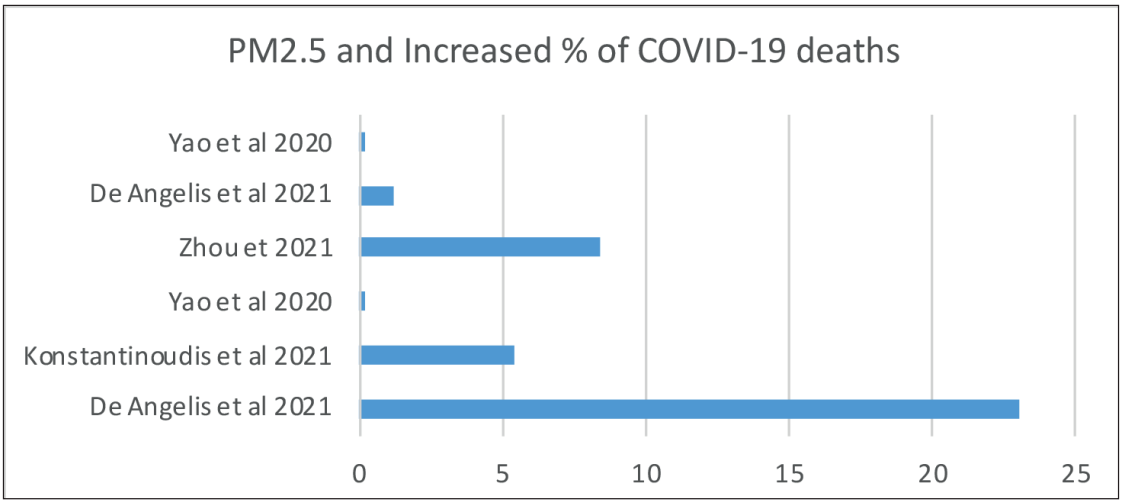

Figure 4. Association of PM2.5 and PM10 with a rising percentage of COVID-19 deaths.

Zhou et al[32] executed a study on the four-week impact of air pollutants on COVID-19 cases and deaths. The authors identified that out of 92 counties, 52 counties in the US had a positive association with PM2.5 and a high risk of COVID-19 cases and deaths. It was found that a day-to-day increase of 10 μg/m^3 in PM2.5 for about one month period was linked with a 12.0% increase in COVID-19 cases. However, in the few counties, an enormous impact of a rise of 10 μg/m^3 in PM2.5 was related to a 65.3% and 71.6% increase in COVID-19 cases. While about deaths, the research team members reported that 17 counties had a positive relationship between PM2.5 and COVID-19 deaths. The everyday increase of 10 μg/m^3 in PM2.5 for about one month was linked to an 8.4% rise in COVID-19 deaths. However, Calaveras, CA, and San Bernardino, CA had the maximum death rate of 52.8% and 65.9%[32]. Curtis[33] conducted a well-designed analysis of many studies on air pollutants, PM2.5, PM10, NO_2, O_3, SO_2, and their outcome on SARS-CoV-2 cases and deaths. The conclusion was based on the global data that each μg/m^3 rise in PM2.5 was projected to increase COVID-19 by as much as 0.22 to 8%. All these pieces of evidence demonstrated an association and a possible causal link between fine and coarse particulate matter PM2.5 and PM10 and incidence and mortality of COVID-19.

Biological Plausibility for SARS-CoV-2 and Air Pollutants

The present study's convincing findings have biological plausibility that air pollutants increase the risk for COVID-19 cases and deaths. Air pollutants predispose people to develop COVID-19 associated enhancing virus-induced tissue inflammation, immunopathology, oxidative stress, and lung damage[34,35]. The air pollutants PM can provide an appropriate atmosphere for transporting the SARS-CoV-2 virus at greater distances, and PM2.5 can cause lung inflammation, increase vulnerability, and COVID-19 disease severity[36-38]. The increasing evidence supports the hypothesis that ambient air pollutants PM2.5 and PM10 provide a suitable platform for carrying the SARS-CoV-2 virus and its transport at the lung levels.

Moreover, SARS-CoV-2 has an affinity for the ACE2 receptor and upregulates ACE2 expression to pollutant allied oxidation and inflammation of the lungs. These facts support the hypothesis that PM can increase the risk of SARS-CoV-2 *via* ACE2 expression and worsen lung injury by increasing inflammation. The available points propose that exposure to air pollutants PM2 causes alveolar ACE-2 receptor overexpression, increases the viral load, depletes ACE-2 receptors, and impairs the host defense mechanism, resulting in a poor outcome[38].

Conclusions

The air pollutants PM2.5 and PM10 increase SARS-COV-2 day-to-day incidence and mortality in various geographical regions worldwide. The study findings can strengthen the hypothesis that air pollution is a leading cause of the COVID-19

pandemic. The health authorities handle this challenging global pandemic through public cognizance and a multidisciplinary scientific approach. The health officials, national and international environmental protection organizations should address the role of air pollution in the spread of SARS-CoV-2 cases and deaths. Moreover, strict policies should be developed to minimize air pollution and combat global health issues like the COVID-19 pandemic.

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Conflicts of interest

The authors declare no conflicts of interest.

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