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The link between COVID-19 mortality and PM_{2.5} emissions in rural and medium-size municipalities considering population density, dust events, and wind speed

Federico Páez-Osuna^{a,b,*}, Gladys Valencia-Castañeda^a, Uriel Arreguin Rebolledo^a

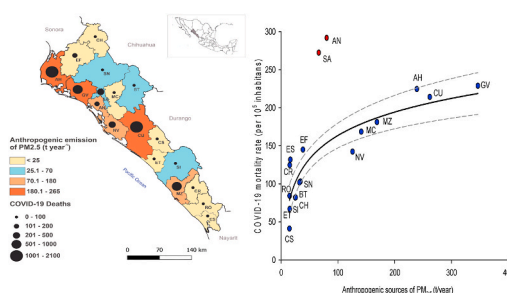
^a Universidad Nacional Autónoma de México, Instituto de Ciencias del Mar y Limnología, Unidad Académica Mazatlán, P.O. Box 811, Mazatlán, 82000, Sinaloa, Mexico

^b Miembro de El Colegio de Sinaloa, Antonio Rosales 435 Poniente, Culiacán, Sinaloa, Mexico

HIGHLIGHTS

- Influence of PM_{2.5} on COVID-19 mortality is examined in 18 rural municipalities.
- PM_{2.5} emissions are estimated from vehicles and anthropogenic sources.
- PM_{2.5} emissions are associated with increases in mortality rates of COVID-19.
- High COVID-19 mortality in rural municipalities could be associated to dust events.
- Expansion of cities should avoid high population density mainly when low wind speed.

GRAPHICAL ABSTRACT



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ABSTRACT

One contemporary issue is how environmental pollution and climate can affect the dissemination and severity of COVID-19 in humans. We documented the first case of association between particulate matter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) and COVID-19 mortality rates that involved rural and medium-sized municipalities in northwestern Mexico, where direct air quality monitoring is absent. Alternatively, anthropogenic PM_{2.5} emissions were used to estimate the PM_{2.5} exposure in each municipality using two scenarios: 1) considering the fraction derived from combustion of vehicle fuel; and 2) the one derived from modeled anthropogenic sources. This study provides insights to better understand and face future pandemics by examining the relation between PM_{2.5} pollution and COVID-19 mortality considering the population density and the wind speed. The main findings are: (i) municipalities with high PM_{2.5} emissions and high population density have a higher COVID-19 mortality rate; (ii) the exceptionally high COVID-19 mortality rates of the rural municipalities could be associated to dust events, which are common in these regions where soils without vegetation are dominant; and (iii) the influence of wind speed on COVID-19 mortality rate was evidenced only in municipalities with <100 inhabitants per km^2 . These results confirm the suggestion that high levels of air pollutants associated with high

* Corresponding author. Unidad Académica Mazatlán, Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México (UNAM), Mazatlán, Sinaloa, Mexico.

E-mail address: paezos@ola.icmyl.unam.mx (F. Páez-Osuna).

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population density and an elevated frequency of dust events may promote an extended prevalence and severity of viral particles in the polluted air of urban, suburban, and rural communities. This supports an additional means of dissemination of the coronavirus SARS-CoV-2, in addition to the direct human-to-human transmission.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic caused by the novel coronavirus SARS-CoV-2 is generating a high number of deaths (~3.94 million people on June 2021, WHO, 2021), with negative effects on the public health and economic systems (Coccia 2020a, 2021d). The main lessons learned from the COVID-19 pandemic are the importance of healthcare expenditures to reduce fatality rates (Coccia, 2021f), the timely application of containment policies, and understanding the influence of climatic factors and air pollution on the spread and severity of COVID-19. Coccia (2021c) proposes that gross domestic product per capita, healthcare spending, and air pollution of nations are critical factors associated with the fatality rate of COVID-19. In addition, Coccia (2021a) found that wind speeds and air pollution may support the dissemination of COVID-19 leading to a higher incidence of infected individuals and deaths; cities with high wind speed have less cases of COVID-19, compared to those with little wind speed and frequent high levels of air pollution. For example, Coccia (2021d) found that nearly 81 % of deaths from the first wave of COVID-19 pandemic in Italy occurred in industrialized regions with high levels of contaminated air.

Atmospheric stability (*i.e.*, low wind speed) reduces the dispersion of gases, and particulate matter (PM) can act as a carrier of the SARS-CoV-2 in the air to sustain the dissemination of COVID-19 in the environment, generating problems in the public health (Coccia, 2021e). The concentration of atmospheric pollutants can also include viral agents such as SARS-CoV-2 (Coccia, 2020c, 2021c). However, a high wind speed maintains the air clean thus it reduces the spread of COVID-19 and other infectious diseases whenever possible (Coccia, 2020c, 2021c; Rosario Denes et al., 2020). Additionally, high wind speed maintains the dilution and removal of droplets, decreasing the concentration of viral agents in the air and the transmission dynamics of viral infectivity among people (Coccia, 2020b, 2021a). Rosario Denes et al. (2020) observed that wind improves air circulation and increases the exposure of the SARS-CoV-2 to solar radiation effects, a factor that shows a negative correlation in the dissemination of COVID-19. Similarly, evidence from the 20 countries with the highest number of confirmed cases suggests that both high temperatures and humidity reduce the viability, stability, survival, and transmission of COVID-19; whereas low temperature, wind speed, dew/frost point, precipitation, and surface pressure extend the activation and infectivity of the virus (Sarkodie and Owusu, 2020).

The viral agent of SARS-CoV-2 may be suspended in the air for various minutes, which can partially explain the transmission dynamics and the high number of infections and deaths in many regions (van Doremalen et al., 2020; Coccia, 2020c). This implies that those environments with a high concentration of air pollutants associated with climatological conditions (low wind speed), may maintain a prolonged permanence of SARS-CoV-2. This would increase the dissemination of COVID-19 and other infectious diseases both with mechanisms of air pollutants-to-human transmission and human-to-human transmission (Coccia, 2020c, 2021e). Moreover, the highest incidence of new coronavirus infections occurs in regions with a high level of air pollution such as certain counties in the United States (Wu et al., 2020; Bashir et al., 2020), Mexico City (López-Feldman et al., 2021), Northern Italian cities (Filippini et al., 2020), and densely populated cities in China (Yao et al., 2020). However, the viability and virulence of SARS-CoV-2 on the surface of particulate matter has not been confirmed (Srivastava, 2021).

Globally, several reviews had confirmed the association between COVID-19 and selected variables of the environment. Rahimi et al. (2021) conclude that the thermal properties of ambient air, as well as

relative humidity, may affect the transmissibility and viability of the virus. Conversely, global studies showed inconsistent results as the association between COVID-19 and humidity were inconclusive in 206 regions. In contrast, there is evidence of a negative association between wind speed and COVID-19 (Islam et al., 2021). Pana et al. (2021) examined the determinants of the severity of the COVID-19 pandemic considering demographic, economic, and environmental parameters, comorbidities, health system parameters, international arrivals, vaccination coverage, UV radiation exposure, and testing capacity. The authors observed that international travel was directly associated with the mortality slope and recommend very early traveling restrictions to control COVID-19 outbreaks. Diao et al. (2021) examined the spread of the COVID-19 pandemic in cities of China, England, Germany, and Japan and found a significant correlation of the spread and decay duration with population density in the four countries. Specifically, spread duration showed a high correlation between population density and humidity, whereas decay duration exhibited the highest correlation with population density, humidity, and maximum temperature. Recurring waves of COVID-19, along with new variants, are other factor apart from climate and atmospheric pollution that can generate different evolutionary dynamic responses over time and space (Coccia, 2020a, 2021b). However, the different implications and mechanisms of how this occurs remain unknown.

These results suggest that the pandemic caused by COVID-19 and similar future epidemics cannot be faced only with studies and practice in medicine. The solution also requires changes in the paradigm regarding strategies and technologies for sustainable development bases on the reduction of air pollution and increase in renewable energy to improve air quality, and consequently public health (Coccia 2020b, 2021f.). Global efforts are urgently needed to improve food production and diets (Willet et al., 2019), as well as renewable energy generation to avoid poor health and environmental degradation, which would also reduce health risks associated to pandemic such as COVID-19.

In general, studies in Latin America show a similar pattern than those from developed countries. Bolaño-Ortiz et al. (2020) evaluated the spread of SARS-CoV-2 in ten cities of Latin America and the Caribbean region and found that temperature and air quality were significantly associated with the spread of COVID-19. Humidity, wind speed, and rainfall showed a significant relationship between the total number of cases and mortality in various cities. These authors suggest that there is a positive and negative relation considering income inequality and poverty in the spread of COVID-19, respectively. Díaz de León-Martínez et al. (2020) developed a review of the social, environmental, and health risk factors in the Mexican indigenous population regarding COVID-19. The authors found that poor access to water, language barriers, and limited access to the internet are factors that limit minimum preventive measures. Biomass burning was identified as a risk factor, and those identified for health were the lack of coverage in comorbidities such as diabetes mellitus, hypertension, respiratory tract infections, and chronic pulmonary diseases. A dilemma in Mexico on the context of COVID-19 data is the low testing rates, as well as the delays in reports of the estimation of the mortality burden associated with the pandemic. Dahal et al. (2021) found that the COVID-19 deaths confirmed by laboratories accounted for only 36.6 % of total all cause excess deaths in 2020. This reveals the effect of low testing rates and/or the increase in number of deaths due to other causes during the pandemic.

Various studies have been carried out regarding the environmental-COVID-19 relation in Mexico. Tello-Leal and Macías-Hernández (2021) analyzed the correlation between air pollutants and confirmed cases of

the COVID-19 pandemic at the micro-level in Victoria City, Mexico, and found a direct influence of air quality on the spread of COVID-19. Kutralam-Muniasamy et al. (2021a) found that the contribution from the Saharan dust events increase PM levels, and as a result, there is a positive association of PM with the number of daily COVID-19 cases and deaths during these events in four eastern regions of Mexico. Two studies have been developed in Mexico City; Kutralam-Muniasamy et al. (2021b) observed a significant association between COVID-19 cases and deaths and the concentrations of PM_{2.5}, CO, and O₃. By examining the impacts of the lockdown on air quality and its association with mortality trends. López-Feldman et al. (2021) found a positive relationship between pollution (exposure to PM_{2.5}) and mortality, which increases with age.

A different case is the study of the effects of environmental pollutants on the incidence and mortality of SARS-CoV-2 infection in wildfire affected counties in California, USA (Meo et al., 2021). The authors observed that the concentration of PM_{2.5} increased by 221 % after

wildfire events. Posteriorly, the number of cases and deaths due to COVID-19 increased by 57 % and 148 %, respectively. These results suggest that the California wildfire produced an increase in ambient levels of toxic pollutants, which were temporally associated with an increase in the occurrence and mortality of COVID-19. Therefore, long-term exposure is not necessarily required to promote the conditions of greater onset and mortality by COVID-19. From such a situation, it is important to examine if this association occurs in different scenarios, such as rural communities, including small and medium municipalities. The main aim of this work is to examine the relationships between the COVID-19 mortality rate and PM_{2.5}, meteorological, and demographic factors in the municipalities of Sinaloa, Mexico. The hypothesis is that COVID-19 severely affects (mortality) communities that have a greater exposure to high levels of PM_{2.5}, a high population density, and low wind speed, including rural towns and small and medium-sized cities.

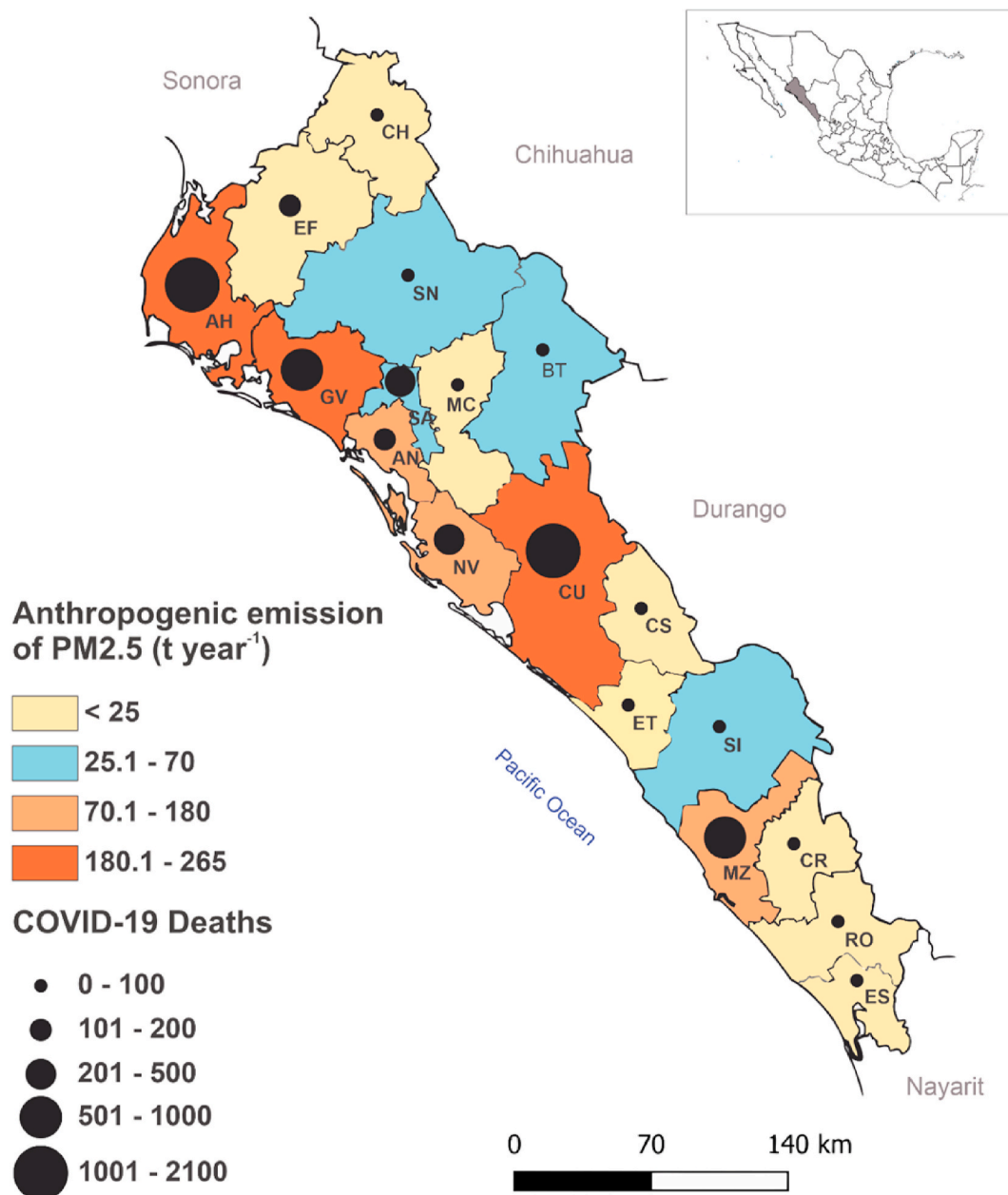


Fig. 1. Distribution of COVID-19 deaths and anthropogenic emission of PM_{2.5} in Sinaloa. Own estimation with data from Huang et al. (2014) and INEGI (2021a). Choix, CH; El Fuerte, EF; Ahome, AH; Guasave, GV; Sinaloa, SN; Salvador Alvarado, SA; Angostura, AN; Mocorito, MC; Badiraguato, BT; Navolato, NV; Culiacán, CU; Elota, ET; Cosalá, CS; San Ignacio, SI; Mazatlán, MZ; Concordia, CR; Rosario, RO; Escuinapa, ES.

2. Materials and methods

2.1. Sample and data

The study case described in this work was carried out in Sinaloa, Northwest Mexico (~3 million people). This state includes 18 municipalities (Fig. 1) which consist of rural communities, towns, and small and medium-sized cities, where a variable incidence and mortality of COVID-19 has been observed. The first case of COVID-19 in Mexico was detected in February 2020 in Culiacan (Sinaloa) by a Mexican citizen that arrived from Italy. Since then, the pandemic has fluctuated in intensity within the country, and the highest number of deaths were recorded in January and February 2021. In particular, this study analyzes the accumulated mortality rate that included the first and second wave of the COVID-19 pandemic in Mexico from February 2020 to April 2021. Mexico had exhibited two peaks based on the number of confirmed cases: one between June 22 and August 17, 2020, and a second more intense between January 7 and February 10, 2021 (WHO, 2021).

The information concerning confirmed COVID-19 cases and deaths in Mexico is available from the Secretaria de Salud, Gobierno de Sinaloa (COVID-19-Sinaloa, 2021) and the Instituto Nacional de Estadística y Geografía (INEGI, 2021a). Climatic factors (temperature, precipitation, wind speed, etc.) are available from meteorological stations in each municipality (es. Weatherspark, 2021), which are summarized in Table 2A. briefly, data on the COVID-19 pandemic used in the present study are per municipality: accumulated deaths, population, people >60 years old, population density, and mortality rate.

2.2. Measures of variables

- The cumulative mortality rate (per 10⁵ people) of COVID-19 in municipalities is calculated using the accumulated number of deaths with the population of each municipality (INEGI, 2021a) until April 11, 2021 (Table 1A supplementary material), during the first and second waves of COVID-19 outbreak in Mexico.
- Air pollution of municipalities is estimated with the emissions of PM_{2.5} calculated from two scenarios considering vehicles and anthropogenic sources modeled by Huang et al. (2014). Table 2A (supplementary materials) shows the specific values of PM_{2.5} emissions for each municipality and the related variables.
- Atmospheric stability is measured with the average wind speed (km/h) of the 18 municipalities utilizing records from 37 years (January 1980 to December 2016) (es. Weatherspark, 2021).
- Demographic data of municipalities are given by: population density of municipalities (inhabitants/km²) 2021; people aged >60 years old (INEGI, 2021a).

2.3. Data analysis procedure

Descriptive statistics is performed classifying municipalities of Sinaloa in groups, considering:

- Wind speed, based on the arithmetic mean of the sample given by 9.3 km/h (Coccia, 2021a), which includes (i) municipalities with high wind speed (>9.3 km/h) indicating a wind force from light to moderate breeze according to the Beaufort wind scale (average wind force of light breeze means that wind is felt on face, leaves rustle, vanes begin to move, whereas a wind force of moderate breeze generates the wind effect of dust, leaves and loose paper lifted, and the movement of small tree branches); and (ii) municipalities with low wind speed (<9.3 km/h) indicating a wind force from calm air to light breeze according to the Beaufort wind scale (Table 2A).
- Population density, which is low in Sinaloa, but was grouped in two categories: (i) municipalities with a low population density between 100 and 200 inhabitants/km²; and (ii) municipalities with very low population density <70 inhabitants/km² (Table 1A).

- Air pollution based on PM_{2.5} emissions estimated from anthropogenic sources that includes: (i) municipalities with moderate or low PM_{2.5} emissions (100–350 t/year); and (ii) municipalities with very low PM_{2.5} emissions (<80 t/year) (Table 2A).

Air quality monitoring stations are absent in most municipalities, except for Culiacan, Los Mochis, and Mazatlán; however, these stations operate irregularly. Therefore, an alternative was used to estimate the exposure to air contaminants. The estimated exposure to PM_{2.5} in each municipality was inferred from their emissions following two scenarios: A) considering only PM_{2.5} emitted from vehicles per municipality, calculating these microparticles from the combustion of gasoline and diesel; and B) considering PM_{2.5} from the primary emissions from combustion and industrial sources according to the global model developed by Huang et al. (2014).

Scenario A: the calculation of the PM_{2.5} emitted from vehicles per municipality was carried out under the following conditions and assumptions: (i) using the consumption (combustion) of fuel in the state of Sinaloa registered in 2017 (2,931,634 m³ gasoline and 1,055,555 m³ diesel, SENER, 2018); (ii) that the consumption of fuel per municipality is proportional to the vehicle fleet, which was estimated according to the population in all cases, except in the main municipalities (Culiacan, Ahome, Mazatlan, and Guasave) where information is available on the fuel consumption and the vehicle fleet; (iii) the consumption of diesel and gasoline is homogenous in the 18 municipalities and equivalent to the global for Sinaloa (73.5 % gasoline and 26.5 % diesel, SENER, 2018); and (iv) the mixed emission factor (EF) for diesel and gasoline was assumed to be 101 mg PM_{2.5} per L of fuel consumed.

There is a wide range of EFs in the literature, depending on the type of fuel, test conditions, vehicle characteristics (size, weight, model (age), engine, power, technology, device-catalyst, etc.), and drive mode. For instance, Zhang and Morawska (2002) found an EF between 169 and 658 mg PM_{2.5}/L of diesel for vehicles of different weights during the 1990s. Yang et al. (2019) examined gasoline vehicles from 2007 to 2016 and found an EF range of 5.6–43.2 mg PM_{2.5}/L, and 25–621 mg/L in diesel vehicles from 2006 to 2011. Kuhns et al. (2004) observed a clear PM increase with vehicle age; the average EFs were reported for the fleet of light-duty gasoline vehicles (60 mg/kg), heavy-duty gasoline vehicles (50 mg/kg), light-duty diesel vehicles (1600 mg/kg), and heavy-duty diesel vehicles (1500 mg/kg). From these results, it is possible to estimate a representative EF for the vehicle fleet of Sinaloa that globally consume diesel (26.5 %) and gasoline (73.5 %) (SENER, 2018), which could be ~182 mg/L of fuel. This last value is similar to the EF (187 ± 144 mg/L) reported by Mancilla and Mendoza (2012) for vehicles in Monterrey, Mexico. However, most of these studies considered vehicles between 2006 and 2011. It is probable that the performance in recent and predominant vehicles (2010–2020) both powered by diesel and gasoline have improved (weight, devices, technology, etc.); therefore, an EF = 101 mg/L was assumed for this exercise (scenario A).

The equation involved in the calculation of the emission of PM_{2.5} from vehicles per municipality (Ev) (t year⁻¹) for scenario A was:

$$E_v = \text{Fuel consumption per municipality (m}^3\text{/year)} \times \text{EF} \times 10^6 \quad [1]$$

The emissions of PM_{2.5} from stationary combustion sources which burn fuel oil (known as combustoleo) in Sinaloa include at least two thermoelectric power plants, as well as PM_{2.5} from internal combustion engines from burning gasoline, diesel, and biomass in rural communities. These three sources and the reduced industry are a significant source of anthropogenic PM_{2.5} primary particles in rural, suburban, and urban areas. Huang et al. (2014) estimated the temporal global trends at a country scale resolution of the primary emissions of PM_{2.5} from combustion and industrial sources. The strategy followed by the authors includes the emission estimation, in which PM_{2.5} was calculated as a product of the source strength (quantities of fuel consumed or material produced) and EFs for that source. In addition to the 65 combustion

sources, 12 material production sources were incorporated in the calculations, including diverse processes (steel and iron industry), production of lime, and fertilizers. Huang et al. (2014) collected as many data as possible, from which distributions of the EFs were derived for a Monte Carlo simulation to characterize the associated uncertainty. The fuel inventory was generated based on subnational fuel data for some countries. Spatial distribution of the PM_{2.5} emissions worldwide including Mexico (and Sinaloa) is shown by Huang et al. (2014). The total anthropogenic emissions of PM_{2.5} (kg/km²/year) per area (E_a) for Sinaloa were estimated directly from Huang et al. (2014) (Table 2A). Therefore, the total anthropogenic emissions of PM_{2.5} per municipality in t year⁻¹ (E_{ta}) was estimated using the following equation:

$$E_{ta} = E_a \text{ (kg/km}^2\text{/year)} \times \text{municipality area (km}^2\text{)} \times 10^{-3} \quad [2]$$

The study analyzes trends with a simple regression model based on a linear semi-log model:

$$y = m \log e + b \quad [3]$$

y = accumulated mortality rate (number of deaths per 10⁵ people); e = PM_{2.5} emission (t year⁻¹); b is a constant; and m is the slope of regression.

Ordinary least squares method is applied (Coccia, 2021b) to estimate the unknown parameters of semi-log model Eq. (3). Statistical analyses were performed with the SigmaPlot 11.0 (Systat Software, Inc.).

Regression analyses confirm relationships between variables. In this study, regression analysis considers that the cumulative mortality rate by COVID-19 on April 11, 2021 in municipalities of Sinaloa (Mexico) (dependent variable y) is a linear function of the explanatory variable of wind speed or population density (explanatory variable x) in a model of simple regression (Coccia, 2021a). According to the assumptions associated with linear regression models (linearity, homoscedasticity, independence, and normality), this is based on a log-log model (Coccia, 2020b, 2021a):

$$\log y = m \log x + b \quad [4]$$

b = constant or intercept; m = slope of regression.

The ordinary least squares method is applied to quantify the unknown parameters of linear models using SigmaPlot 11.0 (Systat Software, Inc.) (Coccia, 2020b).

The calculation involved in the equation (4) using the explanatory variable of population density and population density, is also performed with the categorization of municipalities according to wind speed (higher or lower than 9.3 km/h). Similarly, the calculation of the equation (3) using the explanatory variable of anthropogenic PM_{2.5} emissions, is also performed with the categorization of municipalities according to moderate or low (100–350 t/y) or very low (<80 t/y) PM_{2.5} emissions.

3. Results

Fig. 1 illustrates the number of deaths and the PM_{2.5} emitted by primary anthropogenic sources in the municipalities of Sinaloa (NW Mexico). The PM_{2.5} emissions estimated from anthropogenic sources were variable within municipalities, with the highest values found in Guasave (346.4 t/year) and Culiacan (261.7 t/year), and the lowest in Cosalá (14.7 t/year) and Rosario (15.0 t/year) (Table 2A). The percentage of PM_{2.5} emitted by vehicles related to total anthropogenic sources varied from 2.8 % in Mocorito to 61.1 % in Culiacan, which is expected considering that the latter city concentrates the highest number of vehicles (512,664 in 2019, INEGI, 2021b) in Sinaloa. The emission of PM_{2.5} associated with the combustion of vehicles in Sinaloa was more elevated in those municipalities with a higher vehicle fleet, such as Culiacan (159.9 t/year), Ahome (60.4 t/year), and Mazatlan (59.6 t/year). Globally, using the assumed EF (101 mg/L), Sinaloa could be emitting ~403 t/year.

The cumulative COVID-19 mortality rate (per 10⁵ inhabitants) in Sinaloa was variable and, ranged from 41.1 for Cosalá to 285.8 for

Angostura (two rural municipalities), with a total of 17,012 and 44,093 inhabitants, respectively. The main municipalities of Sinaloa, Culiacan (1,003,530 people), Ahome (459,310), and Mazatlan (501,441), exhibited an intermediate-high mortality rate of 214.1, 224.5, and 181.1, respectively. Considering the cumulative mortality rate for Mexico (until April 11, 2021) of 166.1, Sinaloa state shows a high value (197.6); nevertheless, it is below Mexico City (353.6), which is the highest in the country.

Table 1 shows that municipalities in regions with low wind speed exhibit a higher number of days <9.3 km/h (300.2 days) compared to municipalities with high wind speed (146.2 days). In contrast, the population density of the first is lower compared with the second; this combination of factors partially explains the comparable incidence mean of the COVID-19 mortality rate between municipalities of high and low wind speed. Table 1 shows also that municipalities with high wind speed (and lower number of days <9.3 km/h) have a greater population density and a higher number of older population than municipalities with low wind speed. These results are compatible with the suggestion given by Coccia (2020c, 2021a), which indicates that high intensity and higher prevalence of wind speed improves the dispersion of particulate matters and polluted gases, and consequently, it can mitigate the dissemination of COVID-19.

Table 2 presents descriptive statistics considering municipalities with low or very low annual emissions of anthropogenic PM_{2.5}. Municipalities with low wind speed (average < 9.3 km/h) also show a lower population density and most people are >60 years old; also, they have low mortality rates, which is explained mainly by the very low load (31.4 t/year) of anthropogenic emission of PM_{2.5}. Contrarily, those municipalities that receive a higher load of anthropogenic emissions of PM_{2.5} (mean, 213.7 t/year) with a more elevated population density, but lower number of days with <9.3 km/h and higher wind speed, as well as an older population, exhibit the highest mortality rate by COVID-19. Los Mochis, Culiacan, and Mazatlan evidence higher PM emissions, and there is evidence that people are exposed to PM_{2.5} levels that exceed the guidelines of the WHO (2016) (annual mean 10 µg/m³) (Ramos-Álvarez, 2020). Table 2 indicates that the COVID-19 mortality rates are moderately higher in those municipalities with high PM_{2.5} emissions compared to those with low emissions; however, the difference between these municipalities is relatively low. The population density and wind speed (and number of days with <9.3 km/h) combined compensate the situation. Municipalities that receive a higher load of PM_{2.5} exhibit a greater wind speed (and lower number of days with <9.3 km/h). Nonetheless, they have a higher population density and number of people >60 years old.

Regarding, the PM_{2.5} emissions, the regression analysis was carried out for the two scenarios. The first, using the cumulative mortality rates and the PM_{2.5} emissions from vehicles, and the second including cumulative mortality rates and the PM_{2.5} emissions from anthropogenic sources. In both regressions, the improved adjust was reached under a positive logarithm in which y (COVID-19 mortality rate per 10⁵ inhabitants) was related to Log x (PM_{2.5} emissions t/year) and the equations were $y = 81.031 \log x + 71.062$ ($r = 0.616, p < 0.005$) when PM_{2.5} emitted only from vehicles was involved, and $y = 111.826 \log x - 42.900$ ($r = 0.746, p < 0.005$) for PM_{2.5} emitted from anthropogenic sources (Fig. 1A). The similarity between the two curves is explainable given that the PM_{2.5} emitted from vehicles are present in most municipalities, and it is the main contributor of the anthropogenic sources. Fig. 2 shows the regression curve of COVID-19 mortality on anthropogenic emissions of PM_{2.5} excluding municipalities Salvador Alvarado (SA) and Angostura (AN) with dust events (Figs. 4A and 5A), the improved adjust is evident, the equation was $y = 44.405 \ln x - 40.999$ ($r = 0.901; p < 0.002$).

Fig. 3 presents the regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} according to municipalities with low (100–350 t/y) and very low (<80 t/year) emissions their equations are: $y = 194.16 x - 253.75$ ($r = 0.953, p = 0.003$), and $y = 251.71 x - 231.20$ ($r = 0.835, p < 0.001$), respectively. As expected, both lines evidence that the increase in PM_{2.5} emissions is associated with an increase in

Table 1
Descriptive statistics of municipalities of Sinaloa according to wind speed (higher or lower than 9.3 km/h).

| Wind speed annual average | Wind speed annual (km/h) | Wind speed number of days <9.3 km/h | COVID-19 mortality rate (per 10 ⁵ inhabitants) | People aged >60 years old (2021) | Population density inhabitants/km ² | Emission of PM _{2.5} anthropogenic (t/year) |
|---------------------------|--------------------------|-------------------------------------|---|----------------------------------|--|--|
| Low (<9.3 km/h) | 8.2 | 300.2 | 130.5 | 11,193 | 36.3 | 46.2 |
| Arithmetic mean | | | | | | |
| Std. error of mean | 0.2 | 23.4 | 23.7 | 5529 | 20.6 | 16.7 |
| N = 9 | | | | | | |
| High (≥9.3 km/h) | 10.2 | 146.2 | 167.4 | 25,214 | 67.9 | 138.2 |
| Arithmetic mean | | | | | | |
| Std. error of mean | 0.3 | 22.8 | 24.3 | 8882 | 16.3 | 40.0 |
| N = 9 | | | | | | |

Table 2
Descriptive statistics of municipalities of Sinaloa according to the anthropogenic emission of PM_{2.5} (higher or lower than 100 t PM_{2.5}/year per municipality).

| Annual emission | Anthropogenic annual emission (t PM _{2.5} /year) | Wind speed annual (km/h) | Wind speed number of days <9.3 km/h | COVID-19 Mortality rate (per 10 ⁵ habitants) | People aged >60 years old | Population density inhabitants/km ² |
|--|---|--------------------------|-------------------------------------|---|---------------------------|--|
| Very low (<80 t PM _{2.5} /year) Arithmetic mean | 31.4 | 8.8 | 260.7 | 126.8 | 6738 | 25.0 |
| Std. error of mean | 6.1 | 0.3 | 27.4 | 22.2 | 1108 | 7.9 |
| N = 12 | | | | | | |
| Low (100–350 t PM _{2.5} /year) Arithmetic mean | 213.7 | 10.0 | 148.2 | 193.2 | 41,135 | 106.2 |
| Std. error of mean | 34.4 | 0.6 | 33.6 | 14.2 | 11,360 | 25.6 |
| N = 6 | | | | | | |

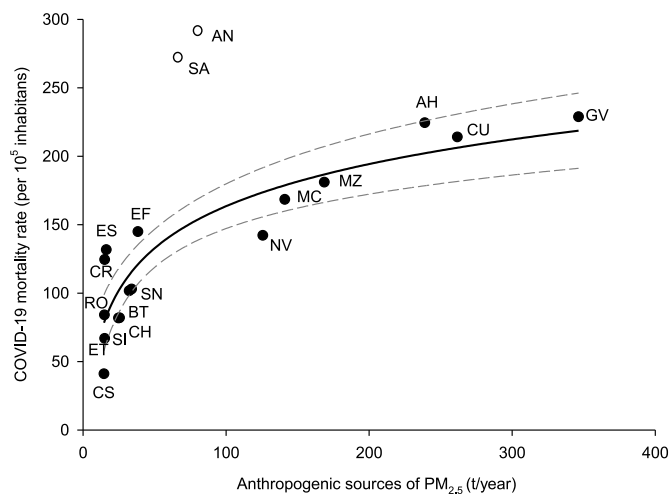


Fig. 2. Regression of COVID-19 mortality on anthropogenic emissions of PM_{2.5} excluding the municipalities with dust events (AN and SA, unfilled circles). Dashed lines indicate the 95 % confidence interval. Abbreviations of municipalities are given in Fig. 1.

COVID-19 mortality. It is interesting that the municipalities grouped as very low (<80 t/year) evidence the presence of a subgroup of “very low emissions and dust events”. Municipalities with dust events known locally as “ventarrones” are common in the north of Sinaloa. However, these are particularly notable in SA and AN where soils without vegetation dominate (Figs. 4A and 5A).

Fig. 4 shows the regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} considering municipalities with low (100–200 per km²) and very low (<70 per km²) population density, and the equations are $y = -67.24x + 377.60$ ($r = -0.561, p = 0.326$), and $y = 115.72x - 53.69$ ($r = 0.662, p = 0.014$), respectively. The positive tendency of increase in mortality with the emission of PM_{2.5} for very low population densities (<70 per km²), which is expected and predictable, contrasts with the negative tendency of the municipalities of low population densities (200–300 per km²). However, if the SA municipality is

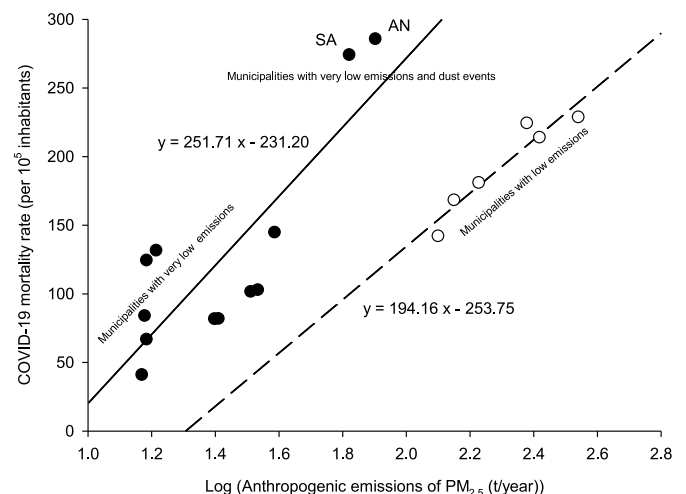


Fig. 3. Regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} considering municipalities with low (100–350 t/y, unfilled circles) and very low (<80 t/year, filled circles) anthropogenic emissions of PM_{2.5}.

eliminated (by their condition of recurrent dust events), the regression line changes to a positive and expected behavior.

Fig. 5 shows the regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} according to the municipalities with low (<9.3 km/h) and high (>9.3 km/h) wind speed, and the equations are $y = 139.47x - 80.04$ ($r = 0.697, p = 0.037$) and $y = 106.85x - 37.93$ ($r = 0.767, p = 0.016$), respectively. Hence, the differences in wind speed are relatively reduced (~5 km/h) between the 18 municipalities of Sinaloa. Furthermore, the change in mortality rate on PM_{2.5} emission (slope) is higher in the municipalities with low wind speed compared with those with high wind speed, which confirms that the dissemination of COVID-19 is higher in municipalities with low wind speed. Conversely, in the municipalities with low wind speed the mortality rate per 10⁵ people increases ~140 per each increase of 90 t/year in the anthropogenic emissions of PM_{2.5}; whilst in the municipalities with high wind speed

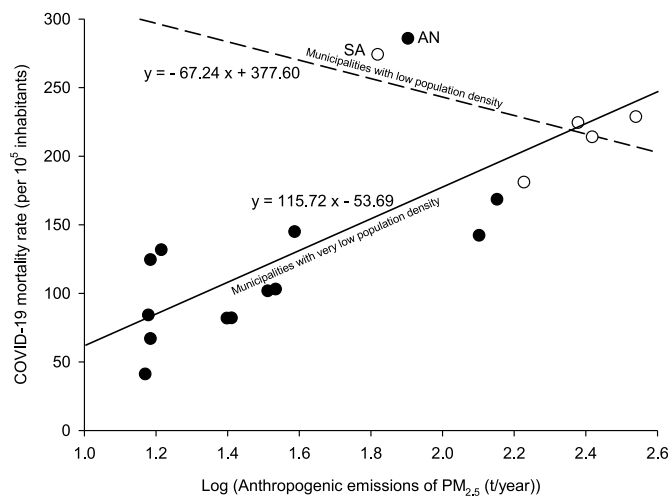


Fig. 4. Regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} considering municipalities with low (100–200 per km², unfilled circles) and very low (<70 per km², filled circles) population density.

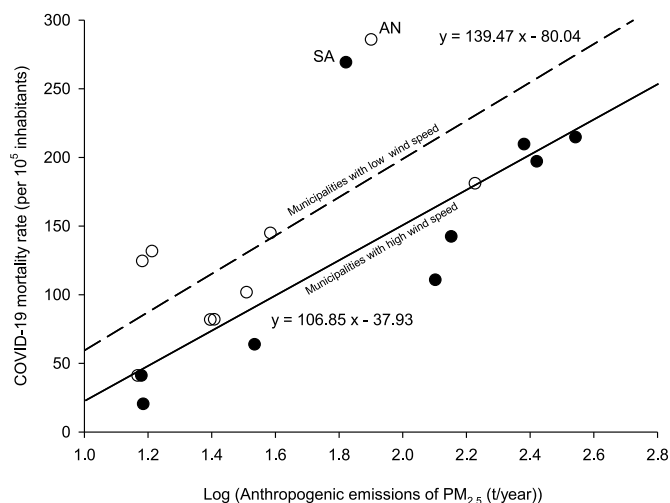


Fig. 5. Regression lines of COVID-19 mortality on anthropogenic emissions of PM_{2.5} considering municipalities with low (<9.3 km/h) (unfilled circles) and high (>9.3 km/h) (filled circles) wind speed.

such increase is of ~107, i.e., mortality elevates ~31% in municipalities with low wind speed compared to those with high wind speed.

Fig. 6 exhibits the regression lines of COVID-19 mortality on population density considering municipalities with low (<9.3 km/h) and high (>9.3 km/h) wind speed, which equations are $y = 0.30x + 1.69$ ($r = 0.631, p = 0.068$) and $y = 0.39x + 1.52$ ($r = 0.721, p < 0.02$), respectively. Fig. 2A (supplementary material) shows the regression lines with the 18 municipalities with the equation $y = 0.3175x + 1.6548$ ($r = 0.699, p = 0.002$); and excluding the municipalities SA and AN with presence of dust events, the equation is $y = 0.2995x + 1.6504$ ($r = 0.7361, p < 0.002$). Fig. 6 shows both lines and evidence that the COVID-19 mortality rate increases with population density. Also, it is evident that the change of mortality rate on the population density is comparable for both municipalities of low and high wind speed. When the Log (Population density) is > 2.0, i.e., >100 inhabitants per km², the mortality rate is more elevated for the municipalities with high wind speed than those with low wind speed. This indicates that the population density has a greater influence when this is > 100. In contrast, for municipalities <100 inhabitants per km², mortality is higher in those with low wind speed. It is important to highlight that this behavior is

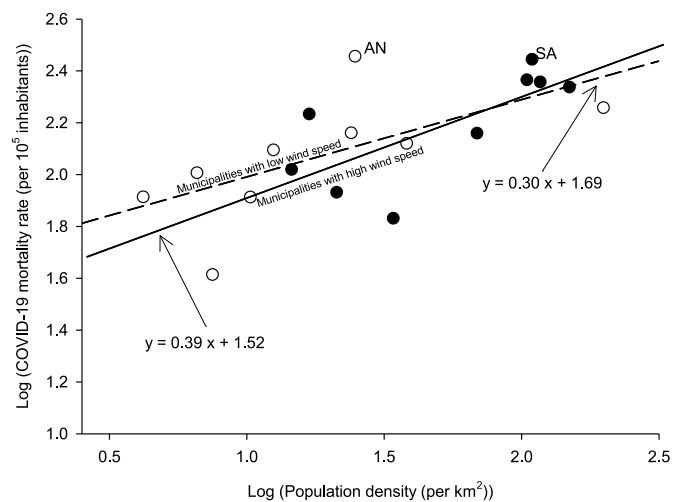


Fig. 6. Regression lines of COVID-19 mortality on population density according to municipalities with low (<9.3 km/h) (unfilled circles) and high (>9.3 km/h) (filled circles) wind speed.

observed where the differences of wind speed (between high and low) are ≤ 5 km/h.

Fig. 7 shows the regression lines of COVID-19 mortality on wind speed, according to low (100–200 per km²) and very low (<70 per km²) population density, which display the equations $y = 0.018x + 2.164$ ($r = 0.467, p = 0.428$) and $y = 0.042x + 1.658$ ($r = 0.212, p = 0.486$). Both lines (with no significant correlations, $p > 0.05$) show a positive tendency to increase the mortality rate with the wind speed, which is contradictory to what is expected, but confirm the observed in Fig. 6, in which the influence of wind speed is only evidenced in very low population densities (<100 inhabitants per km²). The influence of the speed of wind is not evidenced by the most influence of the other factors (mainly population density and polluted air).

4. Discussion

This study elucidates how COVID-19 is disseminated and how it causes differences in mortality in NW Mexico through its relationship with environmental, demographic, and atmospheric factors that affect its spread and severity, as seen in other studies (Coccia, 2020b, 2021a, 2021c, 2021e; Islam et al., 2021; Kutralam-Muniasamy et al., 2021a;

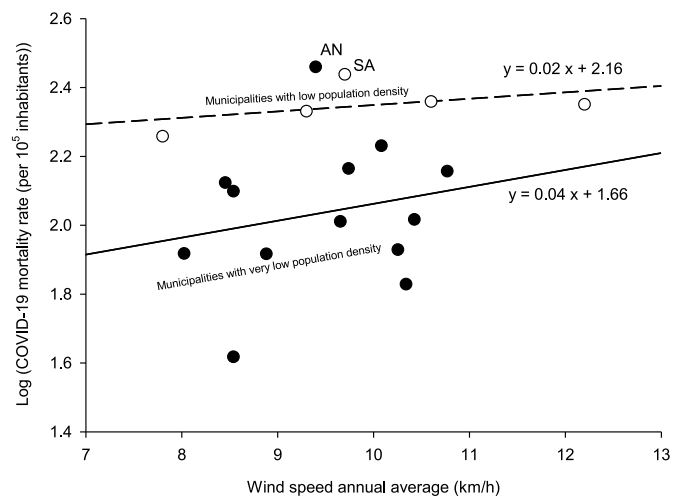


Fig. 7. Regression lines of COVID-19 mortality on wind speed, according to low (100–200 per km², unfilled circles) and very low (<70 per km², filled circles) population density.

Rosario Denes et al., 2020). In the present study, PM_{2.5} anthropogenic emissions were used to estimate the PM_{2.5} exposure in each municipality since most rural communities and small and medium-sized cities lack direct air quality monitoring. The results suggest that COVID-19 mortality rate in the municipalities of Sinaloa was higher in those with superior anthropogenic PM_{2.5} emissions and elevated population density. The influence of other factors such as wind speed, dust events, and people >60 years old, were evidenced limitedly. This study suggests that the low wind speed is evidenced only in municipalities with very low population densities (<100 inhabitants per km²); in contrast, this effect is opposite when population densities are > 100, i.e., mortality is increased with the wind speed. This indicates that the population density has a great influence than wind speed (certainly with narrow differences) when municipalities in Sinaloa have > 100 inhabitants per km². This does not agree with the observed by Coccia (2021a) in Italian cities. However, the situation is different between the two regions in at least two aspects: low (100–350 inhabitants per km²) or very low (<100) population densities and an average wind speed between 7.2 and 12.2 km/h in Sinaloa, while in Italy, the population densities are more elevated (~1000–2000) and wind speed variations are wider (0.2–23 km/h).

Although the differences in wind speed are relatively reduced (~5 km/h) between the 18 municipalities of Sinaloa, Fig. 5 shows that the increase of mortality rate on emission of PM_{2.5} is higher ($\Delta y/\Delta x = \sim 140$ per 10⁵ inhabitants per 90 t/year of increase in the PM_{2.5} emission) in those with low wind speed compared with those with high wind speed ($\Delta y/\Delta x = \sim 107$). This confirms that the spread of COVID-19 is higher in municipalities with low wind speed, and that reduced wind can increase the stagnation of polluted air embodying viral agents (SARS-CoV-2). Consequently, this supports the dissemination of viral infectivity, creating problems for public health (Coccia, 2021a). These results are consistent with those found by Coccia (2021a), Ahmadi et al. (2020), and Rosario Denes et al. (2020), which conclude that wind speed has an inverse or negative correlation with the rate of confirmed cases of COVID-19, or in our case, with COVID-19 mortality. Moreover, these results are concordant with those described by Bolaño-Ortiz et al. (2020), Cohen (2020c), Diao et al. (2021), Rahimi et al. (2021), and Coccia (2021a), in which the propagation dynamics of the novel coronavirus is impacted by different environmental factors, such as climate conditions.

The positive association found (Figs. 1A, 2, 3, and 4) indicates that a higher PM_{2.5} emission is associated with higher cumulative COVID-19 mortality, a behavior similar to that observed in northern Italy by Filippini et al. (2021), and in the cities of China by Yao et al. (2020), although the curves involved are different. The association between mortality and air pollution found by Filippini et al. (2021) exhibited a non-linear shape, with a rapidly increasing rate at the highest levels of polluted air (nitrogen oxide); while Yao et al. (2020) found a linear correlation using COVID-19 fatality and PM_{2.5} exposure. These differences could be caused by the multiple factors (demographic and meteorological) involved in COVID-19 mortality and the differences in the toxicity of the PM_{2.5} from each locality. Microparticulate PM_{2.5} is a complex matter that consists of various components, and their respective contributions to the toxicity of PM_{2.5} remains undetermined. For example, Tao et al. (2021) found that different fractions of PM_{2.5} diesel exhaust (soluble and non-soluble in water and heptane) can induce different levels of pulmonary inflammation and acute phase response.

The contrasting mortality rates in AN (285.8 per 10⁵ inhabitants) and SA (274.2) (44,093 and 79,492 inhabitants, respectively) with the municipalities of Culiacan (214.1) and Mazatlan (181.1) with 1,003,530 and 501,441 inhabitants, respectively. This seems to contradict what has been interpreted about the mortality of COVID-19, which refers to population density or close contact among people and is comparatively high in urban areas rather than in rural areas (Saadat et al., 2020). However, it is complex and multifactorial; the factors involved in the risk increase of contracting COVID-19 are numerous, but some include household size, social distancing level, and people with other chronic

diseases (diabetes, chronic respiratory, cardiovascular, high blood pressure, and cancer; Fang et al., 2020; Giannis et al., 2020; Coccia, 2021a). Moreover, different socioeconomic groups do not have access to the same level of healthcare services (Saadat et al., 2020). This would be particularly common, especially in rural communities and small municipalities in Mexico such as AN and SA, where the access to medical services population is restricted to most people.

In addition, the high COVID-19 mortality rates of SA and AN, could also be associated to the effects of dust events in these municipalities. This also increases particulate matter concentrations (Kutralam-Muniasamy et al., 2021a), with the consequent and anomalous increase of COVID-19 mortality rates. The presence of “ventarrones” that persist for a few hours or days are common in northern Sinaloa, and they are particularly notable in these two municipalities, where soils without vegetation are dominant (Figs. 4A–5A, supplementary material). Hence, it would be important to evaluate the duration and, frequency, as well as the concentrations of particulate matter generated to evaluate its effect on human health. Clearly, this is a critical point that requires consideration in future studies.

Although this study is limited to rural communities and small and medium-sized cities, our results suggest that the COVID-19 mortality rate is significantly associated with PM_{2.5} and population density in the municipalities examined in the present study. Wind speed exhibited an evident effect only in very low population densities (<100 per km²). These findings are consistent with previous studies in the context of the association between COVID-19 mortality versus air pollution. Air pollutants and viruses, such as SARS-CoV-2, provoke negative immunological responses and share similar mechanisms of action (Espejo et al., 2020). Therefore, they can have an additive or synergetic effect in viral diseases. The link between PM_{2.5} and COVID-19 severity has been explained essentially by the overexpression of the angiotensin-converting enzyme 2 (ACE-2) on epithelial cell surfaces of the respiratory tract (Paital and Agrawal, 2021). ACE-2 is a receptor for coronavirus, including the severe acute respiratory syndrome coronavirus 1 and 2, and it is overexpressed under chronic exposure, or, when extreme exposure occurs to air pollution (NO₂ and PM_{2.5}) during wildfires (Meo et al., 2021) or dust events, as observed in AN and SA, or in eastern regions of Mexico impacted by the Saharan dust (Kutralam-Muniasamy et al., 2021a). The high ACE-2 expression in respiratory epithelial cells under air pollution explains the positive correlation between the severity in COVID-19 patients and elevated NO₂ and PM_{2.5} levels (Paital and Agrawal, 2021).

This study is limited in several points, including the duration of the study period. Cumulative COVID-19 mortality rates were calculated from the start of the pandemic in Mexico. Nonetheless, the PM_{2.5} emissions from vehicles calculated were developed based on information from 2017, and PM_{2.5} emissions from anthropogenic sources were calculated using data from 2007 (EFs, fuel consumption database, fertilizers industry, steel, thermal power plants, etc.) and from 2005 to 2013 (Huang et al., 2014). In addition, the EF assumed (101 mg L⁻¹) for the scenario A could be different between the municipalities depending on the characteristics of the fleet of vehicles (age, technology, weight, etc.). Second, as it occurs in this type of studies (López-Feldman et al., 2021), the available information does not allow us to control people's choice of residence or their avoidance behavior, which could cause nonrandom assignment of pollution exposure and hence, failure to establish a causal association. Third, the heterogeneity of air pollution within each municipality is ignored. Fourth, it is assumed that the people of each municipality reside effectively in such location, although it is well known that some people in Sinaloa eventually reside in the main cities and in rural towns. In this exercise, individuals who were considered were theoretically exposed to PM_{2.5} in the long term or during the study period, originating from the anthropogenic sources based on residence in their municipality. Fifth and last, only PM_{2.5} emissions were used in this exercise, and not PM_{2.5} exposure, which may imply significant failures for the reasons discussed in the methodology.

Apart from these limitations, our work reveals important part of the COVID-19 situation in rural communities and suburban areas regarding the link between COVID-19 and air pollution.

5. Conclusions

We documented the first case of association between PM_{2.5} and COVID-19 mortality rates that involved rural communities, as well as small and medium-sized municipalities from Mexico. In addition to major cities, industrial regions, and localities with wildfires, the link between COVID-19 and air pollution can also involve rural and small municipalities, which can in turn be related to conventional sources (vehicles, industrial sources, and burning of biomass). Furthermore, those derived from agriculture produce large emissions of ammonia forms (NH_y), which are important precursors of PM_{2.5} (EPA, 2009; Patel and Rastogi, 2020).

Among the specific suggestions on environmental, health, and social policies that can be deduced from this study and be applied in other regions, are those aimed at reducing the risks linked to the main factors involved in the spread and mortality of COVID-19: (i) it is important to develop reforestation programs in soils without vegetation in regions prone to dust events; (ii) the introduction of cleaner technologies that decrease the emissions of contaminants and reduce climate change is crucial in municipalities where the polluted air is aggravated by industries and thermoelectric power plants that operate by burning fuel oil; (iii) similarly, future expansion of low and medium cities require better planning to avoid high population density, particularly in those municipalities where the wind speed is low (<9.3 km/h) and dust events are recurrent.

Although reiterative, it is important to emphasize on the management of the COVID-19 pandemic needs of stringent lockdown and massive polymerase chain reaction (PCR) testing, which in most of the underdeveloped and developing countries is a serious problem in addition to the insufficient healthcare services and the lack of air quality monitoring stations. Finally, it is important to highlight the value of the studies carried out to comprehend the role of the factors involved in the spread, health, and the social policy related to COVID-19. Understanding these factors is key to implement effective policy responses, apply new and adequate technologies, and make health investments to mitigate the impacts of COVID-19 outbreaks, as well as other epidemics (Coccia, 2021b and referenced therein).

Author statements

Federico Páez-Osuna: Conceptualization, Visualization, Writing-original draft, Funding Acquisition, Funding Acquisition, Supervision, Project Administration, Gladys Valencia-Castañeda: Investigation, Methodology Writing –Review & Editing, Uriel Arreguín Rebolledo: Investigation, Methodology, Writing & Editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.chemosphere.2021.131634>.

References

- Ahmadi, M., Sharifi, A., Dorost, S., Jafarzadeh, G.S., Ghanbari, N., 2020. Investigation of effective climatology parameters on COVID-19 outbreak in Iran. *Sci. Total Environ.* 729, 138705. <https://doi.org/10.1016/j.scitotenv.2020.138705>.
- Bashir, M.F., Ma, B.J., Komal, B., Bashir, M.A., Farooq, T.H., Iqbal, N., Bashir, M., 2020. Correlation between environmental pollution indicators and COVID-19 pandemic: a brief study in Californian context. *Environ. Res.* 187, 109652. <https://doi.org/10.1016/j.envres.2020.109652>.
- Bolaño-Ortiz, T.R., Camargo-Cañedo, Y., Puliafito, S.E., Ruggeri, M.F., Bolaño-Díaz, S., Pascual-Flores, R., Saturno, J., Ibarra-Espinoza, S., Mayol-Bracero, O.L., Torres-Delgado, E., Cereceda-Balic, F., 2020. Spread of SARS-CoV-2 through Latin America and the Caribbean region: a look from its economic conditions, climate and air pollution indicators. *Environ. Res.* 191, 109938. <https://doi.org/10.1016/j.envres.2020.109938>.
- Coccia, M., 2020a. An index to quantify environmental risk of exposure to future epidemics of the COVID-19 and similar viral agents: theory and Practice. *Environ. Res.* 191, 110155. <https://doi.org/10.1016/j.envres.2020.110155>.
- Coccia, M., 2020b. How (un)sustainable environments are related to the diffusion of COVID-19: the relation between coronavirus disease 2019, air pollution, wind resource and energy. *Sustainability* 12, 9709. <https://doi.org/10.3390/su12229709>.
- Coccia, M., 2020c. Factors determining the diffusion of COVID-19 and suggested strategy to prevent future accelerated viral infectivity similar to COVID. *Sci. Total Environ.* 729, 138474. <https://doi.org/10.1016/j.scitotenv.2020.138474>.
- Coccia, M., 2021a. How do low wind speeds and high levels of air pollution support the spread of COVID-19? *Atm. Pollut. Res.* 12, 437–445. <https://doi.org/10.1016/j.apr.2020.10.002> Get rights and content.
- Coccia, M., 2021b. The impact of first and second wave of the COVID-19 pandemic in society: comparative analysis to support control measures to cope with negative effects of future infectious diseases. *Environ. Res.* 197, 111099. <https://doi.org/10.1016/j.envres.2021.111099>.
- Coccia, M., 2021c. High health expenditures and low exposure of population to air pollution as critical factors that can reduce fatality rate in COVID-19 pandemic crisis. *Environ. Res.* 199, 111339. <https://doi.org/10.1016/j.envres.2021.111339>.
- Coccia, M., 2021d. Effects of the spread of COVID-19 on public health of polluted cities: results of the first wave for explaining the déjà vu in the second wave of COVID-19 pandemic and epidemics of future vital agents. *Environ. Sci. Pollut. Res.* 28, 19147–19154. <https://doi.org/10.1007/s11356-020-11662-7>.
- Coccia, M., 2021e. The effects of atmospheric stability with low wind speed and of air pollution on the accelerated transmission dynamics of COVID-19. *Int. J. Environ. Stud.* 78 (1), 1–27. <https://doi.org/10.1080/00207233.2020.1802937>.
- Coccia, M., 2021f. The relation between length of lockdown, numbers of infected people and deaths of Covid-19, and economic growth of countries: lessons learned to cope with future pandemics similar to Covid-19 and to constrain the deterioration of economic system. *Sci. Total Environ.* 775, 145801. <https://doi.org/10.1016/j.scitotenv.2021.145801>.
- COVID-19 Sinaloa 2021. COVID-19 Enfermedad por el Nuevo coronavirus, 69157j0i22i30i2.1156j0j15&sourceid=chrome&ie=UTF-8. <https://www.google.com/search?q=COVID-19-Sinaloa%2C+2021&oq=COVID-19-Sinaloa%2C+2021&aqs=chrome> (accessed: April 2021).
- Dahal, S., Banda, J.M., Bento, A.L., Mizumoto, K., Chowell, G., 2021. Characterizing all-cause excess mortality patterns during COVID-19 pandemic in Mexico. *BMC Infect. Dis.* 21, 432. <https://doi.org/10.1186/s12879-021-06122-7>.
- Diao, Y., Koderá, S., Anzai, D., Gomez-Tames, J., Rashed, E.A., Hirata, A., 2021. Influence of population density, temperature, and absolute humidity on spread and decay durations of COVID-19: a comparative study of scenarios in China, England, Germany, and Japan. *One Health* 12, 100203. <https://doi.org/10.1016/j.onehlt.2020.100203>.
- Díaz de León-Martínez, L., Sierrade la Vega, L., Palacios-Ramírez, A., Rodríguez-Aguilar, M., Flores-Ramírez, R., 2020. Critical review of social, environmental and health risk factors in the Mexican indigenous population and their capacity to respond to the COVID-19. *Sci. Total Environ.* 733, 139357. <https://doi.org/10.1016/j.scitotenv.2020.139357>.
- EPA, 2009. Environmental protection agency. Integrated science assessment for particulate matter. EPA/600/R-08/139F.
- es. Weatherspark, 2021. <https://es.weatherspark.com/y/3075/Clima-promedio-en-Chix-M%C3%A9xico-durante-todo-el-a%C3%B1o> (accessed June 20, 2021).
- Espejo, W., Celis, J.E., Chiang, G., Bahamonde, P., 2020. Environment and COVID-19: pollutants, impacts, dissemination, management and recommendations for facing future epidemic threats. *Sci. Total Environ.* 747, 141314. <https://doi.org/10.1016/j.scitotenv.2020.141314>.
- Fang, L., Karakiulakis, G., Roth, M., 2020. Are patients with hypertension and diabetes mellitus at increased risk for COVID-19 infection? *Lancet Respir. Med.* 8 (4), e21. [https://doi.org/10.1016/S2213-2600\(20\)30116-8](https://doi.org/10.1016/S2213-2600(20)30116-8).
- Filippini, T., Rothman, K.J., Goffi, A., Ferrari, F., Maffei, G., Orsini, N., Vicenti, M., 2020. Satellite-detected tropospheric nitrogen dioxide and spread of SARS-CoV-2 infection in Northern Italy. *Sci. Total Environ.* 739, 140278. <https://doi.org/10.1016/j.scitotenv.2020.140278>.
- Filippini, T., Rothman, K.J., Cocchio, S., Narne, E., Mantoan, D., Saia, M., Goffi, A., Ferrari, F., Maffei, G., Orsini, N., Baldo, V., Vinceti, M., 2021. Associations between mortality from COVID-19 in two Italian regions and outdoor air pollution as assessed through tropospheric nitrogen dioxide. *Sci. Total Environ.* 760, 143355. <https://doi.org/10.1016/j.scitotenv.2020.143355>.
- Giannis, D., Ziogas, I.A., Gianni, P., 2020. Coagulation disorders in coronavirus infected patients: COVID-19, SARS-CoV-1, MERS-CoV and lessons from the past. *J. Clin. Virol.* 127, 104362. <https://doi.org/10.1016/j.jcv.2020.104362>.

- Huang, Y., Shen, H., Chen, H., Wang, R., Zhang, Y., Su, S., Chen, Y., Lin, N., Zhuo, S., Zhong, Q., Wang, X., Liu, J., Li, B., Liu, W., Tao, S., 2014. Quantification of global primary emissions of PM_{2.5}, PM₁₀, and TSP from combustion and industrial process sources. *Environ. Sci. Technol.* 48, 13834–13843. <https://doi.org/10.1021/es503696k>.
- INEGI, 2021a. Visualizador analítico para el COVID-19. Gaia.inegi.org.mx/covid19/ (Accessed: April 2021).
- INEGI, 2021b. Vehículos de motor registrados en circulación. <https://www.inegi.org.mx/app/buscador/default.html?q=Sinaloa#tabMCCollapse-Indicadores> (accessed: April 2021).
- R.B. Islam, N., Bukhari, Q., Jameel, Y., Shabnam, S., Erzurumluoglu, M., Siddique, M.A., Massaro, J.M., Agostino, D., 2021. COVID-19 and climatic factors: a global analysis. *Environ. Res.* 193, 110355. <https://doi.org/10.1016/j.envres.2020.110355>.
- Kuhns, H.D., Mazzoleni, C., Moosmuller, H., Nikolic, D., Keilsar, R.E., Barber, P.W., Li, Z., Etyemezian, V., Watson, J.G., 2004. Remote sensing of PM, NO, CO, CO and HC emission factors for on-road gasoline and diesel engine vehicles in Las Vegas. *NV. Sci. Total Environ.* 322, 123–137. <https://doi.org/10.1016/j.scitotenv.2003.09.013>.
- Kutralam-Muniasamy, G., Pérez-Guevara, F., Roy, P.D., Elizalde-Martínez, I., Shruti, V. C., 2021a. Impacts of the COVID-19 lockdown on air quality and its association with human mortality trends in megapolis Mexico City. *Air Qual. Atmos. Health.* 14, 553–562. <https://doi.org/10.1007/s11869-020-00960-1>.
- Kutralam-Muniasamy, G., Pérez-Guevara, F., Elizalde-Martínez, I., Chari, S.V., 2021b. Particulate matter concentrations and their association with COVID-19-related mortality in Mexico during June 2020 Saharan dust event. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-021-14168-y>.
- López-Feldman, A., Heres, D., Marquez-Padilla, F., 2021. Air pollution exposure and COVID-19: a look at mortality in Mexico City using individual-level data. *Sci. Total Environ.* 756, 143929. <https://doi.org/10.1016/j.scitotenv.2020.143929>.
- Mancilla, Y., Mendoza, A., 2012. A tunnel study to characterize PM_{2.5} emissions from gasoline-powered vehicles in Monterrey, Mexico. *Atmos. Environ. Times* 59, 449–460.
- Meo, S.A., Abukhalaf, A.A., Alomar, A.A., Alessa, O.M., Sami, W., Klonoff, D.C., 2021. Effect of environmental pollutants PM_{2.5}, carbon monoxide, and ozone on the incidence and mortality of SARS-CoV-2 infection in ten wildfire affected counties in California. *Sci. Total Environ.* 757, 143948. <https://doi.org/10.1016/j.scitotenv.2020.143948>.
- Paital, B., Agrawal, P.K., 2021. Air pollution by NO₂ and PM_{2.5} explains COVID-19 infection severity by overexpression of angiotensin-converting enzyme 2 in respiratory cells: a review. *Environ. Chem. Lett.* 19, 25–42. <https://doi.org/10.1007/s10311-020-01091-w>.
- Pana, T.A., Bhattacharya, S., Gamble, D.T., Pasdar, Z., Szlachetka, W.A., Perdomo-Lamignano, J.A., Ewers, K.D., McLernon, D.J., Myint, P.K., 2021. Country-level determinants of the severity of the first global wave of the COVID-19 pandemic: an ecological study. *BMJ Open* 11, e042034. <https://doi.org/10.1136/bmjopen-2020-042034>.
- Patel, A., Rastogi, N., 2020. Oxidative potential of ambient PM and related health endpoints over South Asia: a review. *Asian J. Atmos. Environ.* 15 (1), 2020123. <https://doi.org/10.5572/ajae.2020.123>.
- Rahimi, N.R., Fouladi-Fard, R., Aali, R., Shahryari, A., Rezaali, M., Ghafouri, Y., Ghalhari, M.R., Asadi-Ghalhari, M., Farzinnia, B., Gea, O.C., Fiore, M., 2021. Bidirectional association between COVID-19 and the environment: a systematic review. *Environ. Res.* 194, 110692. <https://doi.org/10.1016/j.envres.2020.110692>.
- Ramos Álvarez, R.A., 2020. Evaluación del impacto en la salud por material particulado (PM_{2.5}) en las principales ciudades de Sinaloa. México. Tesis Doctoral. Facultad de Ciencias Económicas y Sociales. Universidad Autónoma de Sinaloa, p. 208. In Spanish).
- Rosario Denes, K.A., Mutz Yhan, S., Bernardes, P.C., Conte-Junior, C.A., 2020. Relationship between COVID-19 and weather: case study in a tropical country. *Int. J. Hyg Environ. Health* 229, 113587. <https://doi.org/10.1016/j.ijheh.2020.113587>.
- Saadat, S., Rawtani, D., Hussain, C.M., 2020. Environmental perspective of COVID-19. *Sci. Total Environ.* 728, 138870. <https://doi.org/10.1016/j.scitotenv.2020.138870>.
- Sarkodie, S.A., Owusu, P.A., 2020. Impact of meteorological factors on COVID-19 pandemic: evidence from top 20 countries with confirmed cases. *Environ. Res.* 191, 110101. <https://doi.org/10.1016/j.envres.2020.110101>.
- SENER, 2018. Evaluación rápida del uso de la energía. Culiacán, Sinaloa, México. Secretaría de Energía. El Banco Mundial, p. 140.
- Srivastava, A., 2021. COVID-19 and air pollution and meteorology-an intricate relationship: a review. *Chemosphere* 263, 128297. <https://doi.org/10.1016/j.chemosphere.2020.128297>.
- Tao, S., Xu, Y., Chen, M., Zhang, H., Huang, X., Li, Z., Pan, B., Peng, R., Zhu, Y., Kan, H., Li, W., Ying, Z., 2021. Exposure to different fractions of diesel exhaust PM_{2.5} induces different levels of pulmonary inflammation and acute phase response. *Ecotoxicol. Environ. Saf.* 210, 111871.
- Tello-Leal, E., Macías-Hernández, B.A., 2021. Association of environmental and meteorological factors on the spread of COVID-19 in Victoria, Mexico, and air quality during the lockdown. *Environ. Res.* 196, 110442. <https://doi.org/10.1016/j.envres.2020.110442>.
- van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *N. Engl. J. Med.* 382 (16), 1564–1567. <https://doi.org/10.1056/NEJMc2004973>.
- WHO, 2016. Ambient Air Pollution: a Global Assessment of Exposure and Burden of Disease, vol. 121. World Health organization.
- WHO, 2021. WHO Coronavirus (COVID-19) Dashboard. <https://covid19.who.int> (accessed: April 2021).
- Willet, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Sibanda, L.M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Reddy, K.S., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* 393, 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4).
- Wu, X., Nethery, R.C., Sabath, M.B., Braun, D., Dominici, F., 2020. Air pollution and COVID-19 mortality in the United States: strengths and limitations of an ecological regression analysis. *Sci. Adv.* 6 (45), eabd4049 <https://doi.org/10.1126/sciadv.abd4049>.
- Yao, Y., Pan, J., Wang, W., Liu, Z., Kan, H., Qiu, Y., Meng, X., Wang, W., 2020. Association of particulate matter pollution and case fatality rate of COVID-19 in 49 Chinese cities. *Sci. Total Environ.* 741, 140396. <https://doi.org/10.1016/j.scitotenv.2020.140396>.
- Yang, H., Dhital, N.B., Wang, L., Hsieh, Y., Lee, K., Hsu, Y., Huang, S., 2019. Chemical characterization of fine particulate matter in gasoline and diesel vehicle exhaust. *Aerosol. Air Qual. Res.* 19, 1439–1449. <https://doi.org/10.4209/aaqr.2019.04.0191>.
- Zhang, J.J., Morawska, L., 2002. Combustion sources of particles: 2. Emission factors and measurement methods. *Chemosphere* 49 (9), 1059–1074. [https://doi.org/10.1016/S0045-6535\(02\)00240-0](https://doi.org/10.1016/S0045-6535(02)00240-0).