Association of COVID-19 distribution with air quality, sociodemographic factors, and comorbidities: an ecological study of US states

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Abstract
This ecological study investigated the association between COVID-19 distribution and air quality index (AQI), comorbidities and sociodemographic factors in the USA. The AQI factors included in the study are total AQI, ozone, carbon monoxide, sulfur dioxide, and nitrogen dioxide (NO2). Other demographic, socioeconomic, and geographic variables were included as covariates. The correlations of COVID-19 variables—proportion of cases and deaths in each population, as well as case fatality rate with independent variables were determined by Pearson and Spearman correlation and multiple linear regression analyses. The results revealed that AQI-NO2, population density, longitude, gross domestic product per capita, median age, total death of disease, and pneumonia per population were significantly associated with the COVID-19 variables (P < 0.05). Air pollutants, especially NO2 in the US case, could be addressed as an important factor linked with COVID-19 susceptibility and mortality.

Keywords COVID-19 · Air quality index · Comorbidities · Population density · Longitude · Income

Introduction
The new coronavirus disease (COVID-19) pandemic has claimed more than 500,000 lives globally, causing massive public health and economic challenges (Liang et al. 2020; Conticini et al. 2020). This infectious disease, emerging in Wuhan, China, causes severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The methods of contagion SARS-CoV-2 is not yet well understood, including what key modifiable parameters may contribute to spread of the virus. The risk factors for COVID-19 - associated severity and death are still under investigation, but some environmental and demographic factors such as air pollution (particle matter, nitrogen dioxide (NO2), ozone (O3)) (Coccia 2020; Fattorini and Regoli 2020; Frontera et al. 2020; Liang et al. 2020), atmospheric patterns (temperature, humidity) (Sajadi et al. 2020; Sarmadi et al. 2020b), and comorbidities (cardiovascular and cerebrovascular disease, and cancer) (Richardson et al. 2020; Tian et al. 2020) might play a plausible role for both susceptibility and vulnerability of populations. The impact of mentioned parameters on excessive morbidity and mortality attributed to other respiratory or chronic diseases has been well-established in recent years (Liu et al. 2019; Shi et al. 2016; Wang et al. 2019; Grande et al. 2020). In order to investigate the correlation between air pollution indicators and various diseases, air quality index (AQI) can be considered as an important parameter that involves many air pollution elements. An analysis of 55 provinces capital in Italy recently revealed that increase in symptomatic COVID-19 infected cases was associated with variations in air pollution level (Coccia 2020). Also, other studies found that prevalence of comorbidities plays a key role in higher mortality of COVID-19 (Richardson et al. 2020; Tian et al. 2020; Ravi 2020). It also has been proven that some medical conditions like diabetes and heart diseases can increase the risk of death in COVID-19 patient (Richardson et al. 2020; Coccia 2020). Additionally,
race and ethnicity were associated with the rate of death in different societies (Rentsch et al. 2020; Gross et al. 2020).

Regarding the possible contribution of air pollution and comorbidities in the risk of COVID-19 infection and mortality, this study aimed to assess the association between air pollutants and infection and mortality rate and whether race and comorbidities act modify the spread of COVID-19.

Materials and methods

Study area, data, and sources

This ecological study was conducted based on data from COVID-19 patients in all 50 US states; the District of Columbia (DC) and Puerto Rico. The USA (24–71°N, 67–172°E) is situated at the North of America continent, covers an area of 9,833,520 km², and has a population about 328,239,523.

For this analysis, data was acquired from the Centers for Disease Control and Prevention (CDC) as the main source of COVID-19 descriptive statistics, including the proportion of cases per 10⁵ persons (PCP), deaths per 10⁵ persons (PDP), and case fatality rate (CFR).

Measures of the study

Parameters such as weighted distribution of population (%) for race and comorbidities include septicemia, malignant neoplasms, diabetes mellitus, Alzheimer disease, influenza and pneumonia, chronic lower respiratory diseases, other diseases of the respiratory system, nephritis, nephrotic syndrome and nephrosis, diseases of heart, and cerebrovascular diseases compiled from the CDC for 22 weeks prior to June 6, 2020. Air quality and socioeconomic and demographic indicators were determined from the US Environmental Protection Agency’s (EPA) AQI (USEPA 2020) and World Population Review website (World Population Review 2020), respectively.

Data analysis procedure

A descriptive analysis was conducted on all the data. Here, t test and one-way ANOVA test were used to compare proportion of cases (PCI), proportion of deaths (PCD), and CFR values between states categories. Pearson and Spearman correlation, as well as linear regression analysis were conducted to assess the association between AQI, comorbidities, and demographic data and the number of cases and deaths from COVID-19 per 100,000 people. We have used log-transformed PCI and PCD as a dependent variable and mean AQI, weighted distribution of population in each state (%), and number of previously mentioned diseases of interest in each population as independent variables. All the statistical analyses were 2-tailed and performed at a 5% significance level using SPSS 16 and Prism version 6 (GraphPad).

Results and discussion

While precise discussions about factors contributing to the novel coronavirus pandemic distribution are inconclusive, some plausible reasons for our findings were reviewed. Air pollution, comorbidities, and socioeconomic–demographic are main factors in contributing to the infection and mortality of COVID-19 spread in-between states of USA.

The number of cases and reported deaths per population in New York was much higher compared with other states (402,914 cases of 2,074,852 individuals and 30,824 of 114,967 deaths) (Fig. 1). Table 1 showed the association of COVID-19 variables (PCI, PCD, and CFR) and some plausible factors contributing to the inter-states COVID-19 distribution. The association between AQI-NO₂ and COVID-19 variables was statistically significant (r = 0.51 for PCD, r = 0.46 for PCI, and r = 0.40 for CFR; P < .05). Also, population density (log density) and total mortality over 22 weeks were positively associated with PCI, PCD, and CFR (P < .001), whereas longitude was inversely associated (Table 2 and Appendix). The correlations were stronger among AQI-NO₂, pneumonia deaths, population density, longitude, and PCD, suggesting these potential key factors may have considerably increased mortality rates.

With regard to high basic reproductive number (Rₐ) of COVID-19, it is apparent that states with high population density have a higher proportion of infected individuals and consequently high mortality rate, as described in previous studies (Wu et al. 2020; Rocklov and Sjödin 2020). The number of total COVID-19 deaths (per population) is correlated with the population density, which is a troublesome issue. Increase in implemented control measures accompanied with increased hospital capacity and testing of asymptomatic patients could also impact the distribution scale of the virus between states (Lau et al. 2020; ContiCini et al. 2020). Between January 19th (report first case) and June 12th, the results showed major infected cases and death numbers of COVID-19 to New York and New Jersey. At the same time (January 1st and June 6th), an explosion of total and pneumonia deaths per population within New Jersey State was detected. This state has the second highest density in the USA.

Air pollution elements such as PM₂.₅, PM₁₀, NO₂, and O₃ are known to play an important role in both infectious and non-infectious diseases (Wang et al. 2019; Liu et al. 2019; Grande et al. 2020; Lin et al. 2007; Chang et al. 2020; Ciencewicki and Jaspers 2007). Some studies have also investigated the association between air pollution and incidence and distribution of COVID-19 in different other countries (Frontera et al. 2020; Fattorini and Regoli 2020). The air
pollution associations revealed in this study were similar to those of prior studies in USA (Liang et al. 2020). A higher value of CFR and PCD was significantly associated with exposure to NO2, but not O3 and PM2.5 (Liang et al. 2020; Anil and Alagha 2020; Islam et al. 2020). On the other hand, Wu et al. 2020 showed that only 1 μg/m3 increase in PM2.5 was associated with an eighth percent increase in the COVID-19 death rate. This study suggested that air pollution exposure may

### Table 1  Correlation (r) between COVID-19 variables and independent variables

| Variable                      | Log PCI    | Log PCD    | CFR    |
|-------------------------------|------------|------------|--------|
| Air pollution                 |            |            |        |
| AQI-total                     | 0.110      | 0.079      | 0.035  |
| AQI-Ozone                     | −0.252     | −0.283     | −0.233 |
| AQI-SO2                       | 0.005      | 0.079      | 0.160  |
| AQI-CO                        | 0.225      | 0.272      | 0.175  |
| AQI-NO2                       | 0.464**    | 0.513**    | 0.399* |
| Race                          |            |            |        |
| Non-Hispanic Black or African American | 0.119      | 0.112      | 0.035  |
| Non-Hispanic American Indian or Alaska Native | −0.281     | −0.403**   | −0.370* |
| Non-Hispanic Asian            | 0.112      | 0.135      | 0.078  |
| Comorbidities                 |            |            |        |
| Total deaths^a                | 0.286*     | 0.366**    | 0.328* |
| Pneumonia deaths^a            | 0.647**    | 0.719**    | 0.642**|
| Influenza and pneumonia^a     | 0.355*     | 0.297*     | 0.295* |
| Nephritis nephrotic syndrome and nephrosis^a | 0.235      | 0.306*     | 0.294* |
| Other diseases of respiratory system^a | 0.383**    | 0.465**    | 0.411**|
| Septicemia^a                  | 0.219      | 0.358**    | 0.358**|
| Socioeconomic-demographic    |            |            |        |
| Log density                   | 0.564**    | 0.652**    | 0.524**|
| HDI                           | 0.230      | 0.218      | 0.188  |
| GDP (SUS)                     | 0.395**    | 0.375**    | 0.224  |
| Median age                    | −0.084     | 0.131      | 0.357**|
| Longitude (°)                 | −0.569**   | −0.612**   | −0.446**|

Other races or comorbidities not significant with low correlation coefficient. ** P < 0.01, *P < 0.05

AQI air quality index, PCP proportion of cases to population per 10^5, PDP proportion of deaths to population per 10^5, CFR case fatality rate (%), HDI human development index, GDP gross domestic product per capita (SUS)

^a Deaths for 22 weeks as up June 6, 2020, per 10^5 population

### Table 2  multivariable linear regression analysis between independent variables and COVID-19 variables (adjusted with HDI)

| Variables                      | PCI F- test | B (SE) | R^2 | Sig. | PCD F- test | B (SE) | R^2 | Sig. | CFR F- test | B (SE) | R^2 | Sig. |
|-------------------------------|-------------|--------|-----|------|-------------|--------|-----|------|-------------|--------|-----|------|
| AQI-NO2                       | 5.10        | 0.02(0.005) | 0.25 | 0.003 | 5.94        | 0.03(0.008) | 0.28 | 0.002 | 4.34        | 0.08(0.04) | 0.22 | 0.04 |
| Log density                   | 8.65        | 0.24(0.06) | 0.26 | <0.001 | 19.47       | 0.45(0.008) | 0.44 | <0.001 | 16.18       | 1.77(0.36) | 0.40 | <0.001 |
| Median age                    | 0.93        | 0.022(0.02) | 0.04 | 0.24  | 1.50        | 0.03(0.027) | 0.06 | 0.34  | 8.44        | 0.35(0.11) | 0.26 | 0.003 |
| Longitude (°)                 | 9.81        | −0.009(0.002) | 0.29 | <0.001 | 20.45       | −0.02(0.003) | 0.46 | <0.001 | 16.55       | −0.06(0.01) | 0.40 | <0.001 |
| Total deaths^a                | 5.71        | 0.002(0.001) | 0.19 | 0.002 | 18.90       | 0.005(0.001) | 0.45 | <0.001 | 24.67       | 0.02(0.004) | 0.50 | <0.001 |
| Pneumonia deaths^a            | 14.70       | 0.01(0.002) | 0.38 | <0.001 | 32.40       | 0.02(0.002) | 0.76 | <0.001 | 24.31       | 0.08(0.01) | 0.50 | <0.001 |
| Influenza and pneumonia^a     | 0.23        | 0.006(0.008) | 0.02 | 0.44  | 1.63        | 0.012(0.011) | 0.06 | 0.29  | 4.24        | 0.08(0.07) | 0.15 | 0.13 |
| Nephritis nephrotic syndrome and nephrosis^a | 0.62      | −0.001(0.008) | 0.03 | 0.93  | 1.67        | 0.005(0.012) | 0.07 | 0.69  | 3.84        | 0.07(0.05) | 0.14 | 0.2 |
| Other diseases of respiratory system^a | 2.22      | 0.021(0.01) | 0.11 | 0.04  | 8.37        | 0.05(0.02) | 0.26 | 0.001 | 11.60       | 0.27(0.07) | 0.33 | <0.001 |
| Septicemia^a                  | 2.44        | 0.03(0.01) | 0.10 | 0.04  | 7.57        | 0.07(0.02) | 0.26 | 0.001 | 14.48       | 0.35(0.08) | 0.40 | <0.001 |

AQI air quality index, PCP proportion of cases to population per 10^5, PDP proportion of deaths to population per 10^5, CFR case fatality rate (%), HDI human development index

**P < 0.01, *P < 0.05

^a Deaths for 22 weeks as up June 6, 2020, per 10^5 population
suppress early immune response to infection through inflammation and cellular damage (Wu et al. 2020), in line with other infectious diseases such as SARS (Cui et al. 2003).

The results of current study showed that longitude was negatively correlated with COVID-19 variables (Appendix). In fact, states in the western USA (high longitude) had lower median age, comorbidities, and air pollution as well as population density (Fig. 1). On the other hand, GDP per capita was positively correlated with PCI and PCD. It appears that the investment in health systems of regions with higher income may support screening programs and tests for fast and high volume diagnosis of patients infected with COVID-19 and/or asymptomatic individuals, and vice versa (Chattu and Yaya 2020; Vasquez et al. 2020; Sarmadi et al. 2020a). Additionally, it seems that prevalence of comorbidities plays a determinative role in COVID-19 incidence and mortality. Similarly, prevalence of heart disease and diabetes was positively associated with risk of death in other studies (Richardson et al. 2020; Coccia 2020). We acknowledge that there are some limitations to this study as follows: The data for number of cases and deaths attributed to COVID-19 are invariably different in each state due to differences in diagnosis criteria, variation in the number of available tests in each state, different sensitivity and specificity of each test, and reporting protocols. Other potential factors discussed in the studies (Sajadi et al. 2020; Sarmadi et al. 2020b). It is also suggested that future studies should address the effect of quarantine policies, adherence, and effectiveness, public awareness, social distancing, length of hospitalization, migration, and other chronic disease.

Conclusion

Despite the inherent limitations of the ecological study design utilized and our subsequent inability to assess associations at an individual and temporal level, our study suggested that air pollution components, especially NO₂, could be contributing factors in the interstate distribution of COVID-19. Population density might be also an effective factor in COVID-19 outbreak. Alongside demographic factors, wearing facemasks and adhering to social and physical distancing guideline are imperative to limit spreading the disease. We also acknowledge that higher incidence rates in some states reflect economic differences, which may impact access and availability of diagnostic services and healthcare provisions. It also seems that Non-Hispanic American Indian or Alaska Native are more resistant against COVID-19. Finally, we believe that health managers and policymakers in the USA should consider the implemented measurements based on social distancing, school closures, and funding for hospital infrastructure, which has the ability to slow the spread of disease, with special attention to providing education and resources to vulnerable and historically marginalized populations with disproportionate exposures to air pollution.

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Authors’ contributions Mohammad Sarmadi: conceptualization, methodology, formal analysis, investigation, project administration, resources, data curation, writing—original draft, writing—review and editing. Vahid Kazemi Moghadam: conceptualization, investigation, writing—original draft, writing—review and editing. Aisha S. Dickerson: methodology, formal analysis, investigation, writing—original draft, writing—review and editing. Luigi Martelletti: investigation, writing—original draft, writing—review and editing. All authors read and approved the manuscript.

Data availability All data generated or analyzed during this study are included in this published article.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Abbreviations AQI, air quality index; CDC, The Centers for Disease Control and Prevention; CFR, case fatality rate; COVID-19, coronavirus disease 2019; EPA, Environmental Protection Agency; GDP, gross domestic product; NO₂, nitrogen dioxide; O₃, ozone; PCD, proportion of death per population; PM, particulate matter; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2; USA, United States of America

Appendix

Scatter plots show standardize coefficients of liner regression model between COVID-19 and independent variables.
Fig. 2. Scatter plots show liner regression model between COVID-19 and independent variables AQI air quality index, PCP proportion of cases to population per 105, PDP proportion of deaths to population per 105, CFR case fatality rate (%), HDI human development index, GDP gross domestic product per capita (SUS).
Fig. 2 (continued)
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