Analyzing the severity of coronavirus infections in relation to air pollution: evidence-based study from Saudi Arabia

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Abstract
COVID-19 is one of the major pandemics in history. It has caused various health problems to majority of countries in the world. Several researchers have examined and developed studies regarding concerns on air pollution being considered a major risk factor causing respiratory infections. Such infections are carried out by microorganisms, thus further affecting the immune system. The present study involves the relationship between air pollutants and the total COVID-19 infections along with the estimation of death rates in several regions of Saudi Arabia. The major goal of this study comprises the analysis of the relationship between air pollutants concentration, such as PM10, NO2, CO, SO2, and O3, and the widespread outbreak of COVID-19. This scenario involves the transmission, number of patients, critical cases, and death rates. Results show that the estimation of recorded COVID-19 cases was in the most polluted regions; the mortality rate and critical cases were also more distinct in these regions than in other regions in Saudi Arabia. The finding of this study demonstrates a positive correlation between the mean values of PM10, NO2, CO, and SO2 pollutants. The results represent the significant relationship between air pollution resulting from a high concentration of NO2 and COVID-19 infections and deaths. In addition, a null hypothesis of the relation between other pollutants and COVID-19 infections cannot be rejected. The study also indicates a significant correlation between the means of NO2 and CO and the total number of critical cases. Negative correlations are obtained between the mean of O3 and the total number of cases, total deaths, and critical case per cumulative days.

Keywords
Air pollution · Ambient air · COVID-19 · Infections · Pollutants concentration · SARS-CoV-2

Introduction
Recently, SARS-CoV-2 has led to the COVID-19 pandemic, thus causing health problems among individuals worldwide. This ongoing pandemic has propagated rapidly and has sparked a universal health crisis (Adly et al. 2020). In July 2020, researchers observed that COVID-19 can be transmitted through droplets released when exhaling and through direct contact with the infected individuals. The COVID-19 pandemic has resulted in 14,747,822 cases worldwide, with 610,791 death rates and 8,803,885 recovery rates (WHO 2020). The infected cases are estimated at 5,333,146 cases, among which 5,273,445 have mild conditions, comprising 99% of the total rates; the remaining 59,701 cases have critical conditions, forming 1% of the rates (WHO 2020). In Saudi Arabia, 250,920 confirmed cases of COVID-19 have been recorded as of October 2020 (Adly et al. 2020). The total number of confirmed cases is 338,539, and the total number of deaths is 4,996 with a fatality rate of 1.5%. Saudi Arabia has been ranked second among the regions with the largest number of COVID-19 cases in the Eastern Mediterranean region, majorly involving the two most sacred religious places for Muslims, i.e., Mecca and Medina. Hence, the expected number of COVID-19 cases, mainly during the Hajj pilgrimage season, must be determined.

The novel coronavirus is considered an explosive outbreak that has resulted in deaths at a rapid rate (Mizumoto and Chowell 2020). Symptoms of COVID-19 include respiratory infections resulting in severe disease among certain groups of people, mainly the older population with health-related problems, such as diabetes and cardiovascular disease (Adler 2020). Epidemiological research on this matter is still ongoing, with the disease exponentially increasing at rapid rates.
The novel coronavirus was detected using a sequence-based analysis done by isolating the sequences from the infected patients. Some of the research studies revealed that the initial infected individuals consumed seafood; however, studies also found that some of the infected individuals did not consume any seafood. These observations proved the spreading capability of the virus among human beings, which has affected almost the whole world at exponential rates. Hence, the severity of the disease has been considered high. The high transmission rates are due to the close contact of one person with an infected person; transmission can occur through coughing, respiratory droplets, and aerosols. These aerosols have the capability of penetrating into the human body, mainly affecting the lungs by inhaling through the nose or the mouth (Phan et al. 2020; Riou and Althaus 2020; Parry 2020; Li et al. 2020).

Abundant research has been conducted on the possible contribution of environmental pollutants to the spread, fatality, and severity of the coronavirus. However, only few studies have investigated the combined impacts of environmental factors and other potential factors, such as population density and the percentage of the elderly population, in a single study. Even fewer works focusing on Saudi Arabia have investigated the association between major air pollutants, such as CO, PM10, NO2, O3, and SO2, and the spread, fatality, and severity of the coronavirus.

The impact of air pollutants among individuals has resulted in deaths associated with respiratory diseases and cardiovascular diseases. The study analysis by the World Health Organization (WHO) has revealed that the health of individuals deteriorates due to exposure to particulate matter for long durations (Ezzati et al. 2002). The major air pollutants that affect human health include NO2, CO, and O3. The level of air pollutants is increasing because of fuel combustion by emissions from different sectors, including transportation, power generation, desalination of seawater, and industrial factories. These industries are responsible for emitting pollutant concentrations and emissions at higher levels in the environment.

Many studies have shown that the major air pollutants causing adverse health effects in Saudi Arabia include particulate matter (PMs), carbon monoxide (CO), carbon dioxide (CO2), sulfur dioxide (SO2), nitrogen dioxide (NO2), and heavy metals (Al Mulla et al. 2015; Argyropoulos et al. 2016; Farahat 2016; Omidvarboma et al. 2018; Saraga et al. 2017). Incomplete burning of Arabian incense generates the emission of CO, PM10, PM2.5, black carbon, and polycyclic aromatic hydrocarbons (PAHs), thus causing adverse health effects on the population exposed to these emissions (Du et al. 2018). These air pollutants tend to cause ischemic heart diseases (IHD), chronic obstructive pulmonary diseases (COPD), and lung cancer among the population of Saudi Arabia (Amoatey et al. 2018; Tageldin et al. 2012; Thurston et al. 2016).

Analyses on health variabilities have revealed that most of the individuals suffering from COVID-19 were already prone to exposure to air pollution, as the regions in Saudi Arabia have high pollution rates. Air pollutants emerging from vehicles and industries in Saudi Arabia have been the major source of pollution. COVID-19 affects the human respiratory system. Hence, individuals who are already prone to respiratory disease are at high risk during the pandemic.

Several Italian studies have revealed that air pollution is a risk factor for COVID-19. A correlation with a higher level of PM has a major impact on the health of individuals in areas of Northern Italy (Domingo et al. 2020; Martelletti and Martelletti 2020; Sciomer et al. 2020; Zoran et al. 2020). Another study analyzed the involvement of PM10 emerging from an industrial site of Bergamo Province, which has been considered the epicenter of the COVID-19 epidemic in Italy (Setti et al. 2020). The results from these sites have revealed that SARS-CoV-2 has shown its presence in the PM during atmospheric stability and at higher concentrations of PM10; these findings represent the first experimental proof for COVID-19 being transmitted through PM (Distante et al. 2020). Researchers have also found that populations dwelling in regions with high concentrations of air pollutants are prone to developing chronic respiratory infections and are more sensitive to infectious agents. Moreover, exposure to air pollution for longer durations results in chronic inflammatory stimulus among young and healthy individuals (Conticini et al. 2020). Another major study revealed a correlation between COVID-19 infections and air pollution, thus indicating a major impact on increasing infection and mortality rates (Frontera et al. 2021).

The lockdowns during the COVID-19 pandemic have shed light on the human activities involving vehicle use and public transportation, along with the involvement of industrial processes (Pata 2020; Gautam 2020; Bashir et al. 2020; Shehzad et al. 2020). Many studies have shown the relevance of air pollution and COVID-19. The transmission of the virus has been found to be prevalent through airborne bioaerosol droplets and various parameters of urban air pollution (Bashir et al. 2020; Fareed et al. 2020). Past exposure to air pollution has increased COVID-19 cases. The evidence of air pollution involves the mortality rates of COVID-19-infected individuals.
with past exposure to air pollutants. The increase of emissions from fuel in the GCC and the Middle East has altered the global atmosphere. In addition, airplanes and ships have contributed to the emissions in this region. CO2 emissions from fossil fuel combustion and industries have increased the volume of pollution. In addition, governance systems and ecological attributes have affected populations in the Middle East and have had a major impact on natural climatic conditions (Sowers et al. 2011).

Air pollution has been linked to chronic rhinitis and rhinosinusitis; these conditions can increase the mucosal permeability of the airways, thus facilitating the penetration of SARS-CoV-2 (Annesi-Maesano et al. 2012; London et al. 2018). In addition, the primary access points of the virus are the nasal epithelial cells, according to recent research (Songbak et al. 2020).

The virus infects cells by binding to the angiotensin-converting enzyme 2 (ACE-2) receptor via the viral structural spike (S) protein. ACE-2 aids in the regulation of angiotensin II (ANG II), a protein that raises blood pressure and inflammation while also increasing damage to blood vessel linings and different forms of tissue injury. ANG II is converted by ACE-2 to other molecules that mitigate its effects. ANG II can exacerbate inflammation and kill cells in the alveoli, which are essential for the body to take in oxygen; ACE-2 can counteract the debilitating effects of ANG II. SARS-CoV-2 targets ACE-2 receptors in various tissues, including those in the cardiovascular system (Zheng et al. 2020).

When SARS-CoV-2 binds to ACE-2, it stops ACE-2 from doing its job of regulating ANG II signaling. As a result, ACE-2 activity is “inhibited,” thus eliminating the brakes on ANG II signaling and allowing more ANG II to reach injured tissues. In COVID-19 patients, this “reduced braking” likely leads to injury, especially to the lungs and heart. The spike protein (S) can bind to the angiotensin-converting enzyme 2 (ACE-2) receptor on cellular membranes, thus stimulating the entry of the virus into the cell (Hoffmann et al. 2020). The overexpression of ACE-2 can increase the risk of the virus attaching to host epithelial cells along the respiratory tracts through its interface spike protein (S). As a result, the virulence of the virus in terms of efficient infection can increase in areas with high levels of air pollution.

In China, the rate of fatality from coronavirus-induced SARS was higher in patients who breathed contaminated air. This risk was due to a higher expression of ACE-2 (Cui et al. 2003). Extreme air pollution, through the intervention of NO2-mediated ACE-2 overexpression, may be responsible for an increase in the rate and intensity of COVID-19 (Alifano et al. 2020).

The present study aims to analyze the relationship between ambient air pollutants and the total infection and death rates of COVID-19 in Saudi Arabian regions. The collected data and their analysis seek to show the correlation of air pollution in various Saudi Arabian regions with COVID-19 cases, including mortality rates and critical cases. The analysis significantly proves the impact of the COVID-19 outbreak in terms of its transmission, number of patients, critical cases, and number of deaths. The impact of past exposure toward air pollutants has affected COVID-19 cases. The present study provides evidence to this impact using facts and figures. Hence, this study is a helpful approach to understand the importance of reducing air pollutant concentrations in the atmosphere for people to lead healthy lives.

Methods

Study area and data

This study included 10 regions out of 13 regions (Makkah Al Mukarramah, Ar Riyad, Eastern Region, Al Madinah Al Munawwarah, Asir, Al Qaseem, Jazan, Tabuk, Al Jouf, Al Baha, Najran, and Northern Region) in the geographic regions of Saudi Arabia, at 45.0792° E and 23.885° N. Fig. 1 shows a map of Saudi Arabia outlining its 13 administrative regions. According to the database collected from the website of the General Authority of Meteorology and Environment Protection (GAMEP) (https://ncm.gov.sa/Ar/Environment/AirQuality/Pages/AQ-Reports.aspx?folderID=351e1157-509d-46d1-8118-bd78d008e33d), air pollutant data including CO, SO2, NO2, O3, and PM10 were identified. Data on COVID-19 cases were extracted from the official website of the Saudi Ministry of Health (https://covid19.moh.gov.sa). In addition, statistical data of population and areas for the various regions of the Kingdom of Saudi Arabia were obtained from the official website of the General Authority for Statistics (https://www.stats.gov.sa/en/43).

Approximately 194,255 COVID-19 confirmed cases had been identified in the 13 regions of Saudi Arabia as of June 30, 2020. Our studied regions covered 70% of confirmed cases. We focused our analysis on these 10 regions of Saudi Arabia because of the limitation of the meteorological data and the air pollution data we obtained. Air pollutant data were only available for 10 regions out of 13 regions of Saudi Arabia. Nevertheless, data on COVID-19 cases were available for all regions at the time of writing.

Statistical analysis

Statistical analysis was done using SPSS version 23. A descriptive analysis was executed for all the data. The extracted data were analyzed using Spearman’s correlation, which depicted the correlation between the mean values of PM10, NO2, CO, SO2, and O3 registered in May 2020 and the COVID-19 cases in terms of the total number of deaths and
critical cases per cumulative days. All analyses in this study were conducted using Spearman’s correlation coefficients among the mean values of PM10, NO2, CO, SO2, and O3. The statistical tests were two sided, and p-values of less than 0.05 were considered statistically significant. The statistical analysis of the study showed a positive correlation among the mean values of PM10, NO2, CO, and SO2 pollutants. The results represent the significant relationship between air pollution resulting from a high concentration of NO2 and COVID-19 infections and deaths. Null hypothesis of the relation between other pollutants and COVID-19 infections could not be rejected. The study also indicated a significant correlation between the mean values of NO2 and CO and the total number of critical cases.

**Findings and discussion**

The present study aimed to analyze the impact of COVID-19 in terms of its transmission, number of patients, critical cases, and number of deaths along with analyzing the relationship among the concentrations of various air pollutants (PM10, NO2, CO, SO2, and O3). In addition, the link between air pollution in various Saudi Arabian regions and COVID-19 cases, mortality rates, and critical cases was represented in the given study to support the efficacy of the study, which aimed to demonstrate the correlation between air pollution and COVID-19 cases. A dataset concerning the air quality was obtained from the database of GAMEP, including CO, SO2, NO2, O3, and PM10, to fulfill the aim of the study. The official site of the Saudi Ministry of Health on COVID-19 was
used for data extraction. The data involved the 13 regions of Saudi Arabia and consisted of COVID-19 cases as of June 30, 2020. The data involved the measurement of the total number of cases of COVID-19 in particular regions of Saudi Arabia, along with the evaluation of the mean values of air pollutants, including PM10, NO2, CO, SO2, and O3, in a particular region of Saudi Arabia in May 2020, 1 month before the start of the wider transmission of the COVID-19 epidemic in the Kingdom and the highest death rate in the country. Hence, the air pollution data of Saudi Arabia during COVID-19 helped in determining the link between air pollution in various Saudi Arabian regions and COVID-19 cases, mortality rates, and critical cases. However, some of the data were missing in the dataset. Table 1 below presents the analysis data of air pollution of Saudi Arabian regions with air pollutant concentrations and COVID-19 cases. Air pollution data for Al Baha, Najran, and Northern Region were unavailable at the time of writing.

Statistical analysis was done using SPSS version 23. A descriptive analysis was executed for all the data. The

Table 1 Distribution of COVID-19 cases on June 30, 2020 (total number of cases, deaths, and critical cases) per Saudi Arabian region and the mean values of PM10, NO2, CO, SO2, and O3 registered in each region in May 2020

| Saudi Arabian regions | Total number of cases (n) | Deaths (n) | Critical cases (n) | Mean PM10 in May 2020 (μg/m^3) | Mean NO2 in May 2020 (ppb) | Mean CO in May 2020 (ppb) | Mean SO2 in May 2020 (ppb) | Mean O3 in May 2020 (ppb) |
|-----------------------|---------------------------|------------|-------------------|-------------------------------|---------------------------|--------------------------|---------------------------|---------------------------|
| Makkah Al Mukarramah   | 57548                     | 954        | 482               | 101.00                        | 0.74                      | 6.24                     | 28.97                     |
| Ar Riyad              | 52932                     | 383        | 512               | 97.48                         | 1.18                      | 2.63                     | 17.85                     |
| Eastern Region        | 48274                     | 157        | 815               | 33.93                         | 10.99                     | 1.67                     | 4.02                      | 19.55                     |
| Al Madinah            | 15106                     | 98         | 82                | 97.09                         | 11.15                     | 0.75                     | 3.35                      | 20.87                     |
| Asir                  | 7936                      | 15         | 194               | 56.00                         | 3.24                      | 0.54                     | 2.86                      | 26.96                     |
| Al Qaseem             | 3812                      | 20         | 82                | 107.55                        | 2.77                      | 0.73                     | 2.16                      | 31.25                     |
| Jazan                 | 2448                      | 30         | 23                | 21.40                         | 5.60                      | 1.01                     | 4.92                      | 8.19                      |
| Hail                  | 1619                      | 3          | 37                | 107.62                        | 4.62                      | 0.55                     | 2.52                      | 41.42                     |
| Tabuk                 | 1555                      | 17         | 5                 | 79.38                         | 5.02                      | 0.68                     | 3.38                      | 39.46                     |
| Al Jouf               | 248                       | 2          | 2                 | 27.64                         | 1.99                      | 0.68                     | 7.61                      | 37.75                     |
| Al Baha               | 684                       | 6          | 7                 | NA                            | NA                       | NA                       | NA                       | NA                       |
| Najran                | 1662                      | 1          | 33                | NA                            | NA                       | NA                       | NA                       | NA                       |
| Northern Region       | 431                       | 15         | 2                 | NA                            | NA                       | NA                       | NA                       | NA                       |

Table 2 Spearman’s correlation coefficients between the mean values of PM10, NO2, CO, SO2, and O3 registered in May 2020 and COVID-19 cases in terms of total number, deaths, and critical cases per cumulative days (data updated as of 30 Jun 2020)

| Correlations                  | Pearson’s coefficient (r-value) | Significance (p-value) |
|-------------------------------|---------------------------------|------------------------|
| Mean PM10 – total number cases| 0.178                           | 0.623                  |
| Mean values of PM10 – deaths  | 0.334                           | 0.345                  |
| Mean PM10 vs. critical cases per cumulative days | -0.046 | 0.8995 |
| Mean NO2 – total number cases | 0.885                           | 0.001                  |
| Mean NO2 – deaths             | 0.713                           | 0.021                  |
| Mean NO2 vs. critical cases per cumulative days | 0.722 | 0.0184 |
| Mean CO – total number cases  | 0.607                           | 0.063                  |
| Mean CO – deaths              | 0.136                           | 0.709                  |
| Mean CO vs. critical cases per cumulative days | 0.7387 | 0.0073 |
| Mean SO2 – total number cases | 0.098                           | 0.290                  |
| Mean SO2 – deaths             | 0.327                           | 0.357                  |
| Mean SO2 vs. critical cases per cumulative days | 0.0017 | 0.996 |
| Mean O3 – total number cases  | -0.372                          | 0.290                  |
| Mean O3 – deaths              | -0.138                          | 0.705                  |
| Mean O3 vs. critical cases per cumulative days | -0.3798 | 0.279 |
extracted data were analyzed using Spearman’s correlation, which depicted the correlation between the mean values of PM10, NO2, CO, SO2, and O3 registered in May 2020 and COVID-19 cases in terms of the total number, deaths, and critical cases per cumulative days. Table 2 illustrates the statistical analysis of the data.

The table above illustrates the relationship between air pollutant concentration (PM10, NO2, CO, SO2, and O3) and the COVID-19 outbreak in terms of the transmission, number of patients, critical cases, and number of deaths. The study correlation was conducted to show the link between air pollution in various Saudi Arabian regions and COVID-19 cases, mortality rate, and critical cases.

Positive correlations were obtained among the total number of cases and mean values of PM10, NO2, CO, SO2, and O3 (showing r-values of 0.178, 0.885, 0.607, and 0.098, respectively). However, the correlation was only significant with NO2 (showing p-value of 0.001). Appreciable correlation was obtained between the mean of CO and the total number cases of COVID-19 in Saudi Arabia. Positive correlations were obtained between the total number of deaths and the mean values of PM10, NO2, CO, and SO2 (showing r-values of 0.334, 0.713, 0.136, and 0.327, respectively). However, the correlation was only found significant with NO2 (showing p-value as 0.021).

In this study, the lower correlation of PM10 with COVID-19 infection, mortality, and severity can be attributed to the larger size of this particulate matter. This size makes it unable to reach type II alveolar cells where the cell entry receptor ACE2 for SARS-CoV-2 is located. PM ≤ 10 μm in diameter (PM10) settles in the upper rather than the lower respiratory tract (Kang et al. 2020). PM10 particles can irritate the nose and the eyes. Fewer particles penetrate deep into the lungs; therefore, they do not cause the same health problems as smaller micron particles do but raise the rates of respiratory disease (Xing et al. 2016).

Positive correlations were obtained between the total critical cases per cumulative days and the mean values of NO2, CO, and SO2 (showing r-values of 0.722, 0.739, and 0.0017, respectively). The correlation was observed to show significance with NO2 and CO with p-values of 0.0184 and 0.0073, respectively. Negative correlations were obtained between the mean of O3 and the total number of cases, total deaths, and critical cases per cumulative days with r-values of −0.372, −0.138, and −0.379. The correlation did not show any significance with all these relations, with p-values greater than 0.1.

The correlation of the mean concentration of CO in May 2020 with the number of critical cases per cumulative days (patient data updated on June 30, 2020) was represented by scatter plotting in Fig. 2.

Fig. 2 shows the relation between CO and the number of critical cases. Most of these cases were in the Eastern Region of Saudi Arabia. Hail and Asir had the lowest number of critical cases among all the 13 regions in the study. Riyadh had more critical cases than Makkah. Meanwhile, Al Qaseem, Jazan, Hail, Tabuk, Al Jouf, Al Baha, and Najran had a lower number of critical cases than other regions selected in this study. Hence, the above results showed that the estimation of the highest number of COVID-19 cases was recorded among polluted regions; the mortality rate and critical cases were also more distinct in these regions than in other regions of Saudi Arabia. The finding of this study showed a positive
correlation between the mean values of PM10, NO2, CO, and SO2 pollutants. The results indicated a significant relationship between air pollution resulting from a high concentration of NO2 and COVID-19 infection and deaths.

For the sake of manageability and to facilitate comparison among different geographical regions on the severity of COVID-19 in terms of the number of cases and mortality rates, the total number of cases and deaths was calculated per 100,000 of the regions’ populations. Figures 3 and 4 present the relationships between ambient NO2 concentration and the total number of cases and deaths in different regions of Saudi Arabia. Fig. 3 shows that the four regions in the Kingdom with the highest concentrations of NO2 had the largest share of COVID-19 cases. The highest number of COVID-19 infections per 100,000 people was recorded in the Eastern Region of the Kingdom, followed by the regions of Makkah Al-Mukarramah and Al Madinah Al Munawwarah, and then Riyadh. In these four regions, the highest levels of NO2 concentrations were monitored, which ranged between 11 and 13.1 ppb. Approximately 90% of COVID-19 infections and 94% of fatalities were also recorded in these four regions. Fig. 4 shows that death rates were the highest per 100,000 people.

Fig. 3 Correlation of the mean concentration of NO2 in May 2020 with the total number of COVID-19 cases per cumulative days (patient data updated on June 30, 2020)

Fig. 4 Correlation of the mean concentration of NO2 in May 2020 with the number deaths due to COVID-19 infection per cumulative days (patient data updated on June 30, 2020)
in the four regions of the Kingdom, which had high concentrations of NO$_2$. The highest death cases were recorded in Makkah Al-Mukarramah, followed by an approximately equal number of cases in Al Riyadh and Al Madinah, and then the Eastern Region.

A recent study found that the threshold levels of NO$_2$ related to the adverse effect of the coronavirus ranged between 15.8 and 22.9 $\mu$g/m$^3$ in three French cities; the reported values were much lower than the average annual concentration limit of 40 $\mu$g/m$^3$ imposed by Directive 2008/50/EC of the European Parliament (Mele et al. 2021). According to this study, NO$_2$ concentrations in the four most polluted regions in the Kingdom ranged between 21 and 24 $\mu$g/m$^3$. These values were either greater than the smaller threshold level or closer or greater than other threshold levels reported in the three French cities.

To highlight the possible impact of population density on the severity of infection with COVID-19, the population density of each region of the Kingdom was calculated using the total population and area data extracted from the General Authority for Statistics website. Table 3 shows the population density and percentage of the elderly population in the different geographical areas in Saudi Arabia. It also includes the distribution of COVID-19 cases in each region in terms of the total number of cases, deaths, and critical cases per 100,000 people.

Table 3 shows that the highest number of COVID-19 cases and deaths was detected in the four most polluted regions in Saudi Arabia. However, no clear relationship between the population density and the severity of the epidemic could be inferred. For example, the highest number of total COVID-19 infections, as well as critical cases per 100,000 people, was monitored in the Eastern Region of Saudi Arabia. The same table shows that the population density in the Eastern Region ranks eighth out of the Kingdom’s 13 regions. Thus, the population density factor has a weak impact on the spread and severity of COVID-19. This finding is in agreement with the findings of several studies, some of which found that the rates of COVID-19 infections and deaths are not related to population density (Carozzi et al. 2020; Hamidi et al. 2020). Other studies indicated a moderate association between the spread of COVID-19 and population density (Bhadra et al. 2021). Another findings reported that air pollution could be worsen in the highly populated regions (Shen et al. 2017; Wang et al. 2021), and therefore air pollution control measures must be adopted in those regions to counteract air pollution.

Despite the findings of this study, the major regions in Saudi Arabia contain the major cities in which the majority of the Saudi Arabian population lives. Such density is due to the increase in the rates of migration from rural to urban areas, which have witnessed a significant increase in recent years, and also due to urban areas becoming an important center for industrial and commercial activities. This situation is often accompanied by strong emissions from household activities (e.g., cooking, heating, and smoking) and local transportations. Furthermore, traffic congestion produced by human urbanization has made the complete combustion of vehicle gasoline difficult. Consequently, the levels of the ambient air pollution have increased tremendously.

The Eastern Region is also regarded as the Kingdom’s most developed area. This province is home to more than 86% of Saudi Arabia’s major industries and petrochemical companies. It also serves as Saudi Arabia’s main oil production center. This study showed that the highest level of CO

| Saudi Arabian regions   | Total number of cases per 100,000 | Deaths per 100,000 | Critical cases per 100,000 | Population density (people/km$^2$) | Percentage of elderly population (above 65 y/o) (%) |
|-------------------------|-----------------------------------|-------------------|---------------------------|----------------------------------|-----------------------------------------------|
| Makkah Al-Mukarramah    | 637.0                             | 10.6              | 5.3                       | 59.0                             | 29.4                                          |
| Ar Riyad                | 611.2                             | 4.4               | 5.9                       | 21.4                             | 18.9                                          |
| Eastern Region          | 937.6                             | 3.0               | 15.8                      | 7.7                              | 10.8                                          |
| Al Madinah              | 674.4                             | 4.4               | 3.7                       | 14.7                             | 8.2                                           |
| Asir                    | 343.8                             | 0.6               | 8.4                       | 30.1                             | 9.8                                           |
| Al Qaseem               | 256.1                             | 1.3               | 5.5                       | 25.6                             | 4.4                                           |
| Jazan                   | 149.5                             | 1.8               | 1.4                       | 140.3                            | 6.8                                           |
| Hail                    | 221.4                             | 0.4               | 5.1                       | 7.0                              | 2.6                                           |
| Tabuk                   | 163.8                             | 1.8               | 0.5                       | 6.5                              | 2.2                                           |
| Al Jouf                 | 46.6                              | 0.4               | 0.4                       | 5.3                              | 1.4                                           |
| Al Baha                 | 137.6                             | 1.2               | 1.4                       | 50.1                             | 2.5                                           |
| Najran                  | 273.1                             | 0.2               | 5.4                       | 4.1                              | 1.9                                           |
| Northern Region         | 112.5                             | 3.9               | 0.5                       | 3.4                              | 1.1                                           |
The concentration was detected in the Eastern Region. The increased concentrations of CO pollutants in this area could be attributed to a diverse range of industrial activities that produce varying emission rates (Anil and Alagha, 2021). COVID-19 cases and casualties had more CO in their arteries and veins than uninfected healthy people, thus making them more vulnerable to infections and complications. Although the increased concentration of NO\textsubscript{2} in the ambient air was associated with a remarkable increase of COVID-19 infections, deaths, and severity, CO was more associated with COVID-19 severity than NO\textsubscript{2}. The highest concentration of CO was observed in the Eastern Region of Saudi Arabia, which was equal to 1.67 ppm; this concentration was associated with 815 critical cases, which constitute about 43\% of the total critical cases in all regions.

Population density and the percentage of the elderly population could be possible reasons for the noticeable increase in the total number of infections and critical cases per 100,000 people in Asir. Given that the impact of air pollution was insignificant in this region, other possible factors should be investigated to reach a reliable conclusion.

In addition to the air pollution factor, the remarkably high number of deaths in the Makkah region could be attributed to population density and the high percentage of elderly people residing in that region, which was approximately 30\% of the total number of the elderly population in Saudi Arabia. A recent study reported that the largest increase in mortality risk was observed in patients aged 60 to 69 years compared with those aged 50 to 59 years (Bonanad et al. 2020).

The study showed that chronic exposure to air pollution potentially produced a favorable condition for the spread and severity of COVID-19 cases. Air pollution and COVID-19 were associated with each other through two routes: the emergence of respiratory diseases due to COVID-19 and air pollution especially via NO\textsubscript{2} emissions and through NO\textsubscript{2}-mediated high expression of ACE-2 in the respiratory cells of human hosts.

Several studies have indicated that exposure to NO\textsubscript{2} may play a role in the emergence of respiratory diseases, such as influenza, asthma, and severe acute respiratory syndrome. Some researchers have reported that NO\textsubscript{2} may increase the susceptibility of adults to virus infections (Goings et al. 1989).

In this study, high levels of NO\textsubscript{2} were observed in large cities in the Kingdom of Saudi Arabia; large cities necessitate further displacements, thus resulting in increased traffic. In addition, vehicles release harmful gases, which are primarily formed and released directly into the atmosphere during the combustion process. As a result, NO\textsubscript{2} and NO are primarily formed and emitted. According to a recent European analysis, 78\% of COVID-19 fatalities occurred in five regions with the highest NO\textsubscript{2} concentrations (Ogen 2020).

The findings of this study are in line with recent research, which suggests that exposure to air pollution can increase the spread and infections of the coronavirus (Shakoor et al. 2020).

Conclusion

The present study involves facts and figures concerning the impact of COVID-19, which has resulted in health-related problems worldwide. The correlation of air pollution with the COVID-19 pandemic has been presented, as respiratory diseases are among the major outcomes of COVID-19. In addition, COVID-19 tends to affect the respiratory system in humans; individuals that have been exposed to air pollutants are more prone to becoming infected. Hence, to show its relevance, the present study explores the relationship between ambient air pollutants and the total COVID-19-related infections and death rates in Saudi Arabian regions. The relationship between air pollutant concentration (PM\textsubscript{10}, NO\textsubscript{2}, CO, SO\textsubscript{2}, and O\textsubscript{3}) and COVID-19 transmissions, patients, critical cases, and deaths has been analyzed in this study. The highest number of COVID-19 cases has been recorded in the most polluted regions, and the mortality rates and critical cases have been found to be more distinct in these regions than other regions in Saudi Arabia. Hence, a positive correlation among the mean values of PM\textsubscript{10}, NO\textsubscript{2}, CO, and SO\textsubscript{2} pollutants is obtained, thus showing a significant relationship between air pollution resulting from a high concentration of NO\textsubscript{2} and COVID-19 infections and deaths. Regions with intensive industrial activities have more CO emissions, thus leading to an increase in critical COVID-19 cases.

Urgent actions must be adopted by concerned authorities in Saudi Arabia to counteract air pollution by implementing appropriate environmental policies and through developing new urban planning interventions. Effective pollution control policies, methods, and technologies should be introduced to lower NO\textsubscript{2} and CO concentrations in the atmosphere significantly and tighten pollutant emissions in densely populated urban regions of Saudi Arabia. Specific efforts should be made to integrate urban–rural development, such as strengthening rural infrastructure and decreasing the wealth gap between the population of urban and rural regions.

Administrative action is urgently needed to improve the air quality level of big urban centers in Saudi Arabia. This improvement can be done by implementing professional programs that enhance the capacity of managers and decision-makers, raising public awareness of environmental pollution issues through various media tools, and improving the coordination among all authorities dealing with air pollution control.

The present study focused on investigating air pollution as a potential contributor to the severity of coronavirus.
infections. It provided a preliminary result on the impact of population density as a possible contributor to the spread and severity of the coronavirus. Future trends should include consideration of other possible contributing factors, such as meteorological conditions, clinical factors, socioeconomic factors, social behaviors of age groups, genetic factors, and economic conditions.

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Author contribution The author (Abdulnoor A. J Ghanim) has the sole responsibility for the study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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Data availability The data supporting the findings of this study were extracted from the Saudi Ministry of Health official website [https://covid19.moh.gov.sa] and the website of the General Authority of Meteorology and Environment Protection (GAMEP) [https://ncm.gov.sa/Ar/Environment/AirQuality/Pages/AQ-Reports.aspx?folderID=351e1157-509d-46d1-8118-bd78d008e33d].

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest The author declares no competing interests.

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