RESEARCH ARTICLE



Spatiotemporal analysis of COVID-19, air pollution, climate, and meteorological conditions in a metropolitan region of Iran

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Abstract

The COVID-19 pandemic has a close relationship with local environmental conditions. This study explores the effects of climate characteristics and air pollution on COVID-19 in Isfahan province, Iran. A number of COVID-19 positive cases, main air pollutants, air quality index (AQI), and climatic variables were received from March 1, 2020, to January 19, 2021. Moreover, CO, NO₂, and O₃ tropospheric levels were collected using Sentinel-5P satellite data. The spatial distribution of variables was estimated by the ordinary Kriging and inverse weighted distance (IDW) models. A generalized linear model (GLM) was used to analyze the relationship between environmental variables and COVID-19. The seasonal trend of nitrogen dioxide (NO₂), wind speed, solar energy, and rainfall like COVID-19 was upward in spring and summer. The high and low temperatures increased from April to August. All variables had a spatial autocorrelation and clustered pattern except AQI. Furthermore, COVID-19 showed a significant association with month, climate, solar energy, and NO₂. Suitable policy implications are recommended to be performed for improving people's healthcare and control of the COVID-19 pandemic. This study could survey the local spread of COVID-19, with consideration of the effect of environmental variables, and provides helpful information to health ministry decisions for mitigating harmful effects of environmental change. By means of the proposed approach, probably the COVID-19 spread can be recognized by knowing the regional climate in major cities. The present study also finds that COVID-19 may have an effect on climatic condition and air pollutants.

Keywords COVID-19 · Air pollution · Climate effect · Meteorological indicators · GIS · Sentinel-5P · Google Earth Engine

Introduction

The novel coronavirus disease 2019 (COVID-19) was recognized in Wuhan, China, in December 2019 (Adelodun et al. 2021; Tang et al. 2020). Due to the global spread of

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the disease, the World Health Organization (WHO) declared COVID-19 as a pandemic on March 11, 2020 (Coccia 2021a; Qi et al. 2020; Rosario et al. 2020; Wu et al. 2020). The first COVID-19 confirmed case was reported in Iran on February 19, 2020. Then, it quickly spread in the Iranian provinces, with the highest rates in Tehran, Qom, and Isfahan provinces (Asna-ashary et al. 2020; Khorsandi et al. 2021; Moein et al. 2020; Ramírez-Aldana et al. 2020).

Many factors can affect a pandemic disease which include demographic characteristics, economic structures, medical care quality, contact patterns, environment, and meteorological variables. Overall, the transmission dynamics of COVID-19 are complex, because different systemic causes are affected on this. Some of these risk factors are similar for all regions such as SARS-CoV-2 characteristics and incubation period. However, other factors such as socioeconomic aspects, demographic characteristics (e.g., immune system, age, sex, and habits), healthcare structure efficiency, social interactions, environmental pollutants, and climatological conditions are different for each region (Coccia 2020a, 2021d). In addition, vitamin D has a critical role in COVID-19 infection reduction. Vitamin D causes a decrease in SARS-CoV-2 replication levels, prevents pro-inflammatory responses, and increases anti-inflammatory levels of cytokines by inducing defensins and cathelicidins. Moreover, several preventive measures have been done to contain the outbreak of COVID-19 (Sarkodie and Owusu 2020). They are dependent on health interventions, for instance, support of the extension of hospital capacity, experiment capabilities to reduce diagnostic delays in infectious diseases, and development of new technology with the creation of effective vaccines, antivirals, and other innovative medicines (Coccia 2020b). Furthermore, some mitigation policies based on social behaviors include remaining at home, school and business closures, physical distancing, handwashing, use of sanitizer, and wearing masks (Bouman et al. 2021; Coccia 2020a, 2021f; Haque and Rahman 2020).

Infectious diseases such as COVID-19 infection and different mortality rates in various areas around the world can be attributed to air quality and climatological conditions (Ahmadi et al. 2020; Berman and Ebisu 2020; Khorsandi et al. 2021; Pourghasemi et al. 2020; Rosario et al. 2020; Wang et al. 2021). Besides, the transmission of respiratory viral diseases has a seasonal cyclic pattern (Wang et al. 2021; Wu et al. 2020) and is under the influence of geographical features of a region (Ahmadi et al. 2020). Thus, municipal geography can be advantageous in determining the spatial patterns of the spread of diseases in each area to prevent the pandemic (Ahmadi et al. 2020; Méndez-Arriaga 2020).

Environmental conditions can influence on survival and spread of viruses that are respiratory disease agents. Climatic variables such as temperature, humidity, wind speed, and rainfall show a critical role in the spread of infectious diseases, especially COVID-19, and they vary among the different areas (Islam et al. 2021; Rosario et al. 2020; Tosepu et al. 2020; Wang et al. 2021). In addition, air pollution can affect the trends of COVID-19 incidence due to susceptible host immunity and vulnerability to viral infections (Filippini et al. 2020; Sangkham et al. 2021). Air pollutants are produced due to the incomplete combustion of fossil fuels that are emitted from artificial activities such as industries. vehicles, and construction processes. As a result of air pollution events, many critical pollutants including particulate matters (PM₂₅ and PM₁₀), carbon monoxide (CO), nitrogen dioxide (NO_2) , sulfur dioxide (SO_2) , and ozone (O_3) are released into the environment in which they could be related to lower rainfall amounts and impact the human respiratory, circulatory, and central nervous systems (Kumar et al. 2021; Sangkham et al. 2021; Singh et al. 2021). As the respiratory system is the main route of COVID-19 transmission, humans exposed to COVID-19 can be infected through person-toperson and airborne transmission (Domingo et al. 2020; Rahimi et al. 2020). Therefore, transmission of COVID-19 through air is more likely than human-to-human transmission (Coccia 2020a, 2021g). This event can be due to the fact that SARS-CoV-2 might be attached to air pollutants, especially particulate matters (PMs), due to the accumulated airborne pollutants. In addition, high levels of air pollutants can be associated with climatological factors such as low wind speed. In general, low wind speed supports longer persistence of SARS-CoV-2 in the air. As a result of low wind speed, transmission of COVID-19 by mechanisms of air pollution-to-human transmission is proven (Coccia 2020a, 2021f, g, e; Shen et al. 2021; Yao et al. 2020).

Isfahan is a metropolitan in the central plateau of Iran with various climates due to different altitudes (Yaghmaei et al. 2009). Some studies reported people in this region are exposed to $PM_{2.5}$, SO_2 , and O_3 at higher levels than the WHO guideline, and most deaths occur due to lung cancer, natural mortality, heart disease, respiratory disease, and stroke related to ambient air pollution (Hajizadeh et al. 2021, 2020).

Recently, some scholars reported climatological and geographical factors related to COVID-19 incidence in Iran. There was an increase in COVID-19 infection due to low levels in wind speed, solar radiation, and humidity in some areas (Ahmadi et al. 2020). According to another research, the global geographic climate had influences on the transmission of COVID-19 and death in Asia and America (Ibrahim et al. 2021). Numerous studies have reported the association between COVID-19 and climatic parameters. Wu et al. (2020) and Wang et al. (2021) reported that relative humidity and temperature were both adversely associated with COVID-19 daily new cases and deaths. However, numerous researches indicated a positive association between temperature and daily cases of COVID-19 (Kumar 2020; Pani et al. 2020; Raza et al. 2020). Moreover, an increase in rainfall and wind speed decreased the cases of COVID-19 in some areas (Coccia 2020c; Pani et al. 2020; Raza et al. 2020).

The potential relationship between air pollutants and the COVID-19 infection rate is investigated in several studies. One study in Tehran, Iran, indicated that the short-term exposure to $PM_{2.5}$, PM_{10} , O_3 , and high temperatures is related to COVID-19 increase during the summer (Khorsandi et al. 2021). However, Sangkham et al. (2021) stated that CO, NO_2 , SO_2 , O_3 , PM_{10} , $PM_{2.5}$, and air quality index (AQI) had a negative relationship with COVID-19 daily confirmed cases in the Bangkok Metropolitan Region (BMR). It also proved that the effect of air pollutants on the number of COVID-19 cases had a decreasing and increasing trend during the period (Keikhosravi and Fadavi 2021).

As preparing a local plan is essential for the management of infectious diseases, it is important to survey the relationship between the infection of COVID-19 and the main influential variables which include meteorological factors and air pollutants in each area. In fact, based on scientific research, there is no evidence about the effect of climate characterization, weather parameters, and air pollution on COVID-19 disease in Isfahan province in Iran. Based on our knowledge, this study analyzed the relationship between the COVID-19 incidence with regional climate, climatological factors, and air pollutants with spatial analysis method as a beneficial tool for the statistical analysis and spatial mapping of data for the first time. In this study, the data was extracted from GIS interpolation and satellite data through Google Earth Engine, and then, the Global Moran's *I* and generalized linear model (GLM) were utilized for statistic calculations.

Methods

Research setting

Isfahan province is located at $30^{\circ}42''$ to $34^{\circ}30''$ N and $49^{\circ}36''$ to $55^{\circ}E$ in the central region of Iran, with a total area of 106,175 km² (Fig. 1). Changes in altitude from 707 and 4000 m have resulted in several climatic regions from arid to humid (Yaghmaei et al. 2009). The total population

of Isfahan province is 5,120,850 based on the last national census in 2016 (Iran Social Science Data Portal 2016).

Data resources

The number of positive cases of COVID-19 and population of all cities of Isfahan province was retrieved from Isfahan University of Medical Sciences Health Center from March 1, 2020, until January 19, 2021, except Kashan and Aran-Bidgol, which are related to Kashan University of Medical Sciences (Fig. 1). Finally, incidence rates were computed using Isfahan counties' population data. Meteorological variables including high and low temperature (°C), wind speed (m/s), solar energy (Kwh), rainfall (mm), precipitation, and cloud cover (%) were retrieved from Weather Spark (https:// weatherspark.com/countries/IR/28) for Isfahan province in the period of the study.

Air pollutant variables consisting of $PM_{2.5}$ concentrations and AQI based on $PM_{2.5}$ were acquired from Isfahan Municipality Traffic Deputy and Health Center. In addition, monthly satellite image data from Sentinel-5P showing NO₂, O₃, and CO levels was earned from the Google Earth Engine. In this study, TROPOspheric monitoring instrument



Fig. 1 The study area map

(TROPOMI) that is a tool onboard the Sentinel-5 precursor (Sentinel-5P) satellite was used to produce the images of spatial patterns of the NO₂, O₃, and CO concentrations data at 0.01 spatial resolution arc degrees. The air pollutant data obtained from offline (OFFL) high-resolution imagery datasets of CO, NO₂ concentrations, and tropospheric column O₃ concentrations by Google Earth Engine. OFFL products prepare better quality than near real-time imagery (NRTI), and therefore, they were used in this study (Ghasempour et al. 2021). These data provided as monthly georeferencing satellite image (GeoTIFF) and daily data related to the Isfahan province from March 1, 2020, until January 19, 2021.

Measures of variables

In this study, patients who had positive reverse transcriptionpolymerase chain reaction (RT-PCR) of COVID-19 were selected and divided into residence cities in Isfahan province. Other patients residing in other regions were excluded from the study. The COVID-19 incidence was classified in each city using ArcGIS 10.8. For each city, AQI and meteorological variables were estimated using the ordinary Kriging and/or inverse weighted distance (IDW) method to build a spatial analysis of AQI and weather condition trend in Isfahan province. Also, monthly satellite images of three air pollutants (NO₂, CO, and O₃ concentrations) were uploaded to ArcGIS 10.8 software. So, the time series trend of the studied variables was showed with monthly maps in the period of this study. Then, quantity of each variable was extracted from raster after interpolation.

Data analysis procedure

Spatial autocorrelation was performed with Global Moran's *I* analysis by ArcGIS 10.8. Moran's *I*, P_{value} , and *Z* score were calculated to investigate the spatially clustered pattern of air pollutant concentrations, meteorological variables, and COVID-19 positive cases.

Moran's I > 0 represents more significant value, positive spatial correlation, and clustered pattern. Moran's I < 0 represents a smaller value, negative spatial correlation, and dispersed pattern. Otherwise, Moran's I = 0 represents a random mode of space. The positively spatial correlation shows that there was a more and more significant correlation with the location.

In addition, a generalized linear model (GLM) using a Gamma distribution with log-link function was conducted to examine the associations of climate region, months of the year, air pollutants, and climatological variables with COVID-19 incidence. The incidence of COVID-19 positive cases was chosen as the dependent variable. A $P_{value} < 0.05$ was considered statistically significant. All the analyses were implemented using SPSS 22.0 software.

Results

The mean and range of positive cases of COVID-19, climatological variables, and air pollutants in Isfahan province based on months are presented in Table S1. According to this table, more cases are shown in October with a mean of 2852. It can be seen that the COVID-19 positive cases increased from the first peak on March 2020 to the second peak on October 2020. In fact, temperature, solar energy, PM₂₅, AQI, and NO₂ increased in the summer, too. Isfahan province is divided into five climate regions according to the De Martonne classification. Figure S1 shows the positive case numbers of COVID-19 in the studied regions. In addition, results indicated that more cases of COVID-19 were recorded in the arid climate in the period of the study as the predominant climate in Isfahan province. Moreover, the time series of the relationship between climate regions and COVID-19 incidence based on months and seasons is shown in Fig. S2. According to Fig. S2, the incidence of the disease had an upward trend in spring and summer and a declining trend in autumn and winter. Also, a high incidence of the disease was recorded in arid and semi-humid regions in spring and summer, while the incidence of COVID-19 was high in arid and semi-arid areas in autumn and winter.

The seasonal trend of the association between the incidence of COVID-19 with O_3 and CO concentrations is presented in Figs. 2 and 3. As can be seen in these figures, the trend of O_3 and CO concentration decreased in spring and summer, while the trend of COVID-19 incidence increased at both seasons. The results prove the inverse effect of O_3 and CO on COVID-19 in Isfahan province.

According to Fig. S3, the results of the seasonal survey show NO₂ concentration and COVID-19 incidence increased in spring and summer, while there was a decrease in the concentration of NO₂ and COVID-19 incidence in autumn and winter.

Since PM_{2.5} is the main pollutant parameter in Isfahan, the AQI is reported based on this parameter. On the other hand, the variance of the input data of AQI was too small to be calculated at some months. It can be said that this parameter did not have a spatial distribution. Therefore, study results are presented as the yearly trend of AQI and COVID-19 positive incidence (Fig. S4). As can be seen in this figure, AQI is in the range of 74–86 and 57–65 in March and April, respectively. Nevertheless, the incidence of COVID-19 and AQI increased from March to December and decreased in January.

The relationship between high and low temperature and COVID-19 as a seasonal trend is indicated in Figs. 4 and 5. According to these figures, COVID-19 incidence and temperature increased in spring; however, they decreased



Fig.2 The association between concentration of tropospheric O_3 and COVID-19 incidence in spring: **a** April, **b** May, and **c** June; summer: **d** July, **e** August, and **f** September; autumn: **g** October, **h** November, and **i** December; winter: **j** January and **k** March



Fig. 3 The relationship between concentration of CO and COVID-19 incidence in spring: a April, b May, and c June; summer: d July, e August, and f September; autumn: g October, h November, and i December; winter: j January and k March



Fig. 4 The relationship between high temperature and COVID-19 incidence in spring: a April, b May, and c June; summer: d July, e August, and f September; autumn: g October, h November, and i December; winter: j January and k March



Fig. 5 The relationship between low temperature and COVID-19 incidence in spring: **a** April, **b** May, and **c** June; summer: **d** July, **e** August, and **f** September; autumn: **g** October, **h** November, and **i** December; winter: **j** January and **k** March

in autumn. The COVID-19 incidence also was increased with reducing high temperature and increasing low temperature in summer. In addition, the high and low temperatures were increased, and COVID-19 incidence was reduced in winter.

According to Figs. S5 and S6, the seasonal trends of wind speed, solar energy, and COVID-19 incidence increased in spring and summer. However, there was a declining trend in autumn. Based on these figures, wind speed and solar energy increased in winter, while the COVID-19 incidence decreased.

It was observed an upward trend of COVID-19 incidence and a declining trend of precipitation and cloud cover in spring and summer 2020. In addition, the COVID-19 incidence and precipitation had a declining trend, and cloud cover had an upward trend in autumn. However, the trend of incidence of COVID-19 and these variables decreased in winter. Since the variance of the input data was too small to calculate precipitation in September, it can be said that this parameter did not have a spatial distribution (Figs. S7 and S8).

The study results about rainfall based on Fig. S9 represented an upward trend of COVID-19 and rainfall in spring and summer and a declining trend in autumn. According to Fig. S9, rainfall and COVID-19 had increasing and decreasing patterns, respectively, in winter.

The results based on Table S2 indicate the clustered pattern of many variables except AQI. In addition, there was a significant spatial autocorrelation (Moran's I = 0.13, P_{value} = 0.03) between COVID-19 incidence and counties in January (Table S2). Moreover, the spatial correlation indicates a particular random global spatial autocorrelation in April and June. Also, high temperature similar to COVID-19 incidence has high spatial autocorrelation in January (Moran's $I = 0.34, P_{value} < 0.001$). However, low temperature shows high spatial autocorrelation in August (Moran's I = 0.37, $P_{\text{value}} < 0.001$). Additionally, the spatial correlation of wind speed indicates a particular random global spatial autocorrelation in November. In contrast, precipitation had high spatial autocorrelation in November (Moran's I = 0.37, P_{value} < 0.001). Also, a negative spatial autocorrelation (Moran's I = -0.01, $P_{\text{value}} = 0.07$) for solar energy in August was observed. In addition, the spatial correlation of cloud cover indicates a particular random global spatial autocorrelation in April (Moran's I = -0.05, $P_{\text{value}} = 0.9$). At the next, the AQI has a random pattern at all months.

Results of the generalized linear model (GLM) indicated climate regions, months of the year, and solar energy were positively related to the yearly data of COVID-19 incidence. Based on the results of GLM, semi-humid and Mediterranean climates in comparison with arid climate cause a 0.28% ($P_{\rm value} = 0.002$) and 0.38% ($P_{\rm value} = 0.008$) reduction in COVID-19 incidence, respectively. In addition, the

relationship between months and the COVID-19 incidence showed the incidence of COVID-19 decreased by 0.69% $(P_{\text{value}} = 0.012)$ and 0.86% $(P_{\text{value}} = 0.006)$ in April and May, respectively. On the other hand, results of other months including July, August, October, November, December, and January indicated a 2%, 2.2%, 1.8%, 3%, 2.7%, and 3.5% increase of the COVID-19 incidence in comparison with March, respectively. In fact, it can be concluded that a 1 Kwh increase in solar energy was associated with a 0.63% $(P_{\text{value}} < 0.001)$ increase in the COVID-19 incidence in the period of the study. In contrast, there was a negative association between the concentration of NO₂ and COVID-19 incidence. So, a 1 molecule/cm² increase in NO₂ concentration was associated with a 0.11% ($P_{value} = 0.006$) reduction in the COVID-19 incidence. Rendering to the model results there was no association between the COVID-19 incidence and other meteorological, and air pollutants variables.

Discussion

The behavior of viruses such as coronaviruses is affected by environmental conditions, especially climatic conditions (Rosario et al. 2020). Also, the terrain and geography can cause different climates in zones. Industrial and economic development also may cause air pollution. Thus, relationships between climatic factors and COVID-19 transmission can change (Fernández-Ahúja and Martínez 2021; Sangkham et al. 2021).

This study investigated the COVID-19 incidence of positive cases by the RT-PCR test in Isfahan province cities from March 1, 2020, until January 19, 2021. The seasonal trend of COVID-19 incidence indicated an increase in spring and summer with 158–582 and 829–1868 positive cases, respectively. Also, it decreased in autumn and winter in the range of 2852–1180 and 391–109 positive cases, respectively. In addition, high incidence was in areas with arid, semi-arid, and semi-humid climates. Mehmood et al.'s (2021) study showed an increase in the total cases of COVID-19 in spring and summer from June 1, 2020, to July 30, 2020, in three cities of Pakistan.

Air pollution exposure may enhance symptoms of COVID-19, and some researchers specified that $PM_{2.5}$, NO_2 , and O_3 exposure could cause respiratory risk infection and increase susceptibility to the SARS-CoV-2 virus (Dales et al. 2021). In addition, in the present study, the concentration of O_3 and CO in spring and summer of 2020 was decreased. However, they had an increasing pattern in autumn and winter in Isfahan province. CO, O_3 , and NO_2 are gaseous pollutants, and CO is a colorless, odorless, tasteless, and nonirritating pollutant. Exposure to extreme amounts of CO causes reduction of the brain and other body organ's oxygen level as a result of the production of

carboxyhemoglobin (COHb) in the blood (Saleh and Hassoon 2021; Sangkham et al. 2021). Also, NO₂ is produced in the atmosphere due to the use of fossil fuel, microbiological reactions, volcanic eruptions, and biomass burning. Moreover, tropospheric O_3 is produced from NO_x (NO + NO_2) as the photochemistry process. Also, anthropogenic sources of NO_x include thermal power plants, industries, and vehicles leading to tropospheric O_3 (Singh et al. 2021). Sangkham et al.'s (2021) study indicated that average CO, NO₂, and O₃ temporal patterns increased between January 1 and March 30, 2020, and reduction in the average concentration of nitrogen monoxide (NO) caused an increase in O₃ level. In the present study, the results presented high NO₂ concentration in spring and summer; however, it decreased in autumn and winter in the period of the study from March 2020 to January 2021. Moreover, a short-term NO₂ level growth can increase the risk of higher respiratory tract infection. Hashim et al. (2021) reported that when O₃ concentrations increased, NO₂ was decreased in Baghdad, Iraq. It supports the results of the present study, and it increase NO emission cause NO release to O_3 , and it converts to atmospheric NO_2 (Monks et al. 2015).

The Isfahan province's $PM_{2.5}$ and PM_{10} potential sources are due to emissions from power plants, industries, steel and sugar factories, and motor vehicles (Hajizadeh et al. 2020). In this study, it was revealed that AQI is in the range of 51–136 with a high value in December (mean = 103). In Sangkham et al.'s (2021) study, AQI was decreased in the Bangkok Metropolitan Region from January 1 to March 30, during the occurrence of the COVID-19 outbreak.

According to one study, high temperature and wind speed were effective parameters on COVID-19 incidence rate. Additionally, high temperature can cause virus inactivation due to decreasing stability of the virus lipid layer (Rosario et al. 2020). In the Isfahan province, high and low temperatures had an upward trend from April to August with average amounts of 14-34 °C and 0-18 °C, respectively. Thus, the temporal trend of temperature decreased from September to March from autumn to winter. In fact, wind speed and solar energy seasonally increased in spring, summer, and winter; however, both decreased in autumn. In contrast, precipitation and cloud cover had a declining trend in spring, summer, and winter, but they had an upward trend in autumn. In addition, the seasonal rainfall patterns increased in spring, summer, and winter and decreased in autumn from October to December.

This study also demonstrated that the incidence of COVID-19 within cities of Isfahan province is spatially correlated and a strong spatial correlation was observed in January (Moran's I = 0.13, $P_{value} = 0.03$). Also, among environmental parameters, high temperature had a high spatial autocorrelation in January, too. Based on the spatial autocorrelation Moran test, all variables had a spatial correlation

and clustered pattern except AQI in the Isfahan province from March to January.

The COVID-19 incidence increased by 3% and 3.5% in November and January, respectively, compared to March. Also, it increased by 2%, 2.2%, 1.8%, and 2.7% in July, August, October, and December, respectively. However, a decrease in COVID-19 incidence in April and May was observed. Méndez-Arriaga (2020) stated the association between COVID-19 transmission rate and regional climate; in a tropical climate, the spread of COVID-19 was low. However, Ibrahim et al. (2021) reported the global geographic climate probably had the least impact on the transmission of COVID-19 in Asia and America. According to the results of GLM, semi-humid and Mediterranean climates compared with arid climate cause a reduction of 0.28% and 0.38% in COVID-19 incidence, respectively. Thus, the COVID-19 incidence in arid regions was higher than that in the other climate regions in Isfahan province. Results of this study are probably linked to the massive use of air conditioning apparatus because in arid and semi-arid climate regions air conditioning instruments to artificially adjust the indoor environment are used (Méndez-Arriaga 2020). This situation promotes suitable conditions for virus survival. Also, people stayed at home in various phases of COVID-19 incidence in Isfahan province. However, Fernández-Ahúja and Martínez's (2021) study proved that areas with warmer climates had a low rate of COVID-19 due to extreme daily sun hours as in Spain. Results of Ahmadi et al.'s (2020) study indicated that regions in Iran with low wind speed, humidity, and solar radiation showed an increase in COVID-19. In addition, Méndez-Arriaga (2020) showed climate classification with confirmed positive cases of COVID-19, and local transmission ratio had a negative association.

Among environmental parameters, solar energy and NO₂ concentration had a meaningful relationship with the incidence of COVID-19 positive cases in the period of the study. There was a positive impact of solar energy and negative effect of NO₂ on the COVID-19 incidence in one year. There are some studies that reported weather parameters impact on COVID-19. Lin et al. (2020) reported among climatic factors, only temperature was significantly correlated with transmission rate of COVID-19, and it was a negative relationship in China. However, results of Azuma et al.'s (2020) study revealed that the COVID-19 epidemic could spread through an increase in daily temperature or number of sunshine hours. Also, person-to-person contact can increase due to an increase in warm and sunny day activities. Thus, COVID-19 transmission will promote this situation. Furthermore, Irfan et al. (2021) reported that low-temperature areas illustrated strong linkages between temperature and COVID-19 transmissibility. In addition, some researchers surveyed the relationship between air pollutants and COVID-19 incidence. Lorenzo et al. (2021) observed a meaningful positive

association between NO₂, PM_{2.5}, and pollutant standards index (PSI) with COVID-19 case numbers. They reported that PM₁₀, O₃, SO₂, and CO had a negative relation with confirmed cases of COVID-19. The results of some studies are similar to the present study. There was a negative correlation between NO₂ concentration and COVID-19 infections in BMR and Milan, Italy (Sangkham et al. 2021; Zoran et al. 2020). This was a result of businesses and schools' closure which caused a reduction in levels of air pollutants due to lower traffic volume (Lorenzo et al. 2021). Also, Qaid et al.'s (2021) study showed a strong negative association between COVID-19 daily new cases and PM_{2.5} in a hot and arid climate region (Bahrain) from April 5, 2020, to January 10, 2021. In contrast, Jiang et al. (2020) reported that daily incidence of COVID-19 was positively correlated with NO₂ level in Wuhan and Xiaogan, China.

Conclusion and policy implications

This study surveyed the association between the regional climate, climatological factors, and air pollution with COVID-19 incidence in Isfahan province from March 1, 2020, to January 19, 2021. The ordinary Kriging and IDW models (beneficial methods) were used for the spatial and statistical analysis of data. After extracting data from GIS interpolation and satellite information through Google Earth Engine, the spatial autocorrelation and relationship between variables were investigated using Global Moran's I and GLM. The results showed that incidence of COVID-19, NO₂ concentration, wind speed, solar energy, and rainfall had an upward trend in spring and summer with cluster patterns. Moreover, the trend of O₃ and CO was increasing in autumn and winter. Precipitation and cloud cover had also an upward trend in autumn. In addition, high and low temperatures had an upward trend from April to August, while all of the parameters had clustered patterns except AQI with a random pattern. This study has found the relationship between the concentration of NO₂ and solar energy with COVID-19 in the period of the study. Based on the GLM statistical model, an increase in NO₂ levels causes a reduction in the incidence of COVID-19 and rising solar energy could increase COVID-19 incidence in Isfahan province.

As the outbreak of COVID-19 depends on multiple factors including climate, social and economic factors, and policy responses of governments (Coccia 2021b), some suitable policy implications should be performed for the control of the COVID-19 pandemic, which consist social distancing policy as a useful procedure for preventing the spread of infection. In addition, washing hands, using face masks, getting vaccinated, and ensuring proper ventilation of indoor areas are other prevention measures. The creation of green jobs via rehabilitating ruin spaces, planting trees, and ecosystem recovery also are helpful to improve climatic conditions as effective factors of COVID-19 transmission (Coccia 2021c; Coccia 2022; Ikram et al. 2020; Yu et al. 2021). In fact, the adoption of green environmental policies such as compulsion to remain at home, lockdown, and less road traffic should be implemented for preventing people to keep in touch with others and also avoiding air pollution (Askitas et al. 2021; Bashir et al. 2020; Du et al. 2021). Furthermore, public policies that have to be considered for improving people's healthcare include increasing expenditures in the health sector and reducing the sources of air pollution (Coccia 2021g).

Nevertheless, the present study had some limitations including our information lacked demographic characterization (e.g., age, gender, nationality, occupation, place of residence, intervention strategies, and socioeconomic factors) of cases and other variables such as traffic flow and smoking status as confounders. However, Paraskevis et al. (2020) stated that weather conditions and air pollution without the intervention of public health measures cannot moderate the incidence of COVID-19. Also, the influence of host-related factors, including population genetics, immunity or susceptibility and resistance of people, social distancing, methods of social isolation, frequent handwashing, and use of personal protective equipment, which had an important role in the COVID-19 incidence could not be addressed (Azuma et al. 2020; Lin et al. 2020; Mehmood et al. 2021).

It is recommended that future studies should accurately consider the effects of the potential confounder factors on COVID-19 transmission. Furthermore, future researchers should update the systematic review and meta-analysis studies on the impact of all of influential factors on COVID-19 transmission when considering a geographical location.

In conclusion, this study provides useful information with the use of GIS as a novel and excellent spatial data processing method for spatial analysis. Also, it advises the use of Google Earth Engine as a tool for satellite imagery and geospatial datasets to the link of environment and infectious disease. Therefore, the results of the present research can be helpful for the World Health Organization (WHO) and Ministry of Health and Medical Education (MOHME) of the Islamic Republic of Iran to decide on mitigating the harmful effects of climate change and air pollution under new research methods.

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Author contribution Malihe Moazeni: conceptualized, software, methodology, writing—original draft, review and editing, and validation. Mohammad Reza Maracy: data curation, formal analysis, and review and editing. Bahare Dehdashti: data curation. Afshin Ebrahimi: supervision, project administration, methodology, and review and editing.

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Declarations

Ethics approval This study was approved by the Medical Ethics Committee of the Isfahan University of Medical Sciences in Iran (IR.MUI. RESEARCH.REC.1399.109) and was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments.

Competing interests The authors declare no competing interests.

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