Environmental Research 191 (2020) 110189

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Asymmetric link between environmental pollution and COVID-19 in the top ten affected states of US: A novel estimations from quantile-on-quantile approach

Asif Razzaq [a], Arshian Sharif [b,c,*], Noshaba Aziz [d], Muhammad Irfan [e], Kittisak Jermsittiparsert [f,**]

[a] School of Management & Economics, Dalian University of Technology, Dalian, PR China
[b] Othman Yeop Abdullah Graduate School of Business, Universiti Utara Malaysia, Sintok, Malaysia
[c] Department of Business Administration, Faculty of Management Sciences, ILMA University, Karachi, Pakistan
[d] Northwest A& F University, Shaanxi, China
[e] Beijing Key Laboratory of New Energy and Low Carbon, Development, School of Economics and Management, North China, Electric Power University, Beijing, 102206, China
[f] Department for Management of Science and Technology Development, Faculty of Social Sciences and Humanities, Ton DucThang University, Ho Chi Minh City, Viet Nam

A R T I C L E I N F O

Keywords:
COVID-19
Air pollution
Ozone O_3 pollution
Quantile-on-quantile

A B S T R A C T

This study draws the link between COVID-19 and air pollution (ground ozone O_3) from February 29, 2020 to July 10, 2020 in the top 10 affected States of the US. Utilizing quantile-on-quantile (QQ) estimation technique, we examine in what manner the quantiles of COVID-19 affect the quantiles of air pollution and vice versa. The primary findings confirm overall dependence between COVID-19 and air pollution. Empirical results exhibit a strong negative effect of COVID-19 on air pollution in New York, Texas, Illinois, Massachusetts, and Pennsylvania; especially at medium to higher quantiles, while New Jersey, Illinois, Arizona, and Georgia show strong negative effect mainly at lower quantiles. Contrarily, COVID-19 positively affects air pollution in Pennsylvania at extreme lower quantiles. On the other side, air pollution predominantly caused to increase in the intensity of COVID-19 cases across all states except lower quantiles of Massachusetts, and extreme higher quantiles of Arizona and New Jersey, where this effect becomes less pronounced or negative. Concludingly, a rare positive fallout of COVID-19 is reducing environmental pressure, while higher environmental pollution causes to increase the vulnerability of COVID-19 cases. These findings imply that air pollution is at the heart of chronic diseases, therefore the state government should consider these asymmetric channels and introduce appropriate policy measures to reset and control atmospheric emissions.

1. Introduction

In general, pandemics do not only increase concerns regarding public health but also instigate ruinous socio-economic crises in the disease-ridden regions. In the present century, human civilization has witnessed several pandemics such as H1N1 in 2009 in Mexico, Ebola in 2014 in West Africa, Polio in 2014 in Middle East, Zika virus in Brazil in 2016 and Ebola again in 2019 in the Democratic Republic of Congo. These outbursts internationally ensued in a huge number of mortalities, diseases, and cost billions of dollars (Allocati et al., 2016; Fan et al., 2019). Since the last month of the year 2019, the world has also been confronted with another epidemic termed as COVID-19 (contagious disease) originated in Wuhan, China (Zhu et al., 2020; Huang et al., 2020). Regardless of the excessive efforts by the Chinese Government in the isolation of Wuhan City from the rest part of China, the epidemic rampantly surrounded the whole sphere including Asia, Europe, Africa, and America, and soon acknowledged as a pandemic by the World Health Organization (World Health Organization, 2020).

The outburst has uncontrollably outstretched to 210 countries and exceeds 16, 465, 707 confirmed infected cases while 653,862 reported

* Corresponding author. Department of Business Administration, Faculty of Management Sciences, ILMA University, Karachi, Pakistan.
** Corresponding author. Faculty of Social Sciences and Humanities, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
E-mail addresses: asifrazzaq@mail.dlut.edu.cn (A. Razzaq), arshian.aslam@gmail.com (A. Sharif), noshaba2016@qq.com (N. Aziz), irfan@ncepu.edu.cn (M. Irfan), kittisak.jermsittiparsert@tdtu.edu.vn (K. Jermsittiparsert).

https://doi.org/10.1016/j.envres.2020.110189
Received 30 July 2020; Received in revised form 24 August 2020; Accepted 7 September 2020
Available online 11 September 2020

Table 1
Top 10 affected (COVID-19 Cases) states and Lockdown status.

States	Confirmed cases	Deaths	Death_100 k	1st COVID-19 case reported	1st Lockdown	Lockdown end[a]	Decrease in Mobility[b]
California	460,550	8445	21	1/26/2020	3/19/2020	5/25/2020	4.04%
Florida	427,698	5931	28	February 3, 2020	3/20/2020	April 5, 2020	1.65%
New York	413,834	32,329	359	February 3, 2020	3/22/2020	5/29/2020	2.39%
Texas	385,923	5713	20	May 3, 2020	February 4, 2020	January 5, 2020	2.09%
New Jersey	179,812	15,804	177	February 3, 2020	3/21/2020	September 6, 2020	1.41%
Illinois	173,897	7608	60	1/24/2020	3/21/2020	5/29/2020	3.08%
Georgia	170,843	3509	33	March 3, 2020	March 4, 2020	4/24/2020	2.44%
Arizona	163,827	3304	46	1/26/2020	3/30/2020	August 5, 2020	2.48%
Massachusetts	115,926	8536	124	January 2, 2020	4/24/2020	5/18/2020	2.79%
Pennsylvania	109,384	7146	56	June 3, 2020	January 4, 2020	5/15/2020	4.07%

Source: CDC Tracker access date: July 29, 2020a, 2020b.

[a] Retail, restaurant dining, houses of worship, entertainment, outdoor recreation, industries are opened. Food and drink bars, stadiums, and conventional halls are closed as per status on 8/13/2020. Lockdown information has been taken from the State's official website and notifications compiled by NYT (2020) and USTODAY (2020).

[b] The share of residents leaving their homes was less than the seven days prior as on 8/13/2020.

cases of deaths as on July 29, 2020 (GIS, 2020). COVID-19 equally spread in both developed and developing countries that have not been completely eradicated, even growing trend is observed in some regions (Bai et al., 2020; Lai et al., 2020). mainly due to the unavailability of the disease-resistant drug and vaccine. Nevertheless, the situation of top ten most affected countries; United States, Brazil, United Kingdom, Mexico, Itlay, India, France, Spain, Peru, Iran, and Russia are imperiled to the peak and gigantic death toll even the United States solely recounted skyrocketing figure such as 4,515,586 confirmed cases and 152,726 deaths as of July 29, 2020 (Worldometers, 2020).

Apart from becoming the huge risk to the worldwide public health and severely smashing the economy of the host countries (Chakraborty and Maity, 2020), COVID-19 is refining the environmental quality in response to the temporary suspension of global economic activities (Zambrano-Monserrate et al., 2020; Tobías et al., 2020; Collivignarelli et al., 2020). Globally, it has been proven by satellite images and ground data that air pollution in the form of nitrogen dioxide (NO_2) emissions in many parts has dropped in a way that the earth's stratosphere ozone layer is recovering (NASA, 2020). The upper atmosphere of the earth (stratosphere) is covered by the Ozone layer that helps to prevent the earth from ultraviolet rays. However, the ground-level O_3 (tropospheric) is considered as a secondary air pollutant produced by composite photochemical reactions encompassing radiations of sun and precursors of ozone (US EPA, 2020a; 1996b).

Since the detection of realms cases of the COVID-19, the rigorous and strict measures that have been executed instantly after the widespread of the COVID-19 have had an outstanding environmental effect by drastically cutting the emissions of pollutants specifically, NO_2 concentration in China as well as in numerous countries of Europe and US (Shrestha et al., 2020; Zhang et al., 2020). The recent studies by Muhammad et al. (2020), Dutheil et al. (2020), and Wang and Su (2020) identified the reduction of NO_2 emissions ranging between 20% and 30% in the USA, China, Spain, France, and Italy. Similarly, Kanniah et al. (2020) proposed that industrial and anthropogenic activities cessation due to COVID-19 lead to a major reduction of harmful pollutants which noticeably stemmed from the retrieval of ecosystems and most prominently O_3 pollution has been found reducing up to some extent. Consequently, the state nowadays is regarded as a "retune" for ecosystem and humans, given the ecosystem a "recuperative time" with decreased interference of humans in the natural environment.

Looking at the flip side relationship between air pollution and COVID-19, prevailing studies in the context of virus-related contagions like SARS, MARS, and COVID-19 found that the exposure to air pollution exacerbates the vulnerability of lungs infections that lead to host morbidity and mortality, and overall exert an adverse impact on the public health status globally (Manisalidis et al., 2020; Pothirat et al., 2019). Surprisingly, it has been argued that COVID-19 is also transmitted through the medium of air from China to other regions, and air pollution is identified as a coronavirus carrier (Wu et al., 2020a, 2020b). Contrarly Bontempi (2020) failed to find the evidence for airborne diffusion of COVID-19 virus from the case study of Lombardy (Italy). Many previous studies also claimed that air pollutants like carbon monoxide, NO_2, particulate matter (PM) in dissimilar fractions such as $PM_{0.1}$μm, $PM_{2.5}$μm and PM_{10}μm, polycyclic aromatic hydrocarbons, volatile organic compounds, and O_3 pollution, etc. Adversely affect the immune and cardio-respiratory systems of the host by altering their resistance to various bacterial and viral infections (Arjomandi et al., 2018).

Numerous medical studies have also shown that O_3 pollution leads to serious health issues such as chronic obstructive pulmonary disease, breath shortness, scratchy throat and further lead to worst diseases of lungs such as asthma, chronic bronchitis and even makes the lungs more prone to allergens and infections (Martelletti and Martelletti, 2020; Wilson et al., 2017) which are similar to the symptoms ascended by COVID-19. Though developed countries have achieved major improvements in public health however the threat of global pandemics continued to expand due to increased mobility and environmental factors (Bontempi, 2020a). In these circumstances, there is a need to spur additional and necessary public health interventions along with adjusted environmental policies that not only enabled us to reassess our lives but also alter in a way that put a minimum impact on the environment as well as on human lives.

Keeping in view the above discussion, the current study is anticipated to answer the environmental as well as the health impact of the current catastrophe in the top 10 most infected states of the US. So far, many studies have explored the impact of COVID-19 on air pollution, but not dig the impact of air pollution on COVID-19, particularly in the US most infected states. Moreover, ozone O_3 pollution in this study deserves consideration due to its relationship with health concerns, and many epidemiological studies already proposed that the susceptibility of respiratory infection and morbidity increases due to enormous exposure to O_3 pollution (Bayram et al., 2001). Ozone pollution and contagion disease nexus are somewhat novel and, in our study, we are tracking the relationship in two ways i.e. anticipated in exploring not only the impact of COVID-19 on the environmental quality but also elucidating the risk of worseness of COVID-19 due to ozone O_3 pollution as a measure of environmental deterioration.

2. Channels between COVID-19 and air pollution

2.1. Impact of COVID-19 on air pollution

Air pollution and COVID-19 are both well known in causing or exacerbating respiratory distress, and recent studies suggest that the two factors may interact (Hadei and Naddafi, 2020). The pollution-reducing effect of COVID-19 is mainly attributed to the measures taken by the

Table 2
Impact of lockdown on the global energy sector.

Country	Lockdown Start	Lockdown End	Energy demand (ED)
Australia	March 23, 2020	May 15, 2020	ED ↓ approx. 8%–10%
Belgium	March 18, 2020	April 19, 2020	ED of industrial and commercial sector ↓ by 70%
China	January 23, 2020	April 8, 2020	ED ↓ by 8% (Jan & Feb compared to the same period in 2019)
France	March 17, 2020	May 11, 2020	ED ↓ by 6%–12%
Germany	March 20, 2020	April 20, 2020	ED ↓ by 4%–6%
India	March 25, 2020	May 4, 2020	ED ↓ by 30%
Italy	March 9, 2020	May 4, 2020	ED ↓ by 10.1% in March and 22% after 22nd March
Portugal	March 13, 2020	April 11, 2020	ED ↓ by 3%–5%
Singapore	April 7, 2020	June 1, 2020	ED ↓ 8%–9%
Spain	March 14, 2020	April 25, 2020	3% ↓ (March), 20% ↓ (April),
Netherlands	March 16, 2020	April 28, 2020	Overall energy demand ↓
UK	March 24, 2020	May 11, 2020	ED ↓ by 10% (after 23rd March)

Source (AEMO, 2020; Rajvikram et al., 2020; S&P Global, 2020):

respective governments to restrict contiguous spread. Social distancing, discontinuity of business operation, or lockdown helps to flatter the COVID-19 curve (Bashir et al., 2020). In doing so, the US state government implement effective lockdown measures to limit travel, curtail movement, and interaction of people. Table 1 shows the detail of statewide COVID-19 cases, lockdown time, and decrease in people's mobility. This indicates that US states government follow different lockdown policies, however, at the end of March, 42 states and more cities and counties were under stay-at-home orders, account for 308 million people, or 94% of the US population. These measures lead to lower economic activity and subsequently decrease energy demand in the US by 9%–13%, and petroleum products demand by 31%, which is the lowest figure since 2001 and 1990 respectively (EIA, 2020). These factors mitigate the level of environmental pollution by 25%–30% as compare to the previous years (Muhammad et al., 2020; Berman and Ebisu, 2020).

From Table 2, similar insights are observed at the global level, where energy demand significantly decreases during the lockdown period that translates into lower environmental pollution (Bashir et al., 2020; Muhammad et al., 2020). Global energy demand is set to fall by 5% in 2020, the largest decline since the great depression (IEA 2020). An intuitive study by Quéré et al. (2020) estimates a 17% average reduction in global emissions during the lockdown period by the end of April as compared to the same period in 2019. However, the emissions reduction effect of COVID-19 depends upon the depth and width of lockdown measures, indicating a 7% reduction in case of stringent confinement (full lockdown), while a 4% reduction in moderate confinement (partial lockdown) (Quéré et al., 2020).

2.2. Impact of air pollution on COVID-19

In addition to air pollution decreasing immune defenses and wane respiratory health (Manisalidis et al., 2020; Martelletti and Martelletti, 2020), it is evident that air pollution in the form of ground-level ozone O_3, PM and NO_2 can act as vectors for the spread and survival of airborne particles such as COVID-19 (Frontera et al., 2020 Sterpetti, 2020). According to WHO (2020), COVID-19 is a respiratory illness and the primary transmission route is through person-to-person contact and through direct contact with respiratory droplets generated when an infected person coughs or sneezes. Setti et al. (2020) estimated that air pollution in the form of a high concentration of PMs acts as vehicles for viral transmission, resultantly increase the number of morbidity and mortality in highly polluted territories in northern Italy. Similar results are echoes by Conticini et al. (2020) from Italian tertiaries. According to IHM (2020), northern Italy accounts for 80% of total deaths and 65% of Intensive Care Units admission, which is mainly attributed to higher air pollution in the region.

Based on the US cross country sample, Wu et al. (2020a, 2020b) estimated that 1 μg/m3 more pollution in the form of PM in the air corresponded to 8 percent more COVID-19-related deaths. This estimation is 16% greater than the prior estimations provided by Setti et al. (2020) from Italy, which is mainly ascribed to differences in population density and lockdown measures. Cole et al. (2020) provide compelling

Table 3
Results of descriptive statistics.

Variables	Mean	Min	Max	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
Panel A: COVID-19 Infected Cases							
New York	0.098	0.003	1.705	0.224	4.246	25.660	3220.883[a]
California	0.072	0.006	0.410	0.082	2.022	6.886	173.027[a]
Florida	0.094	0.001	1.099	0.153	3.364	17.865	1464.180[a]
Texas	0.094	0.005	1.099	0.156	3.712	19.427	1787.312[a]
New Jersey	0.091	0.098	1.099	0.176	2.816	12.266	646.662[a]
Illinois	0.085	0.134	0.619	0.123	2.104	7.315	199.818[a]
Arizona	0.088	0.008	0.693	0.131	2.778	10.632	490.160[a]
Georgia	0.088	0.016	1.224	0.160	3.868	22.709	2465.620[a]
Massachusetts	0.088	0.644	1.299	0.189	4.122	22.388	2441.028[a]
Pennsylvania	0.087	0.138	1.099	0.159	3.346	17.267	1365.867[a]
Panel B: Ozone O_3 Pollution							
New York	0.001	−0.779	0.722	0.243	−0.073	4.598	14.170[a]
California	0.001	−0.591	0.531	0.183	−0.269	3.672	14.077[a]
Florida	−0.003	−0.711	0.693	0.211	−0.163	4.183	8.287**
Texas	−0.004	−0.762	0.758	0.224	0.388	5.000	25.300[a]
New Jersey	−0.005	−0.693	0.661	0.237	0.182	4.017	6.423**
Illinois	0.000	−0.563	0.505	0.199	−0.405	3.818	7.290**
Arizona	0.001	−0.393	0.313	0.104	−0.225	4.420	12.206**
Georgia	0.001	−0.693	0.981	0.246	0.759	5.564	48.848[a]
Massachusetts	0.004	−0.759	0.651	0.229	−0.415	4.278	12.779[a]
Pennsylvania	0.002	−1.44	1.15	0.27	−0.61	10.57	323.50[a]

Source: Author Estimations.
[a] And ** represents level of significance at 1% and 5% respectively.

Table 4
Results of BDS test for nonlinearity 1996.

Country	m = 2	p-value	m = 3	p-value	m = 4	p-value	m = 5	p-value	m = 6	p-value
COVID-19 Infected Cases Equation Residual										
New York	26.486	0.000	28.976	0.000	39.523	0.000	41.681	0.000	49.934	0.000
California	18.143	0.000	19.848	0.000	27.073	0.000	28.551	0.000	34.205	0.000
Florida	30.199	0.000	33.038	0.000	45.063	0.000	47.524	0.000	56.934	0.000
Texas	34.484	0.000	37.725	0.000	51.458	0.000	54.267	0.000	65.012	0.000
New Jersey	27.346	0.000	29.917	0.000	40.806	0.000	43.034	0.000	51.555	0.000
Illinois	46.789	0.000	51.187	0.000	69.819	0.000	73.631	0.000	88.210	0.000
Arizona	40.301	0.000	44.089	0.000	60.138	0.000	63.421	0.000	75.979	0.000
Georgia	33.348	0.000	36.483	0.000	49.762	0.000	52.479	0.000	62.870	0.000
Massachusetts	29.843	0.000	32.648	0.000	44.532	0.000	46.964	0.000	56.262	0.000
Pennsylvania	15.367	0.000	16.811	0.000	22.931	0.000	24.183	0.000	28.971	0.000
Ozone O_3 Pollution Equation Residual										
New York	17.356	0.000	20.636	0.000	26.600	0.000	28.968	0.000	29.214	0.000
California	20.286	0.000	24.120	0.000	31.091	0.000	33.858	0.000	34.146	0.000
Florida	28.156	0.000	33.477	0.000	43.152	0.000	46.993	0.000	47.392	0.000
Texas	8.561	0.000	10.179	0.000	13.121	0.000	14.289	0.000	14.410	0.000
New Jersey	11.088	0.000	13.184	0.000	16.994	0.000	18.506	0.000	18.663	0.000
Illinois	34.398	0.000	40.899	0.000	52.719	0.000	57.411	0.000	57.899	0.000
Arizona	21.105	0.000	25.094	0.000	32.346	0.000	35.225	0.000	35.524	0.000
Georgia	29.081	0.000	34.577	0.000	44.570	0.000	48.537	0.000	48.949	0.000
Massachusetts	32.894	0.000	39.111	0.000	50.414	0.000	54.901	0.000	55.368	0.000
Pennsylvania	20.442	0.000	24.306	0.000	31.330	0.000	34.118	0.000	34.408	0.000

Source: Authors Estimation

evidence of a positive relationship between air pollution, and particularly $PM_{2.5}$ concentrations, and COVID-19 cases, hospital admissions, and deaths in the Netherland. Their study estimated that a 1 μ/m3 increase in $PM_{2.5}$ concentrations is associated with 9.4 more COVID-19 cases, 3.0 more hospital admissions, and 2.3 more deaths. These studies argued that higher exposure to a polluted environment increases the vulnerability of respiratory diseases and reduces the immune system thus inhabitants are more prone to get COVID-19 infection amongst

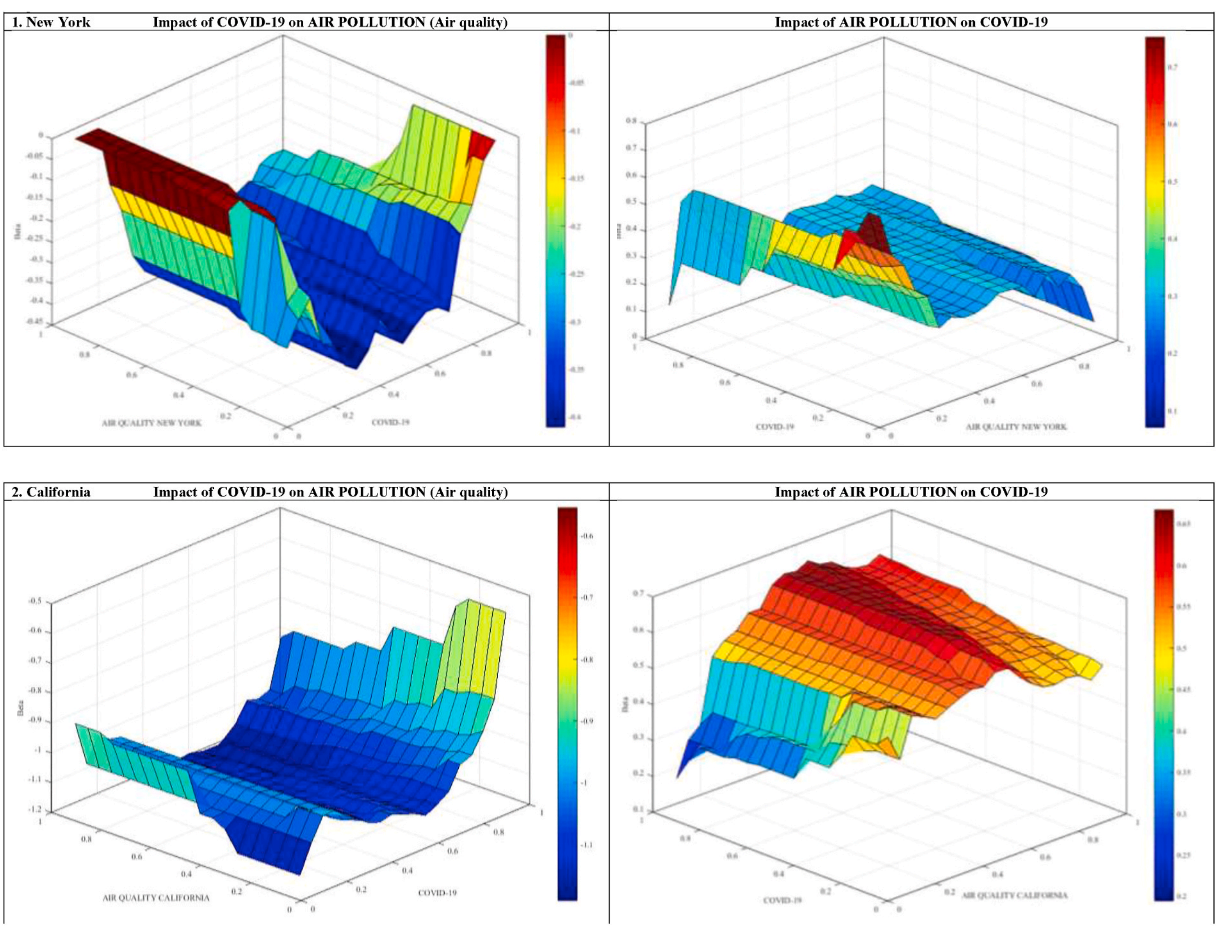

Fig. 1. Results of Quantile on Quantiles Estimates 1. New York. 2. California. 3. Florida. 4. Texas. 5. New Jersey. 6. Illinois. 7. Arizona. 8. Georgia. 9. Massachusetts. 10. PennsylvaniaNote: 1- The graphs show the estimates of the slope coefficient β_1 in the z-axis against the quantiles of AIR POLLUTION (COVID-19) in the y-axis and the quantiles of COVID-19 (AIR POLLUTION) in the x-axis. 2-.

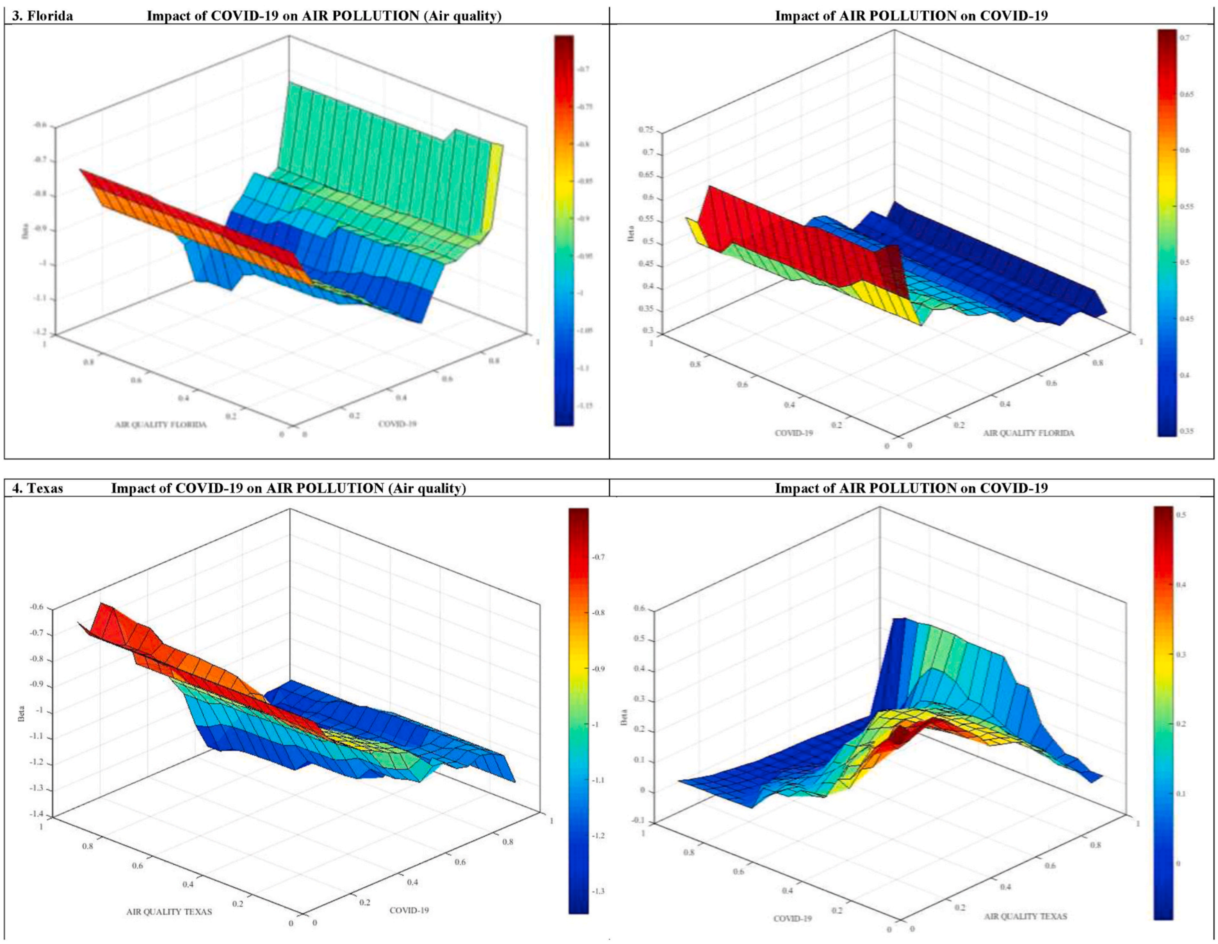

Fig. 1. (*continued*).

other diseases. Concludingly, the prevailing literature provides two channels; first, the transmission of COVID-19 is inflated with a higher level of pollution; second, exposure to a higher level of pollution weakens the immune system and caused respiratory diseases, which leads to higher vulnerability of COVID-19 infection and subsequent deaths.

3. Data and methodology

The current study draws a link between air pollution and COVID-19 pandemic in the top ten infected states of the US (see Table 3). In doing so, the study uses ground-level Ozone pollution (O_3) as a measure of air pollution and the number of confirmed COVID-19 cases as a proxy of COVID-19 by following Yongjian et al. (2020). The daily mean data of O_3 pollution (ppm) is sourced from EPA, while the number of confirmed COVID-19 cases has taken from the official website of US facts. The data of each series has transformed in log return that includes 133 observations starting from February 29, 2020 to July 10, 2020. Table 3 reports descriptive statistics of both series, where New York shows the highest number in COVID-19 infected cases, while California shows lowest. Similarly, Georgia corresponds to the highest O_3 emissions while Arizona shows the lowest level. The Jarque-Bera (JB) test statistics are significant at a 1% level of significance, which exhibits that COVID-19 infected cases and O_3 pollution are not normally distributed in any of the states under consideration. Similarly, from Table 4, the non-linearity among series is further endorsed by BDS (1996) test, where the null hypothesis of non-linearity is accepted in both series across all States. Based on the JB test and BDS test of nonlinearity, it is evident that both variables having a nonlinearity in all states, therefore, the estimations of quantiles are recommended following (Shahbaz et al., 2018; Mishra et al., 2019; Sharif et al., 2019a; Sharif et al. 2019b, 2020; Chang et al., 2020; Arain et al., 2020).

In the presence of non-normality of data and non-linearity, quantile on quantile regression is the most appropriate technique which produced robust estimates whilst allowing basic data distribution assumption. Therefore, the present research employs quantile-on-quantile (QQ) approach presented by Sim and Zhou (2015), to scrutinize the asymmetric relation between COVID- 19 and air pollution (O_3) in top 10 most infected states of US. Shahbaz et al. (2018) argued that the QQ method integrates the features of both quantile regression as well as a non-parametric approach to detect the model's asymmetric and spatial features over time. The non-parametric quantile regression model applied in the study is shown in the following equation:

$$COVID19_t = \gamma^{\sigma}(O_{3t}) + \mu_t^{\sigma}$$

$$O_{3t} = \gamma^{\sigma}(COVID19_t) + \mu_t^{\sigma}$$

where $COVID19_t$ represent the number of confirmed COVID-19 cases, $O3_t$ denotes country's air pollution (ozone O_3), t denotes time, the conditional σth quantile distribution of O_3 is denoted by σ, the quantile error term, whose conditional σth quantile is equivalent to 0 is designated by $\mu_t^{\sigma}.\gamma^{\sigma}$ (.) is an unidentified function as no former evidence on inter-linkages between O_3 pollution and COVID-19 is available. In non-parametric QQ estimations, the bandwidth (k) selection is imperative as it regulates the estimated coefficients' smoothness. We have used 5% (h = 0.05) bandwidth of density function for optimal parameters by following Sim and Zhou (2015). The QQ regression offers detailed information on how different quantiles of COVID-19 influence different

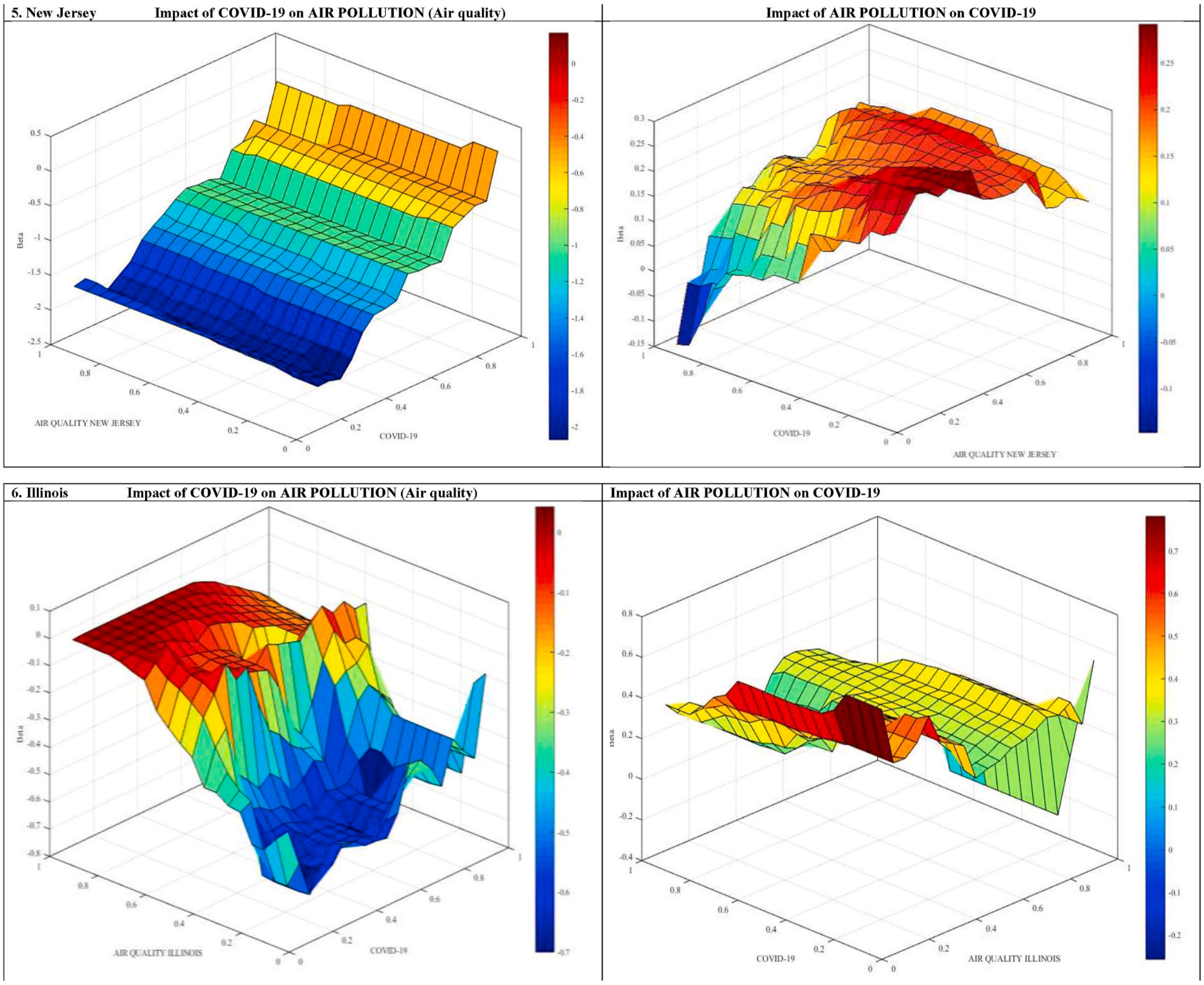

Fig. 1. (*continued*).

quantiles of O_3 pollution and in turn how O_3 pollution responds to COVID-19 across diverse quantiles by giving a more reliable visual representation of desired variables. Besides, QQ approach has a vital advantage of elasticity as it assesses the valuable dependence between O_3 pollution and COVID-19 in the regions that are not formerly presumed.

4. Results and discussion

Fig. 1 represents the visual depiction of QQ estimates. In the case of New York, visual 1 depicts a strong negative influence of COVID-19 on air pollution in the grid of middle to higher (0.4–0.8) quantiles of COVID-19. This effect is persistent across all corresponding qualities of air pollution. Interestingly, extreme lower and extreme higher quantile of COVID-19 shows the minimal effect on reducing air pollution yet negative. These results indicate that at the initial level of pandemic the pollution is not substantially reduced, however, with the increase in COVID-19 intensity (cases) the pollution-reducing effect of COVID-19 becomes stronger. There is theoretical and practical plausibility of the results, as at the initial stage of COVID-19 the businesses were usually operating, however, after severity in infected cases in the start of April 2020, the government decided to shut down or early closure of several businesses including schools, transportation, manufacturing, and industrial units, that leads to lower energy and fuel consumption and subsequent air pollution (Berman and Ebisu, 2020). After the peak stage of the pandemic, the lower negative coefficient at extreme high quantile corresponds to the current situation, where the government beginning to lift lockdown, people are moving towards their routine life and businesses. The visuals of California and Florida represent a strong negative influence of COVID-19 on air pollution in the grid of lower to higher (0.2–0.8) quantiles, and medium to higher (0.6–0.8) quantiles, respectively.

The patterns of Texas is also not entirely different, where extreme higher quantiles (0.8–0.9) show the highest negative effect of COVID-19 on air pollution, however, this effect turns week across lower quantiles of air quality. Though all states produce the negative effect of COVID-19 on environmental pollution, however, the intensity of this negative effect varies across different quantiles of COVID-19 and air pollution. Conversely, the patterns of New Jersey and Georgia reflect that the negative effect of COVID-19 on air pollution is highest at the lowest (0.2–0.6) quantiles and lowest at highest quantiles (0.8–0.9) of COVID-19. Following a similar pattern, Arizona shows the highest negative effect of COVID-19 on air quality at the lowest quantiles (0.1–0.2) of both COVID-19 and air pollution, however, this negative effect diminishes with higher quantiles of COVID-19. This intensity is equally observed from the corresponding quantiles of air pollution. Unlike other states, the graphical depiction of Illinois shows a strong negative effect of COVID-19 on air pollution from lower to higher (0.2–0.8) quantiles of COVID-19, however, this high negative effect persist only for lower to medium quantiles (0.2–0.4) of air pollution, after which it become less pronounce (0.6–0.8 quantiles). Lastly, Massachusetts shows a moderate negative effect of COVID-19 on air pollution from medium to higher (0.4–0.9) quantiles of COVID-19 yet this negative effect turns weaker across corresponding higher quantiles of air pollution (0.6–0.9).

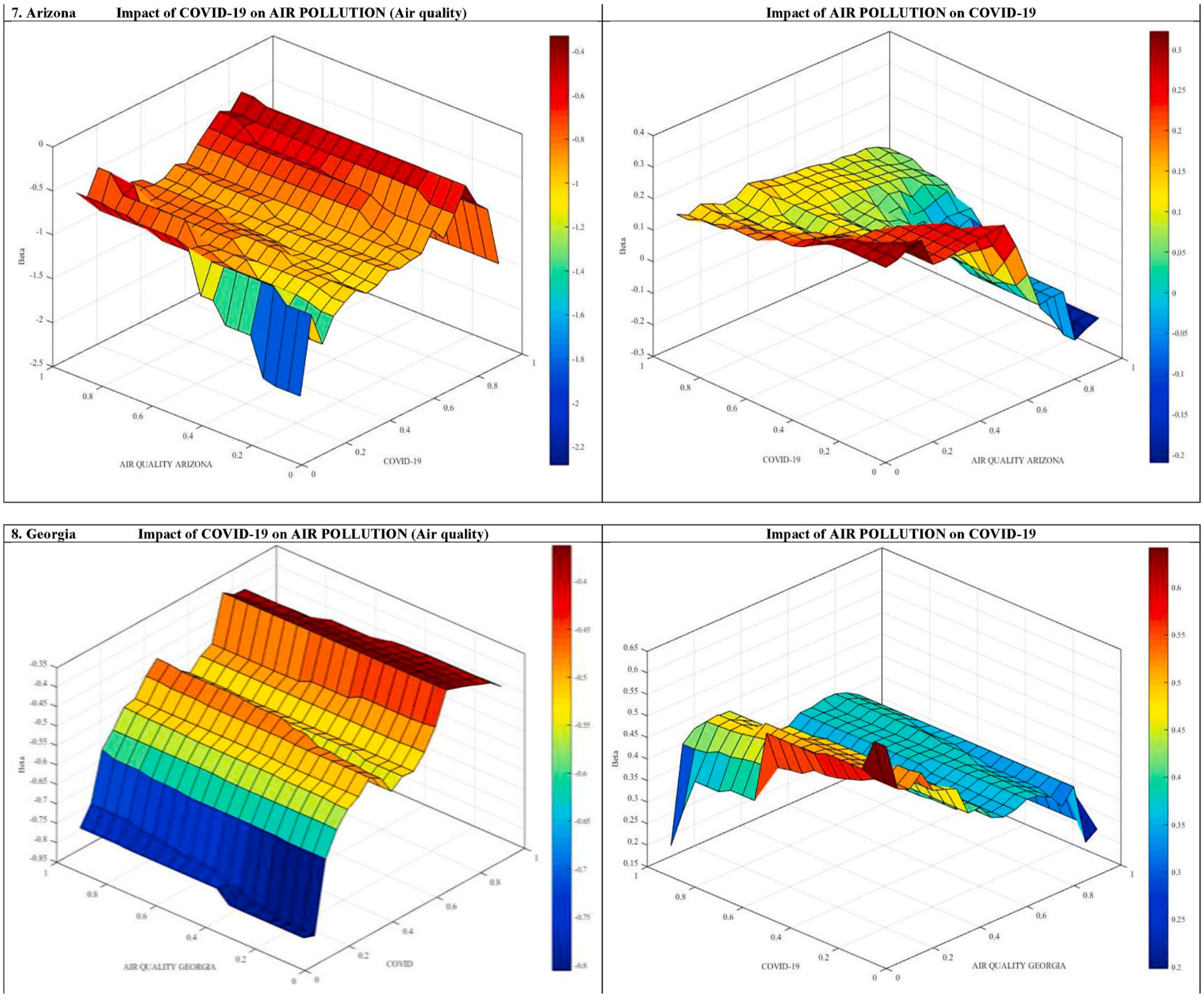

Fig. 1. (*continued*).

Interestingly, lower quantiles of COVID-19 and air pollution (0.1–0.3) reflect the highest pollution-reducing effect of COVID-19. Conversely, Pennsylvania exhibit the negative effect of COVID-19 on air pollution only at medium to higher quantiles (0.5–0.9) of COVID-19, while lower quantiles of COVID-19 and air pollution shows a positive impact of COVID-19 on air pollution, indicating that at the initial level of COVID-19 chaotic movement of people and transport increase air pollution. The pollution-reducing effect of COVID-19 is mainly attributed to partial or complete lockdown (see Table 1 for detail), lower human and industrial activity, that ultimately reduces fuel and energy consumption, and resultantly lower air pollution across all US states. These results are consistent with a major strand of literature (Shrestha et al., 2020; Zhang et al., 2020; Bashir et al., 2020).

Now moving to the flip side of the relationship between air pollution and COVID-19, which produces diverse outcomes across the grid of quantiles. While examining the influence of air pollution on COVID-19 in New York, Florida, and Georgia, we observe a weak positive effect of air pollution on COVID-19 mainly in the area of middle to higher (0.4–0.9) quantiles of air pollution. This weak positive effect is equally spread over the corresponding quantiles of COVID-19 except for lower to medium (0.2–0.6) quantiles in Georgia, where a strongly negative effect holds. The lower quantiles of air pollution (0.1–0.3) correspond to relatively higher values of COVID-19 cases. Although Pennsylvania and California show a strong positive influence of air pollution on COVID-19 across medium to higher (0.5–0.8) quantiles, however, this positive effect gradually decreases when moved from medium to lower quantiles (0.4–0.2) of air pollution. In the case of Texas and Illinois, the influence of air pollution on COVID-19 is highest at lower quantiles (0.1–0.3) of air pollution and COVID-19. This positive effect is weaker at the highest (0.8–0.9) quantiles of COVID-19 against all quantiles of air pollution in Texas.

Unlike previous explanation, where the effect of air pollution on COVID-19 varied across quantiles but remains positive, the influence of air pollution on COVID-19 is strongly positive from medium to higher (0.4–0.8) quantiles in New Jersey, from lower to medium quantiles (0.1–0.5) in Arizona, and turns negative for extreme high quantile of COVID-19 in New Jersey and extreme high quantile (0.8–0.9) of air pollution in Arizona. In Massachusetts, air pollution strongly influences COVID-19 in higher quantiles (0.8–0.9) of air pollution, while this effect turns negative from medium to lower quantiles (0.4–0.1). This effect is equally distributed across the quantiles grid of COVID-19. This section of the findings aligns with recent literature and scientific outcomes, which claims that in the presence of ozone pollution, when inhaled, ozone can damage the lungs, caused chest pain, shortness of breath, coughing, and throat irritation. It may also worsen chronic respiratory diseases such as asthma as well as compromise the ability of the body to fight respiratory infections (Martelletti and Martelletti, 2020; US EPA, 2020a; 1996b). These symptoms are highly linked to COVID-19 (Manisalidis et al., 2020); thus, the overall positive effect attribute that in the presence of higher air pollution (Ozone O_3), the tendency and vulnerability of COVID-19 cases increases (Wu et al., 2020a, 2020b; Cole et al., 2020).

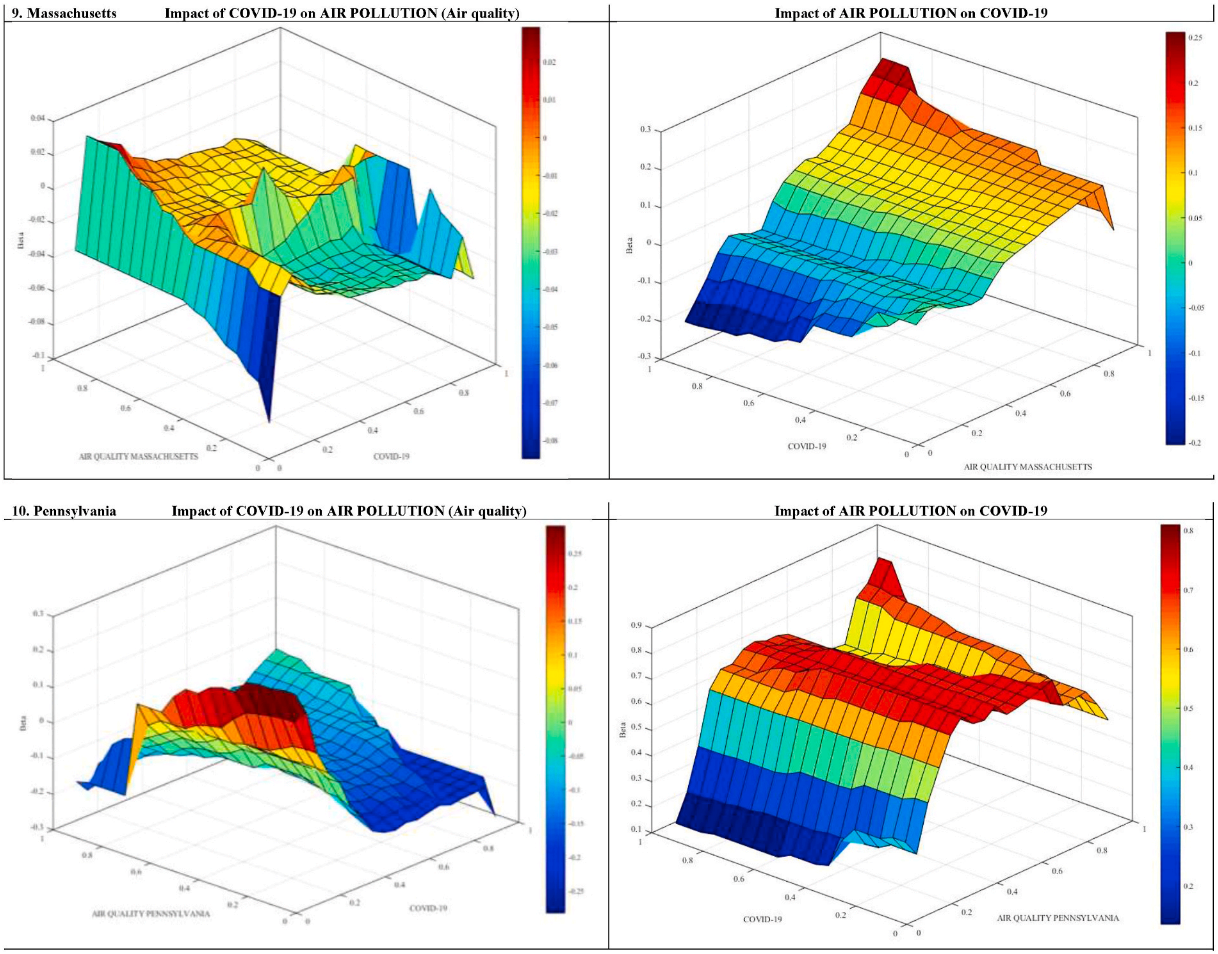

Fig. 1. (*continued*).

5. Conclusion and policy recommendation

This paper concurrently examines the effect of COVID-19 on air pollution and the effects of air pollution on COVID-19 in the topmost infected states of the US. The results of QQ approach confirm overall dependence and asymmetricity between COVID-19 and air pollution. In this study, air pollution is measured as ground-level ozone O_3 pollution, which is the most relevant pollution that increases the vulnerability of chronic respiratory diseases such as COVID-19. The result confirms that an increasing number of COVID-19 cases temporarily reduce O_3 pollution almost in all US states due to the slow down of economic activities and partial/complete lockdown in US states. On the flip side, higher environmental pollution leads to a higher number of COVID-19 cases amid raising respiratory disorder and weakening the immune system of the inhabitant lived in highly polluted areas. The intensity of these negative and positive effects on the environment and human lives are diverse across quantiles, which are mainly attributed to the different demographic characteristics, distinct social distancing, and lockdown measures taken by the US states.

In case of New York/Massachusetts, the pollution-reducing effect of COVID-19 is highest at the range of middle to higher quantiles (0.4–0.8) of COVID-19, while California/Illinois, Florida, and Texas exhibit a strong negative influence of COVID-19 on air pollution in the grid of lower to higher (0.2–0.8) quantiles, medium to higher (0.6–0.8) quantiles, and extreme higher quantiles (0.8–0.9), respectively. These results indicate that at the peak of COVID-19 intensity (higher quantiles), the pollution reduction effect of COVID-19 is highest, which is mainly attributed to strict lockdown measures taken by respective states. Contrarily, New Jersey, Georgia, and Arizona represent the highest negative effect of COVID-19 on air pollution at the lower (0.2–0.6) quantiles and lowest at highest quantiles (0.8–0.9) of COVID-19. These results indicate that at a mid-high level of COVID-19 intensity, the pollution-reduction effects of COVID-19 were higher and vice versa. The asymmetrical link between COVID-19 and pollution is primarily recognized with the depth and width of different lockdown measures (see Table 1 for detail).

On the other hand, New York, Florida, and Georgia show a moderate positive influence of air pollution on the intensity of COVID-19 cases at the middle to higher (0.4–0.9) quantiles of air pollution. In the case of Pennsylvania and California, a strong positive influence of air pollution on COVID-19 cases is observed across medium to higher (0.5–0.8) quantiles. However, the intensity of COVID-19 cases gradually declines with the reduction in air pollution from higher to lower quantiles (0.4–0.2). These results imply that higher levels (higher quantiles) of pollution corresponds to a higher number of COVID-19, while a lower level of pollution is associated with a lower number of COVID-19 cases. From a policy perspective, we observed that there is a murky relationship between air pollution and COVID-19 spread, which may mean that tackling air pollution will be a crucial part of easing lockdown to encounter socio-economic challenges that emerged from halted economic activities.

The results imply that environmental pollution is a man-made phenomenon and people are harming the natural environment in which they live. For this reason, perhaps, COVID-19 will take its place as a pandemic that increased human awareness about environmental issues. However, the impacts and consequences of the coronavirus pandemic on our lives, societies, and economies are more perilous such a sharp rise in global unemployment distorting our socio-economic balances. The maintainers and creation of jobs in a sustainable manner and improvement in healthcare systems are imperative measures to be taken. In doing so, new engagements from the government to improve climate conditions could be found helpful in generating green jobs and put the foundation for sustainable recovery. Many countries, like Pakistan and Nepal, have initiated such projects that can help the government's Green Wagers Initiative through which green jobs and fiscal stimulus programs could be instigated through tree plantations and ecosystem restoration. Moreover, enhanced focus on forestry projects under the current situation can also assist the forest community to augment livelihoods through the sustainable harvest of timber and other products. Also, developing sustainable infrastructure over degraded public areas could assist in creating green employment and augment environmental resilience.

Credit author statement

Asif Razzaq: Conceptualization, Writing - original draft, Arshian Sharif: Supervision; Methodology and Analysis. Noshaba Aziz: Writing - original draft & Editing, Muhammad Irfan: Writing - review & editing, Kittisak Jermsittiparsert: Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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