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ORIGINAL ARTICLE

COVID-19 outbreak and air quality of Lahore, Pakistan: evidence from asymmetric causality analysis

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Abstract
This paper aims to examine the impact of COVID-19 restrictions on the air quality of Lahore city of Pakistan for the period 26th February, 2020 to 31st August, 2020. The study employs asymmetrical Granger causality tests for analyzing the effects of COVID-19 cases and deaths on particulate matter ($PM_{2.5}$) emissions in the city. The results show positive shocks in COVID-19 cases and deaths improve the air quality of the city. This implies that the pandemic has lowered down environmental pressure in one of the top most polluted cities of the world. Further, the problem of hazardous air pollution in Lahore city is manmade mainly caused by everyday human activities. When these human activities were restricted owing to a rise in COVID-19 cases and deaths, the air pollution in the city resultantly reduces. Therefore, this study recommends controlling unnecessary production and consumption activities that degrades the environment so that air pollution in the city can be manageable after the COVID-19.

Keywords Asymmetric causality · Pandemic · Environmental pollution · Particulate matter ($PM_{2.5}$) emissions · Air quality

Abbreviations

$PM_{2.5}$ Particulate matter with an aerodynamic diameter less than 2.5 microns

Introduction

Air pollution has always been a matter of concern all over the world. Lahore suffers from a significantly high level of air pollution since early 2017. The renowned Swiss air quality company IQAir Visual ranked the city as one of the top polluted cities globally. Further, the company recently declared Lahore as the second most polluted city in the world, after Delhi. According to the World Health Organization, air pollution is principally proxied by the concentration of $PM_{2.5}$ particles in the atmosphere as they impose significant health hazards compared to any other pollutant in the atmosphere. These emissions mostly cause respiratory diseases as they are rich in sulphate, nitrates, ammonia, black carbon and sodium chloride (Khan et al. 2017).

Air pollution in Lahore is caused by numerous factors. Emissions from vehicles and industries are the most common cause of air pollution in the city. Similarly, smoke from brick kilns, residue from crop burning and negligence to recycle general waste are also major causes of air pollution in Lahore. Therefore, human activities and anthropogenic air pollution are highly interlinked.

With the incidence of the COVID-19 pandemic in Pakistan, the authorities have imposed several restrictions to control the spread of the virus. The first confirmed case of COVID-19 in Pakistan was identified on February 26, 2020. After that, the country has reported large-scale outbreak of the pandemic in the mid of March and currently has the 3rd highest number of confirmed cases in South Asia after India and Bangladesh. Lahore is the second largest city in Pakistan with the highest recorded COVID-19 cases and deaths in the city. Half of the total cases of the Punjab province of Pakistan are also reported from Lahore. Therefore, the city has been the top most infectious hotspot in the country. With these adverse conditions of COVID-19, the authorities immediately imposed a strict wide lockdown in the country. These restrictions were mainly aimed to prevent the further spread of the infectious virus. The restrictions were imposed

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primarily on banning public transport, closure of businesses, offices, institutions and industries (Bherwani et al. 2020). Resultantly, human as well as economic activities were put on hold thereby producing several socio-economic disturbances. These disturbances also have a direct or indirect effect on the environment as according to Wang et al. (2020) socioeconomic factors are primarily responsible for environmental performance.

A growing body of research on COVID-19 and the environment pointed both the positive and negative impact of the pandemic on air quality. For instance, a study by Gautam (2020) reported that air quality improves due to COVID-19 lockdown. The author advocated that upon imposition of COVID-19 restrictions, the transportation activities are brought drastically down. This decrease in transportation activities reduces oil demand and consequently declines in energy consumption as a result pollution in the city lowers down. On the other hand, a study by Zambrano-Monserrate et al. (2020) reported an increase in environmental pollution due to COVID-19 lockdown. The authors argued that as lockdown restriction are imposed the mobility of common man were restricted. This decrease in mobility also reduces recycling activities. As people get confined in their homes they get reluctant to properly dispose and recycle their waste. As a result environmental pollution increases. Further, restriction of staying at home also increases domestic waste consequently raises pressure on the environment. Thus, the pandemic has both favourable and adverse effects on the quality of the environment.

As the impact of COVID-19 on the environment has been the focus of attention among researchers since the incidence of the pandemic, increasing research has been done on analyzing how COVID-19 is affecting environmental quality. Most of the studies in this emerging domain have done country-specific analysis focusing on a specific country situation of COVID-19 and environment. Like studies such as Gautam (2020) has been conducted on Wuhan city of China, Xu et al. (2020) on Central China, Xing et al. (2020) and Li et al. (2021) on Northern cities of China, Tobias et al. (2020) and Baldasano (2020) on Spain, Kerimray et al. (2020) on Almaty Kazakhstan, Dantas et al. (2020) on Rio de Janeiro Brazil, Sharma et al. (2020) on 22 Indian cities, Asna-ashary et al. (2020) on Iran, Pata (2020) on the US, Mahato et al. (2020) exclusively on Delhi city of India, Li et al. (2020) on the cities of Yangtze River Delta region, Jephcote et al. (2021) and Ropkins and Tate (2021) on the UK, Donzelli et al. (2021a) on Valencia city and lastly Mor et al. (2021) on air quality of Chandigarh city of India.

Therefore, this study contributes to the existing literature by analyzing the impact of COVID-19 on the air quality of Lahore city Pakistan. To the best of our knowledge, no study in this domain of research has been conducted so far on specifically Lahore and overall within Pakistan. The analysis of Lahore is particularly significant and crucial to investigate as currently there are 48,971 total confirmed COVID-19 cases in the city. The number of cases and deaths is reported to be on the rise in Lahore compared to other districts of Punjab province of Pakistan. Lahore is also reported to be one of the top polluted cities in the country for the last few years. Lahore is the second top most polluted city in the world (IQAir 2019). Hence, in these circumstances there is a dire need to investigate the impact COVID-19 cases and deaths on the environmental quality of Lahore city of Pakistan.

Most importantly, this study investigates the nonlinear impact of COVID-19 cases and deaths on the air quality of the city. The existing studies have used several linear econometric approaches to examine the effects of the pandemic on the environment. For instance, Sharma et al. (2020) employed WRF-AERMOD modelling for analyzing the COVID-19 effect on environment, Mahato et al. (2020) analyzed the effect through Spatial mapping, Li et al. (2020) using WRF-CAMx modelling system, Ropkins and Tate (2021) by Breakpoint testing technique, Xing et al. (2020) by employing response-based inversion model, Jephcote et al. (2021) through Business-as-usual modelling method, Mor et al. (2021) using principle component analysis and Donzelli et al. (2021b) by conducting normality analysis.

However, assuming symmetry in the selected variables and analyzing the effect through symmetric modelling techniques can give misleading results. In reality, there is a positive shock in COVID-19 but no negative shock is seen, in the selected time period, no cure of the virus was existing. However, in $PM_{2.5}$ emissions there are both positive and negative shocks. Therefore, investigating the effects of both shocks as an aggregate ignores hidden causal associations among the variables. Thus, this study explores the possible causality relationships by segregating the variables into positive and negative shocks. There is only one existing study that assumes nonlinearity in COVID-19 and environmental pollution (Pata 2020). But the study by Pata (2020) is conducted on US cities, therefore, its findings cannot be generalised for the rest of the world countries specifically for developing country like Pakistan having a city (Lahore) with second highest number of COVID-19 cases and deaths and being one of the top most polluted city of the world. Most importantly, unlike Pata (2020) this study employed nonlinear asymmetric causality.

Therefore, this study aims to answer the following questions: First, does the number of cases and deaths caused due to COVID-19 improve the air quality of Lahore. Second, what are the effects on positive and negative shocks of air quality when there is a positive shock in COVID-19 cases and deaths in the city. To find answer to these questions, this study measures the air quality of the city through $PM_{2.5}$ emissions in two different localities (Met Station and Town Hall) of Lahore city. Our study analyses whether there exists a causal relationship from positive shocks of COVID-19 to positive and negative shocks in $PM_{2.5}$ emissions in Lahore. We have investigated symmetry and asymmetric relations through the granger causality test. The daily data from 26th February, 2020 to 31st August, 2020 is used in the analysis. To the best of our knowledge, this study is the first of its kind for Lahore city which is currently the hotspot for both the pandemic and air pollution.

The rest of the study is structured as follows: Sect. 2 provides a discussion on data and methodology used in the study. Section 3 presents results and a detailed discussion on them. In the last, Sect. 4 concludes the study and highlights important future policy implications.

Methodology

This study aims to find the asymmetric causality effects of COVID-19 on air pollution in Lahore. To achieve this objective, the following model is utilized to investigate the asymmetric association of COVID-19 cases and death on $PM_{2.5}$ emissions:

$$\text{COVID - 19 cases}^{+} = f\left(PM_{2.5}\text{emissions}^{+},\ PM_{2.5}\text{emissions}^{-}\right), \tag{1}$$

$$\text{COVID - 19 deaths}^{+} = f\left(PM_{2.5}\text{emissions}^{+},\ PM_{2.5}\text{emissions}^{-}\right), \tag{2}$$

where COVID-19 cases^{+} is the positive shock in the number of cases due to the pandemic, COVID-19 deaths^{+} is the positive shock in deaths caused by the virus, $PM_{2.5}$ emissions^{+} is the partial sum of positive change in particulate matter emissions and $PM_{2.5}$ emissions^{-} is the decomposition of partial sum of negative change in particulate matter in the atmosphere. The study examines the effects on two localities of Lahore (Met Station and Town Hall) from the time period February 26, 2020 to August 31, 2020. Since the data of other areas of Lahore are unavailable, therefore, only selected two locations are included in the analysis. The data of COVID-19 cases and deaths are taken from Our World in Data (2021) whereas the data of $PM_{2.5}$ emissions (μg/m^{3}) for Lahore is collected from the website of the Environment Protection Department, Government of Punjab. All the variables of the study are converted to a natural logarithm for obtaining a stable variance.

Econometric model

The study adopted Shin et al. (2014) method of breaking down selected variables into their negative and positive components. Thus, using the method we have positive series of COVID-19 cases^{+}, COVID-19 deaths^{+}, $PM_{2.5}$ emissions^{+} and negative components as $PM_{2.5}$ emissions^{-} written as:

$$\begin{aligned}\text{COVID - 19 cases}_t^{+} &= \sum_{n=1}^{t} \Delta\text{COVID - 19 cases}_t^{+}\\ &= \sum_{n=1}^{t} \max\left(\Delta\text{COVID - 19 cases}_t^{+}, 0\right),\end{aligned} \tag{3}$$

$$\begin{aligned}\text{COVID - 19 deaths}_t^{+} &= \sum_{n=1}^{t} \Delta\text{COVID - 19 deaths}_t^{+}\\ &= \sum_{n=1}^{t} \max\left(\Delta\text{COVID - 19 deaths}_t^{+}, 0\right),\end{aligned} \tag{4}$$

$$\begin{aligned}PM_{2.5}\ \text{emissions}_t^{+} &= \sum_{n=1}^{t} \Delta\ PM_{2.5}\ \text{emissions}_t^{+}\\ &= \sum_{n=1}^{t} \max\left(\Delta PM_{2.5}\ \text{emissions}_t^{+}, 0\right),\end{aligned} \tag{5}$$

$$\begin{aligned}PM_{2.5}\ \text{emissions}_t^{-} &= \sum_{n=1}^{t} \Delta\ PM_{2.5}\ \text{emissions}_t^{-}\\ &= \sum_{n=1}^{t} \max\left(\Delta PM_{2.5}\ \text{emissions}_t^{-}, 0\right),\end{aligned} \tag{6}$$

where $\text{COVID - 19 cases}_t^{+}$ is the positive shocks in the COVID-19 cases and t is the time period. Similarly, $\text{COVID - 19 deaths}_t^{+}$ is the positive shocks in number of deaths caused by the virus. Likewise, $PM_{2.5}$ emissions + and – subscripts represents positive and negative shocks in the series, respectively.

Asymmetric causality inference

Initially, the idea of segregating data into cumulative positive and negative components is proposed by Granger and Yoon (2002). The authors transformed the variable for analyzing hidden cointegration because of positive and negative changes in the series. Hatemi-J (2012) and Hristu-Varsakelis and Kyrtsou (2013) extended the work of Granger and Yoon (2002) for causality analysis referring to it as asymmetric causality testing since both positive and negative shocks may behave differently in causality estimates. The author assumed the integrated variables y_{1t} and y_{2t} having random walk processes in the following way:

$$y_{1t} = y_{1t-1} + \varepsilon_{1t} = y_{1,0} + \sum_{i=1}^{t} \varepsilon_{1i}, \tag{7}$$

$$y_{2t} = y_{2t-1} + \varepsilon_{2t} = y_{2,0} + \sum_{i=1}^{t} \varepsilon_{2i}, \tag{8}$$

where $t = 1, 2,..T$, $y_{1,0}$ and $y_{2,0}$ are the initial values and ε_{1i} and ε_{2i} are white noise disturbance terms. These disturbance terms are transformed into positive $\varepsilon_{1i}^{+} = \max\left(\varepsilon_{1i}, 0\right)$ and $\varepsilon_{2i}^{+} = \max\left(\varepsilon_{2i}, 0\right)$ and negative shocks $\varepsilon_{1i}^{-} = \min\left(\varepsilon_{1i}, 0\right)$ and $\varepsilon_{1i}^{-} = \min\left(\varepsilon_{2i}, 0\right)$. Therefore, after decomposing the initial shocks are written as: $\varepsilon_{1i} = \varepsilon_{1i}^{+} + \varepsilon_{1i}^{-}$ and $\varepsilon_{2i} = \varepsilon_{2i}^{+} + \varepsilon_{2i}^{-}$. Thus, Eqs. 7 and 8 can be presented as

$$y_1 = y_{t-1} + \varepsilon_{1i} = y_{1,0} + \sum_{i=1}^{t} \varepsilon_{1i}^{+} + \sum_{i=1}^{t} \varepsilon_{1i}^{-} \tag{9}$$

$$y_2 = y_{t-1} + \varepsilon_{2i} = y_{2,0} + \sum_{i=1}^{t} \varepsilon_{2i}^{+} + \sum_{i=1}^{t} \varepsilon_{2i}^{-} \tag{10}$$

Lastly, the cumulative forms of the positive and negative shocks can be written as $y_{1t}^{+} = \Sigma_{i=1}^{t}\varepsilon_{1i}^{+}$, $y_{1t}^{-} = \Sigma_{i=1}^{t}\varepsilon_{1i}^{-}$, $y_{2t}^{+} = \Sigma_{i=1}^{t}\varepsilon_{2i}^{+}$, $y_{2t}^{-} = \Sigma_{i=1}^{t}\varepsilon_{2i}^{-}$. In the next step, the causal relationships between the transformed components are to analyzed using vector autoregressive introduced by Hatemi-J (2012). Now assume the following VAR (p) process:

$$y_t = \eta + A_1 y_{t-1} + A_p y_{t-p} + \varepsilon_t, \tag{11}$$

where $\varepsilon_t = \left(\varepsilon_{1t, \ldots,} \varepsilon_{kt}\right)'$ is a zero mean of error term with non-singular covariance matrix Σ_ϵ and $j = 1, \ldots, k,\ E\left|\varepsilon_{jt}\right|^{2+\tau} < \infty$ for $\tau > 0$. Now, assuming the following hypothesis

$$H_0 = Z_{12,i} = 0 \quad \text{for } i = 1, \ldots, p-1. \tag{12}$$

Here y_t vector has y_t^1 and y_t^1 sub-vectors and Z_i is matrices. If the above hypothesis is true then y_t^2 does not granger cause y_t^1. Using the matrix donation, the VAR matrix having constant term (A) can be written compactly as:

$$Y = AZ + \delta. \tag{13}$$

Now the Eq. 13 is estimated using the OLS method. In the next step, the whole VAR model is estimated through Zellner's Iterative Seemingly Unrelated Regression (ISUR) method. The ISUR technique, estimate the parameters using maximum likelihood methods. The unrestricted regression is labeled as $\hat{\delta_U}$ and restricted one as $\hat{\delta_R}$. The Rao F-test for estimating Granger causality can be written as follow:

$$\text{RAO} = \left(\frac{\varphi}{q}\right)\left(U^{\frac{1}{s}} - 1\right), \tag{14}$$

where $\varphi = \Delta s - r$, $\Delta = T - (k(kp+1) - Gm) + \frac{1}{2}[k(G-1) - 1]$ and the restriction imposed in H_0 is $r = q/2 - 1$, $U = \det S_R / \det S_u . q = Gm^2$. Here, G is p restriction in Eq. 11 and m is y_t^1 dimension. The s is mathematically written as follow:

Table 1 Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Kurtosis
Met Station $PM_{2.5}$	3.133	3.135	4.469	1.945	2.512
Town Hall $PM_{2.5}$	2.982	3.004	4.097	0.859	3.466
Total cases	7.904	7.658	12.460	6.118	6.353
Total deaths	3.418	3.295	8.098	0.693	4.069

$$S = \sqrt{q^2 - 4/k^2(G^2 + 1) - 5}. \tag{15}$$

The RAO test is distributed as $F = q,\ \varphi$ in null hypothesis and later decomposes into standard F-statistics when $k = 1$.

Statistical analysis

The data of COVID-19 and $PM_{2.5}$ emissions are subjected to descriptive statistics using EViews 10. Table 1 shows the concentration of $PM_{2.5}$ emissions in the Met Station and Town Hall localities of Lahore and the descriptive details of the number of COVID-19 cases and deaths in the city. The statistics show average, median, maximum and minimum concentrations of $PM_{2.5}$ in the focused hotspots from 26-2-2020 to 31-08-2020. The $PM_{2.5}$ concentrations fall with a mean of 3.133 µg/m^3 and 2.982 µg/m^3 in Met Station and Town Hall area, respectively. Similarly, the maximum values of the concentrations are 4.469 µg/m^3 and 4.097 µg/m^3. Whereas, the minimum reported statistics are 1.945 and 0.859. The same trend is observed in the median values of the concentration in both the localities. Related to the total number of cases and deaths due to COVID-19, the average values are 7.904 and 7.658, correspondingly. Furthermore, our statistics show that the maximum number of cases reported in the selected period is 12 with a maximum 8 deaths in a day. However, the minimum number of COVID-19 cases is 6 with 1 death in a day in the focused period.

Results and discussion

Unit root analysis

In this initial phase of the investigation, the stationary properties of the variables mentioned in the model (1) and (2) have been analyzed. The findings of the unit root process obtained through the Phillips-Perron test are shown in Table 2. The purpose to study stationary properties is to investigate the order of integration of the variables and to ensure the authenticity of estimated correlation coefficients. The Phillips-Perron test is a modified test to check the unit root process. It also takes care of the problems of

Table 2 Estimates of Phillips-Perron unit root test

Variables	Level	First difference
Met Station $PM_{2.5}$	− 3.047 (0.130)	− 9.583*** (0.000)
Town Hall $PM_{2.5}$	− 1.304 (0.615)	− 9.034*** (0.000)
Total cases	1.445 (0.963)	− 10.441*** (0.000)
Total deaths	1.604 (0.973)	− 10.236*** (0.000)
Total cases$^+$	1.345 (0.955)	− 11.134*** (0.000)
Total deaths$^+$	1.572 (0.971)	− 8.313*** (0.000)

Probability values in parentheses (***$p<0.01$). Where, Met Station $PM_{2.5}$ is the concentrations of respirable particulate matter at met station jail road Lahore, Town Hall $PM_{2.5}$ is the concentrations of respirable particulate matter at Town Hall Lahore, Total Cases is total COVID-19 cases, Total Deaths is the total number of deaths due to COVID-19, Total Cases$^+$ is positive shocks in COVID-19 cases and Total Deaths$^+$ is positive shocks in the number of deaths caused by COVID-19

autocorrelation and heteroscedasticity in the error term and helps obtain robust findings. The results show that all the variables of the model (1) and (2) have a unit root process at the level but they become stationary at first difference. For instance, Table 2 illustrates that the $PM_{2.5}$ concentrations in both localities of Lahore are non-stationary at level I(0). Further, the positive components of COVID-19 cases and deaths also have unit root process (non-stationary) at I(0) and later become stationary at I(1). To put it differently, the findings of the Phillips-Perron test specifies that no I(0) and I(2) variables are used in the study analysis as all the series are integrated of order one I(1) and hence stationary with no shift overtime at first difference.

Causality of COVID-19 cases on $PM_{2.5}$ emissions

To predict how COVID-19 is correlated to the air quality of Lahore, symmetric and asymmetric Granger causality tests have been employed. This investigation helps us in discovering with evidence about how the positive component of COVID-19 causes affect positive and negative shocks in $PM_{2.5}$ concentrations in the atmosphere of Lahore. To find the answer to this question, the model in Eq. 1 is estimated. The result of this query is reported in Table 3. As indicated in the model, the positive shocks in the number of COVID-19 cases affect positive and negative components of $PM_{2.5}$ emissions. The asymmetric causality analysis shows that positive shocks in COVID-19 cases significantly increase negative shocks in particulate matter emissions. The finding is the same in both Met Station and Town Hall localities of Lahore. Studies by Pata (2020) and Mahato et al. (2020) also reported a similar result. Our estimates suggest that an increase in the number of cases granger causes negative shocks in the emissions by 8.500 $\mu g/m^3$. It is because as the number of cases increases COVID-19 lockdown restrictions get imposed. This imposition of the restriction limited human anthropogenic activities thereby enhance the trend of reduced Particulate emissions (negative shocks) in the Lahore atmosphere. Further, the economic crisis has seemed to solve the problem of air pollution. Hence, as COVID-19 has hits Pakistan's economy consequently leading to improved air pollution.

Concerning the causality between positive shocks in the cases and the emissions, the estimated statistics are insignificant indicating no significant causality association between the two. This finding is in accordance with the result of Pata (2020) who also reported no association between positive shocks in COVID-19 cases and the emissions in the USA. It is noted that in the Pandemic era, industrial production lowered down and vehicle use has decreased (Pata 2020; Ropkins and Tate 2021). Further, energy consumption and oil demand have also declined imposing less environmental pressure in the atmosphere (Gautam 2020; Mahato et al. 2020; Li et al. 2021). In addition, social activities have lowered down during pandemic which consequently affected the environment of especially high population countries (Pata 2020). The increased use of technology has elevated environmental pressure (Nakada and Urban 2020).

The causality estimates of symmetric effect suggest that number of COVID-19 cases granger cause $PM_{2.5}$ emissions only in Met Station locality of Lahore. Our analysis indicates that in the overall causality effect of COVID-19 cases on air quality, there is only the effect on the negative component of $PM_{2.5}$ emissions. The comparison of symmetrical and asymmetric causality suggests that incorrect and misleading results can be advocated when asymmetries in the association of COVID-19 and air quality are not analyzed.

Table 3 Causality test for COVID-19 cases

	Symmetric causality	Asymmetric causality	
Null hypothesis	$\text{lnCases} \nrightarrow \text{lnPM}_{2.5}$	$\text{lnCases}^+ \nrightarrow \text{lnPM}_{2.5}{}^-$	$\text{lnCases}^+ \nrightarrow \text{lnPM}_{2.5}{}^+$
Localities	F statistics		
Met Station	8.499*** (0.001)	8.500*** (0.000)	0.758 (0.469)
Town Hall	1.598 (0.222)	2.599* (0.013)	2.061 (0.100)

Probability values in parentheses (*$p<0.1$, **$p<0.05$, ***$p<0.01$)

Table 4 Causality test for COVID-19 deaths

	Symmetric causality	Asymmetric causality	
Null hypothesis	$\ln Deaths \nrightarrow \ln PM_{2.5}$	$\ln Deaths^{+} \nrightarrow \ln PM_{2.5}^{-}$	$\ln Deaths^{+} \nrightarrow \ln PM_{2.5}^{+}$
Localities	F statistics		
Met Station	1.773 (0.188)	2.176*** (0.009)	0.848 (0.430)
Town Hall	4.607** (0.056)	3.266*** (0.040)	1.826 (0.199)

Probability values in parentheses (*$p<0.1$, **$p<0.05$, ***$p<0.01$)

Causality of COVID-19 deaths on $PM_{2.5}$ emissions

To investigate how causal associations exist between COVID-19 deaths and atmospheric particulate matter, an asymmetric causality test has been performed. This investigation of Eq. 2 enables us in analysing the disaggregated causality effect on transformed positive and negative components of $PM_{2.5}$. The result of this query is illustrated in Table 4. The results show that there is positive granger causality between positive shocks in the number of deaths and negative shocks in atmospheric particulate matter irrespective of the level of concentrations in different localities of Lahore. In other words, as there is the rise in positive shocks in COVID-19 deaths, it granger cause negative shocks in the emission to increase thereby improve air quality. The coefficients suggest that positive shocks in COVID-19 deaths positively granger cases 2.176 $\mu g/m^3$ and 3.266 $\mu g/m^3$ of $PM_{2.5}$ emissions in Met Station and Town Hall areas of Lahore. This finding is supported by the result of Pata (2020) who also reported positive asymmetric causality between COVID-19 deaths and air quality. The main sources of $PM_{2.5}$ emissions are fossil fuel and biomass combustion, industrial production, motor vehicle usage and road dust (Song et al 2007; Kim and Hopke 2008); therefore, the occurrence of increased death due to the pandemic has enacted lockdown response procedure thereby restricted all main sources of the atmospheric particulate matter and improved air quality. Lahore is one of the hubs of the country's industrial production and is an economic city. Further, the city has the highest urban population so the environmental issues of unplanned urbanization and haphazard economic production have been improved due to adopted measures regarding the control of deaths due to the pandemic. The result implies that air pollution in the city is largely associated with several economic related activities (such as urban energy consumption, industrial production and motor vehicle usage for commodities supply) which have deteriorated both the quality of human life as well as the environment. The result indicates that lockdown has helped clean the air of Lahore city by raising negative shocks in particulate matter. Moreover, COVID-19 deaths have clean skies and offer comparatively cleaner breathable air for the inhabitants of Lahore.

The decline in energy consumption due to a reduction in commodities supply of industries also has positive effects on environmental quality (Li et al. 2020; Jephcote et al. 2021). Further, the demobilization of combustion engine vehicles during the pandemic era has reduced the emissions of fine particulates which in turn lowered $PM_{2.5}$ emissions (Baldasano 2020; Xu et al. 2020; Jephcote et al. 2021; Mor et al. 2021). The temporary shutdown of non-necessities production factories has also elevated environmental pressure (Rodríguez-Urrego and Rodríguez-Urrego 2020; Ropkins and Tate 2021).

Conclusions

This study presents the results of asymmetric Granger causality between the COVID-19 pandemic and air quality of Lahore, Pakistan. To the best of our knowledge, this is the first study to analyze asymmetric causality from COVID-19 to positive and negative shocks in atmospheric particulate matter of different (Met Station and Town Hall) localities of Lahore. Based on the findings of the study, it is conducted that both the number of cases and deaths caused by COVID-19 has positive causality to the negative shocks in $PM_{2.5}$ emissions in the city. To put it differently, the finding suggests that COVID-19 cases and deaths decrease the emissions in Lahore during the lockdown period. This implies that the air quality of Lahore has improved as a by-product of the lockdown restriction due to positive shocks in COVID-19 cases and deaths in the city. Further, the study conducted that no significant causality run from COVID-19 to positive shocks in $PM_{2.5}$ concentrations. In addition, it is also revealed that there is positive symmetric causality when no shock in atmospheric particulate matter is considered. This implies that assuming symmetric causality may give incorrect and misleading results therefore asymmetric is important and crucial to analyze in COVID-19 effects on air quality.

The COVID-19 pandemic period has taught us that clean atmospheric air in Lahore can be attained if the main sources of hazardous atmospheric particulate matter may be controlled. This may be done by controlling air polluting industrial, energy and transportation activities and substituting them with environmentally friendly means of achieving economic growth. The current pollution havens are simply manmade putting human pressure on the environment. Therefore, this pandemic has made us realize that improvement in air quality is achievable ensuring the minimization of hazardous risk to human health.

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Ethical approval The manuscripts based on secondary data set that never need any ethical approval.

Consent to participate There is no ethical committee at institutional level for secondary data, so it is not applicable in our case.

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