



# A blessing in disguise: new insights on the effect of COVID-19 on the carbon emission, climate change, and sustainable environment

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## Abstract

COVID-19, declared by the World Health Organization (WHO) to be a pandemic, has affected greenhouse gas emissions and contributed to the uncertainty of environmental activities. This study demonstrates the effect of lockdowns, the number of new confirmed cases, and the number of newly confirmed deaths due to COVID-19 on CO<sub>2</sub> emissions. The data series used are for the UK from 23 March 2020 to 31 December 2020 and for Spain from 14 March 2020 to 31 December 2020. This research adopted the Augmented Dickey–Fuller (ADF) test for a stationarity check of the data series, the Johansen cointegration test for determining cointegration among variables, and the vector error correction model (VEC) Granger causality test for directional cause and effect between exogenous and endogenous variables. The VEC model shows a bidirectional relationship between CO<sub>2</sub> emissions and lockdown and a unidirectional relationship with newly confirmed cases and deaths for the UK. The results of Spain confirmed the unidirectional relationship of CO<sub>2</sub> emissions, lockdown, new confirmed cases, and deaths. The Granger causality test reconfirms the relationship of variables except for newly confirmed deaths for the UK and newly confirmed cases for Spain. Conclusively, the pandemic breakout reduced the emission of CO<sub>2</sub>. The directional relation of variables supported the short-run relationship of CO<sub>2</sub> emissions with newly confirmed cases and deaths, while a long- and short-run relationship was shown with lockdown. The directional and relational behavior of lockdown potentially linked the CO<sub>2</sub> emissions with daily life activities.

**Keywords** CO<sub>2</sub> emission · Climate change · Sustainable environment · UK; Spain; COVID-19

## Introduction

The way the pandemic spread to humans suggested a bidirectional process among animals' habitats and those of humans. Human activities and the rapid restructuring of

animal habitats are the reason for the initial outbreak. The survival of human beings and animals centers on environmental sustainability. However, the meat consumption rate has almost doubled in the last 50 years and is still growing, which has heightened the risk of pathogenic diseases. The human population faces pathogenic pandemics due to human–animal conflict, the increased intermingling in livestock, and the cultivation of wild animals. Extreme environmental impacts increase the likelihood of new, deadly pandemics. Human beings are disturbing wild animals' habitats and resultingly becoming the host of new pathogenic pandemics. Global warming and climate change positively support anthropogenic activities and add to the likelihood of pandemics. The growth of the worldwide population and natural environmental exploitation also enhances the number of zoonotic pathogens. The careless behaviors of human beings disrupt the leading determinants of a healthy environment, i.e., water, air, and soil. Zhang et al. (2020) recently observed high levels of arsenic (III) with high metal pollution in water,

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which increases bacterial antibiotic resistance (BAR) and increases water-borne epidemiological threats to human beings to an alarming level.

Since the dawn of human civilization, pandemics and epidemics have impacted human societies with unintended consequences. The situation changed drastically for humans when one of the most deadly viruses in human history broke out, with dire consequences for humankind. In December 2019, an outbreak of the highly contagious coronavirus labeled COVID-19 suddenly emerged from Wuhan, China (Hui and Zumla 2019). The origin of SARS-CoV-2, as it is known scientifically, quickly affected several regions, causing the World Health Organization (WHO) to declare it as a global pandemic on 11 March 2020 (Azhar et al. 2019). The prolonged spread of COVID-19 has led to global consequences for human health, plus economic repercussions.

Nonetheless, the clinical representation of COVID-19 provides a deep insight into natural human history. The evolutionary history of the epidemiological syndrome caused many countries to experience its vulnerabilities, resulting in an increased mortality rate. The high efficacy of this pandemic has damaged several countries, exerting immense pressure on the global health sector. Research shows that the outbreak of this infectious bacteria has produced a particularly devastating effect on countries such as the UK, Italy, France, China, and Spain (Corman et al. 2018). The deadly characteristics of COVID-19 have had an antagonistic effect on a large population, leading to a substantial death rate. As of 16 July 2021, the worldwide cumulative confirmed COVID-19 cases were 188.93 million, and the disease had caused 4.08 million people to lose their lives (Johns Hopkins, 2021). This life-threatening pathogen has pushed the global health care industry to its breaking point, with consequences for the worldwide cumulative fatality rate.

Despite the technological advancements in the health sector in recent decades, humanity still struggles hard against the pandemic disaster. The COVID-19 vulnerability has put the world on the edge of experiencing an uncontrollable mortality rate. In such circumstances, to suspend the spreading of the disease, most countries proactively tackle the transmission of new emerging variants. The recent literature suggests the effective management of the virus through extensive lockdowns has limited its spread, thereby indirectly improving the world's overall environmental quality. Environment quality plays an integral role in promoting a healthy lifestyle. Environmental pollution includes the emission of poisonous substances such as dirt, smoke, intoxicants, and gases (e.g., carbon dioxide and nitrogen dioxide). The emission of CO<sub>2</sub> appears to be a dominant source in producing air pollutants. Research shows that long-term exposure to toxic environmental conditions brings enormous health risks, with a significant population dying every year due to air pollution (Manisalidis et al. 2020). CO<sub>2</sub> is

considered a frequent cause of health problems, fundamentally increasing the death ratio (Huang et al. 2017).

However, according to recent statistics, 91% of the world's population lives in areas where minimal environmental standards are followed, as defined by the World Health Organization (WHO, 2020). Therefore, this topic has significant importance for the world's meteorologists. Social responsibility ensures a hazard-free environment, limiting the secretion of containments such as smoke, CO<sub>2</sub>, and NO<sub>2</sub>, into the atmosphere. Substantially, many countries have started improving air quality to allow residents to live a healthy lifestyle to achieve environmental sustainability. With the increasing importance of CSR, countries are adopting green initiatives for controlling the extensive emission of toxicants. Hence, it is essential to ensure safe environmental conditions to protect the interests of the natural world, thus providing a healthy environment to preserve human lives.

Therefore, despite the disruption caused by COVID-19, the virus appears to be beneficial in enhancing worldwide atmospheric conditions. A significant decrease in air pollution has been observed during the worldwide lockdown arrangements. Research shows that, with the exponential increase in confirmed cases, governments of different countries mandated lockdown restrictions to limit the spread of the virus. Depending upon the severity of the local COVID-19 wave, governments have laid rules such as travel restrictions, social distancing, and the closure of businesses such as industries and markets.

The lockdown conditions have brought significant changes to people's daily lives, ensuring serious implementation of WHO guidelines. By March 2020, the lockdown situation extended isolation attempts across many Western nations, including the UK, France, Germany, Italy, and Spain. However, the extension in lockdown depended upon the severity of confirmed cases across different regions. Hence, due to several lockdown intervals occurring in the UK and Spain, results are collected from those countries accordingly (i.e., 23 March 2020 to 31 December 2020 and 14 March 2020 to 31 December 2020, respectively).

The COVID-19 pandemic completely changed the societal structure and living style of many people. In addition, the worldwide movement restrictions and mandatory checks also altered the emission of greenhouse gases. This research aims to identify the influence of pollutant elements and greenhouse gas emissions during the COVID-19 period. In that period, industrial and human activities were closed; hence, the emissions should be fewer and more sustainable. Significantly, this study sheds light on the effect of COVID-19 in shaping environmental policies to gain sustained development in main cities of the world. The lockdown measures have resulted in the closure of many sources of air pollutants. Hence, the study aims to identify the impact of lockdown on carbon emissions in the UK and Spain. The

research analyzes the fundamental relationship between carbon dioxide emission and COVID-19.

The research suggests that lockdown activities have been successful in minimizing the ambient level of air pollutants. The results showed that different variants of air pollution have drastically fallen during the pandemic crisis. The data gathered from the UK and Spain indicated that the prolonged period of COVID-19 has fundamentally improved air quality. The current study examines the concentrating effects of carbon dioxide on meteorological conditions, investigating the relationship between COVID-19 and environmental quality. The study focuses on identifying the impact of annual emissions of air pollutants (i.e., CO<sub>2</sub>) during COVID confinement periods. Purposely, this paper underscores the significance of maintaining the continued weather conditions, even after lifting lockdown restrictions. Hence, the study provides countries an opportunity to realize the importance of climate sustainability while recovering environmental quality.

The remainder of the research article is structured as a literature review based on current research work in this field. The following section outlines the materials and methods undertaken for the analytical method of this research. The empirical results come next. The implications of the analytical methods help to attain some specific results for directional guidance. Then, the discussion section compiles the overall impact of this research work and the solution for the problem discussed. Finally, the conclusion is based on a conclusive summary of the study and showing the practical implications to enhance the quality of the environment.

## Literature review

The negative impact of COVID-19 has been observed in every single field of life except environmental quality and sustainability. The global emergency necessitated restricting people from coming out of their homes to avoid the spread of COVID-19. This pandemic emergency applied to the urgent management of myocardial infection. There was no other option but to impose the primary restrictions and precautions for coronary interventions as the direct therapeutic option. The UK government implemented restrictions starting from 24 March 2020. During the near-worldwide restrictions, all the main venues, shops, restaurants, and bars were closed in the UK. The lockdown measures were enforced under the surveillance of police officers, thereby closing all non-essential social and economic activities. The pandemic's seriousness had increased, resulting in 2.50 million confirmed cases and 73,622 deaths (Ritchie et al. 2020). The lockdown situation in the UK during the initial COVID-19 lockdown made people understand the intensity of the disease, causing them to restrict their movements, subsequently affecting environmental conditions. Hence, the lockdown measures in the UK

successfully prevented a surge in COVID cases, improving the atmospheric quality of major cities across the region in the meantime (Higham et al. 2021).

Similarly, the uncontrollable situation of COVID-19 in most European countries caused severe difficulties, with Spain experiencing the highest tier of restrictions during the first wave of COVID-19. Spain is the sixth most populous country in Europe, with a population of 47 million as of 2021, and it also strictly adopted quarantine policies. In response to the growing number of cases in Spain (i.e., 1.93 million), the Spanish government announced a temporary closure on all the non-essential activities from 14 March 2020. Aggressive measures were taken by the Spanish government, thus imposing a night-time curfew to control the spike of COVID-19 infections. The disease had a severe effect in Spain, resulting in 50,837 people losing their lives in the first wave (Ritchie et al. 2020). Research suggests that the Spanish government's "red zone" curfew policies positively affected improving atmospheric conditions. For example, results from a recent study show that the policies imposed by the Spanish government have fundamentally improved the air quality of the region (Briz-Redón et al. 2021). Moreover, after observing the air quality data, a massive waste reduction was documented in the major areas of Spain (i.e., Madrid, Valencia, Barcelona, and Bilbao). The COVID-19 mobility restrictions have drastically affected the air pollution in Spain, resulting in 70% to 80% waste reduction (Cárcel-Carrasco et al. 2021).

Therefore, the findings indicate that the majority of Western countries have experienced a decline in air pollutants. The government initiative of imposing lockdowns has limited the spread of the highly contagious disease while also causing a decrease of pollutants such as CO<sub>2</sub> and NO<sub>2</sub> (EPA, 2020). Results show that the environmental conditions during the global pandemic have controlled the toxic concentration of CO<sub>2</sub> (Rojas et al. 2021), thus improving the air quality. During the lockdowns, all social and economic activities were prohibited, as people were urged to stay in their homes. This disturbance to daily lives, transportation, and business stopped the excessive addition of air pollutants to the atmosphere. It suggests that the emission of air pollutants such as carbon dioxide depends on the use of vehicles, human movement, and economic activities. Hence, the suspension of these activities during COVID-19 has resulted in a sharp decline in carbon dioxide levels. Indeed, the preventive measures taken by different governments have produced a positive impact on the atmosphere, reducing the discharge of waste material (i.e., CO<sub>2</sub>, NO<sub>2</sub>, and SO<sub>2</sub>) across global cities. The halting of air aviation businesses has also positively contributed to environmental sustainability during the COVID-19 period. The pandemic highlighted the importance of green business practices (GBPs), and as companies worked to meet renewed regulatory COVID-safe demands,

short- and long-run costly processes were jettisoned. The analytical approaches of Amankwah-Amoah (2020) and Rehman et al. (2021a, b) pointed out the upgrade and demand for environment-friendly aircraft with a lesser carbon emission footprint, i.e., aviation’s emission reduction schemes, carbon off-setting, and the European Union Emissions Trading System. The research findings indicated that environmental sustainability could be achieved by meeting environment-friendly commitments, reducing cost pressures and survival threats and prioritizing ecological sustainability initiatives (Ozturk et al. 2021; Rehman et al. 2021a, b).

**Material and methods**

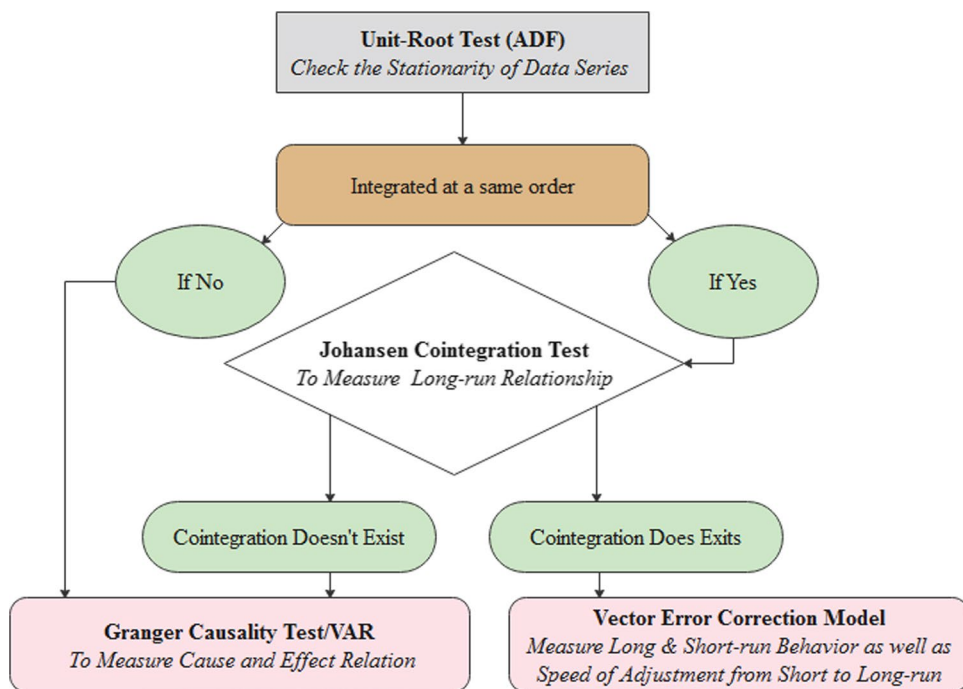
**Data description**

We used daily time series data of carbon emission, daily new cases, daily new deaths, and lockdown to identify the impact of COVID-19 on CO<sub>2</sub> emission. The CO<sub>2</sub> emission is well-thought-out as the dependent variable, while daily new cases (NC), daily new deaths (ND), and lockdown are considered independent variables. The data of the dummy variable was generated according to the confinement index of 0 and 1. The digit 0 symbolically represents nationwide restriction and 1 as a regional policy that restricts an entire city of countries. The lockdown data is different for Spain and THE UK; that’s why the spam of time series is different for both countries. The lockdown was imposed on 23 March 2020, in Spain, so all data series contains data from 23 March 2020 to 31 December 2020, while lockdown was strictly imposed on

the UK on 14 March 2020, so data series of the UK covering data from 23 March 2020 to 31 December 2020. The data series are synchronized to get accurate results by employing divergent econometric methods. Data on carbon emission has been extracted from <https://www.icos-cp.eu/gcp-covid> 19 and daily new cases and deaths obtained from the WHO ([www.who.int/](http://www.who.int/)) while data of lockdown duration from the following websites <https://www.ijidonline.com> and <https://commonslibrary.parliament.uk>.

In this research, different econometrics tools and techniques are used to determine the relationship among CO<sub>2</sub> emission, daily new confirm cases, daily new confirm the death, and lockdown for Spain and the UK. A flow chart of methodology can be visualized in Fig. 1, which is employed for the analytical relational purpose of variables. The augmented Dickey–Fuller (ADF) is implemented to detect the presence of unit root in the data series. The lag selection is preceded based on different criteria. After confirming stationarity of data series on the same order, the Johansen cointegration test is employed to check the long-run relationship among CO<sub>2</sub> emission, lockdown, new daily cases, and death of COVID-19 in Spain and the UK. The vector error correction model (VECM) has been implemented to measure short-run relationships and the speed of adjustment from the short- to the long-run in individual variables. Last but not the least, the Granger causality test is used to point out the casual direction, effect, and relationship between variables. Furthermore, it’s declared cause and effect of every couple of variables.

**Fig. 1** Methodological flow chart



**Unit root test**

The unit root test measures the chronological integration of variables. The augmented Dickey–Fuller is renowned for determining the integration order of variables. This research employed ADF for the unit root test due to its accuracy and high support from existing literature. The fundamental equation of ADF is given below:

$$\Delta Y_t = \alpha + \beta_t + \rho Y_{t-1} + \sum_{i=1}^k \gamma_i \Delta Y_{t-1} + e_t \tag{1}$$

$\Delta Y_t = Y_t - Y_{t-1}$  and  $\Delta Y_{t-1} = Y_{t-1} - Y_{t-2}$

In Eq. 1, the sign of delta ( $\Delta$ ) measures a change of variables from one period of time to another period ( $t$ ). Fluctuation of time period is usually based on analytical data intervals, i.e., daily, monthly, quarterly, biannually, and annually. In this research, daily data series are used for analytical purposes, so variables’ behavior and their change are based on the daily variation. It is assumed that  $Y_t = (Y_{1t} Y_{2t} Y_{3t} \dots Y_{kt})$  is as  $k$ -dimensional stochastic time series as well as  $y_t \sim I(1)$ , each  $y_{it} \sim I(1)$ ,  $i = 1, 2, 3 \dots, k$ . The sign of alpha ( $\alpha$ ), beta ( $\beta$ ), and rho ( $\rho$ ) are indicators of constant, coefficient of time trend, and several lags, respectively. The first two terms, alpha ( $\alpha$ ) and beta ( $\beta$ ), are part of unit root calculations, and rho ( $\rho$ ) are included later to test the significance of the coefficient (MacKinnon et al. 1999; Ntshangase et al. 2016). The selection of lags is empirically determined by using log-likelihood (LL), likelihood ratio (LR), final prediction error (FPE), Akaike information criterion (AIC), Schwarz information criterion (SC), and the Hannan–Quinn information criterion (HQ) (Hatemi and Hacker 2009; Ivascu et al. 2021). After possible removal of autocorrelation among error terms and selection or rejection of null hypothesis, it can be decided either unit root present in data series (reject  $H_0$ ) or data series are stationary (accept  $H_1$ ).

**Cointegration test**

The cointegration test is generally employed to measure the long-run relationship between variables with a linear combination of variables. This research used the Johansen cointegration test, which will approve the stability and long-run relationship of variables. It is assumed that  $Y_t = (Y_{1t} Y_{2t} Y_{3t} \dots Y_{kt})$  is as  $k$ -dimensional stochastic time series (Jian et al. 2019; Jisheng and Hao 2011; Zou 2018) as well as  $y_t \sim I(1)$ , each  $y_{it} \sim I(1)$ ,  $i = 1, 2, 3 \dots, k$  is influenced by exogenous time series of  $d$ -dimension  $x_t = x_{1t} x_{2t} x_{3t} \dots x_{dt}$  than following equation of the VAR model is established:

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \dots + A_p y_{t-p} + Bx_t + \mu_t \tag{2}$$

If the VAR model has shown affected time series by exogenous time series of  $d$ -dimension  $x_t = x_{1t} x_{2t} x_{3t} \dots x_{dt}$  so the cointegration model will be

$$\Delta Y_t = \Pi_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-1} + Bx_t + \mu_t \tag{3}$$

$$\Pi = \sum_{i=1}^p A_i - I \text{ and } \Gamma_i = - \sum_{i=t+1}^p A_j$$

The adjusted disequilibrium matrix is indicated by  $\Pi$  and short-term dynamic adjustment represented by  $\Gamma$  in Eq. 2. The stacking coefficient  $A$  is boosted up endogenous factors’ speed of change counter to disequilibrium. This test’s null hypothesis ( $H_0$ ) has shown cointegration among variables, and the alternative hypothesis ( $H_1$ ) indicated the presence of integration among data series.

If  $y_t$  is not influenced by exogenous time series of  $d$ -dimension  $x_t = x_{1t} x_{2t} x_{3t} \dots x_{dt}$ , so the equation of the VAR model will be changed and written as

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \dots + A_p y_{t-p} + \mu_t \tag{4}$$

In Eq. 2, the term  $Bx_t$  is used for an exogenous variable in case of “no effect of exogenous;” it will be removed from the model equation or say that its worth will be zero. After removal of  $Bx_t$ , Eq. 4 will be an accurate picture of the model. If we use the equation for cointegration transformation of formula, we will get the following formula for cointegration:

$$\Delta Y_t = \Pi y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-1} + \mu_t \tag{5}$$

**Vector error correction model**

The causality direction of the selected set of independent and dummy variables is determined by employing the vector error correction model. The cointegration relationship of variables is confirmed the implication of VECM is valid and takes the results toward an accurate direction. The VECM framework is structured as follows:

$$\begin{bmatrix} \Delta LD - 1_t \\ \Delta NC - 2_t \\ \Delta ND - 3_t \end{bmatrix} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} + \begin{bmatrix} d_{11m} d_{12m} d_{13m} d_{14m} \\ d_{21m} d_{22m} d_{23m} d_{24m} \\ d_{31m} d_{32m} d_{33m} d_{34m} \end{bmatrix} \times \begin{bmatrix} \Delta LD - 1_{t-1} \\ \Delta NC - 2_{t-1} \\ \Delta ND - 3_{t-1} \end{bmatrix} + \dots + \begin{bmatrix} d_{11m} d_{12m} d_{13m} d_{14m} \\ d_{21m} d_{22m} d_{23m} d_{24m} \\ d_{31m} d_{32m} d_{33m} d_{34m} \end{bmatrix} \times \begin{bmatrix} \Delta LD - 1_{t-1} \\ \Delta NC - 2_{t-1} \\ \Delta ND - 3_{t-1} \end{bmatrix} + \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{bmatrix} (ECM_{t-1}) + \begin{bmatrix} \epsilon_{1t} \\ \epsilon_{2t} \\ \epsilon_{3t} \end{bmatrix} \tag{6}$$

where the coefficients  $\lambda_1 - \lambda_3$  are indicated the error correction term, the homoscedastic disturbance term is denoted by  $\epsilon_{1t} - \epsilon_{3t}$ , and  $ECM_{t-1}$  represents long-run equilibrium and speed of adjustment. In the above matrix of VECM, each combination is an error correction model.

**Granger causality test**

The Granger causality test determines the causality relationship of  $X$  and  $Y$  by following two fundamental principles, i.e., the cause happens before its effect, and the cause has *unique* information about the future values. The combination and influence of variable  $X$  that evolves as per time Granger cause another sprouting variable  $Y$ . The predicted value of  $Y$  based on its past values and  $X$ 's previous values is better than  $Y$ 's prediction based only on  $Y$ 's past values. The following equation estimates the Granger causality test:

$$X_t = \alpha_0 + \sum_{j=1}^k \alpha_{1s} X_{t-s} + \sum_{i=1}^m \alpha_{2i} Y_{t-m} + \epsilon_{1t} \tag{7}$$

$$Y_t = \beta_0 + \sum_{j=1}^n \beta_{1j} Y_{t-j} + \sum_{h=1}^p \beta_{2h} X_{t-h} + \epsilon_{2t} \tag{8}$$

Both error terms ( $\epsilon_{1t}, \epsilon_{2t}$ ) of Eqs. 5 and 6 are uncorrelated with each other as  $E(\epsilon_{1t}, \epsilon_{2t}) = 0 = E(\epsilon_{2t}, \epsilon_{1s}) \dots s \neq t$ . The unidirectional causality from CO<sub>2</sub> emission to new confirmed cases and newly confirmed deaths and lockdown as a dummy variable has shown in the equation. If estimated coefficient  $\alpha_{2i}$  is statistically significant, so  $\alpha_{2i} \neq 0$  then  $Y \rightarrow$  Grangercauses  $\rightarrow X$  and vice versa for  $Y$  variables ( $\beta_{2h} \neq 0$ ). The significance of  $\alpha_{2i}$  and  $\beta_{2h}$  is confirmed mutual dependency of two specific variables. The terms  $Y$  and  $X$  will be independent if the  $\alpha_{2i}$  and  $\beta_{2h}$  are not other than zero.

**Empirical results**

Table 1 presents the summary of the unit root test for Spain and the UK. The CO<sub>2</sub> emission as a dependent and lockdown, daily new confirmed cases, and deaths of COVID-19 as independent variables have shown their significance at 1% level at first difference. The endogenous and exogenous variables have failed to reject the null hypothesis at a level (Ivascu et al 2021; Naseem et al. 2021a, b; Sarfraz et al. 2021; Mohsin et al. n.d). The first column of the table after abbreviations of variable contains unit root integration order. The symbolical word ‘‘I’’ is used for integration, and digits 0 and 1 are considered level and first difference, respectively. After employing the ADF test on Spain and the UK data series, variables confirmed their significance at the first difference, essential for applying the cointegration test.

Table 2 contains the VAR lag order selection criterion in which the appropriate lag selection process has been done. The lag order selection criteria for the UK and Spain are supported lag 4 because lag 4 has been confirmed by 4/6 criteria, i.e., likelihood ratio, final prediction error, Akaike

**Table 1** Summary, unit root test

Variables	Unit root test	UK		Spain	
		Augmented Dickey–Fuller (ADF) test		Augmented Dickey–Fuller (ADF) test	
		<i>t</i> stats	<i>P</i> value	<i>t</i> stats	<i>P</i> value
CO <sub>2</sub>	I (0)	–2.0266	(0.2754)	–2.46435	(0.1254)
	I (1)	–3.86613*	(0.0026)	–3.38861*	(0.0122)
LD	I (0)	–1.42523	(0.5699)	–1.52756	(0.5184)
	I (1)	–16.7332*	(0.000)	–17.000*	(0.000)
NC	I (0)	3.403021	(1.000)	–1.33818	(0.6123)
	I (1)	–14.6069*	(0.000)	–4.79123*	(0.0001)
ND	I (0)	–2.39405	(0.1444)	–1.85364	(0.3541)
	I (1)	–4.01553*	(0.0016)	–11.6506*	(0.000)

\*, \*\*, and \*\*\* are representative of 1%, 5%, and 10% level of significance, respectively

information criterion, and Hannan–Quinn information criterion (Hatemi and Hacker 2009; Ivascu et al. 2021; Mohsin et al., n.d). The lag 3 is selected by Schwarz information criteria has chosen lag 3 as a suitable lag for both countries.

The results of the cointegration test are presented in Table 3. The cointegration test is generally run to check the long-run relationship among variables. The Johansen cointegration test further elaborates the trace test and max eigenvalues. The trace test strongly rejected the null hypothesis  $r = r^* < k$  and accepted the alternative hypothesis  $r = k$ . The null hypothesis of max eigenvalues is similar to the null hypothesis of trace test, but the alternative is  $r = r^* + 1$ . The significance and cointegration confirmation have been done under none with trace test value 58.57448 for the UK and 57.48816 for Spain at a 1% significance level. The maximum eigenvalues are also significant under the none condition. The max eigenvalue of the UK is 37.85666 and 29.50804 for Spain as well as both are significant at 1% and 5% levels, respectively.

In Table 4, the results of log-likelihood ratio-based cointegration equation results are displayed, generated by utilizing the trace and max eigenvalues test results. In this process, the linear combination between the UK, Spain, and the selected variables is individually scrutinized from the cointegration equation. This cointegration equation can recheck the long-run relationship among variables. The cointegration equation confirms the long-run relationship, but the relationship’s nature is mixed, i.e., negative and positive. The new confirmed death cases and the lockdown have shown positive, while new confirmed cases of COVID-19 show a negative trend toward CO<sub>2</sub> emission in the UK and Spain.

The results of the vector error correction model are presented in Table 5 and Table 6. Table 5 contains the results of the UK. The VECM elaborates the short- and long-run

**Table 2** VAR lag order selection criteria

UK						
Lag	Log L	LR	FPE	AIC	SC	HQ
1	-4641.87	NA	$3.03 \times 10^{9a}$	33.1848	33.23673	33.20563
2	-3044.3	3138.083	37,661.21	21.88788	22.14751	21.99202
3	-2859.49	357.7546	11,278.09	20.68204	21.14937*	20.86948
4	-2826.32	63.24769*	9978.611*	20.55944*	21.23447	20.83020*
Spain						
Lag	Log L	LR	FPE	AIC	SC	HQ
1	-4763.77	NA	$2.51 \times 10^{9a}$	32.99495	33.0457	33.01529
2	-3462.38	2557.755	343,864.7	24.0995	24.35323	24.20117
3	-3264.71	383.0161	97,819.79	22.84231	23.29903*	23.02531
4	-3248.44	31.0778*	97,652.49*	22.84044*	23.50014	23.10478*

\* indicates lag order selected by the criterion  
 LR, sequential modified LR test statistic (each test at 5% level)  
 FPE, final prediction error  
 AIC, Akaike information criterion  
 SC, Schwarz information criterion  
 HQ, Hannan–Quinn information criterion  
 a represents the value in exponential form

**Table 3** Unrestricted cointegration rank test (trace) and max eigen statistics

A					
UK					
Hypothesized No. of CE(s)	Eigenvalue	Trace statistic	Critical value (0.05)	Prob.**	
None *	0.12604	58.57448	47.85613	0.0036	
At most 1	0.039158	20.71781	29.79707	0.3755	
At most 2	0.029629	9.493072	15.49471	0.3217	
At most 3	0.003699	1.041484	3.841466	0.3075	
Spain					
Hypothesized No. of CE(s)	Eigenvalue	Trace statistic	Critical value (0.05)	Prob.**	
None *	0.097384	57.48816	47.85613	0.0048	
At most 1	0.072374	27.98013	29.79707	0.0798	
At most 2	0.015669	6.34375	15.49471	0.6549	
At most 3	0.006215	1.795471	3.841466	0.1803	
B					
UK					
Hypothesized No. of CE(s)	Eigenvalue	Max eigen statistic	Critical value (0.05)	Prob.**	
None *	0.12604	37.85666	27.58434	0.0017	
At most 1	0.039158	11.22474	21.13162	0.6249	
At most 2	0.029629	8.451588	14.2646	0.3346	
At most 3	0.003699	1.041484	3.841466	0.3075	
Spain					
Hypothesized No. of CE(s)	Eigenvalue	Max eigen statistic	Critical value (0.05)	Prob.**	
None *	0.097384	29.50804	27.58434	0.028	
At most 1*	0.072374	21.63638	21.13162	0.0425	
At most 2	0.015669	4.548279	14.2646	0.7974	
At most 3	0.006215	1.795471	3.841466	0.1803	

\*, \*\*, and \*\*\* are representative of 1%, 5%, and 10% level of significance, respectively

**Table 4** Normalized cointegration coefficient

UK			
CO <sub>2</sub>	LD	NC	ND
1.000	0.046284	$-2.54 \times 10^{-06a}$	0.000301
Standard error	-0.02243	$-9.30 \times 10^{-07a}$	$-4.30 \times 10^{-05a}$
Log-likelihood	-2845.684		
Spain			
CO <sub>2</sub>	LD	NC	ND
1.000	0.038358	$-8.34 \times 10^{-06a}$	0.000257
Standard error	-0.01722	$-1.30 \times 10^{-06a}$	$-3.70 \times 10^{5a}$
Log-likelihood	-3187.462		

*a* represents the value in exponential form

relationship with the causal direction of relationship among variables individually. The carbon dioxide emission at the 3rd difference is unidirectionally related to lockdown  $CO_{23} \rightarrow LD_3 \neq CO_{23}$  with a negative sign at a 1% level of significance. The negative sign of CO<sub>2</sub> value -4.647136 shows that strict lockdown becomes the reason for CO<sub>2</sub> emission reduction (Andreoni, 2021). A bidirectional relationship between lockdown and CO<sub>2</sub> emission  $LD \leftrightarrow CO_2$  is also observed at the 4th difference with a 1% level of significance. The new confirmed cases of COVID-19 have a unidirectional relationship  $NC \rightarrow CO_2$  with CO<sub>2</sub> emission at a 1% significance level. A bidirectional relationship between new confirmed cases and newly confirmed deaths

$NC_1 \leftrightarrow ND_1, NC_4 \leftrightarrow ND_4$  is orderly 10% and 1% level significance at the 1st and 4th difference. New confirmed cases and new confirmed death of COVID-19 complement each other as if the new confirmed cases were going to increase, and the death rate undoubtedly is increased. The rapidly growing death rate increases the chances of caring staff, medical staff, and family members indulging in pandemics and becoming new prey of COVID-19. The new confirmed cases with the 2nd difference  $NC_2 \rightarrow ND \neq NC_2$  of new deaths and CO<sub>2</sub> emission with the 3rd and 4th  $NC_2 \rightarrow CO_2 \neq NC_2, NC_3 \rightarrow CO_2 \neq NC_3$  the difference have a unidirectional relationship with a 10% level of significance. The newly confirmed deaths have shown a unidirectional relationship with lockdown  $ND_1 \rightarrow LD_1 \neq ND_1$  at 10% level with the first difference. At the 2nd difference, new death cases unidirectional related to CO<sub>2</sub> emission and lockdown  $ND_2 \rightarrow CO_{22} \neq ND_2, ND_2 \rightarrow LD_2 \neq ND_2$  at 10% and 5% levels of significance. All series except new cases also confirm the long-run relationship. The CO<sub>2</sub> emission, lockdown, and new deaths are significant at a 1% level for the long-run.

In Table 6, the extracted results of short- and long-run for Spain by using VECM are presented. Approximately 93.7% of total CO<sub>2</sub> emissions in Spain and megalopolitan countries were changed due to close manufacturing, wholesale, retail trade, transport accommodation, food services sector, air aviation, etc. This research and analytical theories also supported a valuable decrease in CO<sub>2</sub> emission

**Table 5** Vector error correction

UK					
The direction of causality					
Short-run					Long-run
Error correction	$\Delta CO_2$	$\Delta LD$	$\Delta NC$	$\Delta ND$	$ECT_{t-1}$
$\Delta CO_2 - 1$	—	-0.710272	-23,077.64	-2130.565	-0.01797*
$\Delta CO_2 - 2$		-0.286349	18,870.38	744.4784	
$\Delta CO_2 - 3$		-4.647136*	-42,938.45	82.80758	
$\Delta CO_2 - 4$		5.624084*	15,289.37	1710.764	
$\Delta LD - 1$	-0.00139	—	-494.2641	-13.21327	-0.34803*
$\Delta LD - 2$	-0.001554		1019.854	50.44897	
$\Delta LD - 3$	-0.002222		-2155.267	-125.9419	
$\Delta LD - 4$	0.00841*		30.47237	-40.34469	
$\Delta NC - 1$	$-2.80 \times 10^{-07*}$	$1.30 \times 10^{-06}$	—	0.006845***	3330.262
$\Delta NC - 2$	$8.01 \times 10^{-08}$	$-1.10 \times 10^{-07}$		0.006875***	
$\Delta NC - 3$	$-1.87 \times 10^{-07***}$	$-2.80 \times 10^{-06}$		-0.003439	
$\Delta NC - 4$	2.03E-07***	$-4.48 \times 10^{-07}$		-0.014625*	
$\Delta ND - 1$	$2.37 \times 10^{-06}$	$7.54 \times 10^{-05***}$	2.547087*	—	-667.4155*
$\Delta ND - 2$	$3.58 \times 10^{-06***}$	$8.89 \times 10^{-05**}$	0.371543		
$\Delta ND - 3$	$4.55 \times 10^{-07}$	$3.29 \times 10^{-05}$	-1.458602		
$\Delta ND - 4$	$1.73 \times 10^{-06}$	$7.90 \times 10^{-06}$	-2.021548***		

\*, \*\*, and \*\*\* are representative of 1%, 5%, and 10% level of significance, respectively



**Table 6** Vector error correction

Spain					
The direction of causality					
Short-run					Long-run
Error correction	$\Delta CO_2$	$\Delta LD$	$\Delta NC$	$\Delta ND$	
$\Delta CO_2 - 1$	—	419,220.8***	-0.455668	7604.837	-0.007557*
$\Delta CO_2 - 2$		-387,672	0.232926	-8121.872	
$\Delta CO_2 - 3$		80,601.95	0.1862	1489.406	
$\Delta CO_2 - 4$		-143,616.9	0.92957	2673.107	
$\Delta LD - 1$	$9.52 \times 10^{-05}$	—	0.000306	39.69086	-0.24102***
$\Delta LD - 2$	$4.78 \times 10^{-05}$		0.001335	8.238611	
$\Delta LD - 3$	-0.000356		-0.002994	-635.4066*	
$\Delta LD - 4$	-0.000313		-0.02291	38.13858	
$\Delta NC - 1$	$-6.21 \times 10^{-08}$ *	-0.805239*	—	-0.004939***	15,929.91
$\Delta NC - 2$	$-6.57 \times 10^{-08}$ *	-0.684711*		0.000175	
$\Delta NC - 3$	$-5.95 \times 10^{-08}$ *	-0.319294*		0.001358	
$\Delta NC - 4$	-0.000313	-3825.053		38.13858	
$\Delta ND - 1$	$1.75 \times 10^{-06}$ **	-2.981155	$3.39 \times 10^{-05}$	—	-1104.53*
$\Delta ND - 2$	$1.95 \times 10^{-06}$ *	-2.636716	$2.59 \times 10^{-05}$		
$\Delta ND - 3$	$2.77 \times 10^{-06}$	-6.425729	$1.75 \times 10^{-05}$		
$\Delta ND - 4$	$-1.13 \times 10^{-07}$	-10.91057	$4.95 \times 10^{-06}$		

\*, \*\*, and \*\*\* are representative of 1%, 5%, and 10% level of significance, respectively. *a* represents the value in exponential form

during the pandemic spread out. The carbon dioxide emission and the lockdown have shown a unidirectional relationship  $CO_{21} \rightarrow LD_1 = CO_{21}$  at 1% level of significance. The lockdown with the 3rd difference at 1% level unidirectionally interlinked with new deaths  $LD \rightarrow ND \neq LD$ . The new confirmed cases have confirmed a unidirectional relationship with  $CO_2$ ,  $ND$ ,  $CO_{21}$ ,  $LD$ ,  $CO_{22}$ , and  $LD$  with the 1st, 2nd, and 3rd difference  $NC_1, NC_2 \rightarrow CO_{22} \neq NC_2, NC_1 \rightarrow LD_1 \neq NC_1, NC_3 \rightarrow CO_{23} \neq NC_3$  at 1% level of significance. The new confirmed cases and lockdown have bidirectional relationship  $NC \leftrightarrow LD$  at the 1st difference and 1% level of significance. With the 2nd difference, new death cases have a relationship with  $CO_2$   $ND_2 \rightarrow CO_{22}$  at 1% level of confidence. The long-run relationship is confirmed by  $CO_2$  emission, lockdown, and new death cases at 1%, 10%, and 5%, respectively (Naseem et al. 2020; Mohsin et al. 2021a).

Table 7 contains the Granger causality test results, which investigate causality between variables in a time series. The Granger causality test cross-checks the directional causalities of Tables 5 and 6. The correlation patterns are founded by using empirical data set and checking probabilistic accounts of causalities. For the UK, lockdown, new confirmed cases of COVID-19, and total independent variables are inveterate the relationship by showing significance at a 1% level. The newly confirmed deaths are not significant in cross-check results because the death rate is probably based on new confirmed cases.

**Table 7** Granger causality test

UK			
Direction of causality	df	Chi-square	Prob
LD	4	11.51397*	0.0214
NC	4	15.39391*	0.004
ND	4	4.633779	0.327
ALL	12	31.50618*	0.0016
Spain			
Direction of causality	df	Chi-square	Prob
LD	4	7.870521**	0.0464
NC	4	0.119544	0.9983
ND	4	26.51612*	0.000
ALL	12	27.39405*	0.0068

\*, \*\*, and \*\*\* are representative of 1%, 5%, and 10% level of significance, respectively

This pandemic is spreading out and not getting proper medical treatment yet, but we cannot say that it will remain the same for all the periods. The medical staff worldwide is still working on finding a proper treatment or vaccine as the death rate is reduced in numbers. In the case of Spain, only new cases are insignificant. The explanation of new cases insignificance is also the same as new deaths for the UK. The scientist will find the proper treatment and get a

vaccination, so both new confirmed cases and newly confirmed deaths will be reduced to their extent.

## Discussion

The high energy consumption rate in daily transport, trade, industrial activities, and others is the major sources of CO<sub>2</sub> emission (Naseem et al. 2021a, b; Mohsin et al. 2021b). The stationarity of the data series is checked by the augmented Dickey–Fuller test, which confirmed the stability of the data series for the UK and Spain at the first difference (Rume and Islam, 2020; Amankwah-Amoah, 2020; Ozturk et al., 2021). The stationarity corroboration of data series makes them accurate to run the cointegration test because the significance of all variables at first difference is the basic condition for applying the cointegration test. In the lag selection process, lag 4 was good to fit for both countries. The cointegration test also verified the long-run cointegration among variables. The directional causality findings of the UK were the carbon dioxide emission at the 3rd difference unidirectionally related to lockdown with a negative sign at the 1% level of significance. The negative sign of CO<sub>2</sub> value  $-4.647136$  shows that strict lockdown becomes the reason for CO<sub>2</sub> emission reduction. A bidirectional relationship between lockdown and CO<sub>2</sub> emission is also observed at the 4th difference with 1% level of significance. The new confirmed cases of COVID-19 have a unidirectional relationship with CO<sub>2</sub> emission at 1% significance level. A bidirectional relationship between new confirmed cases and newly confirmed deaths orderly is 10% and 1% level significance at the 1st and 4th difference. New confirmed cases and new confirmed death of COVID-19 complement each other as if the new confirmed cases were going to increase; the death rate will surely increase (Abbasi et al. 2021; Long and Li 2021).

The rapidly growing death rate increases the chances of caring staff, medical staff, and family members indulging in pandemic and becoming new prey of COVID-19. The new confirmed cases with the 2nd difference of new deaths and CO<sub>2</sub> emission with the 3rd and 4th difference have a unidirectional relationship with at 10% level of significance. The newly confirmed deaths have shown a unidirectional relationship with a lockdown at 10% level with a first difference. At the 2nd difference, new death cases are unidirectionally related to CO<sub>2</sub> emission and lockdown at 10% and 5% significance levels. The long-run relationship is also confirmed by all series except new cases (Mohsin et al. 2021a). The CO<sub>2</sub> emission, lockdown, and new deaths are significant at 1% level for the long-run. The directional relationship of variables for Spain was the carbon dioxide emission and lockdown have shown a unidirectional relation at 1% significance level (Rume and Islam 2020; Amankwah-Amoah

2020; Ozturk et al. 2021). The lockdown with the 3rd difference at the 1% level unidirectionally interlinked with new deaths. The new confirmed cases have confirmed a unidirectional relationship with CO<sub>2</sub>, ND, CO<sub>2</sub>, LD, CO<sub>2</sub>, and LD with the 1st, 2nd, and 3<sup>rd</sup> difference at the 1% level of significance. The new confirmed cases and lockdown have a bidirectional relationship at the 1st difference and 1% significance level (Rehman et al. 2021a, b). With the 2nd difference, new death cases have a relationship with CO<sub>2</sub> at 1% level of confidence. The long-run relationship is confirmed by CO<sub>2</sub> emission, lockdown, and new death cases at 1%, 10%, and 5%, respectively.

## Conclusion

This research explored the effect of COVID-19 on CO<sub>2</sub> emission reduction and producing cleaning air with fewer pollutant particles. In this study, we focused on the UK and Spain for analytical purposes. The daily data series of CO<sub>2</sub> emissions, lockdowns, newly confirmed cases, and newly confirmed deaths were selected for analysis. Econometric tools and techniques were employed to check the hypothetical relation among the dependent and independent variables. For example, gasoline consumption dramatically decreased in the specific time span of COVID-19 due to air aviation restrictions. The ADF test confirms the stability of the data series. It makes it possible to run a cointegration test because the significance of all variables at the first difference is the primary condition to apply the cointegration test. The lag selection criterion has selected the 4th lag, which confirms the fitness of the chosen model for the UK and Spain. The cointegration test authenticates the long-run relationship among variables selected. The VEC model shows a bidirectional relationship between CO<sub>2</sub> emissions and lockdowns and a unidirectional relationship with newly confirmed cases and new deaths for the UK. The results of Spain confirmed the unidirectional relationship of CO<sub>2</sub> emissions, lockdowns, newly confirmed cases, and deaths. The Granger causality test reconfirms the relationship among variables. The findings of Granger causality have shown the insignificance of newly confirm deaths for the UK and newly confirmed cases for Spain, while both countries' results strongly supported the relationship between lockdowns and CO<sub>2</sub> emissions.

The pandemic directly caused the world's activities to come to a near-standstill of shutdown or strictly prohibited daily activities. Conferences, parties, official and unofficial gatherings, and travel of all types ceased at that specific time. In the very curtailed situation of lockdown and the growing rate of death from COVID-19, the emission of carbon dioxide dramatically decreased all over the world. The refining level of breathing air was improving and becoming cleaner during the pandemic. As per data coverage, our findings are focused on the UK and Spain, but the results of this

research are comprehensive in nature and broadly applicable across much of the developed world.

This research highlights some key points learned during the COVID-19 crisis. A sustainable environment is most important for human survival and preparedness. In this specific period, global environmentalists, policymakers, and states realized that different shutdowns are necessary to breaking the chain of future pathogenic diseases, with environmental sustainability and healthy ecosystems being key preventers of outbreaks in the first place. This research also elucidated the link between the human response to COVID-19 and reduction in greenhouse gases emission. The situation made clear that the carbon footprint can be minimized by reducing unnecessary travel. Globally, this is a time to analyze our daily activities and be global citizens to fight against pollutions and eco-unsustainability. We should realize that this is not the first pathogen nor the last to which all of humanity will be vulnerable due to compromising on the protection of the environment and wildlife. A sustainable environment must be achieved to avoid future pandemics, and the lessons learned from COVID-19 regarding greenhouse gas emissions can inform this effort.

**Author contribution** Conceptualization, Muddassar Sarfraz and Muhammad Mohsin; methodology, Sobia Naseem; formal analysis and investigation, Muddassar Sarfraz and Sobia Naseem; writing—original draft preparation, Muhammad Mohsin; writing—review and editing, Muddassar Sarfraz; funding acquisition, Muhammad Mohsin; resources, Sobia Naseem; supervision, Muddassar Sarfraz. All authors approved the current study.

**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate** All procedures performed were in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standard.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

- Abbasi KR, Hussain K, Noureen RS, Bashir U (2021) Linking protective strategies effects to manage the COVID-19 risk on global environment: fresh evidence from the best responsive approach. *Int J Energy Econ Policy* 11(5):389–401
- Amankwah-Amoah J (2020) Stepping up and stepping out of COVID-19: new challenges for environmental sustainability policies in the global airline industry. *J Clean Prod* 271:123000. <https://doi.org/10.1016/j.jclepro.2020.123000>
- Andreoni V (2021) Estimating the European CO<sub>2</sub> emissions change due to COVID-19 restrictions. *Sci Total Environ* 769:145115. <https://doi.org/10.1016/j.scitotenv.2021.145115>
- Azhar EI, Hui DSC, Memish ZA, Drosten C, Zumla A (2019) The Middle East respiratory syndrome (MERS). *Infect Dis Clin North Am* 33:891–905. <https://doi.org/10.1016/j.idc.2019.08.001>
- Briz-Redón Á, Belenguer-Sapiña C, Serrano-Aroca Á (2021) Changes in air pollution during COVID-19 lockdown in Spain: a multi-city study. *J Environ Sci* 101:16–26
- Cárcel-Carrasco J, Pascual-Guillamón M, Langa-Sanchis J, (2021) Analysis of the effect of COVID-19 on air pollution: perspective of the Spanish case. *Environ Sci Pollut Res* 1–14.
- Corman VM, Muth D, Niemeyer D, Drosten C (2018) Hosts and sources of endemic human coronaviruses. *Adv Virus Res* 100:163–188. <https://doi.org/10.1016/bs.aivir.2018.01.001>
- Hatemi AJ, Hacker SR (2009) Can the LR test be helpful in choosing the optimal lag order in the VAR model when information criteria suggest different lag orders? *Appl Econ* 41:1121–1125. <https://doi.org/10.1080/000368406011019273>
- Higham JE, Ramírez CA, Green MA, Morse AP (2021) UK COVID-19 lockdown: 100 days of air pollution reduction? *Air Qual. Atmos Heal* 14:325–332
- Huang T, Zhu X, Zhong Q, Yun X, Meng W, Li B, Ma J, Zeng EY, Tao S (2017) Spatial and temporal trends in global emissions of nitrogen oxides from 1960 to 2014. *Environ Sci Technol* 51:7992–8000. <https://doi.org/10.1021/acs.est.7b02235>
- Hui DSC, Zumla A (2019) Severe acute respiratory syndrome: historical, epidemiologic, and clinical features. *Infect Dis Clin* 33:869–889
- Ivascu L, Sarfraz M, Mohsin M, Naseem S, Ozturk I (2021) The causes of occupational accidents and injuries in Romanian firms: an application of the Johansen cointegration and Granger causality test. *Int J Environ Res Public Health* 18:7634. <https://doi.org/10.3390/ijerph18147634>
- Jian J, Fan X, He P, Xiong H, Shen H (2019) The effects of energy consumption, economic growth and financial development on CO<sub>2</sub> emissions in China: a VECM approach. *Sustainability* 11:4850
- Jisheng M, Hao H (2011) Based on the VAR (vector auto regression) dynamic analysis on the dynamic analysis the relationship between carbon emission and economic growth in China based on VAR. *Inq into Econ Issues* 5:20–25
- Long H, Li W (2021) Does COVID-19 pandemic impact on China's economy structure and sustainability of deep economic determinants? *Int J Econ Financ Issues* 11(3):81–88
- MacKinnon JG, Haug AA, Michelis L (1999) Numerical distribution functions of likelihood ratio tests for cointegration. *J Appl Econom* 14:563–577
- Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E (2020) Environmental and health impacts of air pollution: a review. *Front Public Heal* 8:14
- Mohsin M, Naseem S, Zia-ur-Rehman M, Baig SA, Salamat S (n.d.) The crypto-trade volume, GDP, energy use, and environmental degradation sustainability: an analysis of the top 20 crypto-trader countries. *Int J Financ Econ*.
- Mohsin M, Zhu Q, Naseem S, Sarfraz M, Ivascu L (2021a) Mining industry impact on environmental sustainability, economic growth, social interaction, and public health: an application of semi-quantitative mathematical approach. *Processes* 9(6):972
- Mohsin M, Naseem S, Sarfraz M, & IVASCU L (2021b) COVID-19 and greenhouse gas (GHG) emission mitigation: modelling the impact on environmental sustainability and policies. *Front Environ Sci* 450.
- Naseem S, Mohsin M, Zia-UR-Rehman M, Baig SA, & Sarfraz M (2021a) The influence of energy consumption and economic

- growth on environmental degradation in BRICS countries: an application of the ARDL model and decoupling index. *Environ Sci Pollut Res* 1–14.
- Naseem S, Fu GL, Mohsin M, Rehman MZU, Baig SA (2020) Semi-quantitative environmental impact assessment of Khewra Salt Mine of Pakistan: an application of mathematical approach of environmental sustainability. *Mining, Metallurgy & Exploration* 37:1185–1196
- Ozturk I, Aslan A, & Altinoz B (2021b) Investigating the nexus between CO2 emissions, economic growth, energy consumption and pilgrimage tourism in Saudi Arabia. *Economic Research-Ekonomska Istraživanja*, 1–16.
- Naseem S, Mohsin M, Hui W, Liyan G, Penglai K (2021b) The investor psychology and stock market behavior during the initial era of COVID-19: a study of China, Japan, and the United States. *Front Psychol* 12:16
- Ntshangase K, Mingiri KF, Palesa MM (2016) The interaction between the stock market and macroeconomic policy variables in South Africa. *J Econ* 7:1–20. <https://doi.org/10.1080/09765239.2016.11907815>
- Rehman, A., Ma, H., Ahmad, M., Ozturk, I., & Işık, C. (2021a). Estimating the connection of information technology, foreign direct investment, trade, renewable energy and economic progress in Pakistan: evidence from ARDL approach and cointegrating regression analysis. *Environ Sci Pollut Res* 1–13.
- Rehman A, Ma H, & Ozturk I (2021b) Do industrialization, energy importations, and economic progress influence carbon emission in Pakistan. *Environ Sci Pollut Res* 1–13
- Ritchie H, Mathieu E, Rodés-Guirao L, Appel C, Giattino C, Ortiz-Ospina E, ... Roser M (2020) Coronavirus pandemic (COVID-19). Our world in data
- Rojas, N.Y., Ramírez, O., Belalcázar, L.C., Méndez-Espinosa, J.F., Vargas, J.M., Pachón, J.E., 2021. PM2.5 emissions, concentrations and air quality index during the COVID-19 lockdown. *Environ. Pollut. (Barking, Essex 1987)* 272, 115973.
- Rume T, & Islam SDU (2020) Environmental effects of COVID-19 pandemic and potential strategies of sustainability. *Heliyon*, e04965. <https://doi.org/10.1016/j.heliyon.2020.e04965>
- Sarfraz M, Mohsin M, Naseem S, Kumar A (2021) Modeling the relationship between carbon emissions and environmental sustainability during COVID-19: a new evidence from asymmetric ARDL cointegration approach. *Environ. Dev. Sustain.* 1–19.
- Zhang M, Wan K, Zeng J, Lin W, Ye C, Yu X (2020) Co-selection and stability of bacterial antibiotic resistance by arsenic pollution accidents in source water. *Environ Int* 135:105351. <https://doi.org/10.1016/j.envint.2019.105351>
- Zou X (2018) VECM model analysis of carbon emissions, GDP, and international crude oil prices. *DiscretDyn Nat Soc* 2018 <https://doi.org/10.1155/2018/5350308>

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