Nonlinearity in the relationship between COVID-19 cases and carbon damages: controlling financial development, green energy, and R&D expenditures for shared prosperity

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Abstract

The world faces a high alert of coronavirus disease 2019 (COVID-19), leading to a million deaths and could become infected to reach a billion numbers. A sizeable amount of scholarly work has been available on different aspects of social-economic and environmental factors. At the same time, many of these studies found the linear (direct) causation between the stated factors. In many cases, the direct relationship is not apparent. The world is unsure about the possible determining factors of the COVID-19 pandemic, which need to be known through conducting nonlinearity (indirect) relationships, which caused the pandemic crisis. The study examined the nonlinear relationship between COVID-19 cases and carbon damages, managing financial development, renewable energy consumption, and innovative capability in a cross section of 65 countries. The results show that inbound foreign direct investment first increases and later decreases because of the increasing coronavirus cases. Further, the rise and fall in the research and development expenditures and population density exhibits increasing coronavirus cases across countries. The continued economic growth initial decreases later increase by adopting standardized operating procedures to contain coronavirus disease. The inter-temporal relationship shows that green energy source and carbon damages would likely influence the coronavirus cases with a variance of 17.127% and 5.440%, respectively, over a time horizon. The policymakers should be carefully designing sustainable healthcare policies, as the cost of carbon emissions leads to severe healthcare issues, which are likely to get exposed to contagious diseases, including COVID-19. The sustainable policy instruments, including renewable fuels in industrial production, advancement in cleaner production technologies, the imposition of carbon taxes on dirty production, and environmental certifications, are a few possible remedies that achieve healthcare sustainability agenda globally.

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Introduction

The coronavirus disease 2019 (COVID-19) belongs to the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus strain family. It has infected more than 113 million individuals in more than 200 countries (Worldometer 2021, 27 February 2021). The virus was first identified in Wuhan, Hubei Province, China, at the end of December 2019 and then spread into the whole world in the next few months of the year. The case-fatality ratio today is more than 2% globally. The COVID-19 pandemic affected healthcare expenditures while distressing inbound foreign direct investment (FDI), R&D expenditures, green energy sources, and carbon damages. The COVID-19 cases can be seen in a given map to shows its concentration level that exacerbates infected cases in a cross section of 65 countries on 18 February 2021 (see Fig. 1).

Figure 1 shows the two more significant zones in coronavirus cases in a panel of 65 countries. The dark blue zone shows the higher intensity of infected cases, while the light blue zone shows the lower intensity level of infected cases. The greater number of infected cases was found in the USA with a number of counts of more than 28 million, followed by India, Brazil, Russia, the UK, and France with an infected case of more than 10 million, nearly 10 million, 4 million, 4 million, and 3.4 million approximately, respectively. Few of the light blue zone countries have reported an infected case of nearly 50,000 in Uruguay, more than 32,000 in Cyprus, nearly 25,000 in Thailand, more than 20,000 in Malta, and nearly 19,500 in Madagascar.

The increased cases of COVID-19 further disrupt the flow of FDI, R&D expenditures, green energy sources, and carbon damages. Figure 2 shows the trend analysis of the stated

factors across 65 selected countries for ready reference. It is evident that the US economy only maintains FDI inflows of 1.640% of GDP at the time of the COVID-19 crisis, while India, Brazil, Russia, UK, and France have an inbound FDI of 1.764%, 3.995%, 1.881%, 0.731%, and 1.879%, respectively. Cyprus is the only country in the selected panel with more than 95% of inbound FDI, while its COVID-19 cases are 32,707. Renewable energy consumption is higher in Madagascar, while its COVID-19 cases nearly reach 19,598. Sweden, Austria, and Japan spend a greater sum of money on R&D activities with a value of 3.339%, 3.171%, and 3.264% of GDP, respectively, while the COVID-19 cases are 617,869; 436,139; and 417,765, respectively. Carbon damages are larger in Ukraine, followed by Kyrgyzstan and South Africa with a value of 5.233%, 4.780%, and 4.560% of gross national income (GNI), respectively, while the COVID-19 cases are 1,280,904; 85,619; and 1,494,119, respectively. The trend analysis confirmed that the greater intensity of the COVID-19 cases distresses socio-economic and environmental activities, which need to be stable through sustainable healthcare policies globally.

The role of process innovation played an enormous role in expanding the green economy. The investment in green projects is helpful to mitigate adverse environmental externalities to move towards sustainable outcomes (Awan et al. 2021). Industrial ecology is another critical factor that supports the green developmental agenda, leading to achieving the United Nations sustainable development goals (Awan 2020). Several recent studies confirmed the viability of green technologies in improving environmental quality levels (see Ullah et al. 2021; Gyamfi et al. 2021; Godil et al. 2021). The study aims to assess the changes in the COVID-19 cases due to changes in financial development, innovation, economic growth, and

Fig. 1 COVID-19 cases in 65 most effected countries of the world. Source: Worldometer (2021, 18 February 2021)

Fig. 2 Trend analysis of economic and environmental factors during the COVID-19 pandemic. Source: Worldometer (2021, 18 February 2021 and World Bank (2021). COVID19 CASES show coronavirus cases, FDI shows foreign direct investment inflows, REC shows renewable energy consumption, RND shows research and development expenditures, and CDAM shows carbon damages

population density in a large cross section of 65 countries. It is hypothesized that the stated factors and their square terms help determine the intensity of the COVID-19 cases over time. In line with the study's aim, the following objectives of the study have been made to reach some conclusive findings:

- To examine the nonlinear relationship between the COVID-19 pandemic and carbon damages controlling other economic and environmental factors in the cross section of 65 countries,
- To analyze the rise and fall in the financial development, R&D expenditures, economic growth, and population density in the time of COVID-19 pandemic, and
- To evaluate the inter-temporal relationship between the factors for the following year's time period.

These objectives are set out in the wide cross-sectional panel of countries to use the switching regression approach and innovation accounting matrix to reach conclusive policy remarks.

Literature review

The study followed the “healthcare signaling theory” concerned with improving healthcare infrastructure to limit coronavirus cases (see Anser et al. 2021b; Chidhau et al. 2021; Popov et al. 2021). In line with the theoretical expectations, the previous studies worked on the linear relationship between different socio-economic and environmental factors and the

COVID-19 pandemic. Simultaneously, there is a considerable gap in evaluating the nonlinearity in the stated factors that allow more in-depth analysis to devise sustainable healthcare policies (Majeed and Ozturk 2020; Rehman et al. 2021; Tarazkar et al. 2021). The study categorizes the following literature to develop the study's hypotheses during the pandemic recession, i.e., financial development, carbon damages, green energy sources, and research and development expenditures. Anser et al. (2020a) reviewed the case fatality ratio in different provinces of Pakistan to assess coronavirus disease vulnerability. The study emphasized the need to increase testing capacity that helps identify the potential prospects of the disease and respond accordingly in early detection. Yu et al. (2021) used the world aggregated data of services value-added. They analyzed the risk factors concerning increasing coronavirus cases, which distress the services sector's contribution relative to the world's GDP. The study suggests that improving information and communication channels, maintaining food prices, and physical distances would help reduce coronavirus cases globally. Anser et al. (2021a) used a large panel of countries to analyze the money supply reaction to the coronavirus disease that is depressed by the strict lockdown measures. The study concludes that financial activities can be stabilized by increasing testing capabilities that would likely give the financial investors the confidence to invest in stock trading to generate economic activities. Dube et al. (2021) argued that the COVID-19 pandemic exerts a high negative impact on the global aviation industry, resulting in severe cash burn and bankruptcy. The aviation industry strives hard to return from

the pandemic by using standardized operating procedures to protect customers' health through compliance safety measures. The aviation industry needs to improve its passengers' and employees' healthcare safety standards, ensure quality standards, and reduce fair charges to run its aviation business smoothly. Albulescu (2021) critically analyze the financial stock volatility by spreading the announcement of the COVID-19 pandemic in the USA. The study argued that financial market volatility is linked to increasing new infected cases and case fatality ratio, which needs extra care and dedicated efforts to sustain financial activities by adopting standardized operating procedures to control the coronavirus disease. Xu (2021) analyzed the stock market response to the COVID-19 pandemic in the USA and Canada. The study found that, in general, an increase in the coronavirus cases decreases stock market capabilities to perform in stock trading. In the USA, uncertainty adversely affects stock trading, leading to disruption in financial activities countrywide. Severo et al. (2021) found that the COVID-19 pandemic dramatically impacts people's change behavior by being more careful in spending on eco-friendly products, buying behavior, and pro-environmental behavior, and being socially responsible. The positive change behavior would help them be more cautious about their health to protect themselves from the contagious disease. A bunch of recent literature is available on different financial factors, and the COVID-19 pandemic that confirmed the volatility in the financial sector remains due to an increase in the different COVID-19 waves. For instance, an increase in cyber risk during the COVID-19 pandemic (Aldasoro et al. 2021), Brexit and the Greece bailout crisis (Adedoyin et al. 2021), risk communication (Ataguba and Ataguba 2020), regulations required in the consumer financing sector (Gębski 2021), stock market returns (Herwany et al. 2021), volatility in the oil prices (Salisu and Obiora 2021), and decline in the aviation transportation (Dube et al. 2021). Based on the current literature, the study hypothesizes the following statement:

H1: There is the likelihood of a rise and fall in financial development because of an increase in the COVID-19 cases across countries.

The direct impact of the COVID-19 pandemic on carbon emissions is widely explored. At the same time, it is less likely to explore the estimated cost of carbon damages concerning increasing COVID-19 cases globally. Thus, this study moves forward to explore the relationship with some controlling factors. The current literature mostly confirmed the relationship between the two stated factors in different economic settings; for instance, Meo et al. (2021) surveyed the various regions of California to assess the different pollutants associated with the wildfires and an increased in the new cases and death rates associated with the coronavirus disease. The results show that

wildfire pollutants are temporarily associated with coronavirus cases and deaths due to increased concentrations of toxic air pollutants. The high need to mitigate toxic air pollutants causing by wildfires need to be controlled for achieving healthcare sustainability in a country. Firozjaei et al. (2021) argued that lockdown measures to control the COVID-19 pandemic improve air quality indicators. More specifically, an improved urban surface ecological status is attained by reducing anthropogenic activities in the urban environment. Ali et al. (2021) surveyed the different provinces of Pakistan to critically review the healthcare and environmental challenges posed by the COVID-19 pandemic. The results show that high carbon damages in a country lead an individual to get respiratory diseases, leading to the high exposure of infection with the coronavirus. Other reasons are the high population density that causes transmitting the disease from one person to another. At the same time, the high exposure of PM_{2.5} concentrations also deteriorates the country's health and wealth, leading to infected coronavirus disease. Healthcare policymakers and environmental specialists should observe the correlation between the stated factors and devise sustainable healthcare policies to control coronavirus cases in a country. Sueyoshi et al. (2021) analyzed the response of COVID-19 on the clean energy system and healthcare insurance in a panel of 33 OECD countries. They found that healthcare insurance outweighs the negative healthcare concerns associated with the COVID-19 pandemic, leading to sustainable energy transition systems across countries. The countries need to improve the healthcare insurance system to respond to contagious diseases and move towards a clean energy transition. Naqvi et al. (2021) found a marked difference in improving air quality index response to the COVID-19 pandemic through strict lockdown in India. However, it is not desirable to prolonged lockdown in a country that creates socio-economic and health-related issues, outweighing the positive aspects of attaining environmental quality during a pandemic crisis. Wang and Xue (2021) concluded that COVID-19 measures to impose lockdown create positive and negative outcomes globally. The positive aspects are related to improved air quality, while the negative aspects include mental illness and increased medical waste, leading to more cumbersome situations. Recycling medical waste and reducing mental suffering required sustainable and long-term socio-economic policies for attaining broad-based growth. Selmi et al. (2021) argued that the COVID-19 pandemic deteriorates many sustainable environmental decisions related to investing in the green energy transitions, which are highly exposed due to high healthcare expenditures that adversely affect the green energy stock markets globally. The recent strikes of the literature confirmed that the environmental pollutants likely to cause spreading of coronavirus cases worldwide (see Anser et al. 2021b; Shahzad et al. 2021; Cao et al.

2021; Gomathy et al. 2021; Casado-Aranda et al. 2021; Aleya et al. 2021). Based on the stated discussion, the study proposed the following statement:

H2: Carbon damages would be likely to cause spreading of coronavirus cases across countries.

Finally, the literature selected to present the possible impact of green energy sources and research and development expenditures in minimizing the COVID-19 cases across countries. Jiang et al. (2021) discussed the challenges facing the energy industry during the COVID-19 pandemic. They confirmed that the COVID-19 pandemic creates an emergency to fulfill the energy demand, and the supply gap leads to deterioration of the responsible consumption of energy demand during a pandemic crisis. There is a need to devise a sustainable energy transition system to attain energy efficiency and save in the pandemic era to resolve the uncertain global situation (Awan et al. 2020a, 2020b). Shah et al. (2021) discussed the possibilities to attain green energy infrastructure during the pandemic era. The air quality level is temporarily improved due to lockdown conditions. At the same time, there is an excellent opportunity to improve air quality standards and searching for green energy sources to mitigate carbon emissions and improve healthcare quality standards. The study concludes that waste-to-energy converted technology through gasification is the desirable policy option for sustainable development. Nilsson et al. (2021) argued that the COVID-19 pandemic and healthcare emergency put tremendous pressure on sustainable development, which is pivotal to mitigate GHG emissions to attain healthy recovery to improve air quality and individuals healthcare issues in the long run. The international cooperation and investment put forward to devise sustainable development policies in reducing healthcare uncertainties and searching for renewable energy sources to build a resilient energy society. Egger et al. (2021) surveyed the large pool of household's data set of nine countries, consisting of more than 30,000 individuals, to evident the falling household income in the pandemic crisis. The survey further shows that household coping strategies and government official assistance programs are insufficient to handle the COVID-19 pandemic, which needs more favorable policies and assistance to reduce income uncertainties and improve their coping strategies through better livelihood conditions. Tang et al. (2021) greatly emphasized the need to promote nanomaterial in utilizing pneumonia treatment to address the COVID-19 pandemic efficiently. Casado-Aranda et al. (2021) found that scientific publications on writing COVID-19 pandemic are flared with the mixing of strategies and policies that need to be confined to strategic thinking and operational procedures the meaningful and smart inferences. The more traces found from the recent literature that confirmed the viability of innovation and green production process to improve healthcare

sustainability agenda, which is likely to reduce coronavirus cases (see Mohideen et al. 2021; Arribas-Ibar et al. 2021; Ranjbari et al. 2021; Dean et al. 2021; Su and Urban 2021; Wang et al. 2021). Based on the stated scholarly contributions, the study proposed the following statement:

H3: Green energy transition and R&D expenditures would likely support healthcare sustainability agendas to cope with coronavirus cases.

This study has a unique contribution in evaluating the non-linear relationship between financial development, green energy, R&D expenditures, carbon damages, and COVID-19 cases using cross-sectional data of 65 countries. The earlier studies mainly confined the relationships between the stated variables in the linear form. At the same time, there is uncertain that the linear form could give important information about the predictors of coronavirus disease. Hence, there is a need to analyze the nonlinearity in the relationship between the factors to get robust policy inferences. Further, the study used many nonlinear functional forms of the variables, including financial development, research and development expenditures, economic growth, and population density in the COVID-19 modeling framework. It would likely give more insights into the co-movement of the predictors of the COVID-19 factor at the later stages of pandemic growth. Finally, the study used switching regression-based modeling that gives information about the predictors at different regimes with standard regime options to utilize the nonlinearity function in healthcare modeling. The stated contribution filled the gap in the stated three dimensions, which is less likely to be explored previously in the schematic fashion.

Data source and methodological framework

The data of the COVID-19 cases (denoted by COVID19_CASES) are taken from Worldometer (2021) on 18 February 2021, whereas inbound FDI (denoted by FD) as % of GDP, renewable energy consumption (denoted by REC) as % of GDP, research and development expenditures (denoted by RND) as % of GDP, carbon damages (denoted by CDAM) as % of GNI, GDP per capita (denoted by GDPPC) as constant 2010 US\$, and population density (denoted by POPDEN) as people per square km of land area are taken from the World Bank (2021) database. The most recent available data series of the stated macroeconomic variables are taken from the World Bank database for analysis. A cross section of 65 countries has been used in this study that is mainly affected by coronavirus disease. The study started with the Solow growth model (Solow 1956). The country's economic output was influenced

by technology, labor, and capital. The study included exogenous shocks in economic modeling where contagious diseases, including the COVID-19 pandemic, were affected by financial development, green energy sources, R&D expenditures, carbon damages, economic growth,

and population density across countries. Based on the stated growth model, the study formulated the following regression equation:

$$\begin{aligned} \text{COVID19_CASES}_{2021,65} &= \beta_0 + \beta_1 \text{FD}_{2021,65} + \beta_2 \text{SQFD}_{2021,65} + \beta_3 \text{REC}_{2021,65} + \beta_4 \text{RND}_{2021,65} \\ &+ \beta_5 \text{SQRND}_{2021,65} + \beta_6 \text{CDAM}_{2021,65} + \beta_7 \text{GDPPC}_{2021,65} + \beta_8 \text{SQGDPPC}_{2021,65} + \beta_9 \text{POPDEN}_{2021,65} \\ &+ \beta_{10} \text{SQPOPDEN}_{2021,65} + \varepsilon_{2021,65} \\ \therefore \partial \left(\frac{\text{COVID19_CASES}}{\text{FD}} \right) &> 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{SQFD}} \right) < 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{REC}} \right) < 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{RND}} \right) > 0, \\ \partial \left(\frac{\text{COVID19_CASES}}{\text{SQRND}} \right) &< 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{CDAM}} \right) > 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{GDPPC}} \right) > 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{SQGDPPC}} \right) < 0, \\ \partial \left(\frac{\text{COVID19_CASES}}{\text{POPDEN}} \right) &> 0, \partial \left(\frac{\text{COVID19_CASES}}{\text{SQPOPDEN}} \right) < 0. \\ \therefore \text{Turning point formula} &= -\frac{\beta_1}{2\beta_2}, -\frac{\beta_4}{2\beta_5}, -\frac{\beta_7}{2\beta_8}, -\frac{\beta_9}{2\beta_{10}} \end{aligned} \quad (1)$$

where COVID19_CASES shows coronavirus cases, FD shows financial development, SQFD shows a square of FD, REC shows renewable energy consumption, RND shows R&D expenditures, SQRND shows a square of R&D, CDAM shows carbon damages, GDPPC shows GDP per capita, SQGDPPC shows a square of GDPPC, POPDEN shows population density, SQPOPDEN shows a square of population density, and ε shows error term.

Equation (1) shows the nonlinear relationship between COVID-19 cases, carbon damage, and some macroeconomic factors. It is the likelihood that there will be a rise and fall in the macroeconomic factors by increasing coronavirus cases, which confirmed the hump-shaped relationship between the variables. Table 1 shows the descriptive statistics of the candidate variables. The COVID-19 cases are highest at 28,381,220 (18 February 2021), with an average value of 1,474,976 across selected countries. The average value of inbound FDI, renewable energy consumption, and R&D expenditures is 4.804% of GDP, 21.086% of GDP, and

1.042% of GDP. The greater average value of renewable energy demand than the financial development and R&D expenditures confirmed the viability of green energy sources to achieve energy efficiency, supporting healthcare sustainability agendas across countries. The cost of carbon emissions is high at 5.233% of GNI, with an average value of 1.615% of GNI. The minimum value of GDP per capita is US\$500.402, and the maximum value of US\$111,062.3, with an average value of US\$21,938.67. The minimum population density value is 4.075 people per square km of land area, while the maximum value is 7,952.999, with an average value of 252.482. The high population density and continued economic growth would likely cause high coronavirus cases across countries.

COVID19_CASES shows coronavirus cases, FD shows financial development, REC shows renewable energy consumption, RND shows research and development expenditures, CDAM shows carbon damages, GDPPC shows GDP per capita, and POPDEN shows population density.

Table 1 Descriptive statistics

Methods	COVID19_CASES	FD	REC	RND	CDAM	GDPPC	POPDEN
Mean	1,474,976	4.8041	21.086	1.042	1.615	21,938.67	252.482
Maximum	28,381,220	95.558	70.174	3.339	5.233	111,062.3	7952.998
Minimum	19,598	−16.061	0	0.015	0.259	500.402	4.075
Std. Dev.	3,917,119	12.919	16.422	0.907	1.192	20,902.78	989.881
Skewness	5.472	5.607	1.072	1.065	1.199	1.626	7.440
Kurtosis	36.226	39.189	3.815	3.231	3.761	6.419	58.159

Table 2 Simple switching regression (BFGS/Marquardt steps) estimates (dependent variable: COVID19_CASES)

Variable	Coefficient	Std. error	z statistic	Prob.
Regime 1				
C	−1,148,487	1,537,730	−0.746872	0.4551
FD	520,894.3	156,076.4	3.337432	0.0008
REC	17,507.75	24,630.13	0.710826	0.4772
RND	2,207,161	991,219.2	2.226714	0.0260
CDAM	−276,826.2	308,803.8	−0.896447	0.3700
GDPPC	−177.724	68.29144	−2.602434	0.0093
POPDEN	19,699.04	3302.069	5.965667	0.0000
Regime 2				
C	−1,204,849	5,068,450	−0.237715	0.8121
FD	404,786.6	393,569.9	1.028500	0.3037
REC	23,950.02	66,395.66	0.360717	0.7183
RND	8,378,780	2,279,412	3.675852	0.0002
CDAM	−1,015,530	1,113,079	−0.912361	0.3616
GDPPC	45.99258	160.0639	0.287339	0.7739
POPDEN	−862.0712	7927.985	−0.108738	0.9134
Common				
SQFD	−47,868.80	14,792.54	−3.236010	0.0012
SQRND	−712,199.9	285,474.1	−2.494796	0.0126
SQGDPPC	0.002842	0.000960	2.958932	0.0031
SQPOPDEN	−2.097493	0.422401	−4.965639	0.0000
LOG(SIGMA)	14.00861	0.163902	85.46939	0.0000
Probability parameters				
P1-C	1.757073	0.593771	2.959177	0.0031
Mean-dependent variable	1,570,101			
SD-dependent variable	4,027,064			
SE of regression	5,856,530			
Sum of squared residuals	1.44E + 15			

The study used two different statistical techniques to estimate the given regression equation, i.e., switching regression approach and innovation accounting matrix.

- I) *Switching regression*: Conventionally, the econometric and statistical analysis is based on linear regression, where regressors explained the regressand assuming various stochastic terms are assumed to be constant. Economic functions have shown some trend values. It can be handled through nonlinear modeling, which gives the parameter estimates free from autocorrelation and heteroskedasticity issues (Cheng et al. 2021; Anser et al. 2020b). The macroeconomic analysis is primarily the regime change subject that is effectively estimated through two-step switching regression-based regime modeling. The given model commonly assumed that each regime is followed with the different regression apparatus with regressors that confirmed the linear specification of the error terms. Numerous earlier scholars widely discussed the viability of nonlinearity in macroeconomic modeling to confirm regime-based analysis in the estimation procedure. For instance, Goldfeld and Quandt (1976), Maddala (1986), and Frühwirth-Schnatter (2006) are a few of them that describe the basic features of the switching regression-based regime. The recent strikes of literature used the stated regression approach in different socio-economic and environmental settings, for instance Anser et al. (2021b), Liu et al. (2021), and Fitawek and Hendriks (2021).
- II) *Innovation Accounting Matrix (IAM)*: The IAM model is usually used in an autoregressive vector framework to cover the multivariate analysis to simplify the significant finite variables' structure. The forecast error decomposition mainly worked on in the variance decomposition analysis (VDA) and fulfilled the multivariate equations modeling exogenous assumptions. The regressand's exogenous shocks allow the forecasting of the comovement between the inter-temporal setting variables, which helps obtain the greater magnitude of influence on the response variable over the time horizon. The current studies mainly used the IAM method to get more insights about future patterns about multifaceted factors (see Nassani et al. 2021; Mujeed et al. 2021; Zaman et al. 2021; Iswan et al. 2021).

Table 3 Turning point estimates

Coefficients	Factors	Coefficient value	Turning point	Decision
β_1	Financial development	520,894.3*	$\beta_1/2\beta_2 = 5.440$	Inverted U-shaped relationship
β_2		−47,868.80*		
β_4	R&D expenditures	2,207,161**	$\beta_4/2\beta_5 = 1.549$	Inverted U-shaped relationship
β_5		−712,199.9**		
β_7	Economic growth	−177.724*	Not applicable	U-shaped relationship
β_8		0.002842*		
β_9	Population density	19,699.04*	$\beta_9/2\beta_{10} = 4695.85$	Beyond the curve
β_{10}		−2.097493*		

Table 4 Sample countries are at initial stage and maturity stage

Factors	Maturity stage	No. of countries at initial stage (<i>N</i>)	No. of countries at maturity stage (<i>N</i>)
Financial development	Hungary, Panama, Georgia, Singapore, Estonia, and Cyprus FD ≥ 5.440	59	6
R&D expenditures	USA, UK, France, Germany, Czechia, Canada, Belgium, Sweden, Austria, Japan, Hungary, Slovenia, China, Singapore, Finland RND ≥ 1.549	15	50
Population density	None of the country fall in the estimated value POPDEN ≥ 4695.85	65	0

FD shows financial development, RND shows research and development expenditures, *N* shows several countries, and POPDEN shows population density

Both the techniques helped to estimate the robust parameter estimates and reached logical inferences.

Results and discussion

Table 2 shows the two-step switching regression-based regime model estimates for the nonlinear relationships between the stated variables. The results show the regime-1 factor analysis that exhibits that financial development, R&D expenditures, and population density directly correlate with COVID-19 cases. At the same time, GDP per capita decreases the COVID-19 cases in selected panel countries. The result implies that along with an increase in financial activities (i.e., commercialization) and population density (i.e., socialization), it leads to an enormous increase in coronavirus cases. In contrast, the increase in economic growth is likely to decrease coronavirus cases through increasing healthcare

spending across countries. The inadequate absorptive and innovative investment capability is likely to increase coronavirus cases. The results of regime-2 regression show that inadequate R&D expenditures remain the significant factor that is likely to increase coronavirus cases in a panel of selected countries. The regime-based analysis further confirmed the nonlinearity in the relationship between the variables. It confirmed the hump-shaped relationship between financial development and coronavirus cases to follow an inverted U-shaped relationship between them. Similarly, the results confirmed the rise and fall in the R&D expenditures and population density due to increased coronavirus cases across countries. The relationship between per capita income and coronavirus cases exhibits a U-shaped relationship between them. Sohrabi et al. (2021) concluded that scientific collaboration and research-based initiatives are leading to international collaboration to reducing coronavirus cases globally. Zaremba et al. (2021) argued that government policies support the financial market

Fig. 3 U-shaped and inverted U-shaped relationships between COVID-19 cases and economic and environmental factors

Table 5 Variance decomposition of COVID19_CASES

2021	COVID19_CASES	FDI	REC	RND	CDAM	GDPPC	POPDEN
April	87.151	0.563	10.001	0.041	1.355	0.088	0.798
May	77.318	1.640	14.445	0.993	2.254	0.715	2.632
June	72.865	1.463	15.938	1.418	2.910	1.548	3.855
July	68.512	1.394	16.989	2.091	4.182	2.359	4.469
August	66.461	1.319	17.316	2.742	4.728	2.569	4.863
September	64.813	1.268	17.413	3.467	5.042	2.672	5.319
October	63.975	1.242	17.297	4.021	5.197	2.722	5.542
November	63.337	1.225	17.195	4.501	5.344	2.744	5.650
December	62.991	1.220	17.127	4.783	5.440	2.746	5.690

Estimation was based on 65 countries. COVID19_CASES shows coronavirus cases, FDI shows foreign direct investment inflows, REC shows renewable energy consumption, RND shows research and development expenditures, CDAM shows carbon damages, GDPPC shows GDP per capita, and POPDEN shows population density

reducing price volatility that is appreciable in the pandemic crisis. Mazumder and Saha (2021) showed that fear of coronavirus disease spread which covered more geographical boundaries and financial markets led them to decrease IPO firms' performance globally. Qin et al. (2021) emphasized the need to ensure sustainable logistics activities in the COVID-19 pandemic to provide safe and sound healthcare logistics services worldwide. Coccia (2021) argued that investment in healthcare infrastructure helps contain contagious diseases while increasing healthy economic activities to prevent them from future pandemics. Han et al. (2021) confirmed that during the COVID-19 pandemic, work at home and teleconferencing helped reduce traffic volume, thus achieving energy efficiency to restore economic activities. Improving and expanding information and communication channels helps decrease carbon emissions and increase healthcare sustainability across the countries.

Estimation was based on 60 countries. COVID19_CASES show coronavirus cases, FD shows financial development, REC shows renewable energy consumption, RND shows research and development expenditures, CDAM shows carbon damages, GDPPC shows GDP per capita, and POPDEN shows population density

Table 3 shows the estimation of turning points of nonlinear functional variables, and the inverted U-shaped relationship was found between financial development and coronavirus cases with a turning point of 5.440% of GDP. Similarly, the hump-shaped relationship followed the inverted U-shaped relationship between R&D expenditures and coronavirus cases with a turning point estimate of 1.549% of GDP. The U-shaped relationship was found between per capita income and COVID-19 cases. At the same time, population density followed an inverted U-shaped relationship with COVID-19 cases with a turning point of 4695.85 people per square km area, far beyond the country's possible point. The result

implies that a higher population density reduced the coronavirus cases, if and only if there is thoughtful planning of cities and infrastructure construction that care healthy reforms and sustainable environment.

Single and double asterisks show that estimates are significant at 1% and 5% levels

Table 4 shows the countries' performance towards achievement of financial development and R&D expenditures, and it was found that out of 65 countries, only six countries fall in the maturity stage to follow the turning point estimates of financial development. In contrast, the remaining countries remain at the initial stage of economic development. Similarly, there are 15 countries at the initial stage, to use inadequately R&D spending to minimize coronavirus cases, while 50 countries spend enormously private research-based investment on reducing coronavirus cases possibly. Figure 3 shows the turning point estimates for ready reference.

Table 5 shows the VDA estimates of COVID-19 cases, and it was found that renewable energy consumption has a greater magnitude to influence COVID-19 cases with a forecast variance of 17.127%, followed by population density, carbon damages, R&D expenditures, and GDP per capita with a variance of 5.690%, 5.440%, 4.783%, and 2.746%, respectively, for the upcoming months of April 2021 to December 2021. The VDA results suggested that renewable energy demand and carbon damages would likely play an essential role in confining coronavirus cases over time.

Conclusions

The uncertainty in the spread of the COVID-19 pandemic negatively impacts financial activities, energy transition process, innovative capabilities, and global sustainable output. It creates many socio-economic and environmental issues that

need to be controlled through investing in green financing projects, renewable energy sources, risk management, and continued sustainable economic activities. Based on the issue's importance, the study initiated an empirical study in a cross section of 65 countries to evaluate the nonlinear relationship between the COVID-19 cases and carbon damages by controlling inbound FDI, renewable energy consumption, R&D expenditures, economic growth, and population density. The results show the rise and fall in financial development, R&D expenditures, and population density by increasing coronavirus cases that exhibit a curvy relationship between the variables. On the other hand, there is a U-shaped relationship between per capita income and coronavirus cases across countries. The innovation accounting estimates suggest that carbon damages and renewable energy sources would likely influence coronavirus cases in the coming months. The following policy implications are proposed to control coronavirus cases by decreasing carbon damages, increasing R&D expenditures, substituting nonrenewable fuels to renewable fuels, and maintaining population distance:

- i) *Improving environmental quality standards to lowering coronavirus cases:* The countries improve air quality standards by using standardized operating procedures to control coronavirus cases, including smart lockdowns and low traffic volume. However, this is a short-term plan; in the long run, the country needs to move forward with go-for-green policies once the pandemic crisis is resolved. The importance of mitigating carbon emissions remains placed at a higher priority. The increasing carbon emissions deteriorate individuals' health, leading to the flawed immune system and respiratory system that would probably be linked to the coronavirus cases. The stringent environmental reforms, including environmental certifications, carbon pricing, and advancement towards achieving energy efficiency through cleaner technologies, would be optimal strategies to improve healthcare sustainability agendas across countries.
- ii) *Innovative and absorptive investment capabilities to contain coronavirus pandemic:* The healthcare sustainability agenda's investment is desirable to reduce coronavirus cases. The need to entrench a separate fund for coping with contagious diseases is vital for achieving healthcare sustainability. Improving the healthcare infrastructure, training medical and paramedical staff about the pandemic situation, and sustainable healthcare logistics supply chain would largely play an important role in minimizing the exposure of coronavirus cases globally.
- iii) *Green energy sources:* The renewable energy demand helps mitigate negative environmental externalities to lower GHG emissions and improve healthcare quality.

Hence, the search for green energy sources are vital to achieving the United Nations sustainable development goal numbers 3 (good health and wellbeing), 7 (affordable and clean energy), and 13 (climate action). The use of green energy sources in improving air quality indicators would improve healthcare services and a pollution-free environment that improves individuals' health and wealth accordingly. Clean and green energy sources provide an opportunity to mitigate climate actions, which ultimately help to reduce contagious diseases and move forward towards sustainable development.

- iv) *Population distancing:* Social distancing is the word-of-mouth nowadays to escape out from coronavirus disease. Simultaneously, this could be achieved only once the economies create a population distancing strategy to reduce population density as people per square km of land area. The densely populated area creates many socio-economic and environmental consequences, including the spread of transmitting diseases quickly from one person to another, which need to devise intelligent cities planning and infrastructure to reduce the exposure of diseases globally.
- v) *Green financing options:* The investment in clean and green energy sources is helpful to attain energy efficiency. Climate financing is considered a viable policy instrument to mitigate adverse environmental externalities and improve healthcare sustainability. The increase in the green financing options would serve two primary outcomes. First, it improves air quality levels while it improves the health hygiene of the familiar people that may resist more in a better way against any contagious diseases.

These policies would reduce the possible exposure of coronavirus disease by achieving environmental sustainability and healthcare reforms across the countries. There is more space to work on the stated topic that is in line with future submissions. The technological innovation and green energy transformations would likely be added in future work. It would directly link it to the green production process and eco-friendly goods exported to support the healthcare sustainability agenda, improving health hygiene and decreasing the susceptibility rate of contagious diseases.

Author contribution MKA: conceptualization, methodology, and writing which includes reviewing and editing. DIG: methodology and formal analysis. MAK: software and formal analysis. AAN: supervision, resources, and software. SEA: formal analysis and resources. KZ: software, formal analysis, and resources. HS: Methodology and formal analysis. S: resources, visualization, and methodology. YI: formal analysis, resources, and methodology. MMQA: resources, visualization, and formal analysis.

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Declarations

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