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Research paper

The roles of globalization, renewable energy and technological innovation in improving air quality: Evidence from the world's 60 most open countries

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ABSTRACT

Air pollution is considered by many researchers to be one of the causes of global warming, with detrimental effects on the environment, economy, and society. Therefore, identifying the roles of some possible factors for air pollution is an important research agenda. To this end, using unbalanced panel data, this study endeavours to explore the roles of globalization, technological innovation and renewable energy in identifying the factors of air pollution and thus in improving air quality for the world's 60 most open countries over the period 1960–2020. A series of econometrics tools, for example Driscoll and Kraay's (1998) standard error technique and the Panel Corrected Standard Error (PCSE) model are used, focusing on of autocorrelation, heteroscedasticity, and cross-sectional dependence problems to obtain robust outcomes. The results demonstrate that trade openness, technological innovation, and per capita GDP have positive effects, and renewable energy and square per capita GDP have negative effects the on air quality. The pair-wise Granger causality also discloses the one-way and two-way causal affiliation between the considered variables. All the findings are valid in terms of both theoretical and empirical grounds and are significant for policy directives.

1. Introduction

The issues of air pollution (higher CO_2 emissions) are great concerns for policy makers and the public in general due to their numerous detrimental effects like extreme weather, a rise in average temperature and sea levels, acidification of oceans, and alteration of precipitation pattern (US EPA, 2021; UN, 2021). To address these adverse consequences, the United Nations Development Program (UNDP) declared their emphasis on combating climate change and global warming with for a focus on air pollution (Goal-13 of SDGs, UNDP, 2015). However, due to the lack of effective policy efforts, the issue is still a matter of investigation for the researchers and scholars. Environmental problems are more severe in more open economies due to their global ranging business activities and higher level of trade volumes (Chen et al., 2021; Pata and Caglar, 2021; Li et al., 2021a,b). Eventually, the development process cannot proceed without considering that the environment generates more pollution and seeking more attention to ensure better air quality.

Against these backdrops, the current study is an attempt to combat air pollution and make an attempt to improve air quality in relation to the world's 60 most open countries[1] (details are in Section 3.1). These countries' total trade value is US$ 11.952 trillion, whereas their total GDP is US$7.779 trillion (WDI, 2021). The trade-GDP ratio of each of these countries is the highest in the world (100 or more). The CO_2 emissions of these countries are 2.64 billion metric tons, which is 50.604% of the world's emissions (WDI, 2021). Thus our attempt is to address the air pollution by identifying the determining factors of CO_2 emissions in these countries to mitigate the environmental problems.

Past studies (see Chen et al., 2021; Rahman et al., 2021; Rahman and Alam, 2021a,b; Shahbaz et al., 2013; Adebayo et al., 2021; Zhang et al., 2017; Mehmood, 2021; Ibrahim and Ajide, 2021; Bayar et al., 2021; Pata and Caglar, 2021; Rahman and Vu, 2020; Nathaniel and Iheonu, 2019; Dauda et al., 2021; Li et al., 2021a,b; Yu and Du, 2019; Su et al., 2020; Amin et al., 2020; Balsalobre-Lorente et al., 2021; Shahbaz et al., 2013; Jamel and Maktouf, 2017; Mahmood et al., 2019; Tenaw and Beyene,

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[1] Data source for these countries: https://en.wikipedia.org/wiki/List_of_countries_by_trade-to-GDP_ratio.

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2021; Pata and Caglar, 2021) have attempted to identify the role of influencing factors on air pollution, but these are incomplete and inconclusive due to the non-consideration of appropriate study areas that should be emphasized. . Moreover the findings of related factors on air pollution are intermingled and inconclusive, which require further detailed exploration. Therefore our current study is based on the right study area, the world's 60 most open countries, and explores the effects of globalization, technological innovation and renewable energy, on air quality. The study uses economic growth as a control variable.

The prime motivation for choosing the studied variables is grounded in both theoretical and empirical rationales. The CO_2 emissions generate air pollution which causes global warming and therefore climate change that threatens the earth regarding its survival (Chen et al., 2021; Rahman et al., 2021; Rahman and Alam, 2021a,b; Musah et al., 2021; Pata and Caglar, 2021; Li et al., 2021a,b). Globalization, proxied by trade openness, increases CO_2 emissions through the carbon emitting production techniques of trade related commodities (Chen et al., 2021; Musah et al., 2021; Pata and Caglar, 2021); on the other hand, this also reduces CO2 emissions due to the global effort of changing production methods (Shahbaz et al., 2013; Adebayo et al., 2021; Zhang et al., 2017). Renewable energy plays a critical role in reducing CO_2 emissions keeping the pace of development constant (Mehmood, 2021; Ibrahim and Ajide, 2021; Bayar et al., 2021), although many researchers do not find any significance in this variable to reduce pollution (Pata and Caglar, 2021; Rahman and Vu, 2020; Nathaniel and Iheonu, 2019). Technological innovation, proxied by patent application, may also increase CO_2 emissions by failing to emphasize green methods (Dauda et al., 2021; Li et al., 2021a,b; Dauda et al., 2019; Yu and Du, 2019); conversely, better innovation considering efficient green technologies may diminish CO_2 emissions (Erdoğan et al., 2020; Su et al., 2020; Amin et al., 2020). Economic growth, according to the environmental Kuznets curve (EKC) hypothesis, at the earlier period of development, produces more CO_2 emissions, but, later, at higher stages of development it generates fewer CO_2 emissions due to the adoption of green growth approaches (Balsalobre-Lorente et al., 2021; Mahmood et al., 2019; Jamel and Maktouf, 2017; Shahbaz et al., 2013; Tenaw and Beyene, 2021; Pata and Caglar, 2021).

The innovative contributions of this work can be explained as: (i) according to the authors' knowledge, this is the first work in the literature that explores the effects of globalization, technological innovation and renewable energy on air quality, particularly in the case of the world's 60 most open countries.; (ii) this work has utilized the most updated and comprehensive data period of 61 years (1960–2020); (iii) the robust results are attained by adopting erudite econometric approaches named Driscoll and Kraay's (1998) standard error technique and panel corrected standard error (PCSE) model; (iv) inclusive and widely concerned policy suggestions are made based on the outcomes which are effective and useful in allowing policy makers and governments to take appropriate policy initiatives in improving the air quality not only in the studied region but also throughout the world.

Previous literature in relation to our study can be classified and discussed as follows:

i. Environmental Kuznets Curve (EKC) framework

We have adopted the environmental Kuznets curve (EKC) hypothesis as a theoretical foundation for our empirical model. Kuznets (1955), observed the inverted U-shaped link between income per capita and inequality, which later received more attention by Grossman and Krueger (1991) and applied in the field of environmental pollution (Rahman, 2017; Zoundi, 2017; Dong et al., 2018; Rahman et al., 2021). The interaction between economic growth and environmental quality is found in the case of three erudite effects, namely, scale effect, composition effect, and technique effect (Rahman et al., 2021, Sahoo et al., 2021; Mosconi et al., 2020; Shahbaz and Sinha, 2019; Kiliç and Balan, 2018). At the primary stage of development, an economy that is uncontrolled utilizes natural resources to quicken its economic growth showing less concern for the environment and exhibiting a scale effect that would reduce environmental quality. Then, at the higher level of income the policy makers become more concerned about the environment and suggest adopting more renewable and clean energy, and fewer emissions. Therefore, at the higher income level, pollution decreases and environmental quality improves. Finally, in the later stage, the economy invests more on research and development to adopt more innovation on environmentally friendly technologies, and effective trade policies to assure green development. As a result, pollution levels reduce further which improves environmental quality. Therefore, the scale effect increases, whereas the composition and technique effects reduce the pollution level enough to create an inverted U-shaped curve between pollution and economic growth.

Under the framework of the EKC hypothesis much of the literature were found (see Balsalobre-Lorente et al., 2021; Mahmood et al., 2019; Jamel and Maktouf, 2017; Shahbaz et al., 2013; Tenaw and Beyene, 2021; Pata and Caglar, 2021; Sinha and Shahbaz, 2018; Sahoo et al., 2021; Ibrahim and Ajide, 2021; Sultana et al., 2021; Zhang et al., 2017; Gozgor, 2017; Zafar et al., 2019; Tachie et al., 2020; Yu et al., 2019). Balsalobre-Lorente et al. (2021) obtained the validation of the EKC hypothesis in the case of 5 EU countries over the data period of 1990–2015 by applying panel cointegration, regression, and causality analysis. Similarly, the validation of the EKC hypothesis has been identified by Shahbaz et al. (2013) for South Africa by adopting Autoregressive Distributed Lag (ARDL) bounds testing approach, Jamel and Maktouf (2017) for 40 European economies by employing fixed effect and random effect models under Cobb–Douglas production function, Mahmood et al. (2019) for Tunisia by using ARDL and non-linear ARDL models, Tenaw and Beyene (2021) for 20 sub-Saharan African (SSA) countries by utilizing panel ARDL model, Pata and Caglar (2021) for China from augmented ARDL approach, Sinha and Shahbaz (2018) and Villanthenkodath et al. (2021) for India adopting ARDL model, Ibrahim and Ajide (2021) for G-7 countries applying pooled mean group (PMG) approach, Sultana et al. (2021) for Bangladesh by adopting ARDL model, Zhang et al. (2017) for 10 newly industrialized countries by employing error correction model, Gozgor (2017) for 35 OECD countries from panel data estimation techniques, Zafar et al. (2019) for emerging economies by using continuously updated fully modified (CUP-FM) and continuously updated bias-corrected (CUP-BC) approaches, Tachie et al. (2020) for 18 EU countries by utilizing mean group (MG) and augmented mean group (AMG), and Yu and Du (2019) for CIS countries by adopting feasible generalized least square (FGLS) estimation. However, the non-confirmation of EKC is also revealed by Rahman et al. (2021) for 10 newly industrialized countries (NICs) by applying pooled mean group (PMG) estimation methods, Koc and Bulus (2020) for South Korea by using ARDL model, Pata and Aydin (2020) for 6 hydropower energy consuming countries from the Fourier bootstrap ARDL procedure, Erdoğan et al. (2020) for 14 G20 countries, Alshehry and Belloumi (2017) for Saudi Arabia from ARDL model, Amri (2018) for Tunisia from ARDL model, and Zoundi (2017) for 25 African countries from panel cointegration analysis. Therefore, more investigation of EKC identification is still important due those ambiguous outcomes by using novel approaches like Driscoll and Kraay's (1998) standard error technique and the Panel Corrected Standard Error (PCSE) model covering larger areas and time periods.

ii. GDP-CO_2 emissions nexus beyond EKC hypothesis

In addition to the EKC approach, the increasing impact of economic growth on CO_2 emissions is revealed by Kashem and

Rahman (2019) and Rahman and Alam (2021a,b) for Bangladesh, Rahman and Vu (2021) for China, Rahman (2020a,b) for the top 10 electricity consuming countries, Rahman and Vu (2020) for Australia and Canada, but the reducing impact is also exposed by Rahman (2020a) for India. The unidirectional causal relationship between economic growth and CO_2 emissions was discovered by Rahman and Kashem (2017) for Bangladesh, Rahman (2017) for 11 Asian populous countries, and Mbarek et al. (2018) for Tunisia. In the same way, the bidirectional causal affiliation was also unveiled by Saidi and Rahman (2020) for 4 out of 5 OPEC countries, and Rahman et al. (2020) for 5 south Asian countries. Thus further exploration is needed to unlock their significance in a more significant way.

iii. Globalization/trade openness-CO_2 emissions nexus

Due to the effects of globalization countries are now more engaged in trade that affects the environment considerably as observed in many literary works (see Chen et al., 2021; Musah et al., 2021; Pata and Caglar, 2021; Li et al., 2021a,b; Dou et al., 2021; Ibrahim and Ajide, 2021; Zamil et al., 2019; Tachie et al., 2020; Yu and Du, 2019; Shahbaz et al., 2013; Adebayo et al., 2021; Khan et al., 2021; Zhang et al., 2017; Shahbaz et al., 2019; Koc and Bulus, 2020; Amin et al., 2020; Gozgor, 2017; Zafar et al., 2019; Wang and Zhang, 2021). In this way, Chen et al. (2021) identified that the trade openness significantly increased the CO_2 emissions in 64 countries comprising the Belt and Road program over the data period of 2001–2019 by using the panel quantile regression approach. A similar observation was also made by Musah et al. (2021) for D-8 countries from Generalized method of moment (GMM) analysis, Pata and Caglar (2021) from augmented ARDL approach and Li et al. (2021a,b) from robust to structural breaks for China, Dou et al. (2021) from heterogeneity analysis for China–Japan–South Korea, Ibrahim and Ajide (2021) for G-7 countries from pooled mean group (PMG) estimation, Zamil et al. (2019) for Oman from ARDL model, and Tachie et al. (2020) for 18 EU countries from augmented mean group (AMG) and Yu and Du (2019) for CIS countries from GLS analysis. On the other hand, Shahbaz et al. (2013) found that trade openness enhances the environmental quality by decreasing CO_2 emissions in South Africa during 1965–2008 by adopting ARDL model. Similarly, the reducing effect of trade openness on CO_2 emissions has been identified by Adebayo et al. (2021) for Sweden from quantile-on-quantile regression (QQ) approach, Khan et al. (2021) for Bangladesh from ARDL model, Zhang et al. (2017) for 10 newly industrialized countries from error correction model, Shahbaz et al. (2019) for the USA from ARDL model, Koc and Bulus (2020) for South Korea from ARDL model, Amin et al. (2020) for 13 Asian countries from fully modified ordinary least square (FMOLS), Gozgor (2017) for 35 OECD countries from panel data estimation techniques and Zafar et al. (2019) for emerging economies CUP-FM and CUP-BC methods. However, Wang and Zhang (2021) revealed that trade openness augmented CO_2 emissions in low-income countries, reduced them in high-income and upper-middle-income countries, but was insignificant in the lower-middle-income countries by employing FMOLS estimation. Rahman and Alam (2021a,b) also found no significant impact of trade openness on CO_2 emissions for Bangladesh. Thus, the rigorous investigation of the true role of trade openness on CO_2 emissions is essential by covering larger study areas along with inclusive method like Driscoll and Kraay.

iv. Renewable energy-CO_2 emissions nexus

Renewable energy generates lower emissions and improves the air quality, as explained in many studies (see Mehmood, 2021; Rahman and Alam, 2021a,b; Ibrahim and Ajide, 2021; Bayar et al., 2021; Shahnazi and Dehghan Shabani, 2021; Azam et al., 2021; Namahoro et al., 2021; Koc and Bulus, 2020; Rahman and Vu, 2020; Zafar et al., 2019; Bekun et al., 2019; Inglesi-Lotz and Dogan, 2018; Sinha and Shahbaz, 2018; Zoundi, 2017; Liu et al., 2017). Mehmood (2021) identified that the renewable energy significantly reduced the CO_2 emissions in the G11 countries for the data period of 1990–2019. Rahman and Alam (2021a,b) observed that clean energy decreased the CO_2 emissions for Bangladesh from ARDL model. Similarly, the significant diminishing impact of renewable energy on CO_2 emissions was also found by Ibrahim and Ajide (2021) for G-7 countries from PMG approach, Bayar et al. (2021) from panel cointegration and causality analyses and Shahnazi and Dehghan Shabani (2021) from spatial dynamic panel data model for EU countries, Azam et al. (2021) for the 10 highest CO_2 emitting countries from panel FMOLS model, Namahoro et al. (2021) for 7 East African countries from nonlinear ARDL model, Koc and Bulus (2020) for South Korea from ARDL model, Rahman and Vu (2020) for Australia from ARDL model, Zafar et al. (2019) for emerging economies from CUP-FM and CUP-BC approaches, Bekun et al. (2019) for 16 EU countries from PMG-ARDL model, Inglesi-Lotz and Dogan (2018) for the 10 main electricity producing African countries from panel estimation techniques robust to cross dependence, Sinha and Shahbaz (2018) for India from ARDL model, Zoundi (2017) for 25 selected African countries from panel cointegration analysis, and Liu et al. (2017) for 4 ASEAN countries from panel cointegration and causality analyses. However, the insignificant role of renewable energy on CO_2 emissions was also experienced by Pata and Caglar (2021) for China from augmented ARDL approach, Rahman and Vu (2020) for Canada from ARDL model, Nathaniel and Iheonu (2019) for 19 African countries from augmented mean group (AMG) estimation technique, Adams and Nsiah (2019) for 28 Sub-Saharan African countries from FMOLS and GMM estimation techniques, and Pata (2018) for Turkey from the ARDL, FMOLS, and canonical cointegrating regression (CCR) estimators. Therefore, these inconclusive results require further investigations.

v. Technological innovation-CO_2 emissions

In terms of technological innovation, many researchers have tried to identify its impact on CO_2 emissions (see Dauda et al., 2021; Li et al., 2021a,b; Dauda et al., 2019; Yu and Du, 2019; Su et al., 2020; Erdoğan et al., 2020; Su et al., 2020; Amin et al., 2020; Ibrahiem, 2020; Zameer et al., 2020; Kumail et al., 2020; Khan et al., 2021). Dauda et al. (2021) obtained the inverted-U shaped association between technological innovation and CO_2 emissions for 9 African countries over the data period of 1990–2016 by employing fixed effect model and GMM methods. Corresponding identification was also revealed by Li et al. (2021a,b) for China by utilizing robust to structural breaks. Dauda et al. (2019) found that the technological innovation increased CO_2 emissions in the MENA and BRICS countries during 1990–2016 from panel fully modified ordinary least square (FMOLS) and panel dynamic ordinary least square (DOLS). Yu and Du (2019) showed that the independent technological innovation, rather than introducing one, increased CO_2 emissions in China during 1997–2015 by utilizing logistic equation. Similar identification was also found by Su et al. (2021) for BRICS countries from Driscoll–Kraay panel regression. In contrast, the declining effect of innovation on CO_2 emissions was also demonstrated by Erdoğan et al. (2020) for 14 of the G20 countries from sectoral analysis, Su et al. (2020) for the USA from ARDL model, Amin et al. (2020) for 13 Asian countries from FMOLS approach, Ibrahiem (2020) for Egypt from ARDL, FMOLS, and Stock and Watson DOLS models, Zameer et al. (2020) for India from ARDL model, Kumail et al. (2020) for Pakistan from ARDL bounds and Bayer and Hanck tests of cointegration tests, Khan et al. (2021) for G7 countries from ARDL model, Hashmi and Alam (2019) for OECD countries from GMM models, Salman et al. (2019) for 7 ASEAN countries from panel quantile regression, Aldakhil et al. (2019) for South Asia from robust least square regression, Ahmad et al. (2019) for 26 OECD from multiple empirical analyses, and Ganda (2019) for the OECD countries from GMM analysis. An insignificant association was also found by Samargandi (2017) for Saudi Arabia from ARDL model, and Chen and Lee (2020) for 96 countries from spatial econometric models. Thus, this indefinite nexus demands for more exploration.

From a thorough investigation of the past and existing literature, no conclusive roles of related variables on CO_2 emissions have been revealed. Moreover, any consideration of the collective effect of globalization, renewable energy, technological innovation, and economic growth on CO_2 emissions is absent in the literature, especially in the context of world's 60 most open countries. This is the main gap in the literature, and our prime effort is to fill up this gap. We have also used the Driscoll–Kraay panel standard error technique, where the Panel Corrected Standard Error (PCSE) model is used for robustness checking for caring missing data and covering larger sample areas to articulate inclusive guidelines. Thus the current study is an effort to consider the most important place of study (world's 60 most open countries) and emphasize the vital factors for improving air quality, which will be regarded as a landmark for the policy makers.

2. Data, model and methodology

2.1. Data

In this study, we have identified the roles of globalization, technological innovation and renewable energy in improving the air quality in the case of the world's 60 most open countries. The countries are Luxembourg, Hong Kong, Singapore, Malta, Ireland, Vietnam, Slovak Republic, Seychelles, United Arab Emirates, Hungary, Belgium, Netherlands, Lithuania, Slovenia, Czech Republic, Estonia, Maldives, Guinea, Bahrain, Congo, Rep., Malaysia, Belarus, Cyprus, Bulgaria, Suriname, Lesotho, Cambodia, North Macedonia, Latvia, Liberia, Thailand, Switzerland, Turkmenistan, Mongolia, South Sudan, Serbia, St. Kitts and Nevis, Moldova, Belize, Georgia, Macao, Mauritania, Mozambique, Libya, Djibouti, Grenada, Montenegro, Austria, Denmark, Cabo Verde, Poland, Honduras, Kyrgyz Republic, Ukraine, Eswatini, St. Lucia, Guyana, Croatia, Dominica, and Togo. These countries are considered as most open in the world in terms of international trade, containing trade/GDP ratio 100 or more.

For this, we have used unbalanced panel data over the period 1960–2020 due to the lack of all the required data for the sample countries for the entire period. All the data except technological innovation (TI) are obtained from the World Development Indicators (WDI, 2021) of World Bank database. The technological innovation (TI) data are collected from World Intellectual Property Organization statistics database (WIPO, 2021).

2.2. Model and econometric approaches

In line with the studies of Dauda et al. (2021), Rahman (2017) and Shahbaz et al. (2013), the following model has been adopted for our empirical investigation:

$$CO_{2it} = f\left(TO_{it}, RE_{it}, TI_{it}, PCGDP_{it},\ PCGDP^2_{it}, \right) \tag{1}$$

The variables of Eq. (1) have been transformed into natural log form to get direct elasticity value and compare them along with the reduction of heteroscedasticity of the variables (Rahman et al., 2021; Rahman and Alam, 2021a,b). The transformed model is now as follows:

$$\begin{aligned}\ln CO_{2it} = \alpha + \beta_1 \ln TO_{it} + \beta_2 \ln RE_{it} + \beta_3 \ln TI_{it} \\ + \beta_4 \ln PCGDP_{it} + \beta_5 \ln PCGDP^2_{it} + \mu_{it}\end{aligned} \tag{2}$$

where, CO_2 displays carbon emissions per capita which is counted in terms of metric tons, used as a proxy of air quality; TO indicates trade openness as a sum of exports and imports of goods and services (% of GDP), used as a proxy for globalization; RE is the renewable energy use as a % of total final energy use; TI denotes the total number of patent applications of residents which is used as a proxy of technological innovation; PCGDP and $PCGDP^2$ are per capita gross domestic product, and square of per capita gross domestic product, and considered as proxies of economic growth. The long-run elasticities of respective variables are shown by β_1, β_2, β_3, β_4, and β_5; μ denotes error term; subscripts i and t exhibit country and time, respectively.

There are a number of econometric tools that have been employed to check the unbalanced panel data. First of all, the detection of autocorrelation, heteroscedasticity, and cross-sectional dependence is important, as these issues are more prevalent in the panel dataset. As these issues provide inefficient and biased outcomes, their consideration should not be overlooked, and use of robust techniques is needed to address them (Qiu et al., 2019; Rahman et al., 2021). Therefore, in this study, the presence of heteroscedasticity and autocorrelation of the dataset are to be checked by Modified Wald statistics for group wise heteroscedasticity, and Wooldridge (2002), respectively (Baum, 2001; Wooldridge, 2002; Simpson, 2012; Attari et al., 2016); Khan et al. 2019; and (Rahman et al., 2021). Similarly, the prevalence of cross-sectional dependence is to be diagnosed through the Pesaran (2004) CD statistic, which is adequate in the case of the unbalanced panel dataset (Hoechle, 2007; Rahman et al., 2021). For the CD test the model below is used:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\sqrt{T_{ij}\widehat{p}_{ij}^{\,2}}\right) \tag{3}$$

where $\widehat{p_{ij}}^2$ denotes the coefficients of residuals of the pairwise cross-sectional correlation, and N and T represent the cross-sectional dimensions and time of the panel, respectively. The null hypothesis of this model is the existence of cross-sectional independence with CD $\sim N$ (0, 1).

Then, efficient and robust estimation with due care of autocorrelation, heteroscedasticity, and cross-sectional dependence is necessary, because with their presence the standard fixed effect model may not generate unbiased and efficient outcomes (Magalhães and Africano, 2007; (Rahman et al., 2021). For this, the study considers Driscoll and Kraay's (1998) standard error technique following the methodology of Hoechle (2007) in the case of linear panel models (Baloch et al., 2019; Baloch and Meng, 2019; Sarkodie and Strezov, 2019; Rahman et al., 2021). This is a sophisticated method which addresses all the problems of autocorrelation, heteroscedasticity, and cross-sectional dependence in the estimated model. Compared to many other methods, Driscoll and Kraay's (1998) standard error technique provides various additional benefits: firstly, this can be adopted under the case of unbalanced panel data; secondly, this approach can be used in the case of missing values of the dataset; thirdly, it is a non-parametric procedure having flexible features and greater time dimension; finally, and most importantly, this approach can accurately cure about heteroscedasticity, autocorrelation, and cross-sectional dependence issues (Hoechle, 2007; Baloch and Meng, 2019,?; Sarkodie and Strezov, 2019; Rahman et al., 2021).

After the estimation of Driscoll and Kraay's (1998) standard error technique, the robustness of the findings are to be checked through another well-known panel corrected standard error (PCSE) model in according to the methodology of Beck and Katz (1995). This model also addresses the issues of autocorrelation, heteroscedasticity, and cross-sectional dependence in the model efficiently and effectively (Cameron and Trivedi, 2009; Ikpesu et al., 2019; Le and Nguyen, 2019; Rahman et al., 2021).

Table 1
The results of descriptive statistics.

Description	CO_2	TO	RE	TI	GDP	GDP^2
Mean	6.217	125.356	19.201	1125.860	14634.430	648000000
Median	5.732	107.430	11.474	271.000	4952.214	24524423
Maximum	30.440	437.327	94.167	10016.000	118981.900	14200000000
Minimum	0.071	43.702	0.000	1.000	95.188	9060.805
Std. Dev.	4.804	67.256	20.477	1908.201	20854.880	1720000000
Skewness	1.776	2.242	1.630	2.563	2.220	4.719
Kurtosis	7.694	8.426	5.390	9.568	8.505	29.305
Jarque–Bera	1040.727	1488.291	490.990	2085.169	1502.414	23462.70
Probability	0.000	0.000	0.000	0.000	0.000	0.000
Sum	4482.695	90381.730	13843.580	811745.000	10551426.00	468000000000
Sum Sq. Dev.	16616.40	3256856.000	301886.600	2620000000	313000000000	2.14E+21

Table 2
The results of heteroscedasticity and autocorrelation tests.

Test	Test statistic	p-value	Presence
Modified Wald test for group wise heteroscedasticity	$\chi^2 = 7313.51$	0.000	Yes
Wooldridge test for autocorrelation in panel data	F-statistic = 5.016	0.031	Yes

Auto correlation: Wooldridge test for autocorrelation in panel data. H0: no first-order autocorrelation.
Heteroscedasticity: Modified Wald test for groupwise heteroskedasticity; Ho: sigma(i)ˆ2 = sigmaˆ2 for all i: No heteroskedasticity.

Table 3
The results of cross-sectional dependence test.

Variables	Pesaran (2004) CD test	p-value
$LNCO_2$	52.416***	0.000
LNTO	60.979***	0.000
LNRE	2.564***	0.010
LNTI	10.348***	0.000
LNPCGDP	187.095***	0.000
$LNPCGDP^2$	186.401***	0.000

Notes: The null hypothesis (H_0) is cross-section independence, CD ∼ N(0,1) P-values near to zero specify data are correlated across panel groups. *** shows rejection of the null hypothesis (H_0) at the 1% significance level.

Table 4
Driscoll–Kraay standard errors model results.

Variables	Coeff. (prob.)
LNTO	0.153*** (0.001)
LNRE	−0.233*** (0.000)
LNTI	0.096*** (0.000)
LNPCGDP	1.083*** (0.000)
$LNPCGDP^2$	−0.062*** (0.000)
_Constant	−3.889*** (0.000)
within R-squared	0.555
F (5, 25)	107.91
Probability	0.000
Number of observations	704
Number of groups	45[a]

Note: *** denote significance level at 1%.
[a]These 15 countries have little or no technological innovation (TI) data and thus the model excludes them (Seychelles, Maldives, Suriname, South Sudan, St. Kitts and Nevis, Belize, Djibouti, Grenada, Eswatini, Guinea, Lesotho, Cambodia, Liberia, Cabo Verde, and St. Lucia).

Finally, the direction of causality between the considered variables is identified through the pair-wise Granger (1969) causality of stacked test (common coefficients). In line with the methodology of Seitaridis and Koulakiotis (2013) and Revathy and Paramasivam (2018), the equations of pair-wise Granger causality can be displayed by:

$$Y_{i,t} = K_{0,i} + K_{1,i}Y_{i,t-1} + \cdots\ldots + K_{s,i}Y_{i,t-1} + R_{1,i}X_{i,t-1} + \omega_{i,t} \quad (4)$$

$$X_{i,t} = K_{0,i} + K_{1,i}X_{i,t-1} + \cdots\ldots + K_{s,i}X_{i,t-1} + R_{1,i}Y_{i,t-1} + \omega_{i,t} \quad (5)$$

where, i indicates the cross-sectional dimensions, and t denotes the time period. The decision rule is, the null hypothesis (H_0): Y does not Granger causes X, and the alternative hypothesis (H_1): Y Granger causes X. Three outcomes may be obtained as: one-way causality, two-way causality, and no causality between the variables.

Table 5
Panel-corrected standard error (PCSE).

Variables	Coeff. (prob.)
LNTO	0.137** (0.021)
LNRE	−0.281*** (0.000)
LNTI	0.162*** (0.000)
LNPCGDP	1.447*** (0.000)
$LNPCGDP^2$	−0.076*** (0.000)
_Constant	−6.134*** (0.000)
R-squared	0.592
Wald $chi^2(5)$	435.25
Probability	0.000
Number of observations	704
Number of groups	45

Note: ***, and ** denote significance level at 1%, and 5%, respectively.

3. Empirical results and discussions

3.1. Descriptive statistics

The descriptive statistics of the used variables have been reported in Table 1. The mean, median, and standard deviation values for the CO_2 emissions, trade openness, renewable energy, technological innovation, GDP, and square of GDP are provided in Table 1. Similarly, the values of Jarque–Bera and the corresponding probabilities of these variables are 1040.727 (0.000), 1488.291 (0.000), 490.990 (0.000), 2085.169 (0.000), 1502.414 (0.000), 23462.70 (0.000), consecutively. In terms of skewness, all the variables show positively skewed, and in case of kurtosis, all the variables exert leptokurtic. The values of minimum and maximum values, sum and sum square deviation have also been noted in Table 1. All the findings are useful for further estimation.

3.2. The results of autocorrelation and heteroscedasticity

The outputs of both of heteroscedasticity and autocorrelation are shown in Table 2. The values of Modified Wald test for the group wise heteroscedasticity test static, and the Wooldridge test for autocorrelation in panel data are 7313.51, and 5.016, which are statistically significant at 1%, and 5% levels, respectively. Therefore, both of the results confirmed the presence of autocorrelation and heteroscedasticity.

Table 6
The results of causality test.

Null hypothesis	F-stat.	Prob.	Decision
LNTO does not cause $LNCO_2$ $LNCO_2$ does not cause LNTO	0.917 7.167***	0.400 0.001	$LNCO_2 \rightarrow$ LNTO (one-way causality)
LNRE does not cause LNCO2 $LNCO_2$ does not cause LNRE	3.46** 3.402**	0.029 0.034	LNRE$\leftrightarrow$ $LNCO_2$ (two-way causality)
LNTI does not cause $LNCO_2$ $LNCO_2$ does not cause LNTI	10.423*** 2.594**	0.000 0.034	LNTI$\leftrightarrow$ $LNCO_2$ (two-way causality)
LNPCGDP does not cause $LNCO_2$ $LNCO_2$ does not cause LNPCGDP	3.331** 5.033***	0.036 0.007	LNPCGDP$\leftrightarrow$ $LNCO_2$ (two-way causality)
$LNPCGDP^2$ does not cause $LNCO_2$ $LNCO_2$ does not cause $LNPCGDP^2$	1.187 24.133***	0.305 0.000	$LNCO_2 \rightarrow LNPCGDP^2$ (one-way causality)

Note: ***, and ** show significance level at 1%, and 5%, respectively.

Table A.1
The results of descriptive statistics.

	CO2	TRADE	RE	TI	GDP	GDP2
Mean	6.217330	125.3561	19.20052	1125.860	14634.43	6.48E+08
Median	5.732128	107.4299	11.47351	271.0000	4952.214	24524423
Maximum	30.43928	437.3267	94.16655	10016.00	118981.9	1.42E+10
Minimum	0.071328	43.70212	0.000000	1.000000	95.18826	9060.805
Std. Dev.	4.803992	67.25631	20.47650	1908.201	20854.88	1.72E+09
Skewness	1.775630	2.241811	1.630425	2.562574	2.219631	4.718614
Kurtosis	7.693756	8.425681	5.389660	9.568265	8.504904	29.30483
Jarque–Bera	1040.727	1488.291	490.9895	2085.169	1502.414	23462.70
Probability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Sum	4482.695	90381.73	13843.58	811745.0	10551426	4.68E+11
Sum Sq. Dev.	16616.40	3256856.	301886.6	2.62E+09	3.13E+11	2.14E+21

Table A.2
The results of heteroscedasticity and autocorrelation tests.

```
. xttest3

Modified Wald test for groupwise heteroskedasticity
in fixed effect regression model

H0: sigma(i)^2 = sigma^2 for all i

chi2 (45)  =    7313.51
Prob>chi2 =      0.0000



. xtserial lnco2 lnto lnre lnti lngdp lngdp2

Wooldridge test for autocorrelation in panel data
H0: no first-order autocorrelation
    F(  1,      40) =       5.016
           Prob > F =      0.0307
```

3.3. The results of cross-sectional dependence test

To discover the results of cross-sectional dependence, the Pesaran (2004) CD test is employed, and the corresponding generated outputs are depicted in Table 3. The results reject the null hypothesis of cross-sectional independence for all variables, which are statistically significant at 1% level and strongly ensure the existence of cross-sectional dependence. This cross-sectional dependence implies the common shock that remains unobserved among the studied cross-sectional variables.

3.4. The results of Driscoll–Kraay standard error estimation

Table 4 reports the findings of Driscoll and Kraay's (1998) robust standard error technique, where all the variables are found statistically significant at 1% level. The coefficients of trade openness, renewable energy, technological innovation, per capita GDP, and the square of per capita GDP are 0.153, −0.233, 0.096, 1.083, and −0.062, respectively. These results imply that 1% increase in trade openness, technological innovation, and per capita GDP raises the CO_2 emissions by 0.153%, 0.096%, and 1.083%, consecutively. Conversely, 1% increase in renewable energy, and square of per capita GDP reduces the CO_2 emissions by −0.233%, and −0.062%, respectively. Therefore, the findings also experience the validation of the EKC hypothesis.

From the outcomes of Table 4, it is observed that the impacts of considered variables on air quality proxied by CO_2 emissions have been attained in a significant way. The trade openness plays role in increasing CO_2 emissions because, if the trade related goods and services are produced through non-renewable energy sources more emissions may be created. This result is pertinent to the finding of Chen et al. (2021), Musah et al. (2021), Pata and Caglar (2021), and Li et al. (2021a,b) but not pertinent to those of Shahbaz et al. (2013) Adebayo et al. (2021), Khan et al. (2021), and Zhang et al. (2017). Renewable energy diminishes CO_2 emissions because it produces fewer emissions and ensures clean economic growth. This outcome is in line with the results of Mehmood (2021), Bayar et al. (2021), and Ibrahim and Ajide (2021), but contradictory to the findings of Nathaniel and Iheonu (2019), Adams and Nsiah (2019), and Pata (2018). Technological innovation without the environmental consideration generates more CO_2 emissions. This result is comparable to the results of Dauda et al. (2021), Yu and Du (2019), and Su et al. (2020), but not in line with the findings of Erdoğan et al. (2020), Amin et al. (2020), and Kumail et al. (2020). The confirmation of the EKC is similar to the findings of Balsalobre-Lorente et al. (2021), Shahbaz et al. (2013), Jamel and Maktouf (2017), and Mahmood et al. (2019), but contradictory with the findings of Rahman et al. (2021), Koc and Bulus (2020), and Pata and Aydin (2020). All the findings show rational and empirical significance.

3.5. Robustness check

The outcomes, achieved by applying Driscoll and Kraay's (1998) robust standard error technique, can also be checked for robustness through adopting Panel-corrected standard error (PCSE)

Table A.3
The results of cross-sectional dependence test.

```
. xtcdf lnco2 lnto lnre lnti lngdp lngdp2

xtcd test on variables lnco2 lnto lnre lnti lngdp lngdp2
Panelvar: c_id
Timevar: year
```

Variable	CD-test	p-value	average joint T	mean ρ	mean abs(ρ)	
lnco2	52.416	0.000	40.96	0.17	0.47	36 combinations of panel units ignored (insufficient joint observations).
lnto	60.979	0.000	28.85	0.24	0.45	121 combinations of panel units ignored (insufficient joint observations).
lnre	2.564	0.010	23.82	0.01	0.48	59 combinations of panel units ignored (insufficient joint observations).
lnti	10.348	0.000	16.17	0.03	0.29	671 combinations of panel units ignored (insufficient joint observations).
lngdp	187.095	0.000	32.37	0.77	0.79	
lngdp2	186.401	0.000	33.88	0.76	0.77	

```
Notes: Under the null hypothesis of cross-section independence, CD ~ N(0,1)
       P-values close to zero indicate data are correlated across panel groups.
```

Table A.4
Driscoll–Kraay standard errors model results.

```
. xtscc lnco2 lnto lnre lnti lngdp lngdp2 , fe

Regression with Driscoll-Kraay standard errors   Number of obs     =       704
Method: Fixed-effects regression                 Number of groups  =        45
Group variable (i): c_id                         F(  5,     25)    =    107.91
maximum lag: 2                                   Prob > F          =    0.0000
                                                 within R-squared  =    0.5551
```

lnco2	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
lnto	.1529801	.0390186	3.92	0.001	.0726198	.2333404
lnre	-.2329304	.0370058	-6.29	0.000	-.3091453	-.1567155
lnti	.096426	.0098448	9.79	0.000	.0761502	.1167019
lngdp	1.0831	.1137114	9.52	0.000	.8489075	1.317293
lngdp2	-.0615814	.0064788	-9.51	0.000	-.0749248	-.0482381
_cons	-3.889182	.4673892	-8.32	0.000	-4.851788	-2.926576

Table A.5
Panel-corrected standard error (PCSE).

```
. xtpcse lnco2 lnto lnre lnti lngdp lngdp2 , correlation(ar1) hetonly

Number of gaps in sample:  28
(note: computations for rho restarted at each gap)
(note: estimates of rho outside [-1,1] bounded to be in the range [-1,1])

Prais-Winsten regression, heteroskedastic panels corrected standard errors

Group variable:    c_id                       Number of obs      =       704
Time variable:     year                       Number of groups   =        45
Panels:            heteroskedastic (unbalanced) Obs per group:
Autocorrelation:   common AR(1)                             min =          1
                                                            avg =  15.644444
                                                            max =         26
Estimated covariances      =        45        R-squared          =    0.5920
Estimated autocorrelations =         1        Wald chi2(5)       =    435.25
Estimated coefficients     =         6        Prob > chi2        =    0.0000
```

lnco2	Coef.	Het-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
lnto	.1369198	.0592356	2.31	0.021	.0208201	.2530195
lnre	-.281042	.0454867	-6.18	0.000	-.3701943	-.1918896
lnti	.1618079	.0164384	9.84	0.000	.1295892	.1940266
lngdp	1.4468	.2024247	7.15	0.000	1.050055	1.843545
lngdp2	-.0764835	.0118592	-6.45	0.000	-.0997271	-.05324
_cons	-6.134057	1.018826	-6.02	0.000	-8.13092	-4.137194
rho	.9122578					

technique. The outcomes of PCSE are reported in Table 5, confirming the robustness of the results of Table 4. The results of Table 5 also show the positive impact of trade openness, technological innovation, and per capita GDP, whereas negative impact of renewable energy, and square of per capita GDP on CO_2 emissions.

3.6. The results of pairwise Granger causality tests

In Table 6, the findings of pairwise Granger causality have been reported, where the values of F-statistic and corresponding probability are being mentioned. The one-way causal link of trade openness and square of per capita GDP, and two-way causal association of renewable energy, technological innovation, and per capita GDP with CO_2 emissions have been recognized.

4. Conclusions and policy implications

This study explores the roles of globalization, renewable energy and technological innovation on the air quality for the world's 60 most open countries over the data period of 1960–2020. A series of econometrics tools like the Driscoll and Kraay's (1998) standard error technique and Panel Corrected Standard Error (PCSE) model along with autocorrelation, heteroscedasticity, and cross-sectional dependence tests have been applied to obtain the robust outcomes. The results demonstrate that trade openness, technological innovation, and per capita GDP have positive, and the renewable energy, and square of per capita GDP have negative effects on the CO_2 emissions. The pair-wise Granger causality also discloses the one-way and two-way causal affiliation between the considered variables. All the findings are pertinent in terms of both theoretical and empirical grounds and significant in articulation of important policy directives. The principal policy implication is: the air quality should be improved by reducing CO_2 emissions and hence appropriate and effective globalization, renewable energy, technological innovation, and economic growth policies are required. In particular, the following recommendations should be considered for improving environmental quality:

i. *Environment friendly trade policy* Trade policy should be undertaken with due care of the environment. In this regard, countries should exchange their expertise regarding the production and trade of commodities that comply with environmental cleanliness. An effective and dynamic trade or globalization policy using carbon reducing production technology can ensure the betterment of air quality of the earth.
ii. *Emphasis on renewable energy:* Renewable energy should be increasingly produced and consumed to decrease CO_2

Table A.6
The results of causality test.

Pairwise Granger Causality Tests Date: 03/22/22 Time: 01:23 Sample: 1960 2020 Lags: 2			
Null Hypothesis:	Obs	F-Statistic	Prob.
LNTO does not Granger Cause LNCO2	1893	0.91715	0.3998
LNCO2 does not Granger Cause LNTO		7.16715	0.0008
LNRE does not Granger Cause LNCO2	1302	3.54586	0.0291
LNCO2 does not Granger Cause LNRE		3.40224	0.0336
LNTI does not Granger Cause LNCO2	898	10.4228	3.E−05
LNCO2 does not Granger Cause LNTI		2.59428	0.0753
LNGDP does not Granger Cause LNCO2	2149	3.33114	0.0359
LNCO2 does not Granger Cause LNGDP		5.03264	0.0066
LNGDP2 does not Granger Cause LNCO2	2201	1.18725	0.3053
LNCO2 does not Granger Cause LNGDP2		24.1331	4.E−11

emissions. Massive installation and implementation of renewable energy sources for example, solar panel, wind power, and hydro power, are required. The capacity of renewable energy sources should also be upgraded; these should be easily available to the public to ensure improved air quality without hampering the overall economic development. In this regard, long term and effective strategies are imperative.

iii. *Adoption of green technological innovation:* More technological innovation through research and development should take place to improve the environmental quality; otherwise this may exacerbate the level of pollution. Thus technological innovation, highlighting green development should get more priority to assure fresh air quality. In this regard, suitable policy formulation for green technological innovation is necessary.

iv. *Sustainable economic growth policy:* Economic growth should continue in such a way that fewer CO_2 emissions are emitted and pays substantial attention to the environment. In this regard, sustainable and efficient growth policy based on green technology, clean energy, and pollution free developmental activities can ensure better air quality to protect the environment and sustain growth in the long run.

Like other studies, this work is also not beyond limitations. . In this study we did not group the countries based on developed vs developing regions, and future researches are being recommended to consider this and provide more practical policy implications.

CRediT authorship contribution statement

Mohammad Mafizur Rahman: Study plan, Conceptual and methodological development, Variable selection, Data and result analysis, Writing abstract, Writing main sections of the paper, Data and result analysis, Polishing and editing, Improving the quality of the manuscript, Overall supervision. **Khosrul Alam:** Literature review, Writing introductory sections, Conclusion and mention policy implications, Helping to complete the paper, Data collection, Writing main sections of the paper, Econometric estimation, Data and result analysis, Undertaking the responsibility of corresponding author of this paper.

Declaration of competing interest

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

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Appendix. The overall software generated results

See Tables A.1–A.6.

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