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Econometric analysis of the effects of globalization, technology innovation and renewable energy consumption on CO_2 emissions: Evidence from top five CO_2-emitting countries

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ABSTRACT

Introduction: Anthropogenic CO_2 emission is a pressing global challenge wreaking serious health, environmental and socioeconomic havocs which require urgent attention. Given these undesirable outcomes and the enormous contribution of some set of countries to global CO_2 emissions; this study investigated the long-run effects of globalization, technology innovation and renewable energy consumption on CO_2 emissions in top 5 CO_2-emitting countries across the globe.

Materials and methods: To achieve the study objective, annual CO_2 emissions, globalization, technology innovation, renewable energy and economic growth data of the top 5 CO_2-emitting countries spanning from 1990 to 2022 was analysed using panel autoregressive distributed lag modelling technique and Dumitrescu-Hurlin panel causality test.

Results: CO_2 emissions, globalization, technology innovation, renewable energy consumption and economic growth were found to have long-run relationship in top 5 CO_2-emitting countries. Particularly, renewable energy consumption was found to have negative effect on CO_2 emissions while globalization and technology innovation were found to have positive direct effects on CO_2 emissions. However, globalization and technology innovation had inhibitive interaction effect on CO_2 emissions. Findings also revealed mutually reinforcing causal relationship between economic growth and CO_2 emissions; and between technology innovation and CO_2 emissions.

Conclusion: The findings underscore the fact that urgent prioritisation of renewable energy consumption and international relationships which encourage the transfer, development and adoption of environment-friendly technological innovations will reduce CO_2 emissions and its undesirable environmental, health and socioeconomic effects in top 5 CO_2-emitting countries.

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Introduction

Undoubtedly, the invention and global adoption of fossil-fuel-powered technology innovations have had significant beneficial influence on virtually all spheres of human lives since the first industrial revolution. However, continuous adoption of fossil-fuel-powered technology innovations has worsened the emission of anthropogenic greenhouse gases and other pollutant responsible for several undesirable environmental, health and socioeconomic outcomes [1]. Particularly, climate change defined as long-run changes in temperatures and whether patterns" is a pressing environmental challenges facing the global community [2]. Although natural causes contribute to climate change; anthropogenic greenhouse gases have contributed more to climate change since the 19th century [3]. Prominent amongst these anthropogenic greenhouse gases is carbon dioxide (CO_2) emissions which currently accounts for the greatest portion of global warming caused by human activities [4].

Specifically, CO_2 emissions from combustion of fossil fuels and industry, makes up about 64% of greenhouse gas emissions and has increased to 167% of its value in the year 1990 [5]. Given the enormity of anthropogenic CO_2 emissions in overall greenhouse gas emissions, there have been several global and national commitments and efforts [such as Kyoto Protocol, Paris Agreement and Sustainable Development Goals (SDGs)] towards reduction of anthropogenic CO_2 emissions and other global threats to the environmental sustainability [6]. As suggested in target 17.7 of United Nations sustainable development goals, such global pollution reduction effort may be operationalised through global promotion of the development, transfer, dissemination and diffusion of environment-friendly technologies [7].

However, the effectiveness of such global CO_2-reduction effort often depend on the extent to which national policies supports the replacement for existing grey technologies with green technology innovations [8-9]. Such national prioritization of the natural environment is suggested in Target 13.2 of United Nations SDGs which charges countries to prioritize reduction of climate change and its impact by increasing environmental-friendliness of national policies, strategies and planning. Notably, a major measure of countries progress towards achievement of this target is the total national greenhouse gas emission per year [10]. Given this indicator, increase in the share of renewable energy in the national energy mix (suggested by Target 7.2 of United Nations SDGs) may be an effective policy instrument for reduction of CO_2 emissions since renewable energy produce minimal greenhouse gas [11].

Although countries all over the world have a role to play in and stand to benefit from global reduction of CO_2 emissions, there have always been agitations that developed and emerging economies should be more committed towards reduction of CO_2 emissions. These agitations is primarily premised on the fact that these countries contribute more to global CO_2 emissions and have better technological/economic capacity to reduce global CO_2 emissions [12]. Consequently, these countries have stepped up their investment in green technology innovations targeted at reducing CO_2 emissions and other greenhouse gases. For instance, in 2024, China, India, Japan and other Asia Pacific countries jointly invested over $1 trillion in green technology investment which represents a 21% growth from previous year and 50% of global energy transition investment. This investment drive is majorly driven by mainland China with a green technology investment of $818 billion which represents about 67% of global growth in green technology investment. However, United States green technology investment was stable at $338 billion while the European Union and United Kingdom experienced decline in green technology investment. In terms of share of GDP invested in green technology investment, China with 4.5% of her GDP invested in green technology tops the top 10 markets followed by Germany, European Union and the United Kingdom [13].

Notwithstanding these efforts, annual investment in green technology is still 37% of the green technology investment required for the rest of this decade if the net zero emission will be achieved in 2050. Consequently, emission of CO_2 and other anthropogenic gases is still a major health, environmental and socioeconomic challenge in top CO_2-emitting countries and across the globe. Particularly, with respect to the countries under study, Fig. 1 shows that technology innovation, globalization and economic growth move in the same direction with CO_2 emissions while renewable energy consumption move in opposite direction of CO_2 emissions during the study period. These plots seem to suggest that increasing CO_2 emissions coexists with increasing technology innovations, globalization and economic growth and that increasing renewable energy consumption occurs alongside diminishing CO_2 emissions. These contradictions provide the justification for further investigation of these intrinsic relationships. Source: Authors computation based on data from World Bank, Organisation for Economic Cooperation and Development Database, KOF Swiss Institute, Global Carbon Atlas.

In a bid to contribute to global efforts to reduce CO_2 emissions and its undesirable health, environmental and socioeconomic outcomes; this article investigated the long-run effects of globalization, technology innovation, and renewable energy consumption on CO_2 emissions in top 5 CO_2-emitting countries in the world. Furthermore, this study will consider the influence of globalization on the effect of technology innovation on CO_2 emissions in these countries. The study analysed unbalanced annual panel data of CO_2 emissions, globalization, renewable energy consumption, technology innovation and per capita gross domestic product (control variable). The unbalanced panel data was estimated using the Pooled Mean Group (PMG) estimator of the panel Autoregressive Distributed Lag model (ARDL) estimation framework and Dumitrescu-Hurlin causality test.

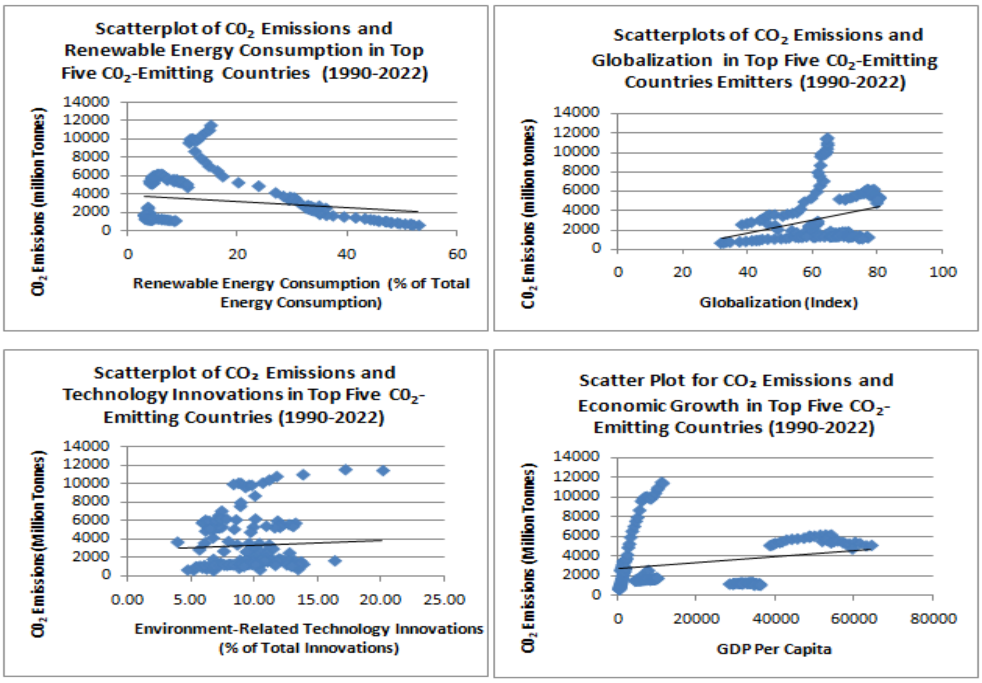

Fig. 1. Scatter plots of CO_2 emissions, renewable energy consumption, technology innovation and economic growth in top five CO_2-emitting countries

According to anthropogenic theoretical perspective to pollution, environment-unfriendly activities like combustion of fossil fuels and deforestation are the primary cause of increasing emission of CO_2 and other pollutants. Following this line of argument, the ecological modernization theory suggests that environmental sustainability can be achieved simultaneously with other human goals by making technology innovations, policies, societal values and behaviours more environment-friendly [14]. Inherent in this theory is the idea that deliberate human efforts towards prioritization of the environment are required for the reduction of CO_2 and other pollutants. Applying these theoretical propositions to the current study, environment-friendly globalization, technological innovation, and energy consumption on environmental pollution are expected to reduce CO_2 emissions. This theoretical proposition has been tested by many empirical studies.

According to a study which assessed the linkages among renewable energy, economic globalization, on environmental sustainability (measured as CO_2 emissions and ecological footprint) using quantile regression analysis; investment in renewable energy consumption inhibits CO_2 emissions and ecological footprint while globalization exacerbates CO_2 emissions and ecological footprint in E7 countries from 1990 to 2016. The study highlighted the need for continuous adoption and development of low-carbon technologies and strategies in for reduction of environmental pollution in E7 countries [15]. The fact that renewable energy use reduce CO_2 emissions also confirmed by another similar study which investigated the heterogeneous effect of renewable energy consumption on per capita CO_2 emissions and ecological footprint in 130 countries from 1992 to 2018. However, such inhibitory effect was more obvious in low-income countries than in middle-income countries [16]. Similarly, the effect of globalization on environmental pollution was found to be influenced by quality of institutions. Particularly, globalization was found to inhibit environmental pollution in democracies but exacerbate pollution in autocracies. However, renewable energy consumption was found to inhibit pollution regardless of the quality of institutions [17].

Another study which examined the mechanism through which green technology progress influence CO_2 emissions using spatial Durbin model found that green technology progress inhibits CO_2 emission via industrial and energy structures, and energy efficiency in a Chinese provinces from 2008 to 2020. The study revealed heterogeneous the effect of green technology progress on CO_2 emissions in Chinese provinces and underscores the importance of green technology towards achievement of low carbon economic development and carbon neutrality [18].

According to a study which investigate the impact of green investment, technological innovation, and globalization on CO_2 emissions in Mexico, Indonesia, Nigeria and Turkey from 2000 to 2020; non renewable energy and technological innovations have exacerbating effect on CO_2 emissions while globalization and investment in green technology have inhibiting effect on CO_2 emissions. The study also reported negative interaction effects of technological innovation and globalization; and negative interaction effect of globalization and investment in environment-friendly technology on CO_2 emissions during the study period. Furthermore, findings from the study also revealed bidirectional causality among green investment, globalisation, technological innovation, non renewable energy and CO_2 emissions [19].

Although there are many empirical evidences which support the inhibiting effect of technology innovations and renewable energy consumption on CO_2 emissions, there are few studies which found exacerbatory effects of these variables on CO_2 emissions. Such studies often attribute this unexpected outcome to rebound effect in which efficiency or environmental gains from advancement in technology innovations are offset by overconsumption; and reliance of green technology innovation on non-renewable components and secondary energy generated from fossil fuel [20, 21]. Similarly, the exacerbating and inhibiting effects of globalization on CO_2 emissions are usually explained using the pollution haven and the pollution halo hypothesis respectively. The pollution haven hypothesis on the one hand suggests that globalization worsen environmental pollution especially in developing countries with less stringent environmental regulation; however, the pollution halo hypothesis suggests that globalization reduce environmental pollution through transfer of environment friendly technologies.

Materials and methods

Model specification

This study is based on the anthropogenic perspective to pollution and the ecological modernization theory which respectively suggests that environment-unfriendly human activities are the primary source of CO_2 and other pollutant and that making this human activities more environment friendly is key to the reduction of CO_2 and other pollutant. Eq. 1 specifies the implicit model.

$$lnCO_2 = f(REN, TEC, lnGLO, lnGLO * TEC, ECO) \quad (1)$$

Eq. 1 is explicitly specified in unrestricted ARDL (2,3,3,3,3) form as

$$\Delta lnCO_{2_{it}} = \beta_0 + \sum_{b=1}^{2} \beta_{1b} \Delta lnCO_{2_{i,t-b}} + \sum_{c=0}^{3} \beta_{2c} \Delta REN_{i,t-c} + \sum_{d=0}^{3} \beta_{3d} \Delta TEC_{i,t-d} + \sum_{f=0}^{3} \beta_{4e} \Delta lnGLO_{i,t-e} + \sum_{e=0}^{3} \beta_{5f} \Delta(lnGLO * TEC)_{i,t-f} + \sum_{g=0}^{3} \beta_{6g} lnECO_{i,t-g} + \pi_1 lnCO_{2_{t-1}} + \pi_2 REN_{t-1} + \pi_3 TEC_{t-1} + \pi_4 lnGLO + \pi_5 (lnGLO * TEC)_{t-1} + \pi_6 lnECO_{t-1} + \mu_{it}$$

(2)

$$\Delta lnCO_{2_{it}} = \beta_0 + \sum_{b=1}^{2} \beta_{1b} \Delta lnCO_{2_{i,t-b}} + \sum_{c=0}^{3} \beta_{2c} \Delta REN_{i,t-c} + \sum_{d=0}^{3} \beta_{3d} \Delta TEC_{i,t-d} + \sum_{f=0}^{3} \beta_{4e} \Delta lnGLO_{i,t-e} + \sum_{e=0}^{3} \beta_{5f} \Delta(lnGLO * TEC)_{i,t-f} + \sum_{g=0}^{3} \beta_{6g} lnECO_{i,t-g}$$

And the error correction form of Eq. 2 is

$$+\theta ECT_{t-1} + \mu_{it} \quad (3)$$

Where:

$lnCO_2$: Natural log of carbon dioxide emissions

REN: Renewable Energy Consumption

TEC: Technology Innovation

lnGLO: Natural log of globalization

lnECO: Natural log of Economic Growth

lnGLO*TEC: Interaction of Natural log of globalization and Technology Innovation

β_0: Intercept

β_{1b}, β_{2c}, β_{3d}, β_{4e}, β_{5f}, β_{6g}: short-run coefficients;

$\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6$: Long-run coefficients;

μ_{it}: is the error term

θ: Coefficient of error correction term ECT_{t-1}

A priori expectation

$\beta_{2c}, \beta_{3d}, \beta_{5f}, \pi_2, \pi_3, \pi_5 < 0$; $\beta_{4e}, \beta_{6g}, \pi_4, \pi_6 > 0$; $-1 < \theta < 0$

Data description and source

This study is based on panel data of China, United States, India, Russia and Japan from 1990 to 2022. The sample countries were selected due to their enormous contribution to global CO_2 emission while availability of data for technology innovation determined the study period. The dependent variable CO_2 emission was proxied by territorial CO_2 emissions measured million tones of CO_2 and sourced from Global Carbon Atlas. The explanatory variables globalization was proxied by globalization index measured as an index ranging from 1 to 100 and sourced from KOF globalization index. The explanatory variables technology innovation was proxied by environment-related technology innovation as percentage of total technology innovation and sourced from Organization for Economic Co-operation and Economic Development database. The explanatory variable renewable energy consumption was proxied by renewable energy consumption as percentage of total energy consumption was sourced from world development indicators. Similarly, control variable economy growth proxied by per capita gross domestic product measured in constant 2015 US dollars was sourced from world development indicators.

The explanatory variables globalization, technology innovation and energy consumption are major economic determinants of CO_2 emissions. However, the status of these variables as drivers or inhibitors of CO_2 emissions depends largely on the extent of their environmental-friendliness. For instance countries which use more of fossil-fuel-powered technology or fossil fuels in production of goods and services are likely to have higher CO_2 emissions than countries which use more of renewable-energy-powered or renewable energy alternatives in production of goods and services. Consequently, these explanatory variables are chosen with the intension of investigating the effectiveness of environment-friendly international economic interdependencies, technology innovation and energy alternatives for reduction of CO_2 emissions. Given that this study follows a macro approach, the explanatory variables (globalization, technology innovation and renewable energy consumption) are measured at their macro or national level. This approach ensures the generalizability of the effects of the explanatory variables on CO_2 emissions in the top five carbon-emitting countries under study. For instance this study viewed technology innovation (at a macro level) in terms of annual share of environment-friendly technology innovations (intended to reduce CO_2 emissions and other threats to the environment) in total technology innovations in the countries under study. Consequently, this study focused broadly on all forms of such environment-related technology innovations such as carbon capture/storage technologies, renewable energy technologies, and electric vehicles.

Estimation technique

This study employed the Pooled Mean Group (PMG) estimator of the panel autoregressive distributed lag model (ARDL) framework having established that variables either integrated of order zero [I(0)] or order one I(1)] and cross-section independent. Particularly, the PMG estimator was adopted based on the assumption that the long-run effects of explanatory variables will be homogenous across the top five CO_2 emitting countries under study. The Im, Peseran and Shin (IPS) and Levin Lin and Chu (LLC) unit root tests were use to reveal the order of integration of the variables while Pesaran cross-sectional dependency test was used to verify absence of cross-section dependence in the variables. Absence of cross-section dependence in the residuals of the estimated model, long-run homogeneity assumption and normality of residuals were respectively verified using Pesaran cross-sectional dependency test, Wald test of coefficient restriction, and Jarque-Bera test. The optimal lags for the variables were automatically selected using the Akaike Information Criterion. The Dumitrescu-Hurlin causality test was used to establish the direction of causality among the variables of interest while descriptive statistics and correlation matrix were respectively used to analyse the descriptive properties of variables; and test for linear relationship between the variables.

Results and discussion

Descriptive properties of C02, REN, TEC, GLO, ECO

As shown in Table 1, there are significant differences between the median and mean values of CO_2, REN, and ECO. This shows the presence of extreme values of the three variables and that median is a better measure of central tendency for these variables. The sum of value of CO_2 reveals that China, United Sates, India, Russia and Japan jointly emitted 547,463.8 million tonnes of CO_2. Given the fact that possible values of REN and TEC ranges from 0% to 100%, the median values of REN and TEC (9.81) reveals that the countries under study jointly performed far below average in terms of renewable energy consumption and green technology innovation. Similarly, the minimum and maximum values REN and TEC also suggests that these high CO_2-emitting countries are still lagging behind in terms of transition to environment-friendly energy consumption and technology innovation. The median value of GLO suggests that the level of globalization of countries under study was above average during the study period.

Table 1. Descriptive statistics

	CO2	REN	TEC	GLO	ECO
Mean	3317.962	15.659	9.737	63.881	19465.370
Median	1764.712	7.300	9.810	64.834	9120.820
Maximum	11447.910	53.000	20.081	80.789	64342.120
Minimum	577.9960	3.200	3.986	31.993	531.898
Sum	547463.800	-	-	-	-
Observations	165	160	165	165	165

Source: Authors' computations

Relationship among C02, REN, TEC, GLO, ECO

As shown in Table 2, renewable energy consumption has weak, moderate and strong negative relationships with technology innovation, economic development and globalization respectively. Furthermore, technology innovation was revealed to have weak positive relationship with globalization and economic growth while globalization was revealed to have strong positive relationship with economic growth. Overall, these correlation coefficients reveal that no pair of explanatory variables has very strong or perfect correlation which may result in to multicollinearity and its undesirable effects in the estimated model. The correlation matrix also reveals that renewable energy consumption and environmental pollution moved in opposite direction in top five carbon-emitting countries in the world. Conversely, the findings revealed significant positive relationship between globalization and environmental pollution and between economic development and environmental pollution. This suggests that globalization and economic development moves in the same direction with environmental pollution in the countries under study.

Table 2. Correlation matrix

	$\ln CO_2$	REN	TEC	lnGLO	lnECO
$\ln CO_2$	1.0000 [..........]				
REN	-0.187* [0.018]	1.0000 [..........]			
TEC	-0.031 [0.699]	-0.312** [0.000]	1.0000 [..........]		
lnGLO	0.297** [0.000]	-0.745** [0.000]	0.275** [0.000]	1.0000 [..........]	
lnECO	0.224** [0.004]	-0.561** [0.000]	0.063 [0.432]	0.765** [0.000]	1.0000 [..........]

H_0= no linear relationship
Probability values in [ ]
*** Correlation is significant at 0.01 level*
** Correlation is significant at 0.05 level*
Source: Authors' computations

Cross-Section dependence test

As shown in Table 3, the null hypothesis (No cross-section dependence in series) is rejected for CO_2 and REN at 5% level of significance; and rejected for TEC, GLO, and ECO at 1% level of significance. These results imply that the CO_2 emissions, renewable energy consumption, technology innovation, globalization and economic growth of the panel of countries under study are not correlated.

Unit root tests

As shown in Table 4, the null hypotheses (unit root) of the Im, Peseran and Shin (IPS) and Levin Lin and Chu unit root tests is rejected for all the variables either at level I(0) or after first difference I(1). This result supports the adoption of panel autoregressive distributed lag model technique which assumes that variables are stationary at level or at first difference.

Table 3. Pesaran cross-section dependency test

Variable	Statistic	Probability
$lnCO_2$	-1.276	0.020*
REN	-1.483	0.038*
TEC	4.321	0.000**
lnGLO	17.497	0.000**
lnECO	6.426	0.000**

H_0: No Cross-Section dependence in Series

*** Probability value significant at 0.01 level*

** Probability value significant at 0.05 level*

Source: Authors' computations

Table 4. Unit root tests

Variable	Statistic	Probability
$lnCO_2$	-1.276	0.020*
REN	-1.483	0.038*
TEC	4.321	0.000**
lnGLO	17.497	0.000**
lnECO	6.426	0.000**

H_0: No Cross-Section dependence in Series

*** Probability value significant at 0.01 level*

** Probability value significant at 0.05 level*

Source: Authors' computations

Causality test

Table 5 reveal significant one-way causality from REN and GLO to CO_2; and from GLO to REN and TEC. These findings suggest that previous levels of renewable energy consumption and globalization determines current level of CO_2 emissions; and that previous levels of globalization determines current level of renewable energy consumption and technology innovation. However, two-way causality is revealed between TEC and CO_2 emissions; ECO and CO_2 emissions; and between ECO and TEC. These findings suggest that previous levels of technology innovation and economic growth determine current level of CO_2 which in turn determines future level of technology innovation and economic growth; and that previous levels of technology innovation determines the current level of economic growth which in turn determines future level of technology innovation. Overall, these findings confirm the usefulness of the REN, TEC, GLO and ECO in explaining CO_2 emissions in top 5 CO_2-emitting countries.

Table 5. Dumitrescu-hurlin panel causality test

Null Hypothesis	W Statistic	Zbar Statistic	Probability
REN → CO_2	10.204	5.069	0.000**
CO_2 → REN	4.477	0.864	0.388
TEC → CO_2	9.956	4.947	0.000**
CO_2 → TEC	13.831	7.820	0.000**
GLO → CO_2	8.374	3.773	0.000**
CO_2 → GLO	2.239	-0.776	0.438
ECO → CO_2	12.105	6.540	0.000**
CO_2 → ECO	6.098	2.086	0.037*
ECO → TEC	6.183	2.149	0.032*
TEC → ECO	6.349	2.272	0.023*
GLO → REN	7.809	3.310	0.001**
REN → GLO	5.795	1.832	0.067
GLO → TEC	6.669	2.509	0.012*
TEC → GLO	2.736	-0.408	0.684

→ does not homogenously cause
*** Probability value significant at 0.01 level*
** Probability value significant at 0.05 level*
Lags = 3
Source: Authors' computations

Long-run estimates of the effects of REN, TEC, GLO, and ECO on CO_2 emissions

Table 6 presents the long-run estimates of the effects of REN, TEC, GLO, GLO*TEC and ECO on CO_2 emissions. The estimates show that all explanatory variables influence CO_2 emissions in the long run. Particularly, the coefficient of REN (-0.031) is the long-run effect of renewable energy consumption on CO_2 emissions. The coefficient implies that 1% rise in renewable energy consumption will lead to approximately 3.1% long-run reduction in CO_2 emissions. This result suggests that inclination towards clean energy sources reduce CO_2 emissions in the countries under study. This finding in consonance with the theoretical suggestion that increase in renewable energy consumption will reduce CO_2 emissions and studies which agrees with this suggestion [22-23]. This finding is however inconsistent with studies which does not support this indirect relationship [24].

The coefficient of TEC (0.390) is the main effect of technology innovation on CO_2 emissions. It implies that in the absence any form of globalization, 1% increase in environment-related technology innovations will yield about 0.39% long-run increase in CO_2 emissions. This suggests that increase in environment-related technology innovations does not necessarily translate to reduction of CO_2 emissions since environment-related technology innovations are just a means to an end and not end in themselves. This finding also emphasised the need to distinguish between the effect of environment-related technology innovation and environment-related technology adoption on CO_2 emissions. This result disagrees with a priori expectation that environment-related technology innovations will result in reduce CO_2 emissions; and studies which found inhibiting effect of technology innovations on CO_2 emissions [25, 26]. This finding however partially or fully agrees with some other studies which concluded that technology innovation worsen CO_2 emissions. According to these studies, exacerbating effect of technology innovation on CO_2 emissions may be due to rebound effect (in which efficiency gains from technology innovations are eroded by increased consumption); reliance of environment-related technology innovation on secondary energy sources such as electricity which are derived from primary energy sources such as fossil fuels; country characteristics; and the fact that technology innovation does not necessarily implies technology adoption [27, 28].

The coefficient of lnGLO (0.850) is the main effect of globalization on CO_2 emissions. It is the effect of globalization on CO_2 emissions in the absence of any form of technology innovation. Particularly, it implies that in the absence any form of technology innovation, 1% rise in GLO will yield about 0.39% long-run rise in CO_2 emissions. This result suggests that globalization which does not promote transfer, development and adoption of environment-friendly technology innovations will worsen CO_2 emissions. This finding is consistent with theoretical proposition that globalization in itself exacerbates CO_2 emissions; and other studies which found exacerbating effect of globalization on CO_2 emission [29, 30]. The finding however disagrees with other studies whose findings suggest that globalization reduce CO_2 emissions. According to these studies globalization reduce CO_2 emissions through direct foreign investments from multinational companies which encourage transfer and adoption of environment friendly technology innovations [31, 32].

The coefficient of lnGLO*TEC (-0.092) is the interaction effect of globalization and technology innovation on CO_2 emissions. In terms of interaction, this coefficient implies that 1% increase in the interaction of globalization and technology innovation reduces CO_2 emissions by 0.092%. In terms of moderation, this coefficient implies that the relationship between technology innovations and CO_2 emissions depends on the level of globalization. Particularly, technology innovation reduces CO_2 emissions at levels of globalization above the critical level (lnGLO = 4.24 i.e. GLO=69.5) but increases CO_2 emissions at levels of globalization below the critical level. Particularly, 1% increase in globalization which occurs at higher level of globalization will increase the CO_2-reduction effect of technology innovation by 0.092% while 1% increase in globalization which occurs at lower level of globalization will decrease the CO_2-increasing effect of technology innovation by 0.092%. In any of the two cases, this result suggests that increase in globalization which encourages transfer, development and adoption of environment-friendly technology innovations reduces CO_2 emissions. Such environment-friendly effect of GLO which occurs through technology innovations agrees with a priori expectation and other extant studies [33, 34]. The finding however disagrees with other studies which conclude that globalization worsens CO_2 emissions through transfer of environment-unfriendly technology innovations [29, 30].

The coefficient of lnECO (0.268) implies that 1% increase in ECO will yield about 0.268% long-run increase in CO_2 emissions. This agrees with the theoretical proposition that economic growth which does not prioritise the environment will worsen CO_2 emissions. The standardized version of the coefficients of the explanatory variables reveals interaction of globalization and technology innovation, technology innovation and renewable energy consumption respectively as the top three predictors which exert the most long-run influence on CO_2 emissions. The coefficient of ECT(-1) (-0.444) implies that approximately 44.4% of the short-run deviation from the long-run equilibrium is corrected annually. This implies that it takes about 2.25 (0.444^{-1}) years to correct the current year's deviation from the long-run equilibrium. This also implies existence of long-run relationship among the variables under study; and joint long-run causality from the explanatory variables to CO_2 emissions.

Table 6. Long-run estimates and error correction term

Variable	Coefficient	Standardized Coefficient	Standard Error	T-statistic	Probability
REN	-0.031	-0.615	0.004	-7.342	0.000**
TEC	0.390	1.255	0.074	5.274	0.000**
lnGLO	0.850	0.224	0.179	4.745	0.000**
lnGLO*TEC	-0.092	-1.292	0.018	-5.185	0.000**
lnECO	0.268	0.522	0.052	5.159	0.000**
ECT(-1)	-0.444	-	0.175	-2.533	0.014*

Dependent Variable: $lnCO_2$
*** Variable significant at 0.01 level*
** Variable significant at 0.05 level*
Source: Authors' computations

Table 7. Model reliability tests

Test	Statistic	Probability
Pesaran CD	0.243	0.808
Jarque-Bera	1.122	0.571
Wald	109.501	0.000**

Pesaran CD Test H_0 : No Cross-Section Dependence

Jarque-Bera Test H_0 : Normally Distributed Residuals

Wald Test H_0 : Long-run coefficients are equal to zero

*** Probability value significant at 0.01 level*

Source: Authors' computations

Post estimation diagnostics

As shown in Table 7, the null hypotheses (cross-section dependence and normality of residuals) of the Pesaran cross-section dependency and Jarque-Bera tests cannot be rejected at 5% level of significance. However, the null hypothesis (long-run coefficients equals zero) of the Wald test of coefficient restriction is rejected at 1% level of significance. These findings suggest that the errors of the autoregressive distributed lag model estimated in this study are normally distributed and free from cross-section dependence; and that the assumption that the effects of REN, TEC, GLO, GLO*TEC and ECO on CO_2 emissions is homogenous across the countries under study is valid.

Conclusion

Following the anthropogenic theoretical perspectives that deliberate human efforts towards increasing the environmental friendliness of human activities is crucial for the reduction of CO_2 emission and its undesirable health, socioeconomic, and environmental outcomes; this study investigated the long-run effects of globalization, technology innovation and renewable energy consumption on CO_2 emission in top 5 CO_2-emitting countries from 1990 to 2022. The pooled mean group estimator of the autoregressive distributed lag modelling framework and the Dumitrescu-Hurlin panel causality test was used to analyse the data of the five countries. Findings from this study support the existence of long-run relationship among CO_2 emissions, globalization, renewable energy consumption, technological innovation and economic growth. The estimated coefficients of globalization and technology innovation respectively supports the notion that globalization in itself worsens CO_2 emission; and the idea that environment-related technology innovation is only a means to an end (CO_2 emissions reduction) and not an end (CO_2 emission reduction) in itself.

This further supports the conclusion that mere increase in environment-related technology innovations does not necessarily translate to reduction of CO_2 emissions.

However, the coefficient of the interaction of globalization and technology innovations support the conclusion that globalization which promotes transfer, development and adoption of environment-friendly technology innovations reduce CO_2 emissions. Similarly, the estimated coefficient of economic growth validates the idea that economic growth in itself exacerbates CO_2 emission. This supports the idea that environment-unfriendly economic growth worsens CO_2 emission. However, the estimated coefficient of renewable energy consumption supports the idea that transition from non-renewable energy sources such as fossil fuels to renewable energy sources such as sun, wind, water and biomass reduces CO_2 emissions. The result of the Dumitrescu-Hurlin panel causality test supports mutually reinforcing causal relationship between technology innovation and economic growth; economic growth and CO_2 emissions; and CO_2 emissions and technology innovation. These findings support the idea that a mutually reinforcing link exists among technology innovation, economic growth and CO_2 emissions top 5 CO_2-emitting countries. The findings from the test also supports the conclusion that globalization triggers technology innovation and renewable energy consumption. Following these conclusions, this study suggests prioritization of renewable energy use; international relationships which encourage the transfer, development and adoption of environment-friendly technological innovations; and green economic growth for reduction of CO_2 emission and its undesirable socioeconomic, health and environmental outcomes in China, United States, India, Russia and Japan. Although there are evidences that continuous production of CO_2 at the current rate may be catastrophic for the whole world; majority of countries across the world still continues to use fossil fuels and emit CO_2 without taking the results of the research into consideration.

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Competing interests

The authors declare no conflicts of interest

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Ethical considerations

Ethical issues (Including plagiarism, Informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors.

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