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RESEARCH ARTICLE

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International trade and environmental performance in top ten-emitters countries: The role of eco-innovation and renewable energy consumption

Shahid Ali[1] | Eyup Dogan[2,3] | Fuzhong Chen[4] | Zeeshan Khan[5]

[1]Department of Economics, University of Swat, Khyber-Pakhtunkhwa, Pakistan
[2]Department of Finance and Economics, University of Sharjah, Sharjah, United Arab Emirates
[3]Department of Economics, Abdullah Gul University, Kayseri, Turkey
[4]School of International Trade and Economics, University of International Business and Economics, Beijing, China
[5]School of Economics and Management (SEM), Tsinghua University, Beijing, China

Correspondence
Fuzhong Chen, School of International Trade and Economics, University of International Business and Economics, Beijing, China.
Email: uibesitechen@126.com

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Abstract
The global economy is rising continuously, with a 3–4% aggregate annual growth in output, which poses a severe threat to the environment due to a consistent rise in the use of fossil fuel. Given the disastrous climate change due to the industrialization and increasingly growing demands for energy, countries around the globe are devising strategies to curb the release of greenhouse gases. This study examines the role of environmental innovation, trade, and renewable energy consumption in the nexus between trade and CO_2 emissions for top 10 carbon emitter countries. The results suggest that there is evidence of cross-sectional dependency, and models are suffered from slope heterogeneity problem test popularized by Pesaran and Yamagata. The results of Westerlund cointegration method suggest that in there is long equilibrium relationship among CO_2 emissions and other variables such as environmental innovation, trade, and renewable energy consumption and income. The results of cross-sectionally augment autoregressive distributed lags (CS-ARDL) method suggest that in the long run, environmental innovation, trade, and renewable energy consumption and income are important factors in explaining consumption-based carbon emission and territory-based carbon emission.

KEYWORDS
consumption- and territory-based carbon emissions, eco-innovation, CSARDL

1 | INTRODUCTION

Environmental degradation represents a major dilemma for human lives. Environmental degradation is the exhaustion of the world's natural resources and hence threatens to undermine sustainable growth (Al-Mulali & Ozturk, 2016). Continuous increase in World's economic activities poses a serious threat to the environment and contributed remarkably to global climate due to consistent growing demand for fossil fuel (Sachs et al., 2019).

The importance of the environmental impact of economic activities and sustainability is well documented in the literature. An increase in output and prosperity is the main objective of government policy. However, the rapid growth in economic activities inescapably results in greater exploitation of natural resources, which ultimately puts a serious threat to the environment (Munasinghe, 1998). Hence, continuous increase in world output results in growing demands for energy, which ultimately exerts greater challenges for environment (Al-Mulali, Ozturk, & Solarin, 2016). The abating of environmental degradation is widely recognized as an important factor in achieving sustainable growth (Alam, 2002).

To serve this purpose, Paris Climate Agreement or COP21 took place in 2015 entered into force on November 4, 2016, and ratified by 187 countries as of November 2019, which aims to improve upon environmental situation and to curb the release of greenhouse gases. COP21 pointed out that continuous increase in output is largely responsible for worsened environmental quality (Özokcu & Özdemir, 2017). However, despite COP21, several countries in several emerging countries like China and India, use of fossil fuels dominates not only investment in energy but also its use for production and consumption purposes. Moreover, most of the emerging countries generate electricity from coal, which is a serious threat to the environment. If the situation continues, the global economy is expected to contract by 5–20% in next 20 years (Noh, 2010).

Given the disastrous climate change due to the industrialization and increasingly growing demands for energy, countries around the globe are devising strategies to curb the release of greenhouse gases. With the introduction of new energy efficiency technologies such as modernizing the grid, electricity usage through renewable resources is helpful in swapping the economic structure to more sustainable energy sources, that is, renewable (Alvarez-Herranz, Balsalobre-Lorente, Shahbaz, & Cantos, 2017; Kammerer, 2009; Zhang, Peng, Ma, & Shen, 2017). Environmental innovation affects CO_2 emissions by reducing the carbon prices and increasing the learning income (Gerlagh, 2007). However, an extensive amount of investment in research and development is required to integrate a variety of energy efficiency technologies into a cohesive energy system (Aragón-Correa et al., 2008). The environment-related patents, represented by eco-innovation, is helpful in for restricting the rising trend in CO_2 emissions (Khan et al., 2020).

Table 1 shows that whether a country is net emissions importer or exporter. To serve this purpose, we find the ratio and difference of consumption-based carbon emissions (CCO_2) and territory-based carbon emission (TCO_2) for sample countries. Countries such as Brazil, Germany, Japan, South Korea, Mexico, and the United States are net emissions importer because the ratio (CCO_2/TCO_2) is greater than one, which implies that these countries import carbon emissions from other countries. Countries such as China, India, Indonesia, and Russian Federation are the net emissions exporter.

This study examines the determinants CO_2 emissions for top 10 carbon emitter countries such as Brazil, China, Germany, India, Indonesia, Japan, South Korea, Mexico, Russian Federation, and the United States.

2 | LITERATURE REVIEW

The issue of determinants of environmental degradation is well highlighted in the literature with contradictory empirical evidences. The issue was initially studied by trade economists by arguing that international trade may transfer polluted industries to other countries and, hence, may enhance CO_2 emissions (Grossman & Krueger, 1991; Shafik, 1994).

2.1 | International trade and CO_2 emissions

The literature provides conflicting results on the possible relationship between trade and environmental quality. The issue is still debatable among researchers. Liu et al. (2018) *argue that trade leads to deteriorate* environmental quality by shifting the pollution intensive industries from one country to another. Rock (1996) argued that due to environmental externality, openness of trade leads to environmental degradation. Alola, Bekun, and Sarkodie (2019) found that trade is responsible for deteriorating environmental quality. Hasanov, Liddle, and Mikayilov (2018) bifurcated trade into exports and imports in order to gauge the impact of subdimensions of trade on CO_2 emissions. The authors used territory and consumption-based measures of CO_2 emissions and found that exports of production require efficient technology and energy system, which negatively affects CCO_2; however, for TCO_2, exports cause a decline. Kurniawan and Managi (2018) introduced coal consumption and urbanization in order to examine the relationship between trade openness and CO_2 emissions. Similarly, Nathaniel (2020) introduced energy use and urbanization in the relationship between trade and CO_2 emissions. Both studies of Kurniawan and Managi (2018) and Nathaniel (2020) found a strong positive impact of trade on increasing CO_2 emissions. According to Kurniawan and Managi (2018), trade intensifies the usage of non-renewable energy sources and hence adds more to environmental pollution. Gozgor and Can (2016) also obtained the positive relationship between trade and CO_2 emissions. Sushmita, Benoit, Hua, and David (2002) found that since more resources are required in the process of globalization, opening of trade is associated with deteriorated environmental quality. Hence, trade openness deteriorates

TABLE 1 Average ratios of CCO_2 to TCO_2

Countries	CCO_2/TCO_2	CCO_2-TCO_2	Decision
Brazil	1.08753	30.4703	Net Emission Importer
China	0.872633	−800.198	Net Emission Exporter
Germany	1.159449	141.1795	Net Emission Importer
India	0.941664	−88.2027	Net Emission Exporter
Indonesia	0.995742	1.158889	Net Emission Exporter
Japan	1.169831	210.622	Net Emission Importer
South Korea	1.1388	56.77792	Net Emission Importer
Mexico	1.041922	19.10744	Net Emission Importer
Russian Federation	0.839677	−260.681	Net Emission Exporter
United States	1.043553	250.0975	Net Emission Importer

TABLE 2 Cross sectional dependency and slope homogeneity test

Pesaran (2004) CD-test		
Variables	**CD-statistic**	**Correlation**
CCO_2	8.32***	0.64
TCO_2	6.96***	0.65
EXP	13.98***	0.52
IMP	14.35***	0.60
GDP	32.73***	0.92
REC	12.85***	0.46
Eco-innovation	12.05***	0.39
Pesaran and Yamagata (2007) slope heterogeneity test		
	Delta_tilde	Adjusted Delta_tilde
Dep: CCO_2	7.862*** (0.000)	8.065*** (0.000)
Dep: TCO_2	6.571*** (0.000)	7.065*** (0.000)

Note: ***, **, and * is for 10, 5, and 10% significance level.

environmental quality (Özokcu & Özdemir, 2017). Moreover, during the process of globalization, countries require more resources and hence, increase CO_2 emissions (Sushmita et al., 2002). However, contrary to the abovementioned studies, several other studies backed the negative impact of trade on environmental quality (see Destek et al. 2018; Nathaniel, 2020; Shahbaz et al., 2019a). Shahbaz et al. (2019a) found that international trade reduces CO_2 emissions. Based on the results of the study for EU countries, Destek et al. (2018) found that trade reduces CO_2 emissions. The theoretical justification for the negative association between trade and CO_2 emission is provided by Nathaniel (2020) who argued that international trade increases CO_2 emissions in the short run; however, in the long run, access to technologies due to trade enables countries to improve their environmental quality. Chen (2008) argued that imports, exports, FDI inflow, and environmental regulation are important factors affecting CO_2 emissions. Khan et al. (2020) bifurcated trade into exports and imports and estimated their impact on CO_2 emissions. The main findings of their study were that trade exerts pressure on environment due to its effect on flow of goods. We establish the hypothesis as:

Hypothesis 1. Trade affects CO_2 emissions.

2.2 | Environmental innovation and CO_2 emissions

On the role of eco innovation and CO_2 emissions, an extensive research is conducted (Alvarez-Herranz et al., 2017; Aragón-Correa et al., 2008; Costantini, Crespi, Marin, & Paglialunga, 2017; Erdoğan, Yıldırım, Yıldırım, & Gedikli, 2020; Henriques & Borowiecki, 2017; Kammerer, 2009; Zhang et al., 2017). Researchers introduce eco-innovation in the empirical model to estimate the determinant of CO_2 emission. Erdoğan et al. (2020) analyzed the importance of environmental innovation reducing CO_2 emissions in G20 countries. The author found that environmental innovation in the industrial sector reduces CO_2 emissions. However, environmental innovation in the construction sector is not helpful for CO_2 abatement. Costantini et al. (2017) analyzed the importance of environmental innovation reducing CO_2 emissions in European industries. The study considers the eco-innovation shall be helpful in support of environmental quality. Alvarez-Herranz et al. (2017) stress the need for low-carbon technologies to promote environmental-friendly growth in 17 OECD countries. The author argued that energy efficiency technologies are helpful in swapping the economic structure to more sustainable energy sources, that is, renewable energies. Hence, eco-innovation is negatively related to CO_2 emissions. Khan et al. (2020) argued that eco-innovation has important implications for the environment. Yang and Li (2017) supported the role of eco-innovation to achieve the low-carbon emissions target. The author found that eco-innovation is helpful in reducing CO_2 emission by improving carbon emission efficiency. Hojnik and Ruzzier (2016) eco-innovation in the form of greener technology has long-term capacity to improve environmental quality. The findings of (Ahmed, Uddin, and Sohag (2016)) for selected European countries confirm that the technological development helps to reduce carbon emissions. Henriques and Borowiecki (2017) considered environmental innovation as important strategy to improve long-run environmental quality in Europe. We establish the hypothesis as:

Hypothesis 2. Environmental Innovation affects CO_2 emissions

2.3 | Renewable energy consumption and CO_2 emissions

In the literature, REC is widely recognized as an important determinant of CO_2 emissions. The research on relationship between renewable energy consumption and environmental quality is an open debate and has extensively investigated by the researchers. The findings of (Mensah et al., 2018) for 28 selected OECD economies confirm that renewable energy consumption helps to reduce carbon emissions. Similarly, the findings of (Inglesi-Lotz & Dogan, 2018) show that REC is effective in the reduction of carbon emissions control as compared to nonrenewable energy consumption. The results of (Hu et al., 2018) for 25 selected developing and (Bölük & Mert, 2015) for Turkey also support the use of renewable energy consumption for controlling carbon emissions in the case of 25 selected developing economies. The findings of Alvarez-Herranz et al. (2017) for 17 OECD countries also confirm that besides environmental innovation, renewable energy is helpful in reducing CO_2 emissions. However, to switch the economy to renewable energy uses, huge investment requires. Private investment is important but insufficient to achieve promotion of environmental-friendly energies; hence, government support is a sufficient condition Azhgaliyeva et al. (2019). The findings of (Al-Mulali et al., 2016) for seven selected regions support the effective role of renewable energy in the reduction of carbon emissions. We establish the hypothesis as:

Hypothesis 2. Renewable energy consumption affects CO_2 emissions

2.4 | Summary of literature review

To sum up, an intensive literature is available on the determinants of CO_2 emissions. In the literature, trade is the most commonly variable used determinant of CO_2 emissions. However, the literature provides conflicting results on the possible relationship between trade and environmental quality. Researchers such as Liu et al., (2018), Alola et al. (2019), Hasanov et al. (2018), Kurniawan and Managi (2018), Gozgor and Can (2016), and Özokcu and Özdemir (2017) found that trade is responsible for deteriorating environmental quality. On the contrary, several other studies such as Destek et al. (2018), Shahbaz et al. (2019a), and Nathaniel (2020) backed the negative impact of trade on environmental quality. In recent times, researchers have introduced eco-innovation in testing the Environmental Kuznets Curve. Several studies such as Aragón-Correa et al. (2008), Kammerer (2009), Henriques and Borowiecki (2017), Alvarez-Herranz et al. (2017), Costantini et al. (2017), Zhang et al. (2017), and Erdoğan et al. (2020) backed the positive impact of eco-innovation on environmental quality. Besides trade and eco-innovation, several studies introduced REC in the model of CO_2 emissions (Alvarez-Herranz et al., 2017; Azhgaliyeva et al. 2019; Bölük and Mert 2015; Inglesi-Lotz and Dogan 2018; Mensah et al. 2018). There is consensus among researchers regarding the positive impact of REC on environmental quality and support the effective role of renewable energy in the reduction of carbon emissions. This study contributes to the existing literature in several ways: First, this study used both consumption-based carbon accounting (CBA) of carbon emission and territory-based accounting (TBA) of carbon emission in different models. Since, both approaches account carbon emissions via different mechanism, it is important to analyze both of the account variables by examining their determinants. The study revisits the determinants of both consumption-based carbon emissions (CCO_2) and territory-based carbon emission (TCO_2). We test the hypothesis: an increase in degree of environmental innovation and renewable energy consumption reduce CO_2 emissions, while an increase in trade increases CO_2 emissions in top 10 carbon emitter countries. Second, the empirical contribution of this study lies in employing second-generation unit root and cointegration methods. Most of the previous studies on CO_2 emissions are criticized on the ground of selection of econometric techniques. The using of the second-generation econometric techniques is likely to have important implications. The second-generation techniques provide unbiased and consistent results in the presence of cross-sectional dependency in panel data. Moreover, the techniques are applicable to models suffer from slope heterogeneity. Further, this study examines the causal relationship of CO_2 emissions with environmental innovation, renewable energy consumption, and trade. Previous studies mainly focused on estimating the determinants of CO_2 emissions. However, due to evidence of causal linkages between CO_2 emission and its determinants, this study also employs pairwise Dumitrescu–Hurlin panel causality test. The results of the study are helpful for evolving policies related to trade, renewable energies, and most importantly eco-innovation.

3 | THEORETICAL APPROACH AND ECONOMETRIC METHODOLOGY

3.1 | Model

To emperically estimate the determinants of CO_2 emissions for top 10 carbon emitter countries, the basic functional form of the model is given as:

$$CO2_{i,t} = f(GDP_{i,t}, EXP_{i,t}, IMP_{i,t}, REC_{i,t}, EI_{i,t}) \quad (1)$$

Where CO_2 represents carbon emissions. Further, we used two proxies to measure CO_2 emissions, consumption-based carbon emissions (CCO_2) and territory-based carbon emission (TCO_2). GDP represents gross domestic product; "Exp" and "Imp" are exports and imports, respectively. REC represents renewable energy consumption, and EI represents environmental innovation. The basic regression model is given as:

$$CO2_{i,t} = \alpha^1 GDP_{i,t} + \alpha^2 EXP_{i,t} + \alpha^3 IMP_{i,t} + \alpha^4 REC_{i,t} + \alpha^5 EI_{i,t} + \eta_{i,t} \quad (2)$$

Following Grossman and Krueger (1991), this study included GDP in the empirical model to estimate the determinants of CO_2 emissions. It is widely recognized that an increase in output contributes to CO_2 emissions due to the growing demand for energy particularly fossil fuel, which ultimately increases the temperature and deteriorates the environmental quality. The continuous increase in output in case of our sample countries poses a severe threat to the environment due to a consistent rise in the use of fossil fuel. Hence, we expect that an increase in output is a severe threat to the environment, that is, $\alpha^1 = \frac{\partial CO2}{\partial GDP} > 0$. Moreover, GDP is expected to increase both CCO_2 and TCO_2 in the long run, that is, $\alpha^1 = \frac{\partial CCO2}{\partial GDP} > 0$ and $\alpha^1 = \frac{\partial TCO2}{\partial GDP} > 0$. In the literature, trade is considered as an important factor in explaining CO_2 emissions. Hence, this study included trade in the empirical model to estimate the determinants of CO_2 emissions. An increase in degree of openness of trade increases CO_2 emissions due to the notion that in the process of openness, countries require more resources, which exerts greater challenges for environment. Moreover, trade results in transformation of pollution-intensive industries to other countries. High level of trade leads to an expansion in economic activities, which in turn deteriorate environmental quality. Nonetheless, we bifurcated trade into exports and imports in order to gauge the impact of subdimensions of trade on CO_2 emissions. Since, exports of production require efficient technology and energy system, which negatively affect CCO_2; however, for TCO_2, exports cause a decline. Hence, we expect a negative impact of exports on CCO_2 and a positive impact on TCO_2 $[\alpha^2 = \frac{\partial CCO2}{\partial Exp} < 0$ and $\alpha^2 = \frac{\partial TCO2}{\partial Exp} > 0]$. Further, imports in top 10 emitter countries are generally linked with increased CO_2 emissions due to the fact that these countries largely import energy-intensive products, which add more to environmental pollution. Hence, we expect a positive impact of imports on CCO_2 and TCO_2 $[\alpha^3 = \frac{\partial CCO2}{\partial Imp} > 0$ and $\alpha^2 = \frac{\partial TCO2}{\partial Imp} > 0]$. In the literature, renewable energy consumption (REC) is generally linked with fewer CO_2 emissions due to the fact that renewable energies utilize cleaner energy sources to meet the growing energy demand. Hence, we expect a negative impact of REC on CCO_2 and TCO_2 [$\alpha^4 = \frac{\partial CCO2}{\partial REC} < 0$ and $\alpha^4 = \frac{\partial TCO2}{\partial REC} < 0$]. Furthermore, environmental degradation is largely affected by the introduction of advance eco-friendly technologies. Eco-innovation is helpful in transforming the economic structure and production process and, hence, improve environmental quality (Zhang et al., 2017). Moreover, energy efficiency technologies are helpful in swapping the economic structure to more sustainable energy sources. Eco-innovation in the form of greener technology has long-term capacity to improve environmental quality. Hence, environmental innovation is an important strategy to improve long-run environmental quality. Following Khan et al. (2020), Yang and Li (2017),Hojnik and Ruzzier (2016), Henriques and Borowiecki (2017), we expect a negative impact of eco-innovation on CCO_2 and TCO_2 [$\alpha^5 = \frac{\partial CCO2}{\partial EI} < 0$ and $\alpha^5 = \frac{\partial TCO2}{\partial EI} < 0$].

3.2 | Data

The study analyzes the determinants of CCO_2 and TCO_2 for top 10 carbon emitter countries over the period of 1990–2017. These countries are important to analyze due to the following facts. First, these 10 countries have significant trade and output figures. Moreover, these countries face serious threat to the environment. Hence, it is imperative to analyze the determinants of CCO_2 and TCO_2 in case of top 10 carbon emitter countries such as Brazil, China, Germany, India, Indonesia, Japan, South Korea, Mexico, Russian Federation, and the United States. The total CO_2 emissions of these countries is 21.5 GT (ranging from 9.3 GT[1] carbon emissions in China to 0.4 GT in Brazil and Mexico). This study uses both consumptions-based and territory-based carbon emissions. Since, both approaches account carbon emissions via different mechanism, it is important to analyze both of the account variables by examining their determinants. TBA measures carbon emissions by including exports, hence, directs the responsibility for the producer of CO_2 emissions (Steininger et al., 2014). On the other hand, CBA measures CO_2 emissions by including imports and excluding imports (Afionis, Sakai, Scott, Barrett, & Gouldson, 2017). The data for CCO_2 and TCO_2 are sourced from Global Carbon Atlas (GSA, 2019). The data for eco-innovation are collected from OECD (2019). The data for rest of the variables are borrowed from World Bank: World Development Indicators.

3.3 | Analytical technique

3.3.1 | Cross-sectional dependency and slope homogeneity test

This study empirically examines the determinants of consumption-based carbon emissions (CCO_2) and territory-based carbon emission (TCO_2) for top 10 emitter countries of the world. For countries in our study, cross-sectional dependency (CSD) may alter the results. Hence, this study assumes empirical analysis that relates CO_2 emissions with environmental innovation, REC, and trade and then employs second-generation econometric methods which take into account dependency among cross sections. To check the CSD, this study applies CD-test popularized by Pesaran (2004). The equation for CSD is given as:

$$CD_{Pesaran\,(2004),i} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{k=i+1}^{N}\hat{\tau}_{ik}\right) \quad (3)$$

Pesaran (2004) CD test assumes zero mean constant and variance. In equation 3, $\hat{\tau}_{ik}$ is for pairwise correlation.

Moreover, in panel data, models often suffer from slope heterogeneity problem, which may distort the results. Hence, we apply slope heterogeneity test popularized by Pesaran (2007). P&Y test improves the reliability of our empirical results. Moreover, P&Y test takes into account CSD in panel data; hence, it is preferable over other slope heterogeneity tests Atasoy (2017). Moreover, for small sample size (N) and large time period (T), P&Y test provides efficient results Pesaran, Ullah, and Yamagata (2008). The test equations for P&Y test are:

$$\tilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-k\right) \quad (4)$$

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-2k\right) \quad (5)$$

3.3.2 | Panel unit root tests

Keeping into account the heterogeneity and CSD across panels, this study employs cross-sectional augmented IPS (CIPS) and Pesaran cross-section augmented Dickey Fuller (PESCADF) panel unit root tests. CIPS test is particularly important due to its applicability to cross-sectionally dependent variables. Moreover, the test provides efficient results in the presence of slope heterogeneity (Pesaran, 2007). The equation of CIPS is given as:

$$\Delta W_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \bar{W}_{t-1} + \sum_{l=0}^{p}\varphi_{il}\Delta\bar{W}_{t-l} + \sum_{l=1}^{p}\varphi_{il}\Delta W_{i,t-l} + \mu_{it} \quad (6)$$

The cross-sectional averages are represented by $\bar{W}_{t-1}$ and $\Delta\bar{W}_{t-l}$. The test statistic for CIPS test is given as:

$$\hat{CIPS} = N^{-1}\sum_{i=1}^{n} CDF_i \quad (7)$$

Moreover, the study uses Pesaran cross-section augmented Dickey Fuller (PESCADF) panel unit root test, which takes into account CSD. However, the major drawback of the PESCADF test is that it does not take into account slope heterogeneity.

3.3.3 | Westerlund cointegration method

Keeping in view the CSD, slope heterogeneity in model, and order of integration of variables, this study employs Westerlund (2007) cointegration method. This test has important implications. The test provides consistent results for small sample size and has high power about residual-based cointegration tests (Bhattacharya, Inekwe, & Paramati, 2018). The test uses four test statistics, two for group means statistics (G_a and G_t) and two for panel statistics (P_a and P_t). The group mean statistics checked cointegration relationship for the whole group, whereas the panel statistics checked cointegration relationship for individual cross sections (Westerlund, 2007).

3.3.4 | Cross-sectionally augmented ARDL (CS-ARDL)

To establish long-run dynamics between carbon emissions (both CCO_2 and TCO_2) and other variables such as environmental innovation, renewable energy consumption, trade, and income, this study applies cross-sectionally augmented autoregressive distributed lags (CS-ARDL) method promoted by Chudik and Pesaran (2013). The test is superior to other cointegration methods due to its applicability to model suffering from slope heterogeneity and endogeneity problems. Moreover, the test takes into account CSD and mix order of integration of variables (Chudik, Mohaddes, Pesaran, & Raissi, 2017). One of the important advantages of using CSARDL is that it provides consistent results in case of small sample size. The test equation is given as:

$$CCO2_t = \emptyset_i + \sum_{i=1}^{p} \theta_{il} \Delta CCO_{2,i,t-l} + \sum_{i=0}^{p} \theta'_{il} X_{t-j} + \sum_{i=0}^{3} \theta'_{il} \bar{Z}_{t-j} + \mu_{it} \quad (8)$$

Where, $\bar{Z}_t$ represents cross-sectional averages ($\bar{Z}_t = \left(\Delta C\bar{C}O_{2,t}, \bar{X}'_t\right)'$, X represents the explanatory variables such as GDP, trade, eco-innovation, and REC. For robustness check, we apply augmented mean group (AMG) method advances by Eberhardt (2012), which takes into account slope heterogeneity, endogeneity, CSD, and nonstationarity.

3.3.5 | Dumitrescu–Hurlin panel causality test

Further, this study examines the causal relationship of CO_2 emissions with environmental innovation, renewable energy consumption, and trade. Previous studies mainly focused on estimating the determinants of CO_2 emissions. However, due to evidence of causal linkages between CO_2 emission and its determinants, this study also employs pairwise Dumitrescu–Hurlin panel causality test. The test is applicable to stationary series Dumitrescu & Hurlin, 2012). Hence, we employ the test by taking first difference of the variables.

4 | RESULTS AND DISCUSSION

The first and most important step in our estimation section is to check the cross-sectional dependency (CSD) of variables and slope heterogeneity in model. The results of CD test and slope heterogeneity test are preseted in Table 2. The results of CD test confirm the evidence of CSD, which is obvious from the statistically significant test values of CSD test. Hence, we reject the null hypothesis of cross-sectional independency at 10% significance level. Moreover, the significant delta tide and adjusted delta tide values confirm the existence of slope heterogeneity in models of CCO_2 and TCO_2. Due to these problems, which are more likely present in panel data, this study employs recently introduced unit root test such as CIPS and PESCADF. The results of PESCADF test in Table 3 suggest that all variables are integrated of order 1, which enable us to employ CSARDL and AMG techniques. However, the results of CIPS test show that except REC, all remaining variables are integrated of order 0.

Keeping into account the heterogeneity and CSD across panels, this study employs Westerund panel cointegration test. We use two proxies to measure CO_2 emissions, CCO_2 emissions and TCO_2 emissions in different models. The results show that there is a stable long-run relationship among the variables presented in both models. We confirm a reasonable convergence to the long-run equilibrium from the negative and significant values of ά in both models. The error correction term (ά) is −0.65 and −0.73 for model 1 and 2, respectively.[2]

Next, this study estimates both models of environmental degradation. The stability of long-run relationship is confirmed from the negative and significant coefficient of ECM (−1) in both Tables 4–6. Hence, we confirm a reasonable convergence to the long-run equilibrium in both models, the results for cointegration are given in Table 4. In the long run, the variables EXP, REC, and EI are negatively related to CCO_2 and imply that an increase in these factors increase CCO_2 in top 10 carbon emitter countries. Moreover, an increase in IMP and GDP leads to reduce CCO_2 emissions in the long run. Further, the variables GDP, REC, and EI are associated with TCO_2 emissions. These results are further confirmed by CS-ARDL results in Table 5.

To be specific, exports are negatively related with CCO_2 emissions in the long run and short run, which needs an explanation. Access to technologies due to trade enables countries to improve their environmental quality. Hence, exports decrease CO_2 emissions. These results are in line with the earlier findings of Nathaniel (2020). However, the results do not support the findings of Alola et al. (2019) and Kurniawan and Managi (2018), who found that exports intensify the usage of nonrenewable energy sources and hence adds more to environmental pollution. The main reason for the negative association between exports and CO_2 emissions is that since exports of production in the sample countries require efficient technology and energy system which negatively affects CCO_2 emissions. Moreover, imports

TABLE 3 Results of panel unit root test

Cross-sectionally augmented IPS (CIPS) Pesaran (2007)					
	Level		First-difference		
Variables	Constant	Trend and constant	Constant	Trend and constant	Order
CCO_2	−2.909***	−2.60	–	–	I(0)
TCO_2	−3.035***	−2.719	–	–	I(0)
EXP	−2.326*	−2.861**	–	–	I(0)
IMP	−2.776***	−2.936***	–	–	I(0)
GDP	−2.561**	−2.425	–	–	I(0)
REC	−0.893	−2.569	−5.060***	−5.176***	I(1)
Eco-innovation	−3.394***	−4.245***	–	–	I(0)
Pesaran cross-section augmented dickey fuller (PESCADF)					
	Level		First-difference		
Variables	Constant	Trend and constant	Constant	Trend and constant	Order
CCO_2	−2.056	−1.842	−2.324**	−3.074***	I(1)
TCO_2	−1.963	−1.599	−2.360**	−3.254***	I(1)
EXP	−1.825	−2.345	−2.637***	−4.186***	I(1)
IMP	−1.964	−2.088	−2.376***	−2.918**	I(1)
GDP	−1.931	−2.334	−2.221*	−3.662***	I(1)
REC	−0.892	−2.477	−2.757***	−2.945**	I(1)
Eco-innovation	−1.523	−2.296	−2.617***	−2.865***	I(1)

Note: ***, **, and * is for 10, 5, and 10% significance level.

TABLE 4 Westerlund (2007) panel cointegration results

Dep: CCO_2	G_t	G_a	P_t	P_a
Statistic	−3.408***	−18.517*	−11.002***	−17.548***
Z-values	−2.528	−1.359	−3.236	−2.365
P-values	.006	.087	.001	.009
Dep: TCO_2	G_t	G_a	P_t	P_a
Statistic	−3.172**	−20.713**	−9.391**	−19.769***
Z-values	−1.744	−2.201	−1.746	−3.208
P-values	.041	.014	.040	.001

Note: ***, **, and * is for 10, 5, and 10% significance level. Dep is for dependent variable.

TABLE 5 Results of cross-sectionally augmented ARDL (CS-ARDL)

Dep: CCO_2	Coefficients	Standard error	Z	*p* Values
Short-run results				
EXP	−0.173**	0.076	−2.27	.023
IMP	0.138**	0.055	2.50	.013
GDP	0.504***	0.148	3.40	.001
REC	−0.231*	0.133	−1.74	.082
EI	−0.077***	0.026	−2.93	.003
ECM(−1)	−0.923***	0.103	−8.93	.000
Long-run results				
EXP	−0.263**	0.117	−2.25	0.025
IMP	0.178***	0.062	2.86	0.004
GDP	0.673**	0.285	2.36	0.018
REC	−0.284*	0.147	−1.92	0.055
EI	−0.094**	0.038	−2.44	0.015

Note: ***, **, and * is for 10, 5, and 10% significance level. Dep is for dependent variable.

are positively related with CCO_2 emissions in the long run and short run, which needs an explanation. Since more resources are required in the process of globalization, opening of trade by increasing imports is associated with deteriorated environmental quality. Hence, imports deteriorate environmental quality. Since, the sample countries of this study import highly energy-intensive commodities, which increase energy consumption and hence lead to increase in CO_2 emissions. Hence, imports are associated with deteriorated environmental quality. These results are in line with the findings of Gozgor and Can (2016) and Sushmita et al. (2002). However, exports and imports do not affect TCO_2 emissions in the long run and short run (Table 6). The results of Tables 4–6 show that income (measured by GDP) is positively related to CCO_2 emissions and TCO_2 emissions in long run and short run. The results are in line with the findings of Al-Mulali and Ozturk (2016), Özokcu and Özdemir (2017), Munasinghe (1999), and Al-Mulali et al. (2016). An increase in output contributes to CO_2

TABLE 6 Results of cross-sectionally augmented ARDL (CS-ARDL)

Dep: TCO_2	Coefficients	Standard error	Z	p Values
Short-run results				
EXP	−0.026	0.110	−0.24	.810
IMP	0.042	0.078	0.55	.585
GDP	0.469**	0.199	2.36	.018
REC	−0.358***	0.108	−3.32	.001
EI	−0.039**	0.018	−2.12	.034
ECM(−1)	−0.787***	0.080	−9.82	.000
Long-run results				
EXP	−0.137	0.167	−0.82	0.412
IMP	0.089	0.098	0.91	0.365
GDP	0.857*	0.452	1.90	0.058
REC	−0.448***	0.131	−3.41	0.001
EI	−0.061**	0.029	−2.07	0.038

Note: ***, **, and * is for 10, 5, and 10% significance level. Dep is for dependent variable, CCO_2 is for consumption-based carbon emissions and TCO_2 is for territory-based carbon emissions.

TABLE 7 Robustness check for CCO_2 using augmented mean group (AMG)

Dep: CCO_2	Coefficients	Standard error	Z	p Values
EXP	−0.211***	0.040	−5.23	.000
IMP	0.124***	0.032	3.83	.000
GDP	0.707***	0.172	4.11	.000
REC	−0.481***	0.177	−2.72	.007
EI	−0.023*	0.013	−1.71	.086
Constant	−4.377**	2.11	−2.07	.039

Note: ***, **, and * is for 10, 5, and 10% significance level. Dep is for dependent variable, CCO_2 is for consumption-based carbon emissions and TCO_2 is for territory-based carbon emissions.

emissions due to the growing demand for energy particularly fossil fuel, which ultimately increases the temperature and deteriorates the environmental quality. The continuous increase in output in case of our sample countries poses a severe threat to the environment due to a consistent rise in the use of fossil fuel. Hence, an increase in output is a severe threat to the environment.

The results show that REC is negatively related to CCO_2 emissions and TCO_2 emissions in long run and short run, which support the findings of Mensah et al. (2018), Hu et al. (2018), and Bölük and Mert (2015). REC is generally linked with fewer CO_2 emissions due to the fact that renewable energies utilize cleaner energy sources to meet the growing energy demand. REC is effective in the reduction of CO_2 emissions as compared to nonrenewable sources. Last, eco-innovation is negatively related with CCO_2 emissions and TCO_2 emissions in the long run and short run, which supports the findings of Henriques and Borowiecki (2017), Alvarez-Herranz et al. (2017), Yang and Li (2017), Zhang et al. (2017), and Khan et al. (2020). Energy efficiency technologies are helpful in swapping the economic structure to more sustainable energy sources, that is, renewable energies. Eco-innovation in the form of greener technology has long-term capacity to improve environmental quality. Environmental innovation in the form of recycling, low carbon technologies, or innovations for water management plays a decisive role in provision of clean energy. Hence, eco-innovation is negatively related to CO_2 emissions. Hence,

TABLE 8 Robustness check for TCO_2 using augmented mean group (AMG)

Dep: CCO_2	Coefficients	Standard error	Z	p Values
EXP	−0.055	0.052	−1.06	.291
IMP	0.064	0.052	1.23	.220
GDP	0.668***	0.095	7.03	.000
REC	−0.390**	0.172	−2.27	.023
EI	−0.018	0.014	−1.24	.213
Constant	−4.148***	1.372	−3.02	.003

Note: ***, **, and * is for 10, 5, and 10% significance level. Dep is for dependent variable.

TABLE 9 Pairwise Dumitrescu–Hurlin panel causality test

Nature of causality	W-stat.	Zbar-stat.	Prob.
From GDP to CCO_2	5.97***	4.85	.000
From CCO2 to GDP	6.45***	5.46	.000
From EXP to CCO_2	6.81***	5.92	.000
From CCO_2 to EXP	4.00**	2.30	.020
From IMP to CCO_2	5.70***	4.50	.000
From CCO_2 to IMP	5.48***	4.21	.000
From REC to CCO_2	4.98***	3.57	.000
From CCO_2 to REC	6.04***	4.93	.000
From EI to CCO_2	3.55*	1.73	.082
From CCO_2 to EI	4.63***	3.12	.001

Note: ***, **, and * is for 10, 5, and 10% significance level.

TABLE 10 Pairwise Dumitrescu–Hurlin panel causality test

Null hypothesis	W-Stat.	Zbar-Stat.	Prob.
From GDP to TCO_2	9.52**	2.14	.032
From TCO2 to GDP	7.04	0.63	.526
From EXP to TCO_2	9.34**	2.03	.041
From TCO_2 to EXP	12.00***	3.65	.000
From IMP to TCO_2	8.48	1.50	.131
From TCO_2 to IMP	8.17	1.32	.185
From REC to TCO_2	9.69**	2.24	.024
From CCO_2 to REC	10.97**	3.03	.002
From EI to TCO_2	9.01*	1.83	.066
From TCO_2 to EI	12.99***	4.25	.000

Note: ***, **, and * is for 10, 5, and 10% significance level.

eco-innovation has important implications for the environment and helpful in supporting the environmental quality. The results for TCO_2 are given in Table 6.

For robustness check, we apply AMG method, which takes into account slope heterogeneity, endogeneity, CSD, and nonstationarity. The result of long-run coefficient from AMG method is consistent with the CSARDL estimates (Table 7). Moreover, robustness results for TCO_2 are given in Table 8.

Due to evidence of causal linkages between CO_2 emission and its determinants, this study also employs pairwise Dumitrescu–Hurlin panel causality test (Tables 9 and 10). We take the first difference of the variables because the test is applicable to stationary series. The results show that changes in GDP, EXP, IMP, REC, and EI granger cause CCO_2 emissions and vice versa. However, any policy to target GDP, EXP, REC, and EI significantly changes TCO_2 emissions, while changes in TCO_2 granger cause EXP, REC, and EI. These results have great policy implication.

5 | CONCLUSION

Hence, worsening environmental quality has disastrous effect on human survival on the planet through a decline in food production and damaging biodiversity. The association between carbon emissions and international trade has been studied extensively; however, a new measure which is adjusted for trade, that is, consumption-based carbon emissions has not been tested that much. Therefore, to fill the gap, this study attempts to investigate the effect of international trade, environmental friendly technological innovation, and renewable energy consumption on consumption-based carbon emissions for top 10 carbon emitter countries, that is, Brazil, China, Germany, India, Indonesia, Japan, South Korea, Mexico, Russian Federation, and the United States from 1990 to 2017. This study also tested similar model for territory-based carbon emissions (TCO_2). The econometric methods offer robust results; (a) We confirm a reasonable convergence to the long-run equilibrium; (b) an increase in exports, renewable energy consumption, and eco-innovation decrease CCO_2; (c) an increase in imports and GDP leads to increase CCO_2 emissions in the long run; (d) the variables GDP, REC, and EI affect TCO_2 emissions; (e) changes in GDP, exports, imports, renewable energy consumption, and eco-innovation granger cause CCO_2 emissions and vice versa.

Based on our findings, the policy implications from this study suggest that (a) promotion of environmental friendly technology through implementation of carbon pricing policy, (b) promote renewable energy promotion through reforms and changes in the current energy mix of the sampled countries, (c) cleaner technology should be encouraged to promote cleaner production processes and also consumption of imported goods that are emissions intensive should be discouraged or may be substituted with other trading partner, (d) since, the sample countries are characterized with greater CO_2 emissions, high population, greater importers of energy-intensive products, and large contribution in world's output, any policy toward switching the economic structure to more sustainable sources of energy will result in paradigm shift of production of environmentally secure commodities, which in turn will reduce CO_2 emissions, (e) to switch the economy to renewable energy uses, huge investment requires. Private investment is important but insufficient to achieve promotion of environmental-friendly energies; hence, government supports is a sufficient condition. For future studies, researchers may check for bilateral trade-emission nexus using the concept of consumption-based carbon emissions.

ORCID

Fuzhong Chen https://orcid.org/0000-0001-9116-3304
Zeeshan Khan https://orcid.org/0000-0003-1374-0836

ENDNOTES

[1] GT represents Metric gigatons.

[2] $\acute{\alpha} = \frac{P_\alpha}{T}$ = -17.548/27 = –0.65 for model 1, –19.769/27 = –0.73 for model 2.

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