Economic Research-Ekonomska Istraživanja

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rero20

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To cite this article: Mei Zhang, Danting Zhang & Tingfeng Xie (2023) Technology innovations and carbon neutrality in technologically advanced economies: imperative agenda for COP26, Economic Research-Ekonomska Istraživanja, 36:2, 2178017, DOI: 10.1080/1331677X.2023.2178017

To link to this article: https://doi.org/10.1080/1331677X.2023.2178017

Published online: 11 May 2023.

ECONOMIC RESEARCH-EKONOMSKA ISTRAŽIVANJA
2023, VOL. 36, NO. 2, 2178017
https://doi.org/10.1080/1331677X.2023.2178017

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Technology innovations and carbon neutrality in technologically advanced economies: imperative agenda for COP26

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ABSTRACT

This article aims to fill the literature gap while examining the role of green innovation, climate change adaptation technologies, technological diffusion, and environmentally related tax revenues in dealing with carbon neutrality among seven technologically advanced economies (T.A.E.-7) from 1990 to 2018. We employ advanced panel estimators to address slope heterogeneity and cross-sectional dependency issues. The long-run results show that green technological innovations and technological diffusions have significantly and negatively impacted carbon emissions in sample countries. Meanwhile, the role of environmental policy is also significant in addressing environmental vulnerabilities. These findings suggest that climate tech is imperative to ensure carbon neutrality in the long run; however, their marginal effects vary in magnitude, particularly concerning diffusion and adaptation. Similar results are endorsed using alternative estimators addressing endogeneity issues and recommending climate tech's inclusive framework to support the green growth agenda.

ARTICLE HISTORY
Received 11 October 2022
Accepted 3 February 2023

KEYWORDS
green technological innovations; technology adaptation; carbon neutrality

JEL CODES
Q5; O3; Q55

1. Introduction

Climate change has become a global concern, specifically in dealing with carbon dioxide emissions to control global warming. However, various approaches mitigate the environmental challenges (Can & Gozgor, 2017; Li & Wang, 2017). For example, the utilisation of low carbon fuel in production-related activities (Farrelly et al., 2013), carbon-capturing and storage (Pokhrel et al., 2021), carbon dioxide removal (C.D.R.) (Turkenburg, 1997), smart agriculture practices, and environmental data-driven supply chain management (Yadav et al., 2021), managing air quality risk (Cleugh & Grimmond, 2012), food-energy-environment tradeoff (Das, 2014), and adopting renewable energy sources (Baloch et al., 2022), respectively. Meanwhile, technological

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change can reduce the amount of carbon generation under different activities (Cheng & Yao, 2021). Technical modifications play a significant role in dealing with carbon emissions. Although not all countries globally have demonstrated their role in carbon neutrality, international cooperation towards technology development for environmental concerns has also been appealed (Gozgor et al., 2018).

A range of studies evaluates the role of technological advancement on environmental issues like carbon emissions (Yuaningsih et al., 2020). These studies focused on low-carbon technologies in the form of renewable energy technologies. A dramatic decline in carbon emission value because of such technological progress (Gozgor et al., 2020; Shan et al., 2021). Addressing the issue of changing climate considers technological innovations where the low-carbon economy provides a baseline for lower energy consumption from traditional sources (Lyu et al., 2020). At the same time, climate technologies offer a meaningful insight to mitigate climate vulnerabilities, shifting the existing production and consumption of energy sources. Therefore, the core of low-carbon technology innovation is the transition toward a low-carbon economy (Saikku et al., 2017). Researchers and scholars have paid substantial attention to the invention of low-carbon technologies, and eco-patent data can be utilised as a proxy for analysing the status of low-carbon energy-saving technology (Mulder et al., 2013). In contrast, such technologies have a higher diversity and novelty towards mitigation of carbon emissions (De Marchi, 2012). The relationship between the low carbon economy and low carbon innovation is entitled to sustainable development (Lyu et al., 2020). Technological growth lowers the aggregate carbon emission level, hence a good way for carbon neutrality (Tokimatsu et al., 2016). However, the 'rebound effect' specifies that every progress in technology in the modern era not only brings sufficient improvement in energy consumption and environmental efficiency but also stimulates the development of the economy (Sorrell & Dimitropoulos, 2008; Vivanco et al., 2016).

Figure 1 provides an outlook for the environment-related technologies (total patents) observed from 2000 to 2018 for the selected seven technologically advanced economies (T.A.E.-7) under the present research. The U.S. and Japan are leading in environment-related technologies, followed by China and Germany. A growing trend in climate technologies among the targeted economies exists

However, the emission-related data reflect that these economies also face a higher carbon emission level during the study period. For example, the carbon emissions in Russia from 2000 to 2018 demonstrate a growth rate of 14.5%. In the case of Singapore, the annual carbon dioxide emission was 48.39 million tons in 2000, which turned into 90.10 million tons in 2009. However, emissions declined to 45.50 million tons by 2020. Furthermore, in the case of China, the carbon emission during 2000–2020 was observed as 3.44–10.67 billion tons. These findings provide enough evidence to claim that emissions and technological advancements show a mixed trend over the past two decades, providing a pivotal motivation to work on the T.A.E.-7.

Based on the above arguments, some exciting research questions are as follows:

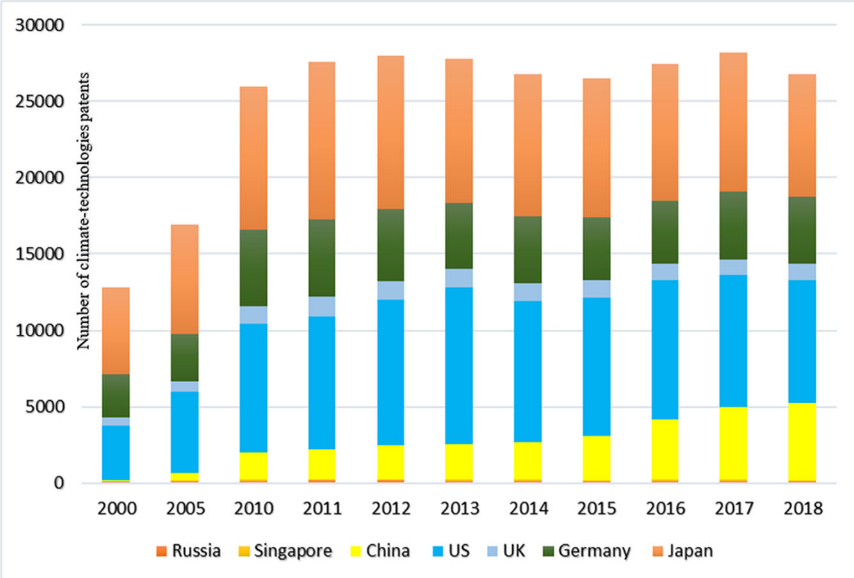

Figure 1. Environment-related technologies in technologically advanced economies (TAE-7).
Note: Y-axis shows the number of climate-technologies patents.
Source: Authors drawing from OECD database.

- How does the development of environmental technologies (green innovations) influence carbon neutrality, specifically from the context of technologically advanced economies?
- How does the adoption and diffusion of such technological innovation lead to carbon neutrality?
- Does environmental regulation play an influential role in carbon neutrality?

In addition, it is a well-known phenomenon that states that environmental pollution usually comes from energy-related greenhouse gas emissions and non-renewable energy sources like oil, petroleum, coal, etc. (Amen et al., 2021; Shahzad, 2020). However, against this backdrop, several instruments and policy-related tools have been utilised in developed and developing economies, such as economic incentives, administrative regulations, and environmental/carbon-related taxes. On the other side, financial incentives are relatively conducive to ecological protection playing a vital role (Perino & Pioch, 2017). Consequently, environmental-related taxes are powerful instruments while mitigating carbon emissions and similar environmental problems like footprints, greenhouse gas emissions, and climate change (Yuyin & Jinxi, 2018). More specifically, environmental-related taxes are products levied on the energy-based emissions emitted in the natural environment (Fullerton et al., 2008; Morley, 2012). Various economies like O.E.C.D. members have introduced environmental and green tax reforms to fight against environmental pollution (OECD Publication, 2001). At the same time, ecological and carbon-related taxes have gained attention in developed and developing economies. More specifically, China introduced an environmental protection tax law in 2018 with the core aim of curtailing ecological pollution and emission (Lin & Jia, 2018). In this regard, it is expected that the country will receive an amount of $7.68 billion yearly against such taxes (Lin & Jia, 2018). Another remarkable achievement linked to Singapore's economy, which introduced environmental taxes on production-related activities. This regulation will emit approximately 25,000 tons of greenhouse gas emissions from 2019 to 2023.

This research provides various contributions based on a detailed review of the literature and trends in environmental technologies, environmental taxes, and carbon neutrality. Firstly, the current study reports some significant and conclusive findings while considering the T.A.E.-7 sample, which is completely missing in the literature. More specifically, this research focuses on environment-related technologies, climate change and adaption technologies, and technological diffusion towards carbon neutrality over the last two decades. Furthermore, green technologies are observed with high value-added solutions in environmental sustainability. Environmental technologies also help promote total green factor productivity and growth. Previously, various technological dimensions were examined on individual grounds for which good motivation is observed to consider under a single empirical investigation. Secondly, this research tries to fill the gap in the literature from the context of environmental-related tax revenues in dealing with the carbon neutrality of T.A.E.-7. Theoretically, it is stated that tax implication would be one way forward for sustainable transformation because regulations for environmental taxes are required to change the pattern of energy consumption and emission of carbon in the natural environment. Based on the above justification, considering environmental-related tax revenue as a proxy for carbon neutrality, this research provided documentary evidence for policymakers and environmentalists.

The remaining parts of the article are organised as follows: the upcoming section is entitled section two, where a literature review is covered. Section three provides a comprehensive outlook for the research methods, measurement of the variables, and data analysis techniques. Section four provides the results and related discussions. Finally, section five concludes the study and offers policy recommendations and limitations.

2. Literature review

The literature's chronological review clears that a series of discussions have been done about green technology innovations (Shan et al., 2021), where the titles like environmentally sound technologies are the earliest concept (Verhoosel, 1998). Meanwhile, Braun and Wield (1994) also delivered the initial idea of green technology while claiming it should capture control over ecological treatment, pollution, recycling, and other environmental concerns. However, one of the critical challenges linked with green technologies is that developing economies still struggle to access modern technologies to create a balance between environment and economy (An et al., 2021; Chien et al., 2021; Guo et al., 2020). After the Paris Agreement, various countries faced challenges linked with a sustainable economy and carbon neutrality with minimum carbon dioxide emissions. Technological innovations have provided a role model in dealing with sustainability issues while lowering energy consumption from some traditional sources. Various studies have examined the trends in technological advancement and their association with environmental challenges. In this regard, Shao et al. (2021) state that the Next-eleven (N11) economies are also under similar environmental pressure. There is little investigation into the role of green technology innovation in ecological degradation. While filling this gap, their study has observed the trends in technological progress and carbon dioxide emission during 1980–2018 while addressing the issues like cross-sectional dependence, slope heterogeneity, and stationarity properties. Finally, the variables' long-run estimation has been examined through C.S.-A.R.D.L. estimation. It is claimed that there is a significant and negative impact of green technology innovation on carbon emissions. The essential suggestions include the policies and practices for the local governments in N11 economies while supporting green technology innovation for environmental sustainability.

Suki et al. (2022) claim that dramatic technological advancement and robotics intelligence growth is observed under the contemporary industrial regime. Their study primarily considers the economy of Malaysia while investigating the trends in technological innovation in determining the carbon emission and ecological footprints, respectively. Evaluating the Environmental Kuznets Curve (E.K.C.) hypothesis while applying bootstrapped autoregressive distributed lag model, their findings disclose that technological innovations help reduce carbon emission and ecological footprint. Additionally, essential suggestions specify that local and international investors in the Malaysian economy should be encouraged to invest in renewable energy and technological innovation. Shan et al. (2021) state that green technology plays a fundamental role in achieving sustainable goals with minimum negative environmental consequences. The target of carbon neutrality refers to the achievement of net-zero carbon emission, which has got a mega interest in recent years. Their study observes the trends in carbon neutrality through green technology for the Turkish economy. The empirical findings confirm that green technology and related innovations significantly reduce carbon emissions, hence a good indicator for carbon neutrality and sustainable development practices.

Technology diffusion has also attracted researchers' attention due to its linkage with carbon intensity and other environmental concerns. For instance, Majumdar and Kar (2017) focus on the emission intensity of India's manufacturing and agriculture sectors. The core objective is to examine the direct association between technological adoption and emission intensity at the industry level during 1996–2009. Their study has considered the environmentally extended input–output model for measuring the emission intensity. The study findings through fixed effect panel data estimation clearly show that technological adoptions help reduce emissions across industries. More specifically, with better technologies for exporting goods, emissions fall effectively. Sano et al. (2013) express that technology diffusion is a good indication in dealing with carbon dioxide emissions; however, various barriers exist under several global warming mitigation technologies. Such walls also significantly impact the diffusion of carbon dioxide capture and storage technology. Although the theoretical and empirical evidence for technology diffusion and carbon emission exists, not much is available on the current evidence specifically while considering the sample of technologically advanced economies.

Qin et al. (2021) state that various economies are paying their attention based on the Paris Agreement to achieve carbon neutrality or net-zero carbon. Their study mainly focuses on green innovation, risk index, and research & development toward carbon neutrality among G7 economies based on E.K.C. Through advanced panel estimation, the role of green innovations, research & development, and renewable energy are observed as good sources toward achieving carbon neutrality among G7 economies. The essential suggestions cover that environmental policies and green innovations should be promoted along with political stability to achieve sustainable practices in G7. Zeng et al. (2022) consider the 30 provinces in China for exploring green technology innovation toward carbon neutrality during 2001–2019 through advance panel estimations.

Moreover, panel threshold techniques with slack-based measures and global Malmquist-Leuenberger index were applied to analyse green technology innovation's spatial spillover and non-linear effect on carbon emission. The study findings confirm that green technology innovation grows yearly, but the targeted efficiency of such innovations is slow. Although there is an upward shift in carbon dioxide emission at a marginal rate, this emission's intensity is declining yearly. Chien et al. (2021) claim that various economic and environmental policies contribute to carbon emissions. The role of green innovations, environmental taxes, and green growth toward carbon neutrality in the U.S. is significant. Their study applies Q.A.R.D.L. estimation and confirms the powerful and negative impact of green change and ecological innovation on emission-related issues.

Furthermore, energy and environment-related taxes are considered determinants of reducing energy demand (Vandyck & Van Regemorter, 2014). However, such taxes have different impacts on the welfare and economy (Hamaguchi, 2020). A similar notion is expressed by Shahzad (2020), who claims that environmental taxes benefit the lower-income groups in developed economies while using the additional revenue for welfare transfer to households. Contrary to this, McLaughlin et al. (2019) expressed that carbon taxes negatively influence households. Such taxes help improve environmental quality and bring long-run benefits to the population. It is claimed that environment and energy-related taxes have double dividend for the government. For instance, such taxes can be utilised for energy efficiency and environmental objectives (Z.-y. Chen & Nie, 2016). In contrast, at the same time, these taxes can be utilised for recycling and utilising different economic activities, health, education, and other development projects (Zhang & Zhang, 2018).

In addition, two significant highlights related to the implications of environmental taxes. Firstly, different firms use non-renewable energy sources for business operations and pay emission-related taxes. Secondly, these organisations can adopt and utilise renewable technologies to avoid environmental taxation. However, the first approach reduces overall business earnings, where such examples were observed in 2013 in the U.K. During that period, electricity generation was 40% from coal, which was 23% in 2015. In this regard, both of the above policies would be pretty beneficial for achieving climate change objectives. In a nutshell, the association between environmental taxes and environmental concerns is not novel in the literature. However, studies have examined the nexus between environmental taxes and environmental quality, like greenhouse gas emissions, ecological footprints, and biodiversity, with mixed findings (Kahn & Franceschi, 2006; Miller & Vela, 2013; Mirzaei & Bekri, 2017; Yuyin & Jinxi, 2018).

Meanwhile, green or pollution-related taxes and technological innovation reduce climate change and mitigate issues. Silva et al. (2020) claim that the need to decarbonise economies and production activities is undeniable. For this reason, energy from some renewable sources and carbon capture and sequestration technologies may play a significant role. Their study has proposed an equilibrium model where an investigation has been conducted to utilise labour and energy. It is stated that the government has implemented green and pollution-related taxes under the shadow of green tax reforms through which revenues have been utilised to finance renewable energy sources and carbon capture and sequestration technologies. Such taxation reforms would substantially benefit decarbonising fossil fuels and similar others. Rodríguez (2019) considers the computable general equilibrium model (C.G.E.) to examine the association between environmental taxes and the environmental economy in Portugal's economy during 1995–2014. It is observed that taxes are significantly improving the environmental quality. Based on the above discussion, it is stated that green technology innovations and regulations like environmental taxes are good signs while reducing environmental pollution, and energy consumption from traditional energy sources and providing a good source of earning for the government and ecological sustainability. Therefore, the present study will consider the role of environmentatax revenues in determining the carbon neutrality for T.A.E.-7, which is not in the researcher's current literature A comprehensive outlook for some essential recent and past studies has been provided in Appendix.

The ecological modernisation theory has been regarded as a theoretical underpinning to support the association between technology and environmental concerns (Buttel, 2000). The initial concept of this theory was presented in the German language by Huber, focusing on protoindustrialisation and technological innovations. One of the core features of ecological modernisation is that it focuses on industrial development as the best option for escaping an environmental crisis, specifically in developed economies (Fisher & Freudenburg, 2001). Meanwhile, during the 1980s, understanding the natural environment in terms of structural problems was observed, resulting in the emergence of environmental disclosure entitled ecological modernisation (Hajer, 1995). Ecological modernisation covers that stated ecological concerns can be internalised through economic, political, and social institutions that help care for sustainability (Ali, 2013). Therefore, the outline of this theory is based on the assumption that environmental degradation can be measured in terms of monetary units while focusing on different branches of social and natural sciences (Ali, 2013). It also describes those environmental concerns addressed through collective actions from the individuals, society, business, and country's management (Ali, 2013). Moreover, both economic growth and sustainability concerns can be reconciled through utilitarian logic. Therefore, the primary focus of this theory is on the economic cost of environmental pollution, which can be reduced through more attention to the conservation of natural resources, recycling, waste control, and technological innovations (Al-Saidi & Elagib, 2018; Clement & Schultz, 2011).

3. Research methods

This research considers the panel data for T.A.E.-7 during 2002–2018. In this regard, the very first characteristic of panel data is to deal with the cross-sectional dependence, for which we apply the Lagrange Multiplier (L.M.) of Breusch and Pagan (1980). This would employ that cross-sectional dependence is a significant issue to address as the findings may be misleading and biased without its consideration. For this research, Breusch and Pagan (1980) Equation has been specified as follows:

$$CD = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \tag{1}$$

The Pesaran C.D. test is examined with the help of Equation (2) of the study.

$$CD = \sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}} \tag{2}$$

Where in the above Equation (1), T indicates the time duration, and N specifies the panel data size. Additionally, ρ_{ij} shows the correlation coefficient. Under the C.D. test, the null hypothesis indicates a cross-sectional dependence between the cross-sectional units, whereas the alternative suggests that cross-sectional dependence exists between sample economies.

After examining the cross-sectional dependence of the study variables, the integration order of the study variables is investigated. For this reason, the Ist generation unit root method as specified by Evin-Lin and Chu and Im, Pesaran, and Shin (I.P.S.) is not sufficient to address the C.D.s' problem as expressed by Xu et al. (2018). This would indicate that the presence of C.D. should be under consideration; hence present study has utilised the second generation cross-sectional augmented I.P.S. (C.I.P.S.) and C.A.D.F. unit root tests. For this purpose, the sample equation is as follows:

$$\Delta CA_{i,t} = \varphi_i + \varphi_i Z_{i,t-1} + \varphi_i \overline{CA}_{t-1} + \sum_{I=0}^{p}\varphi_{iI}\Delta\overline{CA}_{t\bar{1}} + \sum_{I=0}^{p}\varphi_{iI}\Delta CA_{i,\ t-1} + \mu_{it} \tag{3}$$

wherein the above Equation (3), the titles like $\overline{CA}_{t-1}$ and $\overline{CA}_{t\bar{1}}$, are showing the averages for the cross-sections under the present study, and the statistics of the C.I.P.S. test is explained as follows:

$$C\widehat{IP}S = \frac{1}{N}\sum_{i=1}^{n}CDF_i \tag{4}$$

where C.D.F.'s title expresses the C.D. augmented Dicky-Fuller in Equation (4) of the study.

While going for the long-run estimation, we examine whether there is a cointegration association between the variables or not. Meanwhile, it is also noted from the existing literature that panel cointegration tests under first and second-generation cannot address the structural breaks and cross-sectional dependence (McCoskey & Kao, 1998; Westerlund & Edgerton, 2007). Furthermore, it is also found that traditional cointegration analysis may generate some biased and deceptive findings and the presence of cross-sectional dependence and heterogeneity. Based on these arguments, this study applies Westerlund and Edgerton (2008) panel cointegration tests to allow C.D., autocorrelation, and structural breaks. Equations (5) and (6) are based on Westerlund and Edgerton (2008) statistics.

$$LM_{\tau} = \frac{\hat{\Phi}_i}{SE(\hat{\Phi}_i)} \tag{5}$$

$$LM_{\Phi} = T\hat{\Phi}_i\left(\frac{\hat{\omega}_i}{\hat{\sigma}_i}\right) \tag{6}$$

Wherein the above equations, titles like $\hat{\Phi}_i$ reflect the estimations for the least square; Φ's SE is $\hat{\sigma}_i$; whereas the reflection of $\hat{\Phi}_i$'s SE is $SE(\hat{\Phi}_i)$. Meanwhile, the Westerlund and Edgerton (2008) cointegration analysis is based on the null hypothesis for cointegration. The alternative indicates a long-run association between the variables of interest. In addition, researchers have used different econometric estimations to examine the effect of explanatory variables on the dependent variables, such as through pooled ordinary least squares (O.L.S.), Generalised Method of Moments (G.M.M.), and many others. However, each estimation has advantages and disadvantages based on the data's nature and study objectives. However, the traditional panel data estimation methods do not address the issue of cross-sectional dependence. Therefore, the present study applies the C.U.P.-F.M. and C.U.P.-B.C. as Bai and Kao (2006) introduced. These models are sufficient while producing accurate findings even with C.D., endogeneity, and autocorrelation in the panel data (Ahmed et al., 2020). These panel estimations are also helpful in correcting the serial correlation. Additionally, these estimation approaches can generate some accurate findings even with no endogeneity. More specifically, the C.U.P.-F.M. estimation method maintains the limited distribution of the parameters in the model. The study parameters are continuously updated through simulations until they are fully converged. Equation (7) described and formalised the following factor model:

$$\hat{\beta}cup,\ \hat{F}cup = argmin\frac{1}{nT^2}\sum_{i=1}^{n}(y_i - x_i\beta)'M_F(y_i - x_i\beta) \tag{7}$$

where $M_F = I_T - T^{-2}FF', I_T$ Indicates the elements, and T's show the identity matrix. Furthermore, the error terms are common latent factors where the initial estimates are allocated to F. This process is repeated until convergence is achieved. Table 1 below describes the variables and their data sources. It is important to note that current research has applied C.U.P.-B.C. to verify the robustness of the model based on the theoretical suggestion of (Bai et al., 2009). Besides, our study considers the role of G.D.P. as a control variable while exploring the relationship between the different dimensions of technologies and carbon neutrality among T.A.E.-7.The

Table 1. Description of data and sources.

Variables	Symbol	Measurement	Final Consideration	Data source
Environment-related technologies	ENRT	It is measured as the relative share of environmental patents compared to total patents.	Natural log of the relative share of environmental patents compared to total patents.	https://stats.oecd.org/
Climate change adaptation technologies	CCA	It is measured as a percentage of adaption technologies to total climate technologies.	Natural log of a percentage of adaption technologies to total climate technologies.	https://stats.oecd.org/
Technological diffusion	TD	It is measured as a total number of patents diffusion in environment-related technologies.	Natural log of the total number of patents diffusion in environment-related technologies.	https://stats.oecd.org/
Environmentally related tax revenues	ERTR	It is measured as the percentage of total gross domestic product.	Percentage of GDP	https://stats.oecd.org/
Carbon neutrality	CN	It is measured in CO_2 emissions from liquid fuel consumption (kt).	Natural Log of CO_2 emissions from liquid fuel consumption (kt).	WDI, World Bank Group.
Gross Domestic Product	GDP	It is measured through the current US$.	Natural log of GDP (current US$)	WDI, World Bank Group.

Source: Author's estimations.

association between different dimensions of technological innovation, environmental regulations, and carbon neutrality is more likely to be affected by reverse causality and endogeneity. For this reason, the simple O.L.S. estimation may lead to biased outcomes. In contrast, the within-group estimator may result in downward biased parameters, as Nickell (1981) stated. Therefore, Anderson and Hsiao (1982) provide a procedure for first-differenced transformation to remove fixed effects from the data. However, the exists of correlation between different regressors may exist. Rellano and Bond (1991) proposed an additional G.M.M. estimator where explanatory variables in the model are instrumented with their lag values to address this issue. The instruments are not correlated with the error terms. However, the instrumental variable (I.V.) approach may not efficiently deal with the endogeneity bias (Razzaq, An, et al., 2021). Therefore, unlike I.V. procedure, current research mainly focuses on the sys-G.M.M. estimator, which uses an internal instrument to control the endogeneity for the explanatory variables of the study.

4. Results and discussion

Table 2 reports descriptive scores through mean, standard deviation, data range, and normality testing through skewness and kurtosis. The highest mean score is recorded for the log of G.D.P., followed by L.C.N. and technological diffusion. This would indicate that consumption-based carbon emission is more than the environment-related technologies, technological diffusion, and environmentally related tax revenues

Table 2. Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
LENRT	3.022	0.802	1.223	4.01
LCCAT	2.276	0.854	0.287	3.479
LTD	4.398	0.713	3.264	5.640
ERTR	1.356	0.790	0.030	2.664
LCN	5.556	0.645	3.712	6.391
LGDP	12.393	0.591	10.954	13.310

Note: LENRT: log of Environment-related technologies, LCCAT: log of climate change adaptation technologies, LTD: log of technological diffusion, ERTR: environmental related tax revenues, LCN: log of carbon neutrality, LGDP; the log of gross domestic product.
Source: Author's estimations.

Table 3. Correlation matrix.

Variables	LCN	LENRT	LCCAT	LTD	ERTR	LGDP
LCN	1.000					
LENRT	0.296* (0.009)	1.000				
LCCAT	0.339* (0.003)	0.954* (0.000)	1.000			
LTD	0.407* (0.007)	0.902* (0.000)	0.922* (0.000)	1.000		
ERTR	0.323* (0.001)	0.288* (0.013)	0.266* (0.022)	0.325* (0.043)	1.000	
LGDP	0.524*** (0.000)	0.125** (0.026)	0.325 (0.159)	0.267*** (0.000)	0.368*** (0.000)	1.000

Note: LENRT: log of Environment-related technologies, LCCAT: log of climate change adaptation technologies, LTD: log of technological diffusion, LERTR: environmentally related tax revenues, LCN: log of carbon neutrality, LGDP; log of gross domestic product.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.
Source: Author's estimations.

Table 4. Cross-sectional dependence output.

Variables	Breusch-Pagan LM	Pesaran Scaled LM	Pesaran CD
LCN	756.201***	42.267***	13.524***
LENRT	506.257***	56.624***	18.652***
LCCAT	626.367***	56.638***	11.204***
LTD	903.638***	70.254***	31.201***
ERTR	520.524***	68.522***	46.320***
LGDP	615.102***	71.510***	39.510***

Note LENRT: log of Environment-related technologies, LCCAT: log of climate change adaptation technologies, LTD: log of technological diffusion, LERTR: environmentally related tax revenues, LCN: log of carbon neutrality, LGDP; log of gross domestic product.
***Significant value at 1%, **significant value at 5%, *significant value at 10%.
Source: Author's estimations.

for the sample economies during the study period. However, the lowest trend in mean scores is linked with the E.R.T.R. (i.e., 1.356), followed by climate change adaptation technologies. Additionally, the trend in standard deviations for the study variables is below 1, where the highest value is 0.854, as reflected by L.C.C.A.T.

The correlation matrix of the study variables is reported in Table 3. It indicates a significant and positive correlation between L.C.N.-E.R.T.R., L.E.N.R.T.-L.C.C.A.T., L.E.N.R.T.-L.T.D., climate change adaptation technologies, and technological diffusion. Furthermore, technological diffusion and E.R.T.R. show significant but positive associations. The rest of the study variables show mixed trends in positive and significant association under Table 3.

Table 4 reports the findings for the cross-sectional dependence as reported with the help of Bruesch-Pagan L.M., Pesaran Scaled L.M., and Pesaran C.D. tests. While

Table 5. CIPS and CADF unit root tests result.

	CIPS		CADF	
Variables	Level	First difference	Level	First difference
LCN	−1.2014	−6.528***	−1.025	−5.035***
LENRT	−2.020	−5.334***	−1.275	−3.521***
LCCAT	−1.310	−4.300***	−2.257	−4.096***
LTD	−2.068	−5.023***	−2.636	−5.057***
ERTR	−1.782	−3.250***	−2.652	−4.529***
LGDP	−1.821	−4.025***	−2.938	−5.540***

Note LENRT: log of Environment-related technologies, LCCAT: log of climate change adaptation technologies, LTD: log of technological diffusion, LERTR: environmentally related tax revenues, LCN: log of carbon neutrality, LGDP: log of gross domestic product.
***Significant value at 1%, **significant value at 5%, *significant value at 10%.
Source: Author's estimations.

Table 6. Results of Westerlund and Edgerton cointegration test.

	No shift		Mean shift		Regime shift	
Model	Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value
LM_τ	−3.258	0.000	−5.32	0.000	−3.257	0.000
LM_φ	−5.557	0.000	−4.325	0.000	−5.087	0.000

Note: Models are run with a maximum of five factors.
Source: Author's estimations.

working with the panel data, dealing with the cross-sectional dependence is essential to generate reliable findings at later stages. The study findings report the existence of cross-sectional dependence between the variables. Therefore, H1 is accepted against the null hypothesis for no presence of C.S.D. among the variables like L.C.N., L.E.N.R.T., L.C.C.A.T., L.T.D., and E.R.T.R., respectively. Such outcomes have reaffirmed that most technologically advanced economies are interlinked in this globalised world. If there is any shock in one of the selected countries, it will spread out over other economies entitled as technologically advanced. Therefore, the study variables are observed as cross-sectionally dependent on each other due to spillover effects. However, the findings might have been unreliable if we had not followed the cross-sectional dependence (Pesaran, 2015).

After analysing the trends of C.D., the next step demonstrates the outcomes for the integrated levels among the variables of interest. For this purpose, findings are reported in Table 5, where C.I.P.S. and C.A.D.F. tests output have been presented. It indicates that study variables are showing mixed integration order. More specifically, Table 5 reports that all the variables are non-stationarity at level; however, they become stationarity at first, with the significance level at 1%. Therefore, it claims that variables are stationary at first difference.

In addition, findings for the Westerlund and Edgerton (2008) tests have been reported in Table 6. There is a long-term connection between the study variables like carbon neutrality, environment-related technologies, climate change adaptation technologies, technological diffusion, and environmentally related tax. More specifically, this connection is significant at 1%, as observed under all three conditions entitled no shift, mean shift, and regime shift.

Table 7 of this study reports the structural breakpoints of T.A.E.-7. It shows multiple structural break periods, as shown in Table 7. These breaks have influenced the

Table 7. Structural breaks of Westerlund and Edgerton (2008).

Country	No shift	Mean shift	Regime shift
Japan	2007	2011	2004
Singapore	2006	2010	2004
China	2007	2011	2016
United States	2007	2003	2007
Germany	2015	2001	2012
Russia	2006	2001	2007
United Kingdom	2006	2007	2007

Source: Author's estimations.

Table 8. Results of CUP-FM and CUP-BC tests: CN.

	CUP-FM		CUP-BC	
Variables	Coefficient	t-statistics	Coefficient	t-statistics
LENRT	−0.365***	−5.204	−.524***	−4.205
LCCAT	−0.569	−1.505	−0.202	−1.204
LTD	−0.625***	−3.258	−0.232***	−3.259
ERTR	−0.258***	−5.205	−0.325***	−5.320
LGDP	0.536***	6.201	0.506***	5.293

Note: LENRT: log of Environment-related technologies, LCCAT: log of climate change adaptation technologies, LTD: log of technological diffusion, ERTR: environmentally related tax revenues, LCN: log of carbon neutrality, LGDP: log of gross domestic product.
***Significant value at 1%, **significant value at 5%, *significant value at 10%.
Source: Author's estimations.

global shocks for each selected economy under the present study. More specifically, during the 2007–2011 global financial crisis it has its regional and global outcomes.

Finally, our study considers the long-term association between the variables of interest through C.U.P.-F.M. and C.U.P.-B.C. methods (robustness check), which are reported in Table 8. Firstly, the study findings confirm a significant and negative impact of environment-related technologies on the L.C.N., for which the coefficient is −0.365 with a t-score of −5.024. It ensures that environment-related technologies among the T.A.E.-7 efficiently handle environmental issues. More specifically, a single unit change in the value of L.E.N.R.T. is causing a change of −0.365 in L.C.N. during the study period. Environment-related technologies are primarily designed to control the adverse effect on the natural environment, like higher carbon emissions and similar other gas emissions in the climate. During the study period, significant growth has been observed in all selected economies regarding the number of patents regarding environment-related technologies. More specifically, in the Russian region, there is a continuation of the reforms and system for dealing with the adverse environmental outcomes through the best available technologies (B.A.T.) approach and efficiency improvement for the natural environment. At the same time, a baseline scenario is also applied to implement energy-related technologies efficiently. In the case of China, there is an announcement for the week of internal environmental technologies during 2022, under which a big promotion of climate technologies in the economy is conducted. The U.S. falls among the largest producers of climate technologies globally, covering $782 billion for such technologies. The environmental technologies' contribution by different U.S. companies belongs to analytical services, wastewater treatment, solid waste management, hazardous waste management, air pollution control, process and prevention technologies, resources recovery, and water utilisation, respectively (Select the USA, 2022). These findings provide some practical support to the claim that targeted economies are showing some serious attention to environmental technologies through which sustainable outcomes in the form of low carbon emission or carbon neutrality are on the right track.

Recent empirical work has been conducted by Hussain and Dogan (2021) while exploring environment-related technologies' role in ecological footprint (a proxy for the environment) in B.R.I.C.S. countries. Second-generation econometric estimations confirm the reduction of environmental pollution through environmental technologies. Based on their findings, it is suggested that B.R.I.C.S. economies enhance E.R.T. investment to achieve a sustainable environment in the future. Santra (2017) shares similar conclusions and claims that environment-related technology has a significant and sound impact on sustainable performance. This would also strengthen the historical argument of Carraro and Siniscalco (1994) and Requate and Unold (2003). They infer that technological progress towards environment/green technology can reduce the generation of environmental pollution without reducing the output level. More specifically, adding green/ecological technology would help business firms and economies control their energy consumption and carbon emission in the natural environment.

Meanwhile, such innovations also increase the productivity of energy utilisation in terms of production-based energy productivity. Furthermore, such technologies may also motivate firms to incur costs on purchasing eco-friendly technologies. Hussain et al. (2022) claim that environment-related technologies and renewable energy are good sources of reducing carbon dioxide emissions. Furthermore, the mechanism behind the negative role of environmental technologies on carbon emission expresses that such technologies reduce the dependency on traditional energy sources while providing sustainable solutions. Therefore, the part of E.R.T. toward carbon neutrality is significant and constructive. Besides, the findings under C.U.P.-B.C. for robustness checking also reflect a substantial and productive impact of L.E.N.R.T. on carbon neutrality among technologically advanced economies. These findings are consistent with C.U.B.-F.M..

Secondly, Table 8 reports that climate change adaptation technologies are insignificant in carbon neutrality. This insignificant impact is observed with a coefficient of −0.569, with a t-score of −1.505 under C.U.P.-F.M., whereas the coefficient under C.U.P.-B.C. is −0.202 with a t-score of −1.204, respectively. Although the impact of climate change and adaption technologies on carbon neutrality in terms of carbon emissions from liquid fuel consumption (kt) is negative; however, this impact is insignificant, implying that climate change and adaption technologies are not playing their role in dealing with the environmental issues specifically among T.A.E.-7. In this regard, various reasons may be identified. For example, one of the core reasons for this insignificant impact of C.C.A.T. towards C.N. specifies that there is little adaptation for such technologies among T.A.E.-7 or that adaptation may be in some emerging phase for which no effect is found.

Another reason might claim that there is a probability of more promotion of such adaption among the technologically advanced economies to achieve fruitful results in the coming time. In this regard, the present study has rejected the statement that technological adaptation significantly influences the climate toward carbon neutrality.

The consistency of the insignificant association between L.C.C.A.T. and C.N. also exists under C.U.P.-B.C., where the coefficient value is −0.202, insignificant at 5%.

Thirdly, Table 8 reports the impact of technological diffusion toward carbon neutrality. Under C.U.P.-F.M., the coefficient of L.T.D. specifies a significant and negative effect of L.T.D. on L.C.N. A higher technological diffusion is a good sign as it lowers the consumption-based carbon emission in technologically advanced economies over the last two decades. More adoption of technologies by the population in the targeted economies plays its role as a panacea for environmental issues like carbon emissions. An exact pathway towards higher carbon neutrality would be achieved. More specifically, the concept of technological diffusion reflects the adoption of a number of technologies by the general population, which is widely observed among the T.A.E.-7 economies. Such practices reduce the dependency on those practices through which more carbon emissions are experienced. Meanwhile, sustaining long-run growth also requires the adoption of new technologies. At the same time, the significance of various new technologies derives from the notion that they spread out in different regions among different users (Stokey, 2021).

In addition, theoretical and empirical literature also observe the linkage between technology diffusion and environmental concerns. For example, Majumdar and Kar (2017) consider the Indian economy to explore the emission intensity of 15 manufacturing and agriculture sectors. The study findings confirm that technology adoptions help decline the total emission intensity across selected industries. Yuren Shi et al. (2012) also investigate the trends in carbon reduction intensity due to technological diffusion in the cement industry and state that a sound output can be generated through technological adoption in carbon reduction. Yingying Shi et al. (2021) explain that different governments in the world economy have adopted various policies for mitigating carbon emissions.

Meanwhile, enterprises and business units have been stimulated to adopt low-carbon technologies because of the higher demand for low-carbon products. Furthermore, H. Chen and Ma (2021) focus on the dynamic trading model among heterogeneous agents to explore the linkage between technology adoption and carbon emission. Study findings confirm that dynamic trading among heterogeneous agents boosts the adoption of new technology, which reduces the total carbon emission. Gu et al. (2021) focus on the global context for the transfer of low-carbon technology in helping carbon reduction. Technology transfer between developed economies helps reduce carbon emissions; however, such transfer is mainly hindered due to institutional barriers. Based on the above findings and discussion, our study inferred that technological diffusion is a good indication of mitigating adverse environmental outcomes like carbon emissions. Besides, the results through C.U.P.-B.C. also confirm the existence of significant and negative relationship between L.T.D. and carbon neutrality among T.A.E.-7 for the robustness checking.

Lastly, Table 8 shows the impact of environmental taxes on carbon neutrality. The coefficients of E.R.T.R. under C.U.P.-F.M. and C.U.P.-B.C. are −0.258 and −0.325, respectively, which means that more revenue from such sources leads to a decline in carbon emission and vice versa. Environmental taxes impose restrictions on energy sources like fossil fuels, which have adverse ecological outcomes, hence playing a significant role in environmental quality. More specifically, different governments worldwide have imposed carbon taxes to improve environmental performance, which has gotten some proper attention over the last couple of decades from researchers and policymakers, as expressed by Gerlagh and Van der Zwaan (2006). They have further claimed that carbon taxes are the cheapest to mitigate climate change. Bruvoll and Larsen (2004) investigate the economy of Norway by exploring the carbon taxes on carbon emissions. It is found that carbon taxes contribute to a 2% reduction in carbon emissions. Tao et al. (2021) considered the effect of environmental taxes and ecological innovation on controlling carbon emissions for the seven emerging countries during 1995–2018. With the help of advanced panel estimation, both in the long and short run, environmental taxes significantly reduce carbon emissions among E7. Safi et al. (2021) cover the significance of environmental taxes in achieving the goal of carbon neutrality for G7 economies. While applying a range of econometric estimations, it is confirmed that environmental taxes significantly change the level of carbon emission; hence, achieving carbon neutrality is possible among G7 member states. Besides, Shahzad (2020) claims that the role of energy efficiency and environmental regulations cannot be neglected to mitigate environmental problems. Their study has conducted a detailed theoretical review to explore ecological taxes' role on carbon emissions. However, it is stated that environmental taxes' role in pollution emission is still ambiguous and needs more in-depth investigation. Based on the stated findings and above arguments, our study confirms that carbon and environmental taxes are good source in dealing with the environmental pollution for which more attention from the policymakers and environmental regulatory bodies would provide some better outcomes. Furthermore, the environmental regulation in the form of carbon tax helps in internalising the externalities as linked with anthropogenic climate change. At the same time, without such taxes, the production and other activities will be relatively too cheap as individuals and industries will not consider the cost of emissions impose on others. Therefore, a significant and negative role of environmental regulations like taxes would help achieve better and sustainable outcomes in the form of low carbon emissions.

Finally, Table 9 reports the findings for the Sys-G.M.M. estimation while considering carbon neutrality as a primary dependent variable. The results confirm that lag

Table 9. Results for Sys-GMM estimation (Dependent variable: carbon neutrality).

Variables	Estimators
Lag CN	0.257** (0.012)
LENRT	−0.167*** (0.008)
LCCAT	−0.357 (0.137)
LTD	−0.257*** (0.001)
ERTR	−0.193** (0.025)
LGDP	0.469*** (0.000)
Intercept	−0.352** (0.017)
Year fixed effect	Yes
Autoregressive II	0.410
Hansen Test (*p*-value)	0.368

CN; carbon neutrality, LENRT; log of environmental technologies, LCCAT; log of climate change adaption technologies, LTD; log of technological diffusion, ERTR; environment-related tax revenues, LGDP; log of gross domestic product.
***Significant value at 1%, **significant value at 5%, *significant value at 10%.
Source: Author's estimations.

values of C.N. are positively and significantly linked with the C.N., where the coefficient is 0.257 with a standard error of 0.012. Furthermore, the findings confirm a significant negative effect of environment-related technologies on carbon neutrality while controlling for the possible endogeneity. Similarly, the findings demonstrate that climate change adaptation technologies are negatively but insignificantly linked with the C.N. These results are consistent with the C.U.P.-F.M. and C.U.P.-B.C. However, through technological diffusion and environment-related tax revenues, our findings support the argument that more technological diffusion and environmental regulations reduce ecological challenges. Finally, the Hansen test confirms the validity of endogenous regressors as instruments based on probability values, where P values (>0.05) cannot reject the null hypothesis.

5. Conclusion and recommendations

Although the issue of environmental sustainability has been discussed through a plethora of theoretical and empirical studies; however, toward achieving more sustainable results, the role of technological innovations is quite apparent. The scale of environmental challenges has increased awareness of the need for technological progression with the growing phase. Therefore, ecological innovations are regarded as any innovation aiming to demonstrate some progression towards sustainable development goals while reducing environmental impact. This nexus between ecological innovations and the environment has provided a key motivation for the present study, specifically among T.A.E.-7 over the past two decades. More specifically, this research contributes to existing literature while examining the effect of climate technologies and their adaption towards carbon dioxide emission with environmental taxes. The reason for selecting the T.A.E.-7 is to explore the overall carbon neutrality trends through selected technology and environmental taxes indicators. A range of econometric estimations was applied to examine the data trends, correlational analysis, cross-sectional dependence, unit root properties, and cointegration characteristics. More specifically, the study results through descriptive scores confirm the normal distribution of the data and good scores in terms of mean and standard deviation.

Additionally, the correlational matrix confirms the existence of a significant and positive association between some of the variables of interest. On the other side, the study findings indicate that variables are stationarity at first difference as examined through C.I.P.S. and C.A.D.F. methods. For the panel cointegration investigation, we applied Westerlund and Edgerton's methods, for which it was found that there exists a long-term connection between the variables. Through C.U.P.-F.M. and C.U.P.-B.C. analyses, we confirm that factors like environment-related technologies, technological adoption, and environmental taxes show their significant role in carbon neutrality for the technologically advanced economies over the study period. The C.U.P.-F.M. shows the coefficients as −0.365, −0.625 and −0.258 for environment-related technologies, technological diffusion, and environment-related tax revenues.

On the other hand, the coefficients for these variables under C.U.P.-B.C. are −0.524, −0.232, and −0.325. The findings under C.U.P.-F.M. and C.U.P.-B.C.

provide interesting facts. For example, the change in carbon neutrality because of environmental taxes shows a better coefficient value than C.U.P.-B.C. However, both of the findings are significant at 1%. On the other side, the adaption of climate technologies does not reflect any essential role in reducing carbon emissions among T.A.E.-7. Finally, technological diffusion shows a better reduction in L.C.N. through C.U.P.-B.C. than C.U.P.-F.M. Besides, for the environment-related tax revenues, the change in L.C.N. is more considerable through C.U.P.-F.M.

Finally, some essential and concrete policy recommendations have been provided. For example, the empirical findings indicate that environment-related technologies have reduced consumption-based carbon emissions in all seven economies over the last two decades. As such, governmental representatives and other legislators should work towards promoting such technologies and having their green output in the upcoming time. In this regard, such technologies should be utilised in those industries where the production of goods depends upon traditional energy sources like fossil fuels and similar others. At the same time, the governments in these economies should also control the import of products with adverse environmental outcomes like carbon and other greenhouse gas emissions. Secondly, although the impact of climate change adaptation technologies is insignificant; however, more attention is required towards such practices so that some fruitful results would be generated in the upcoming time. Thirdly, technological diffusion and environmental taxes significantly reduce carbon emissions. Fourthly, policymakers must examine the targeted economies' current growth models. This is because contemporary economic models directly contribute to environmental pollution, for which a solid need exists to convert them into sustainable dimensions. In this regard, green technology innovations are healthier for the economy and the environment. Therefore, economic development must reflect healthy and sustainable development with lower environmental outcomes. Significantly, authors like Pigato (2020) focus on the significance of technology-push policies and claim that such practices would be helpful for economies that are seeking the low-carbon-technology and innovations.

For this reason, promoting more technology diffusion may generate better results in the upcoming time while considering factors like quality of technological innovation, communication of information to the general public regarding usage of such technology and dividing the population into different segments where such promotion is more beneficial. At the same time, environmental regulations like carbon taxes are significant enough for carbon neutrality. Therefore, it is further suggested that similar ecological policies must be continued to safeguard the environment.

Although the current study has provided excellent theoretical and empirical insight regarding climate technologies, taxes, and carbon neutrality, some limitations are also associated. For example, the observed outcomes in this study demonstrate value of environmental technologies, climate taxes, and carbon neutrality. However, the cost of such technologies and related environmental regulations are not examined, hence missing in this research. Additionally, this study has only considered the ecological perspective of sustainability, whereas its social, economic, and financial dimensions are also missing. Furthermore, the impact of environmental-related technologies, technological diffusion, and environmental-related tax revenues on different industries is also missing. Besides, there are various data-related limitations like measuring carbon neutrality at the national level indicator; therefore, we are restricted to considering carbon emission reduction as a measure of carbon neutrality. Based on these limitations, future studies are highly recommended to provide meaningful contributions while considering a significant sample size for technologically advanced economies.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

Variables	Regional focus	Main findings	Source
Green technology innovation, renewable energy, carbon neutrality, population, personal income.	Turkish economy	Green technology innovation and renewable energy reduce CO_2 emissions.	Shan et al. (2021)
Green technology innovation, carbon emission.	Panel data for 71 economies.	Green technology innovation does not help in reducing carbon dioxide emissions.	(Du et al., 2019)
Green technology innovation, consumption-based carbon emission.	BRICS countries	GI mitigates carbon emissions only at higher levels of emissions.	(Razzaq, Wang et al., 2021)
Green and low carbon technological innovations.	Western Europe, North America, and developing economies.	Positive journey exists for the low and green carbon technology innovations.	(Shi & Lai, 2013)
Kyoto Protocol, diffusion of renewable technologies.	133 countries.	Protocol increased international patent applications.	(Miyamoto & Takeuchi, 2019)
Technological diffusion, climate change mitigation.	–	A methodological contribution towards examining the role of technological diffusion towards climate change mitigation.	(Mandel et al., 2020)
Green growth, environmental taxes, carbon emission, human capital.	G7 economies.	Environmental taxes, human capital and renewable energy improve the natural environment.	(Hao et al., 2021)
Eco-innovation, environmental taxes, carbon neutrality targets.	Emerging seven economies.	Eco-innovation helps in improving environmental quality.	(Tao et al., 2021)