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THE TECHNOLOGY INNOVATION PARADOX IN ASIA'S LEADING INNOVATIVE ECONOMIES: THE IMPORTANCE OF RENEWABLE ENERGY AND GREEN FINANCING

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Abstract. The present study investigates the influence of green energy, technological innovation, financial development, natural resources, trade, and economic growth on environmental quality in four technologically innovative economies in Asia using data from 1990 to 2021. By adopting a holistic approach, it addresses gaps in the literature that often focus on isolated factors or regions. The findings provide actionable insights for policymakers to reconcile economic growth with ecological sustainability, offering a blueprint for sustainable development in Asia's technological hubs. The Panel ARDL approach is used to evaluate the impacts in both the long and short term. Furthermore, we performed robustness tests using panel least squares, panel FMOLS, and panel DOLS techniques. The study's findings indicate that technological innovation, financial development, and trade all have a long-term positive impact on environmental quality in Asia's technologically innovative economies. However, green energy, natural resources, and economic progress had a negative impact on CO_2 emissions. The findings from panel least squares, panel FMOLS, and DOLS also showed that technological innovation, financial development, and trade enhance the environmental quality. This investigation aims to assist policymakers in creating comprehensive plan that promotes environmental sustainability via technological improvements and renewable energy sources, with an emphasis on economic growth.

Keywords: green energy, technological innovation, CO_2 emission, environmental sustainability, financial development, natural resources.

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1. Introduction

Globally, economic activities have increased over the past few decades, sparking potential concerns about long-term environmental viability. For example, this economic growth has resulted in approximately 25% of CO_2 emissions from energy production and consumption (Ji et al., 2021). Rapid economic changes, frequent structural transformations, increased industrialization, urbanization, and energy consumption have all contributed to the constant rise in CO_2 emissions (Çetin et al., 2018). However, these challenges are becoming more severe in emerging Asian economies such as China, Japan, and South Korea, raising concerns about environmental sustainability. These countries have achieved remarkable economic progress in the last few decades, significantly contributing to the global GDP by 24% (World Economics Research, 2024). Increasing energy use and resource exploitation over the last few decades have made these nations, despite their remarkable economic success, a bigger danger to environmental sustainability (Razzaq et al., 2022; Wang, 2021a, 2021b). Asian economies have experienced rapid GDP growth through industrialization, which has had a substantial impact on ecological sustainability in recent years (Ahmed et al., 2022). Polluted water and air, diminished natural resource availability, and unexpected shifts in weather patterns are all consequences of increasing industrialization, population increase, and urbanization (Zhang & Liu, 2015). The utilization of natural resources has had a significant effect on environmental quality in countries undergoing economic expansion, leading to a worldwide increase of 35% in carbon emissions (Worldometer, n.d.; Sun et al., 2022; Shao & Razzaq, 2022). Therefore, balancing sustainable energy practices, green financing, natural resource utilization, and technological innovation poses a complex challenge for these countries as they navigate advancements in technology, financial expansion, and ecological sustainability. The journey toward a sustainable future emphasizes a unified approach that integrates technological expertise with ecological preservation in emerging Asian innovation hubs. For example, China, a nation with a rapidly expanding population, has seen increased energy consumption through natural resource exploitation, resulting in a larger environmental footprint. These economies have developed and enforced environmental regulations to reduce their ecological footprints in response to mounting environmental pressure.

Moreover, the association between the green economy, technological innovation, and finance has recently become a hot topic, with environmental sustainability emerging as one of the world's most pressing challenges, particularly for leading Asian technological innovator countries (Mahmood et al., 2023). Environmental sustainability is already facing challenges from climate change and natural disasters (Ahmad et al., 2024), while man-made disasters pose additional threats, drawing the attention of researchers and policymakers toward improving the environment. The implementation of eco-friendly innovations and technological breakthroughs is crucial for improving environmental quality, especially in response to anthropogenic disasters. By reducing pollution and energy consumption, these technologies may disrupt the economic system (Acheampong et al., 2022). Efforts toward green technological innovations not only boost economic activities and sustainable production but also reduce environmental degradation and promote long-term viability (Ashraf et al., 2024; Çetin et al., 2024). Technological innovations have resulted in substantial alterations in several human activities, particularly those adversely affecting environmental sustainability (Omri, 2020). Additionally, technological advancements may serve as crucial components in alleviating the negative consequences of ecological development. Consequently, several initiatives have been undertaken to enhance environmental sustainability by incorporating clean energy sources to decrease greenhouse gas emissions (Mehmood, 2021; Çetin & Ecevit, 2015). The environmental quality of the Asian region has been greatly affected by the rapid industrialization and economic growth driven by globalization in recent years (Jahanger et al., 2023). Issues related to water, land, and air pollution have intensified, and natural resources have been depleted due to rising populations, industrialization, and urbanization. Conversely, new information and technologies have emerged from globalization, which can be leveraged to address environmental problems (Sethi et al., 2020).

Natural resources have great prospective for fiscal and sustainable expansion (Topcu et al., 2020; Yang & Mo, 2020). However, despite the plethora of natural resources, economic development may exhibit volatility, a phenomenon referred to as the "resource curse" (Tian, 2017). The resource curse concept was first introduced by Auty (2002), indicating that plentiful natural resources do not facilitate economic development in mining economies (Wang et al., 2021a; Xue & Wang, 2021). Resource-rich countries successfully manage their resources without any curse, whereas the lack of capital and technological innovation in underdeveloped countries often focuses on developing and exporting natural resources (Sun et al., 2024). Increases in both manufacturing productivity and GDP have led to the significant exhaustion of these natural and energy resources by neglecting the broader concerns of the environment and humans; therefore, Asian countries are actively investing in green financing and technological innovation for environmental sustainability (Ma et al., 2023).

There are two distinct theoretical frameworks regarding the link between economic progress and its ecological consequences. The influence of fiscal expansion on ecological contamination is noteworthy, as an enhanced financial system enables the provision of funds for various energy-intensive manufacturing initiatives (Shahbaz et al., 2017). Furthermore, improving the environment is one of the many functions performed by evolving financial institutions, which promote the use of energy-efficient technology (Tamazian & Rao, 2010). These empirical investigations align with the first theoretical perspective that emphasizes the significance of financial development in shaping temporal variations in CO_2 emissions. For instance, the expansion of trade and financial connections has contributed to economic progress among BRICS economies (Haseeb et al., 2018).

This study makes a unique contribution in various distinctive ways by addressing critical research gaps and offering a fresh perspective on the interplay of key factors influencing environmental quality. The first contribution is that this investigation sheds light on the complex interaction between technological innovation and natural resources in four leading technological innovator countries in Asia. Despite its critical importance for environmental sustainability, this topic remains relatively underexplored. This approach elucidates the interrelated impacts of green energy, technological innovation, natural resource use, and economic development on environmental quality, thereby offering an integrated framework that encompasses all these dimensions.

This study investigates the causal associations among green energy, technological and financial development, natural resources, trade, economic growth, and CO_2 emissions, therefore addressing a significant gap in the literature. It provides deeper insights into the underlying mechanisms driving environmental outcomes in technologically advanced economies. Additionally, the methodology employs state-of-the-art econometric techniques to assess both short- and long-term effects on environmental quality, resulting in robust estimates. This methodological rigor enhances the analysis and facilitates the derivation of more accurate policy implications. Lastly, the study offers actionable policy recommendations aimed at fostering environmental sustainability through the implementation of renewable energy, technological and financial advancement, sustainable resource use, and low-carbon initiatives. These recommendations are highly relevant for policymakers in Asia's leading technological economies and provide valuable lessons for other regions facing similar environmental challenges.

Based on these objectives, we will tackle the following research questions: What are the complex interactions between technological innovation and natural resources in major technological innovator countries in Asia, and how do these interactions affect environmental quality? Additionally, what are the long- and short-term impacts of green energy, technological innovation, and economic development on environmental quality, and how can these findings assist in policy strategies for achieving sustainability goals?

2. Literature review

2.1. Green financing

Financial development plays a crucial role in development, sustainability, and green innovation. This has led to a deluge of studies looking at its effects on energy use and ecological consequences. However, there is still no certainty about the findings of these studies. According to investigations by Zhang (2011) and Fang et al. (2020), increased energy consumption and CO_2 emissions are a direct outcome of economic expansion and the development of the financial system. Financial development has a negative impact on environmental quality, as demonstrated by Çetin et al. (2023). Umar et al. (2020a) concluded that financial evolution does not result in heightened CO_2 emissions; however, financial development substantially influences environmental quality. Similarly Çetin et al. (2022) shown that financial development positively influences environmental degradation. The distinct phases of ecological and economic advancement may result in divergent perspectives about the function of finance in development. According to Hsu et al. (2014), the Green Technology Innovation (GTI) model places significant emphasis on the interplay between financial models and their capacity to effectively address the evolving demands of the economy. Initially, small-scale economies face fewer environmental issues; however, as economies expand, environmental concerns become more persistent, involving independent innovation with high risks and uncertainties (Mayer, 2002). Trade openness is also considered a factor that contributes to CO_2 emissions and economic progress. Therefore, in such cases, green finance emerges as a critical determinant in encouraging sustainable development by addressing environmental challenges. Prior studies have shown the favorable effect of environmentally conscious investment on long-term environmental sustainability (Zhou et al., 2020; Nassani et al., 2017). The application of green financing aims to mitigate greenhouse gas emissions, industrial solid waste, and wastewater, thereby enhancing environmental quality (Poberezhna, 2018). A green economy may be more easily achieved with the help of green financing, which promotes eco-friendly technology (Ziaei, 2015). Financial institutions that prioritize green credits discourage high-polluting firms from seeking financial support (Wen et al., 2021). This redirection of financial resources motivates those firms to alter their production practices, ultimately improving environmental quality (Chiu & Lee, 2020). Additionally, the profitability of green investments incentivizes stakeholders to issue green credits to adopt environmentally friendly practices (Yuan et al., 2020).

However, green credit implementation impedes the monetary institutes' capacity to distribute financing, thereby diminishing the effectiveness of renewable energy investments in endorsing ecological sustainability (He et al., 2019). Therefore, the link between investments for green innovation plays an essential role in this complex relationship. Owen et al. (2018), Tang and Zhang (2020) have suggested the significance of green financing in facilitating early-stage green innovation activities. Liu et al. (2019) highlighted the significance of green financing as a crucial catalyst for environmentally conscious businesses to implement green initiatives and procedures. According to Kudratova et al. (2018), the financial viability of ecological enterprises plays an essential role in attracting investors, thereby fostering the expansion of sparkling vitality research and development. Nevertheless, the majority of research endeavors primarily investigate the unidirectional contributory interaction among green and clean innovation, green investment, and ecological sustainability. For example, Wang et al. (2021b) presented a spatial model suggesting bidirectional benefits, and their findings indicate that green finance not only enhances green innovation but also improves environmental quality.

2.2. Natural resources

The longstanding problem involves addressing whether natural capital contributes positively or negatively to financial expansion and environmental degradation. Natural resources may help to promote economic development quite constructively, which contradicts the conventional notion of the resource curse (Davis, 1995). Similarly, Alexeev and Conrad (2009) specified that natural capital, such as petroleum and mineral deposits, significantly influences the fostering of sustained economic development within an economy. In contrast, an abundance of natural resources can hinder financial evolution and act as a global resource curse (Wang et al., 2022b). Consequently, Stijns (2005) applied the resource curse concept and confirmed its validity in China. Recent literature has highlighted the crucial relationship between natural assets and ecological worth, prompting the use of several econometric methodologies to explore this dynamic association. Research in this area highlights the multifaceted connections between resource abundance, ecological footprints, and environmental outcomes. Ecological footprints, natural resource richness, and human capital all correlate negatively (Langnel et al., 2021). Similarly, Zafar et al. (2019) demonstrated that human capital and natural resources mitigate ecological footprints in the United States by investigating the interplay among these three factors. Further, natural resources have a favorable impact on ecological worth when considering carbon emissions. However, the concentration of pollutants rises when natural resources are abundant (Shen et al., 2021).

Several studies have shown that natural assets enhance ecological value in relation to carbon emissions (Khan et al., 2020). Natural capital has indeed led to increased pollution levels. Financial development, the availability of plentiful natural resources, and its effect on the ecological footprint have shown an adverse relationship (Saud et al., 2023). This indicates that greater natural capital richness correlates with a reduced ecological footprint that produces CO_2 emissions. However, the duality of this outcome underscores the interaction between natural resources and the health of ecosystems. Researchers have shown that sustainable energy, depletion of natural reserves, fossil fuel use, and globalization are critical variables contributing to the intensification of environmental pollution in the United States (Yi et al., 2023). Some studies indicate that natural capital, development, technological progress, and the use of alternative energy are significant contributors to environmental concerns.

2.3. Technological innovation

Technological innovation has lately emerged as a crucial element of sustainable economic growth. The significance of technological advancement in enhancing resource efficiency is paramount. Implementing innovative energy-saving technology may mitigate environmental issues linked to energy consumption (Wang et al., 2023). Empirical evidence shows that technological development in China experienced an average annual increase of 2.02% in total factor productivity from 1999 to 2012 (Liu et al., 2016). Avcı et al. (2024) also pointed out that the adoption of green technological innovations helps reduce pollution and sustains environmental quality. Therefore, economies should focus on investments in low-carbon technological innovations to tackle climate change issues. The implementation of technological innovation positively affects the innovative capabilities and competitiveness of institutions (Lei et al., 2022). Furthermore, the application of stringent ecological control measures encourages corporations to allocate resources toward technological innovation (Marin, 2014). The efficacy of green technology innovation is contingent upon its alignment with the economic development stage and resource composition framework. Conversely, the execution of inappropriate technological advances has the potential to exacerbate ecological challenges (Jin et al., 2019; Wang et al., 2021c). Environmental problems and green innovation literature primarily concentrate on their influence on environmental sustainability. Chen and Lee (2020) and Wang et al. (2022a) conducted investigations to examine the potential benefits of green innovation in enhancing environmental quality. Typically, major corporations actively encourage environmentally friendly innovation to save the atmosphere (Schiederig et al., 2012). The influence of firms on both business operations and environmental quality is significant. Singh et al. (2020) investigated the impact of new green technology adoption. Improved human resource management and the expansion of environmentally friendly intellectual capital are two ways the technological revolution is enhancing environmental conditions (Kraus et al., 2020). Innovation in green technology positively correlates with enhanced environmental quality. Studies by Seman et al. (2019) and Lin et al. (2013), among others, demonstrate that advancements in green technology continually improve environmental quality by decreasing prices, waste, and adverse environmental effects. Recent investigations have examined the connection between technology development and its environmental impacts. Zhang and Liu (2015) identified a link between technological innovation and reduced pollution levels in China from 2000 to 2010. Adebayo et al. (2023) analyzed data from 1990 to 2019 and discovered that carbon emissions in India, China, Russia, South Africa, and Brazil were reduced by the integration of sustainable energy, natural capital, and technological advances. According to Gyamfi et al. (2022), technological advancement mitigates carbon emissions in BRICS economies. Hashmi and Alam (2019) observed the diminishing influence of ecological rights and the systematic transformation regarding environmental pollution. Consequently, it is well acknowledged that green innovation enhances environmental quality, providing several competitive benefits (Fousteris et al., 2018). Wei et al. (2023) examined the correlation between scientific innovation and environmental impact, concluding that sustainable energy, technological breakthroughs, and worldwide trade mitigate environmental damage, but economic expansion has a detrimental influence.

The literature assessment indicates that prior research has examined the contributions of green finance, natural resources, and technological innovation separately within a singular framework. In contrast, this study examines the distinct linkages among green energy, technological innovation, financial development, natural resources, trade dynamics, economic progress, and environmental degradation.

3. Methods and data

3.1. The data and source

This research considers panel data from the four primary technologically advanced economies in Asia, including South Korea, Singapore, China, and Japan. These nations were chosen based on their rankings in the "Global Innovation Index" conducted by The Global Economy Index found at (https://www.theglobaleconomy.com/rankings/gii_index/Asia/). The selection criteria were determined by the data accessibility for each parameter. The key aim was to evaluate the influence of green energy, technological innovation, financial development, natural resources, trade dynamics, and economic growth on environmental quality. The dataset for these variables originates from the World Development Indicators (2022), including the period from 1990 to 2021 (https://data.worldbank.org/). This study utilizes data from 1990 due to the unavailability of more recent information. Table 1 delineates the variables examined along with their respective units and sources.

Figure 1 illustrates the fundamental elements involved in the mechanism of carbonization within technological advancement economies. This study primarily examines how technological innovation impacts the environment. According to Grossman (1995), carbon emissions increase during the initial stages of economic development but decline as economies mature and adopt cleaner technologies. The transformative potential of technological innovations is crucial for achieving long-term sustainability, particularly in the energy sector. Furthermore, green finance theory elucidates how financial systems facilitate investments in sustainable projects, thereby promoting environmental sustainability (Sharma et al., 2022). The natural resources possessed by a country also significantly influence ecological sustainability. The resource curse hypothesis provides insight into the detrimental influence of excessive reliance on natural resources and the associated challenges to sustainable development. Additionally,

Table 1. Details of study variables

Variables	Definition	Sources of data
Environmental quality	Inverse of carbon dioxide emission (kt)	WDI
Green energy	Renewable energy (percentage of total final energy consumption)	WDI
Technological innovation	Patent applications by residents and non-residents	WDI
Financial development	Percentage of domestic credit to the private sector relative to GDP	WDI
Natural resources	Natural resource rents as percentage of GDP	WDI
Trade	Trade (percentage of GDP)	WDI
Economic growth	GDP (percentage of annual growth)	WDI

Figure 1. The research variables mechanism to carbonization in technological innovative economies

trade serves as a significant factor affecting environmental sustainability. The Pollution Haven Hypothesis must be considered when assessing the impact of trade policies on environmental outcomes, specifically whether an open trade system fosters undesirable environmental practices.

3.2. Model specification

This study investigates the interaction among the Asian emerging economies (South Korea, Singapore, China, and Japan) concerning potential carbon emissions in the context of renewable energy, financial development, natural resources, trade, and economic growth. We utilized panel datasets spanning from 1990 to 2021 for this analysis. To establish the interaction, we can describe the following model as:

$$CE = f\left(GE, TI, FD, NR, TR, EG\right). \tag{1}$$

We can extend the Equation (1) further as follows:

$$CE_{it} = f\left(GE_{it}^{\xi 1}, TI_{it}^{\xi 2}, FD_{it}^{\xi 3}, NR_{it}^{\xi 4}, TR_{it}^{\xi 5}, EG_{it}^{\xi 6}\right). \tag{2}$$

The Equation (2) can be expressed both in functional and logarithmic forms as follows:

$$LCE_{it} = \xi_0 + \xi_1 LGE_{it} + \xi_2 LTI_{it} + \xi_3 LFD_{it} + \xi_4 LNR_{it} + L\xi_5 LTR_{it} + L\xi_6 LEG_{it} + \varepsilon_{it}. \tag{3}$$

CE represents the logarithm of inverse carbon dioxide emissions in Equation (3). GE symbolizes the logarithm of renewable energy (green energy), while TI indicates the logarithm of technological advancement in the most innovative Asian countries. FD shows the logarithm of financial development, NR represents the logarithm of natural resources, TR denotes the logarithm of trade, whereas EG represents the logarithm of economic growth. "*t*" denotes the time dimension of the panel, whereas "*I*" signifies the measurement of the entity.

3.3. CSD test with slope homogeneity method

This study examines CSD (Cross-Sectional Dependence) and slope homogeneity because it uses panel data, which may introduce cross-sectional dependency between countries. Based on empirical data, the second-generation approach, which considers factors such as CSD and slope homogeneity, outperforms first-generation approaches. Before starting the initial inquiry, verifying the stationarity of panel data is essential. However, the integration of unit root methodologies into panel data series may be ineffectual owing to concerns of cross-sectional dependence and slope homogeneity (Pesaran, 2015). In the analysis of extensive panel data sets, particularly those characterized by many cross sections, the Pesaran scaled LM testing and the Breusch-Pagan LM technique are two CSD tests that provide dependable results. However, these two approaches are incapable of yielding strong statistical outcomes for smaller panel series with restricted cross-sections. Pesaran (2015) suggested cross-sectional testing as a viable solution to the issue of tiny sample prejudice in panel data analysis. Cross-sectional testing may be interpreted in an alternative manner as follows:

$$CD = \sqrt{\frac{2T}{N\left(N-1\right)}}\left(\sum_{m=1}^{N-1}\sum_{k=m+1}^{N}\mu_{mk}\right). \tag{4}$$

Prior to executing the first query, the stationarity of the panel data must be ascertained. However, when utilized with panel data series, cross-sectional dependence and slope uniformity impede the efficacy of unit root methodologies. Two reliable CSD tests, the BPLM test and the Pesaran scaled LM analysis, are effective for analyzing large panel data sets, especially those with many cross sections. However, for smaller panel series with limited cross sections, none of these assessments provide dependable statistical outcomes. Pesaran (2015) presented cross-sectional tests to mitigate the bias linked to panel data analysis derived from small samples. The following presents an alternative viewpoint on the results of the cross-sectional study:

$$\tilde{\Delta} = \sqrt{N}\left(N^{-1}S\tilde{W} - \frac{n}{2n}\right) \sim X^2. \tag{5}$$

Furthermore,

$$\tilde{\Delta}_{ad} = \sqrt{N}\left(N^{-1}S\tilde{W} - \frac{n}{v\left(T,n\right)}\right) \sim N\left(0,1\right), \tag{6}$$

where N indicates the sum of economies chosen for the investigation, "n" demonstrate an independent variable, "v (T, n)" show the inclusive term, and "SW" indicates the Swami's statistics in the Equation (6).

3.4. Second-generation unit root testing technique

The non-stationary data leads to unreliable results; therefore, it is essential to assess stationarity with unit root testing. Cross-sectional dependency (CSD) and unpredictability render first-generation unit root tests unsuitable for panel data sets. For enhanced accuracy, it is advisable to use second-generation unit root assessments, such the CIPS testing projected by Im et al. (2003), Pesaran and Yamagata (2008). This test offers an alternative approach that yields more dependable outcomes. Such analyses commonly employ the CIPS unit root test, formulating the relevant test equation as follows:

$$\Delta M_{it} = \beta_{it} + \beta_i Z_{it-1} + \beta_i \overline{M_{t-1}} + \sum_{m=0}^{v} \beta_{im} \overline{M_{t-1}} + \sum_{m=0}^{v} \beta_{im} Z_{it-1} + \varepsilon_{it}. \tag{7}$$

In Equation (7), the symbol $\overline{M_{t-1}}$ represents the cross-sectional means. Moreover, the CIPS may be computed with the following Equations:

$$\widehat{CIPS} = \frac{l}{2} \sum\nolimits_{i=1}^{n} CADF_i. \tag{8}$$

Equation (8) signifies the CADF (Cross-Sectional Augmented Dickey-Fuller technique).

3.5. Panel cointegration technique

In order to determine whether the variables have a long-term connection, cointegration tests were performed. The confirmation of long-term relationships among the chosen series was achieved through second-generation cointegration analyses. As described by Persyn and Westerlund (2008), the results remain reliable even in the absence of cross-sectional dependency. To assess the validity of the null hypothesis, we will analyze how our dependent variables are linked to it. The panel cointegration technique may be expressed as:

$$\Delta X_{it} = \xi_i \gamma_t + \varphi_i X_{it-1} + \xi_i Y_{it-1} + \sum_{m=0}^{vi} \varphi_{im} \Delta X_{it-m} + \sum_{m=-ri}^{v} \varphi_{im} Y_{it-1} + \varepsilon_{it}. \tag{9}$$

After eliminating out the prospect of unpredictability, we may conclude that the data series do, in fact, exhibit cointegration.

3.6. Specification of Panel ARDL technique

This study utilized panel autoregressive distributed lag analysis to identify the interactions between the variables, including both long-term and short-term predictions. Generally, the autoregressive distributed lag approach requires the following prerequisites:

$$X_{it} = \sum_{l=1}^{r} \pi_{il} (X_i)_{t-l} + \sum_{l=0}^{r} \xi_{il} (Z_i)_{t-l} + \varepsilon_{it}. \tag{10}$$

In the Equation (10), X_{it} represents the CO_2 emission, and Z_i characterizes a vector of independent variables. These variables include renewable energy, technological innovation, financial development, natural resources, trade, and economic progress. We can use the following expression to describe how parameters respond in the short and long run, considering the unconstrained error correction framework:

$$\Delta X_{it} = \lambda_i \left(X_{i,t-1} - \xi_i Z_{i,\, t-1} \right) \sum_{l=1}^{r-1} \pi_{il} \Delta (X_i)_{t-l} + \sum_{l=0}^{r-1} \xi_{il} \Delta (Z_i)_{t-l} + \varepsilon_{it}. \quad (11)$$

Z_i indicates the coefficients for the long run, while X_i denotes the error correction term included in the Equation.

3.7. DH panel causality technique

Utilizing the Dumitrescu Hurlin panel causality technique, as proposed by Dumitrescu and Hurlin (2012), this study subsequently examines the interaction among carbon emissions, renewable energy, financial development, natural resources, trade, and economic growth. Understanding the causal links between these factors can provide policymakers with valuable insights for encouraging sustainable production. The consequences of the DH causality test display variations in all values across different sectors. We can represent the causality test mathematically as follows:

$$Y_{it} = \alpha_i + \sum_{s=1}^{n} \lambda_i^{(s)} Y_{i,t-s} + \sum_{s=1}^{n} \gamma_i^{(s)} X_{i,t-s} + \varepsilon_{i,t}. \quad (12)$$

In Equation (12), the symbol "n" demonstrates the lag duration for the parameters, the slope constant that varies between successive cross-sections is denoted by $\gamma_i^{(s)}$, whereas the autoregressive restriction is represented by $\lambda_i^{(s)}$.

4. Results and discussion

4.1. Descriptive statistics

Table 2 offers an inclusive analysis of the variables, focusing on the mean, standard deviation, minimum, and maximum values about green energy, technological advancement, financial development, natural resources, trade, economic growth, and carbon emission. Table 3 illustrates that the average value, often referred to as the mean, serves as a statistical measure

Table 2. Descriptive analysis for the variables

	LCE	LGE	LTI	LFD	LNR	LTR	LEG
Mean	20.247	1.019	10.648	4.785	–2.994	4.249	1.367
Median	20.542	1.264	10.615	4.819	–3.356	3.953	1.613
Maximum	22.741	3.523	13.583	5.383	2.266	6.080	2.675
Minimum	17.242	–1.660	7.600	3.883	–8.684	2.755	–3.737
Std. Dev.	1.744	1.433	1.533	0.356	2.886	1.027	1.081
Skewness	–0.327	0.190	0.008	–0.669	0.041	0.587	–1.885
Kurtosis	1.917	1.763	2.006	3.135	2.383	2.004	8.225
Jarque-Bera	8.529	8.929	5.262	9.652	2.063	12.651	22.153
Probability values	0.014	0.011	0.071	0.008	0.356	0.001	0.000

that represents the central tendency of a given dataset, offering a concise overview of the collective values. In contrast, the standard deviation serves as an indicator of the degree to which the observations differ from the average value, providing valuable insights into how points are distributed. The quantitative range indicates the extent to which data is spread out. Moreover, Table 3 exposed the outcomes of the correlation investigation carried out on the variables, revealing that all variables exhibit statistical correlation.

Table 3. Correlation investigation for the variables

	LCE	LGE	LTI	LFD	LNR	LTR	LEG
LCE	**1.000**	0.912	0.725	0.353	0.829	–0.842	0.004
LGE	0.912	**1.000**	0.560	0.382	0.802	–0.718	0.016
LTI	0.725	0.560	**1.000**	0.696	0.411	–0.724	–0.349
LFD	0.353	0.382	0.696	**1.000**	0.069	–0.406	–0.528
LNR	0.829	0.802	0.411	0.069	**1.000**	–0.538	0.244
LTR	–0.842	–0.718	–0.724	–0.406	–0.538	**1.000**	0.247
LEG	0.004	0.016	–0.349	–0.528	0.244	0.247	**1.000**

4.2. CSD (Cross-Sectional Dependence) test outcomes

We began by constructing the study model using the CSD test. Next, we employed the Pesaran CD, Pesaran scaled LM, Breusch-Pagan LM, and bias-corrected scaled LM techniques to conduct panel unit root tests. Results from Table 4 show that our panel dataset is significantly affected by cross-sectional dependency. Considering the interdependence of certain economies, it is essential to utilize advanced second-generation methods to assess cross-sectional dependency effectively.

Table 4. CSD outcomes

Tests	LCE	LGE	LTI	LFD	LNR	LTR	LEG
Breusch-Pagan LM	30.622*** (0.000)	94.270*** (0.000)	94.095*** (0.000)	84.878*** (0.000)	22.054*** (0.001)	74.154*** (0.000)	10.212 (0.116)
Pesaran-scaled LM	7.107*** (0.000)	25.481*** (0.000)	25.430*** (0.000)	22.770*** (0.000)	4.634*** (0.000)	19.674*** (0.000)	1.215 (0.224)
Bias-corrected scaled LM	7.043*** (0.000)	25.416*** (0.000)	25.366*** (0.000)	22.705*** (0.000)	4.569*** (0.000)	19.609*** (0.000)	1.151 (0.249)
Pesaran CD	1.164 (0.244)	0.670 (0.502)	3.032*** (0.002)	2.584*** (0.009)	1.940* (0.052)	8.155*** (0.000)	2.231** (0.025)

Note: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$).

4.3. Outcomes of second generation unit root testing

The unit root estimates obtained from the provided dataset show that both the first and second-generation series show stationarity at the first difference level, represented as I(1). Following this, it is imperative to deliberate the level of connection among the components via the process of cointegration. Therefore, the phenomenon of cointegration occurs when variables demonstrate incoherent unpredictability but maintain a regular pattern and display simultaneous or correlated movements. The results of the second-generation unit root testing are provided in Table 5.

Table 5. Second-Generation unit root testing results

Methods	CE	GE	TI	FD	NR	TR	EG
Levin, Lin and Chu (Level)	–1.146 (0.125)	0.731 (0.767)	–1.617* (0.052)	–0.241 (0.404)	0.366 (0.642)	–0.785 (0.216)	–3.961*** (0.000)
Levin, Lin and Chu (First difference)	–2.775*** (0.002)	–1.928*** (0.000)	–5.647*** (0.000)	–3.117*** (0.000)	–2.728*** (0.003)	–5.024*** (0.000)	–7.509*** (0.000)
Im, Pesaran and Shin (Level)	–1.173 (0.120)	3.080 (0.999)	0.356 (0.639)	1.157 (0.876)	–0.328 (0.371)	0.067 (0.526)	–4.207*** (0.000)
Im, Pesaran and Shin (First difference)	–6.567*** (0.000)	–4.426*** (0.000)	–5.519*** (0.000)	–4.883*** (0.000)	–4.826*** (0.000)	–5.426*** (0.000)	–11.412*** (0.000)
ADF – Fisher (Level)	–1.159 (0.123)	2.983 (0.998)	0.339 (0.633)	1.253 (0.895)	–0.308 (0.378)	0.101 (0.540)	–3.965*** (0.000)
ADF – Fisher (First difference)	–5.933*** (0.000)	–4.045*** (0.000)	–5.191*** (0.000)	–4.746*** (0.000)	–4.681*** (0.000)	–5.162*** (0.000)	–8.849*** (0.000)
PP – Fisher (Level)	–2.808*** (0.002)	0.952 (0.829)	0.895 (0.814)	1.670 (0.952)	–0.621 (0.267)	0.194 (0.577)	–6.00*** (0.000)
PP – Fisher (First difference)	–8.544*** (0.000)	–7.193*** (0.000)	–7.502*** (0.000)	–6.330*** (0.000)	–6.459*** (0.000)	–7.736*** (0.000)	–7.744*** (0.000)

Note: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$).

In addition, the investigation used CADF and CIPS tests to analyze the variables associated with CO_2 emissions, green energy, technological innovation, financial development, natural resources, trade, and economic growth at both the level and first difference scenarios. Therefore, we conducted a thorough investigation to confirm the existence of long-term cointegration. Throughout the investigation, however, the Shin (CIPS), cross-sectionally enhanced Im, Pesaran, and cross-sectionally enhanced Dickey-Fuller (CADF) approaches did not reveal any integration of the components at I(2). Table 6 presents the findings for CADF and CIPS.

Table 6. CADF and CIPS unit root test outcomes

Variables	CADF		CIPS	
	Level	Ist Diff.	Level	Ist Diff.
LCE	–1.795	–3.626***	–1.376	–5.111***
LGE	–1.258	–4.050***	–2.044	–5.307***
LTI	–2.527*	–4.651***	–2.494**	–4.993***
LFD	–2.353	–3.718***	–2.070	–4.792***
LNR	–2.184	–4.072***	–2.092	–4.328***
LTR	–1.384	–3.342***	–1.515	–4.381***
LEG	–4.138***	–5.636***	–4.827***	–5.368***

Note: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$).

Furthermore, the investigation used the Johansen and Fisher (J.F) group test for the variables that were chosen, and Table 7 displays the outcomes of this investigation. The results demonstrate the long-term interaction among the components under investigation.

Table 7. Cointegration test of Johansen Fisher Panel

Hypothesized No. of CE(s)	F-Stat. (from trace test)	Prob.	F-Stat. (from max-eigen test)	Prob.
None	104.5***	(0.000)	99.18***	(0.000)
At a maximum of 1	34.53***	(0.000)	17.24**	(0.027)
At a maximum of 2	19.79**	(0.011)	8.108	(0.423)
At a maximum of 3	14.55*	(0.068)	6.040	(0.642)
At a maximum of 4	12.05	(0.148)	4.072	(0.850)
At a maximum of 5	14.52*	(0.069)	10.36	(0.240)
At a maximum of 6	17.23**	(0.027)	17.23**	(0.027)

Note: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$).

4.4. Panel short and long-run

The interpretation of the panel short- and long-run results can be seen in Table 8. The coefficients for the variables technological innovation, financial development, and trade are positive (0.196), (0.365), and (0.224), respectively. The findings indicate that the factors of interest positively influence the environmental quality of technologically advanced economies across Asia. The significance of technological innovation in fostering prosperity is paramount, as it facilitates the advancement and modernization of industrial processes. This claim aligns with the outcomes of Zeraibi et al. (2020), who recognized technological innovation as a crucial catalyst for financial and human progress. To enhance competitiveness and advancement, resources should be directed towards innovation, research and development, and investments in novel techniques must be undertaken. The investigation indicated that factors such as green energy, natural resources, and economic expansion negatively affect the environmental quality of Asia's foremost technologically innovative countries. One major disadvantage of depending on natural resources for energy generation is the burning of fossil fuels producing carbon molecules that enter the atmosphere (Žarković et al., 2022; Sharma et al., 2021). Mohamed et al. (2022) support the notion that the financial sector significantly influences environmental outcomes, impacting individuals' standards of living and fostering economic growth in both public and private spheres. This growth can lead to enhanced workforce education, improved access to stock markets for investors, more resources for research and development, and the creation of innovative products. As consumers' purchasing power rises, there is a corresponding increase in interest in energy-intensive goods, which contributes to a greater environmental impact. Kihombo et al. (2021), Tahir et al. (2021), and Hao et al. (2020) advocate for the promotion of eco-innovation, technological advancements, and reduced energy consumption as rationales for endorsing these initiatives. Alper and Oguz (2016) and Ntanos et al. (2018) assert that the promotion of renewable energy usage has become critically important due to the adverse environmental consequences and limited output related with traditional energy production and consumption. Furthermore, emerging countries recognize energy consumption as a reliable indicator to evaluate their progress in enhancing living standards.

Table 8. Results of panel short and long-run

Variables	Coefficients	SE	t-Stat.	Prob.
Long run estimation				
LGE	–0.310**	0.124	2.490	0.015
LTI	0.196***	0.046	4.230	0.000
LFD	0.365**	0.164	2.223	0.029
LNR	–0.071**	0.031	2.271	0.026
LTR	0.224	0.147	1.525	0.132
LEG	–0.400**	0.164	2.435	0.017
Short run estimation				
COINTEQ01	–0.590	0.105	–0.569	0.571
D(CE(–1))	–0.184	0.155	–1.188	0.239
D(GE)	–0.033	0.129	–0.256	0.798
D(GE(–1))	0.014	0.056	0.251	0.802
D(TI)	–0.045	0.087	–0.516	0.607
D(TI(–1))	–0.112	0.083	–1.340	0.184
D(FD)	0.403	0.281	1.433	0.156
D(FD(–1))	0.388	0.366	1.058	0.293
D(NR)	–0.010	0.016	–0.620	0.536
D(NR(–1))	–0.027*	0.014	–1.927	0.058
D(TR)	0.013	0.062	0.212	0.832
D(TR(–1))	–0.538*	0.459	–1.171	0.054
D(EG)	–0.014	0.017	–0.823	0.413
D(EG(–1))	–0.025	0.021	–1.208	0.231
C	0.860	1.581	0.544	0.588
MD var	0.012	SDD var		0.116
S.E. of regression	0.093	AIC		–2.916
SQ resid	0.536	SC		–1.445
Log likelihood	252.632	HQC		–2.318

Note: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$).

On the other hand, the short-term estimate suggests an annual correction of 59 % of the disequilibrium. In the short term, the only factors that significantly impact the environment are trade and natural resources. These results align with prior studies, as corroborated by Managi et al. (2009), Çetin and Ecevit (2015), and Umar et al. (2020b).

4.5. Panel least squares technique

The investigation used the panel least squares approach to examine the interaction among green energy, technological innovation, financial development, natural resources, trade, economic growth, and CO_2 emissions in order to assess the robustness of the series. Table 9 reveals that there is a positive coefficient (0.357) for technological innovation, indicating a positive influence on environmental quality in technologically innovative economies in Asia. This finding is supported by a probability value (0.000). Furthermore, it is worth noting that financial development and trade display positive coefficients (0.567) and (0.438) respectively, with corresponding probability values (0.000) and (0.000). The consequences of this investigation demonstrated that the aforementioned factors have a positive effect on overall environmental quality. However, the coefficients for green energy, natural resources, and economic growth indicate a detrimental effect on CO_2 emissions. The statistical values of the R^2, Adj-R^2, and F-statistics are (0.968), (0.966), and (0.000) respectively.

Table 9. Panel least squares

Variables	Coefficients	SE	t-Stat.	Prob.
LGE	–0.507***	0.046	11.018	0.000
LTI	0.357***	0.036	9.707	0.000
LFD	0.567***	0.143	–3.956	0.000
LNR	–0.133***	0.019	6.818	0.000
LTR	0.438***	0.051	–8.431	0.000
LEG	–0.090***	0.034	2.636	0.009
C	20.773***	0.564	36.816	0.000
(R^2) (0.968) (Adj-R^2) (0.966) (F-stat) (616.852***) Prob(F-stat) (0.000)		(AIC) (0.599) (SC) (0.755) (HQC) (0.663) (DW Stat) (0.469)		

Note: *** designated ($p < 0.01$).

4.6. Panel FMOLS and DOLS techniques

Furthermore, the investigation has used the panel FMOLS and DOLS techniques to examine the interaction between factors, with the intention of improving the series' robustness. The results of Table 10 show that technological innovation, financial development, and trade have positive coefficients of (0.043), (0.434), and (0.123), respectively, indicating their positive influence on environmental quality. The outcomes of the investigation show that the availability of green energy, natural resources, and economic expansion has a negative impact on the environmental quality of technologically advanced countries. The R^2, Adj-R^2, and long-term variance have statistical values of (0.996), (0.995), and (0.018), respectively.

Table 10. Panel FMOLS

Variables	Coeff.	SE	t-Stat	Prob.
LGE	–0.051	0.047	–1.088	0.278
LTI	0.043*	0.026	1.642	0.103
LFD	0.434***	0.088	4.920	0.000
LNR	–0.020*	0.011	–1.780	0.077
LTR	0.123*	0.065	1.903	0.059
LEG	–0.001	0.017	–0.087	0.930
R^2	0.996	MD var		20.257
Adj-R^2	0.995	SDD var		1.746
SER	0.111	SS resid		1.415
Long-run var	0.018			

Note: * designated ($p < 0.1$), *** designated ($p < 0.01$).

Furthermore, the findings of the DOLS procedure are shown in Table 11, which exposes that technological innovation, financial development, and trade positively impacted the environmental quality with coefficients of (0.038), (0.368) and (0.234) respectively. The variables green energy, natural resources, and economic growth adversely affected environmental quality, with coefficients of (–0.091), (–0.017), and (–0.087), respectively.

Table 11. Panel DOLS

Variables	Coeff.	SE	t-Stat.	Prob.
LGE	–0.091	0.096	–0.947	0.350
LTI	0.038	0.041	0.927	0.360
LFD	0.368***	0.135	2.723	0.010
LNR	–0.017	0.022	–0.786	0.437
LTR	0.234	0.185	1.260	0.216
LEG	–0.087	0.061	\1.430	0.161
R^2	0.998	MD var		20.260
Adj-R^2	0.995	SDD var		1.748
SER	0.117	SS res.		0.467
Long-run var	0.005			

Note: *** designated ($p < 0.01$).

4.7. DH panel causality technique

We also employed the panel DH causality test to establish variable causality. Table 12 demonstrates that the countries in Asia with the greatest levels of technological innovation are those that prioritize green energy, technological innovation, financial development, natural resources, trade, economic progress, and carbon emissions. We conducted the examination using a panel data series. The findings of the investigation indicate that a majority of the variables exhibit bidirectional causation.

Table 12. Panel DH causality test results

Null Hypothesis	W-Stat.	Z-Stat.	Prob.
LGE «not» LCE	3.339	2.801***	0.005
LCE «not» LGE	10.637	11.836***	0.000
LTI «not» LCE	10.739	11.963***	0.000
LCE «not» LTI	3.287	2.737***	0.006
LFD «not» LCE	1.883	0.998	0.318
LCE «not» LFD	2.822	2.161**	0.030
LNR «not» LCE	5.295	5.223***	0.007
LCE «not» LNR	3.433	2.917***	0.003
LTR «not» LCE	3.456	2.946***	0.003
LCE «not» LTR	2.123	1.296	0.194
LEG «not» LCE	1.344	0.331	0.740
LCE «not» LEG	5.648	5.660***	0.008
LTI «not» LGE	6.282	6.445***	0.010
LGE «not» LTI	2.615	1.904*	0.056
LFD «not» LGE	4.931	4.771***	0.006
LGE «not» LFD	1.268	0.237	0.812
LNR «not» LGE	1.471	0.488	0.625
LGE «not» LNR	3.424	2.906***	0.003
LTR «not» LGE	13.150	14.948***	0.000
LGE «not» LTR	1.000	–0.095	0.924
LEG «not» LGE	4.053	3.685***	0.000
LGE «not» LEG	2.998	2.379**	0.017
LFD «not» LTI	3.891	3.484***	0.000
LTI «not» LFD	6.869	7.172***	0.003
LNR «not» LTI	2.088	1.252	0.210
LTI «not» LNR	3.472	2.965***	0.003
LTR «not» LTI	3.920	3.520***	0.000
LTI «not» LTR	1.061	–0.018	0.985
LEG «not» LTI	2.338	1.561	0.118
LTI «not» LEG	7.550	8.014***	0.005
LNR «not» LFD	2.526	1.794*	0.072
LFD «not» LNR	4.827	4.644***	0.006
LTR «not» LFD	0.163	–1.130	0.258
LFD «not» LTR	0.866	–0.260	0.794
LEG «not» LFD	0.341	–0.910	0.362
LFD «not» LEG	8.610	9.327***	0.000
LTR «not» LNR	6.528	6.749***	0.000
LNR «not» LTR	0.908	–0.208	0.835
LEG «not» LNR	1.438	0.447	0.654
LNR «not» LEG	2.633	1.927**	0.054
LEG «not» LTR	0.260	–1.010	0.312
LTR «not» LEG	2.119	1.290	0.196

Notes: * designated ($p < 0.1$), ** designated ($p < 0.05$), *** designated ($p < 0.01$); "«not»" shows does not homogeneously cause.

5. Conclusions and policy implications

This study analyzed the influence of green energy, technological innovation, financial development, natural resources, trade, and economic growth on environmental quality in four technologically advanced economies in Asia. The investigation used several empirical methods within the ARDL model to assess both short-term and long-term impacts. We additionally used panel least squares, panel FMOLS, and panel DOLS procedures to evaluate the robustness of the series. We conducted the Granger causality test on the variables to analyze their underlying interactions regarding their cumulative influence on carbon dioxide emissions. The results indicate a sustained positive correlation among technological innovation, financial development, trade, and carbon dioxide emissions. In contrast, we identified adverse impacts of natural resources, green energy, and economic growth on environmental quality. Analyses using panel least squares, panel FMOLS, and DOLS indicate an association among technological innovations, economic growth, trade, and environmental quality. However, we observed a negative link among natural resources, green energy, economic growth, and environmental quality. These results assist policymakers in devising a comprehensive strategy that may foster environmental sustainability via technological innovation and the implementation of sustainable energy sources, especially for economies aiming to bolster economic development.

5.1. Policy implications

Governments should implement policies that facilitate the transition to renewable energy sources. Such policies may include tax incentives, subsidies, or grants for companies that adopt green energy technologies and infrastructure. Planned investments in technological innovations related to energy generation, transmission, and storage are essential. Establishing clear long-term targets for renewable energy will guide investments and create a stable regulatory environment. Financial development is crucial in supporting green innovation. Policymakers should create financial mechanisms, such as green bonds, low-interest loans, and grants, to promote private sector investment in sustainable technologies. Additionally, policies that encourage the sustainable extraction and utilization of natural resources are imperative. Governments should encourage industries to adopt environmentally friendly extraction methods, minimize waste, and utilize resources more efficiently while ensuring strict adherence to environmental standards to mitigate the impact of resource exploitation on ecosystems.

5.2. Study limitations and future directions

The current research faces several challenges. One notable limitation is its inadequate consideration of factors beyond green energy, technological advancement, monetary expansion, trade, and economic growth in relation to environmental quality. Therefore, we cannot generalize the findings of this study to other economies. Furthermore, while future research may concentrate on exploring energy-specific technologies to evaluate their effectiveness in reducing carbon emissions, this investigation employs a more holistic technique to assessing the influence of technological advancements.

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