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The role of innovation in environmental-related technologies and institutional quality to drive environmental sustainability

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In this study, we examine the long-run effect of environmental-related technological innovation, institutional quality, trade openness, energy consumption, and economic growth on CO_2 emissions in APEC countries from 2004 to 2018. Firstly, panel unit root tests were used to explore the stationarity of each data series. The panel unit root test findings showed that all data series are stationary at the first difference. Second, the Westerlund panel cointegration test was used to deal with heterogeneity and cross-sectional dependence. Thirdly, the empirical findings from the augmented mean group (AMG) and common correlated effects mean group (CCEMG) estimators indicate that environmental-related technological innovation and institutional quality destructively affect CO_2 emissions. In contrast, trade openness, energy consumption, and economic growth positively impact CO_2 emissions. While causality analysis refers to the unidirectional causality runs from trade openness, energy consumption to CO_2 emission and bidirectional causality relationships are between technological innovation, institutional quality, GDP, CO_2 emission. Based on the findings, we proposed that APEC countries should raise investment in environmental-related technological innovation and improve the quality of the institutional environment to achieve sustainable development targets.

KEYWORDS

institutional quality, technological innovation, CO_2 emissions, sustainable development, APEC countries

1 Introduction

Environmental degradation and global warming are now top priorities for emerging and advanced countries (Ahmad and Zheng, 2021; Khan A et al., 2022; Obobisa et al., 2022b; Rehman et al., 2023; Rehman and Islam, 2023). Over the past few decades, the consumption of fossil fuels and other energy sources in emerging countries has increased dramatically to achieve economic growth (Obobisa et al., 2022b; Zhang et al., 2022). Therefore, the pace of greenhouse gas (GHG) emissions has increased due to this circumstance, resulting in catastrophic variations in weather patterns, including tornadoes, hurricanes, volcanic eruptions, and earthquakes. Besides, these changes have significantly affected human welfare, wildlife, and ecosystems (Obobisa et al., 2022b). In addition to other GHGs, CO_2 is considered major pollution in emerging and advanced nations. Therefore, limiting the pace of CO_2 emissions has been a contentious issue for world leaders, which has tripled since 1960 due to using solid, liquid, and gaseous fuels (Ahmad and Zheng, 2021). In this regard, the innovation in environmental-related technologies and the development of institutional frameworks have become essential factors in reducing the adverse effects of CO_2 on human health and the environment, as well as stimulating the transformation of global economic development (Khan A et al., 2022; Zhang et al., 2022).

The basic idea behind environmental-related technological innovation is the identification of new products and improvements in existing products, processes, or organizational systems that can reduce energy consumption, minimize pollutant emissions, enhance environmental quality, and encourage the growth of a greener economy (Khan et al., 2021; Ahmad and Zheng, 2021; Obobisa et al., 2022a). Recently technological innovation has played the most important role in mitigating global climate change. Several researchers have shown that technological innovation is a fundamental driver of industrial transformation, as well as updating and increasing quality and efficiency in the modern era (Wang and Li, 2020). Moreover, technological innovation is important in economic restructuring and optimization (Raihan and Tuspekova, 2022). Especially environment-related technology innovation is a powerful technology that has a more significant positive impact on the environment than traditional technological innovation (Dong et al., 2022). Technological innovation benefits the environment by utilizing green energy and reducing the usage of fossil fuels. These technologies may assist countries in improving the efficiency of their production operations. It is essential to prevent climate change (Zhang et al., 2016), encourage green economic growth, and significantly lower CO_2 emissions (Dong et al., 2022).

In addition to developing environmental-related technological innovations, institutions' quality can also contribute to helping environmental protection measures lower CO_2 emissions and enhance environmental quality (Obobisa et al., 2022b). In the environmental context, economics, scientists, and policymakers have recently focused on institutional quality (Salman et al., 2019a). They show that institutional quality is important in environmental governance policy implementation and pollution control. Strong institutional frameworks combat corruption, support establishing the rule of law, reduce military participation in politics, and increase public financial management. On the other hand, poor institutional quality has a long-term impact on a country's economy (Hassan et al., 2020a).

Furthermore, institutional quality is related to policies the country's institutions implement to establish cultural and legal structures that facilitate socioeconomic and financial activities and directly impact attempts to decrease environmental pollution (Hassan et al., 2020b). The importance of institutions in determining environmental quality is significant and valuable. It also supports the idea that high-quality institutions can help countries achieve higher incomes by lowering the expenses associated with economic growth (Rizk and Slimane, 2018). Intense institutional rules and a strict rule of law can force businesses to reduce their carbon dioxide (CO_2) emissions. Better institutional quality is essential to decrease pollution and ensure environmental sustainability (Asongu and Odhiambo, 2019).

However, some studies suggest that improving institutional quality will increase pollutant emissions (Le et al., 2020), and others argue that improving institutional quality will help the environment (Xue et al., 2021). Abid (2017) and Amin et al. (2021) have demonstrated that institutional quality (such as corruption, the rule of law, political stability, government regulation, and government efficacy) significantly impacts environmental policies and carbon-cutting strategies. Well-organized institutions reduce transaction costs while enabling transactions to increase financial efficiency. Therefore the countries are implementing a strong and efficient institutional structure to combat corruption, improve financial management, and improve environmental conditions (Obobisa et al., 2022b). The researchers (Ibrahiem, 2020; Ahmad and Zheng, 2021) have demonstrated that a country's ability to address environmental degradation depends on effective institutions. Additionally, some researchers report that stronger institutions are required in developing countries to enforce policies and execute ambitious solutions to decrease greenhouse gas emissions (Hassan et al., 2020b; Ahmad and Zheng, 2021; Obobisa et al., 2022c). Furthermore, institutions can also impact the environment through policies such as carbon taxation, feed-in tariffs, and eliminating fossil fuel subsidies (Haldar and Sethi, 2021).

However, to examine the effect of environmental-related technological innovation and institutional quality to achieve environmental sustainability, this study has focused on Asia–Pacific Economic Cooperation (hereafter APEC) group of countries established in 1989. Whose major goal is to enhance the region's sustainable economic growth and prosperity. APEC is one of the most important and high-level multilateral alliances and platforms in the Asia-Pacific region, with major worldwide influence (Parreñas, 2007). It comprises rapidly expanding countries and has developed into a powerful global growth engine, accounting for 48% of world trade and 60% of global GDP in 2018[1]. According to their economic performance, APEC countries have achieved substantial economic success by embracing technological innovation and high-quality institutions. This has changed member economies by bringing millions out of poverty and into the middle class (APEC, 2019). Besides this, most APEC countries are still expanding, necessitating a significant amount of fossil fuel usage to achieve economic growth. As a result, six of the top ten world carbon emitters are APEC members. Consequently, it is a crucial ideal group of economies where the development of their economies has been significantly influenced by environmental-related technological innovation and high-quality institutional settings. Therefore, it is required to pay close attention to examine the nexus between technological innovation, institutional quality, and environmental sustainability, which is the main interest of this study.

This study examines the effects of environmental-related technological innovation and institutional quality on achieving

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[1] For further detail please visit https://www.apec.org/about-us/about-apec/achievements-and-benefits.

environmental sustainability in APEC countries from 2004 to 2018. The econometric analysis involved the application of the latest methods, which can simultaneously account for cross-sectional dependency and slope heterogeneity issues in the data. Initially, panel unit root tests were used to explore the stationarity of each data series. The panel unit root test findings showed that all data series are stationary at the first difference. Besides this, the Westerlund panel cointegration test was used to deal with heterogeneity and cross-sectional dependence. Finally, the empirical findings from the augmented mean group (AMG) and common correlated effects mean group (CCEMG) estimators show that environmental-related technological innovation and institutional quality destructively affect CO_2 emissions. In contrast, trade openness, energy consumption, and economic growth positively impact CO_2 emissions. While causality analysis refers to the unidirectional causality runs from trade openness and energy consumption to CO_2 emission and bidirectional causality relationships are between technological innovation, institutional quality, GDP, CO_2 emission.

This study contributes to the existing literature in the following way. Although few researchers have analyzed the role of technological innovation and institutional quality on environmental sustainability at the country-specific, regional, and global levels (Chaudhry et al., 2021; Abid et al., 2022; Liu et al., 2022; Wang and Yang, 2022; Zheng et al., 2022; Amin et al., 2023; Wang et al., 2023), the majority of them have mainly concentrated on determining the effects of technological innovation and institutional quality on CO_2 emissions. Therefore, to fill this gap, our study examines the role of technological innovation and institutional quality in improving environmental sustainability. To the best of our knowledge, the mechanism that influences technological innovation, institutional quality, and environmental sustainability have not been clarified, especially for APEC countries, which are considered the dynamic engine of economic growth of world trade. Besides, there are significant differences in the technological innovation, institutional quality, and environmental sustainability nexus between different APEC countries. Therefore, the effect of technological innovation, institutional quality, and environmental sustainability in APEC countries will be heterogeneous and asymmetric. Nevertheless, relatively few researchers have thoroughly shown heterogeneous and asymmetric analyses to link these two variables.

The remainder of the research is structured as follows. A comprehensive literature review of the study variables is presented in Section 2. Section 3 describes the data source and summarizes the theoretical framework. Section 4 presents the discussion of the finding and detailed results, and lastly, in Section 5, the study concludes with policy implications and future research direction.

2 Literature review

Numerous researchers have identified possible aspects contributing to increased carbon emissions. However, few studies have investigated the variables that can help reduce or control carbon emissions. So the literature review of the current study is threefold: The first section presents a theoretical and empirical review of past studies that develop the relationship between technological innovation and the environment. In addition, this section also explains how it is measured. The second section explains the theoretical background and the role of institutional quality in developing a sustainable environment. The last section reports the Literature gap.

2.1 Nexus between technological innovation and environment

Earlier studies identified environmental innovation as a critical driver of the green economy and transformation. Environmental-related technological innovation can mitigate environmental damage and enable the integration of innovation resources, boosting core competitiveness, innovation, and green economic systems at the regional level (You et al., 2022). Furthermore, environmental-related technical innovation has developed a significant instrument for organizations to accomplish market reputation, sustainable development, and compliance with local or international environmental laws and standards (Xu et al., 2020). It also provides a promising means of achieving sustained advancement by creating goods, practices, or procedures. Additionally, it helps the commercial sector establish new markets and enhance competitiveness (Ben Amara and Chen, 2020; You et al., 2022).

Technological innovation is a complex concept that involves economic input–output. Therefore, several researchers have investigated the relationship among technological innovation and environmental quality in different aspects. They have used several proxies to measure technological innovation, such as R&D, efficiency, patent development, foreign direct investment (FDI), total factor productivity (TFP) and research and development spending (Khan H et al., 2022; Shabir, 2022). The author (FernándezFernández et al., 2018; Petrović and Lobanov, 2020) used the R&D as the proxy to measure the level of technological innovation and to investigate the effects of technological innovation on CO_2 emissions. Moreover, energy efficiency is also considered an essential indicator for measuring technological innovation (Shabir, 2022). The researcher (Tajudeen et al., 2018) reported that energy efficiency plays a relatively significant role in reducing CO_2 emissions. The authors (Wang et al., 2019; Dong et al., 2020) find similar outcomes among energy efficiency and CO_2 emissions. Finally, patent development is also seen a vital proxy of technological innovation, which is extensively used in the earlier studies to analyze the nexus among technological innovation and CO_2 emissions for instance (Álvarez-Herránz et al., 2017; Cheng et al., 2019; Hashmi and Alam, 2019; Erdoğan et al., 2020). The author (Irandoust, 2016) proposed foreign direct investment (FDI) to measure technological innovation. (Solow, 1956) used total factor productivity (TFP) for technological innovation. (Keller, 2002) employs research and development spending to measure technological innovation. While (Khan A et al., 2022), utilize the spending on research and development in agriculture as a proxy for technological innovation.

Moreover (Adebayo et al., 2023), examine the effect of technological innovation, renewable energy consumption, and natural resources on carbon emission in the BRICS countries and shows that technological advancement reduces CO_2 emissions for selected countries (Ahmad et al., 2023). determine the impact of technological innovation on sustainable development and environmental degradation in China. Their empirical finding shows that technological innovation positively impacts sustainability growth and lowers environmental pollution. The researcher (Wei et al., 2023) show that technological innovation and renewable energy improve Brazil's environmental quality. (Raihan and Tuspekova, 2022) analyze the impact of technological innovation, renewable energy, and economic growth on environmental sustainability in Kazakhstan. The results show that technical innovation and renewable energy sources help attain environmental sustainability by reducing CO_2 emissions, while economic growth and fossil fuel consumption increase CO_2 emissions. Similarly (Mughal et al., 2022), demonstrate that technological innovation is critical to minimizing environmental degradation and improving economic prosperity. (Hasan and Du, 2023) reveal that green technical and financial innovation is vital for achieving environmental sustainability.

Moreover (Sohag et al., 2015), illustrate that technical advancements improve energy efficiency and lower CO_2 emissions. (Sun et al., 2008) state that technological innovation considerably reduces carbon emissions. (Lantz and Feng, 2006) indicate that technical innovation and economic structure changes will aid in reducing carbon emissions. (Hodson et al., 2018) show that technological innovation decreases carbon emissions due to the efficient use of energy and cost-effective ways to lower carbon dioxide emissions.

(Cagno et al., 2015) showed how innovation encourages energy efficiency and reduces non-renewable energy use, lowering pollution.

Conversely, some researchers have shown that technological innovation adversely impacts environmental quality. For instance (Usman and Hammar, 2021), demonstrate that technological developments in APEC countries harm the environment over time. Similarly (Acemoglu et al., 2012), demonstrate that while technological innovation encourages economic growth, it can also raise carbon emissions. It is highlighted that governments must employ cutting-edge technology to encourage industry, stressing that technological innovation raises industrial production levels and destroys the environment. In contrast (Dauda et al., 2021), examined the association between innovation, carbon emission, and trade openness in African countries and found an inverted U-shape relationship between innovation and carbon emission. Thus, there is still disagreement in the literature regarding the effects of technological innovation on CO_2.

2.2 Institutions and environmental quality

Institutions play a critical influence in a country's growth and reduction of pollution emissions (Obobisa et al., 2022b). Theoretical perspectives and empirical evidence of the relationship between institutions and pollution are mainly inconclusive and are still being researched in the literature (Jiang et al., 2022). Recently (Egbetokun et al., 2020) have proposed that a country's environmental quality is defined by its governmental institutions, despite the economic level, because pollution increases in countries with less functional environmental legislation. Countries also require competent institutions to encourage the use of renewable energy and achieve sustainable development. Therefore, better institutions are the appropriate ways and dealings for addressing CO_2 emissions caused by human activity and climate change (Obobisa et al., 2022a). Over the past few years, numerous researchers have supported these conclusions. For instance (Wang et al., 2023), explored the impact of institutional quality, environmental governance, and technological innovations on consumption-based resource footprints in the selected EU economies. Their findings show that environmental governance and institutional quality reduce material footprints. (Haldar and Sethi, 2021) highlight that poor institutional quality has a negative impact on CO_2 emissions in emerging countries. (Wawrzyniak and Doryń, 2020) demonstrated that better government effectiveness reduces CO_2 emissions in emerging and developed countries. Obobisa et al. (2022b) show that green technical innovation and institutional quality effectively reduce CO_2 emissions and support sustainable development. (Jiang et al., 2022) noted that improving institutional quality and increasing the usage of renewable energy are mitigating factors for carbon emissions. (Salman et al., 2019b) examined the relationship among institutional quality, economic growth, and CO_2 emissions in Indonesia, South Korea, and Thailand. They show a specific and extensive role of institutional quality in decreasing emissions and increasing economic growth. Khan and Rana (2021) also revealed that institutional quality decreases CO_2 emissions.

On the other hand (Teng et al., 2021), documented that institutional quality positively affects CO_2 emissions. Azam et al. (2021) report that institutional quality significantly positively affects the environment in developing nations. Similarly (Hassan et al., 2020b), also show that institutional quality causes an increase in CO_2 emissions in Pakistan. Based on the literature analysis listed above, it is clear that more investigation is required into the empirical relationship between institutional quality and CO_2 emissions in APCE countries.

2.3 Literature gap

The above analysis shows that some scholars have focused on the nexus between technological innovation, institutional quality, and CO2 emissions. However, some research gaps still exist. First, even though some scholars have started to focus on the impact of technological innovation and institutional quality on CO2 emissions in different regions of the world, knowledge of the effects of such technological innovation and institutional standards on CO2 emissions is still insufficient, especially for APEC countries. Second, in the previous literature on technological innovation, institutional quality, and CO2 emissions nexus, the potential cross-sectional dependence and slope heterogeneity within the panel data are often ignored and, thus, may result in misleading estimations.

TABLE 1 Variables descriptive statistics.

Variable	Obs	Mean	Std.Dev.	Min	Max
CO_2	180	1.089	1.177	1.514	2.975
TI	180	9.306	2.152	5.680	14.249
IQ.	180	1.102	0.762	−0.471	2.361
TOP	180	4.267	0.829	3.164	6.093
ECO	180	6.8	5.158	4.38	10.004
GDP	180	8.946	1.470	3.164	6.093

3 Data and theoretical framework

3.1 Data

Our research intends to examine the influence of environmental-related technology innovation and institutional quality on reducing GHG emissions and mitigating climate change in the APEC region between 2004 and 2018. Carbon emissions (CO_2) are employed as a proxy for the dependent variable in the context of environmental sustainability (Umar et al., 2020). Technological innovation (TI) and institutional quality (IQ) are independent variables. While economic growth (GDP), trade openness (TOP), and energy consumption (ECO) are employed as the control variable. The data of this study are taken from World Bank's Global Financial Development Database and World Development Indicators. Table 1 describes the detail of the variables used in this study.

Our key dependent variable is environmental sustainability. Environmental sustainability is a global concern, as the United Nations has cautioned. It is driven by deforestation, solid waste, grazing, sulfur emissions, carbon emissions, erosion, water pollution, etc. We follow the existing literature and use CO2 emissions as the dependent variable to measure environmental sustainability (Baajike et al., 2022). Such a decision is based on the following reasons. First, there is insufficient data on the other proxies of environmental sustainability. Second, among the three types of Greenhouse gas emissions, CO2 emissions constitute about 75% (Abbasi and Riaz, 2016), with nitrous oxide, methane, and fluorinated gases forming the remaining 15% share. Greenhouse gas emissions mainly cause global climate change. CO2, primarily a by-product of energy generation and use, is responsible for most greenhouse gases linked to global warming (Ahmad M et al., 2022). Third, it is empirically supported in the literature as most studies proxy GHG with CO2 emissions (Baajike et al., 2022; Oteng-Abayie et al., 2022; Saud et al., 2023).

Moreover, environmental technologies are among the most well-known and successful ways to reduce ecological harm. Eco-innovation helps nations shift their sectors towards environmentally friendly technology like renewable energy sources (Acheampong et al., 2022). Technological innovations, specifically in the clean and green energy format, helps in protecting environmental pollution while reducing the dependency on fossil fuel energy. Several studies have investigated the relationship between technological innovations and environmental proxies. We followed the previous studies and used the patent applications (resident + non-resident) as a proxy of environmental-related technological innovation. At the same time, we were following the studies of (Shabir et al., 2021; Wang et al., 2023), and using Worldwide Governance Index (WGI) as a measure of institutional quality (IQ), which included the following six indicators: corruption control (CC), government effectiveness (GE), political stability (PS), regulatory quality (RQ), rule of law (RL), and democracy (VA). The above data were obtained from the World Development Indicators (WDI) and in the range of–2.5 to 2.5. All the other variables were chosen based on theory and previous research, such as the work of (Ahmad S et al., 2022; Baajike et al., 2022; Shabir et al., 2022; Amin et al., 2023).

3.2 Theoretical framework and model specification

This study investigates the effect of innovation in environmental-related technologies and institutional quality on CO_2 emissions. Other explanatory factors such as trade openness, energy consumption, and economic growth, are also included for a more robust and comprehensive analysis. In terms of the variables mentioned earlier (technological innovation, institutional quality, trade openness, energy consumption, and economic growth), our plan CO_2 the function is as follows:

$$CO_2 = \int (TI, IQ, TOP, ECO, GDP) \tag{1}$$

$$\ln CO_{2it} = \alpha_{it} + \beta_1 \ln TI_{it} + \beta_2 IQ_{it} + \beta_3 \ln TOP_{it} + \beta_4 \ln ECO_{it} + \beta_5 \ln GDP_{it} + \varepsilon_{it} \tag{2}$$

Where CO_2 stands for carbon dioxide emissions, representing our main dependent variable; TI indicates environmental-related technological innovation; IQ denotes institutional quality; TOP stands for trade openness; ECO shows energy consumption; and GDP demonstrates economic development. $\beta 1, \ldots, \beta 5$ indicates the coefficient of parameters, and i and t, respectively, reflect individual cross-sections and time.

3.3 Econometric methodology

3.3.1 Cross-sectional dependence (CSD) test

We apply the CSD test in the first estimation strategy to determine whether our dataset has cross-sectional dependence. CSD analysis is the initial step in panel data analysis. Because the APEC economies are linked through trade and integrated financial systems, common shocks are predicted to have a simultaneous impact. Common stocks tend to induce dependency among the units in the panel, even if their impact is inconsistent among cross-section units. We use the Pesaran (2004) CSD test to assess the CSD among variables. CSD test, which is H_0: $\theta_i \neq 0$ and H_A: $\theta_i = 0$ and represented as

$$CD = \sqrt{\frac{2T}{N(N-1)}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}}\right)} \sim N(0,1)i,j \tag{3}$$

$$M = \sqrt{\frac{2T}{N(N-1)}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho_{ij}}\right)}\ \frac{(T-k)\hat{\rho}_{ij}^{2} - E(T-k)\hat{\rho}_{ij}^{2}}{Var(T-k)\hat{\rho}_{ij}^{2}} \tag{4}$$

$\hat{\rho}_{ij}^{2}$ Indicate the residual pair-wise correlation sample estimate.

3.3.2 Slope homogeneity test

The next step is to establish slope homogeneity among the cross-sections. The assumption of slope homogeneity cannot obtain heterogeneity due to the country's distinctive characteristics (Khan et al., 2019). Therefore, we apply the Pesaran and Yamagata (2008) test to detect slope heterogeneity among cross-sectional units.

3.3.3 Panel unit root tests

After examining the CSD and slope homogeneity, we use the second-generation unit root test to examine the unit's root properties, such as augmented Dickey-Fuller (CADF) and cross-sectional augmented Im-Pesaran-Shin (CIPS) founded by Pesaran (2007). They are superior to the first-generation test in robustness, handling heterogeneity, and accounting for CSD. The CADF test is expressed as follows:

$$\Delta y_{it} = \alpha_i + \beta_i y_{it-1} + \gamma_i \bar{y}_{it-1} + \theta_i \Delta \bar{y}_t + \varepsilon_{it} \tag{5}$$

where i and t stand for cross-sectional units and periods, respectively. After achieving the CADF statistics, CIPS statistics can be measured as follows:

$$CIPS = N^{-1}\sum_{i=1}^{N} CADF_i \tag{6}$$

3.3.4 Westerlund test for panel cointegration

Before evaluating the long-run parameters, we confirm whether cointegration exists between the primary variables. The traditional cointegration test does not consider slope heterogeneity and cross-sectional correlation (Pedroni, 1999). Therefore this study used the cointegration estimation method established on the error correction model introduced by (Westerlund and Edgerton, 2007), called a second-generation cointegration test (Khan et al., 2019), to find more efficient long-term estimation. This test presented four statistics as $P_t, P_a, G_t, and\, G_a$. The rejection of H_o for $P_t\, and\, P_a$ indicates the presence of cointegration in the panel, while similarly, the rejection of H_o for $G_t\, and\, G_a$ suggests the presence of at least one cross-section. It can be described in the equation as;

$$\Delta Y_t = \delta_i' d_t + \alpha_i Y_{it-1} + \sigma_i' X_{it-1} + \sum_{j=1}^{\rho_i}\alpha_{ij}\Delta Y_{it-1} + \sum_{j=-qt}^{\rho_i}\gamma_{ij}\Delta X_{it-1} + \mu_{it} \tag{7}$$

3.3.5 Augmented mean group (AMG) test

Next, we use the AMG test presented by Eberhardt and Bond (2009). This model is more robust to slope heterogeneity, CSD and deals with endogeneity and non-stationarity problems (Eberhardt, 2012). Besides, the AMG estimator addresses the cross-sectional dependencies by including common dynamic effect parameters and estimated by using a two-stage method (Wang and Dong, 2019) that can be written as follows:

AMG-Stage 1

$$\Delta y_{it} = \alpha_i + \beta_i \Delta x_{it} + \gamma_i f_t + \sum_{t=2}^{T}\delta_i \Delta D_t + \varepsilon_{it} \tag{8}$$

AMG-Stage 2

$$\hat{\beta}_{AMG} = N^{-1}\sum_{i-1}^{N}\hat{\beta}_i \tag{9}$$

Where $y_{it}\, and\, x_{it}$ represent the observables, Δ denote the first difference operator, α_i represent intercept, β_i indicate the country-specific coefficients, f_t indicate unobserved common factors, δ_i illustrate the time dummies coefficient, $\hat{\beta}_{AMG}$ stand mean group estimator for AMG, and ε_{it} denote the error term.

3.3.6 FMOLS and DOLS

We take the FMOLS and DOLS to observe the long-term dynamic effect between the selected variables in this study for a robustness check. FMOLS supports using Newey-West for correction, while DOLS adds more lagged and lead variables (Nasir et al., 2019), which estimate the outcomes further significant and robust. The significant difference between the two methods is how to correct the autocorrelation in regression. The FMOLS (Aïssa et al., 2014) is applied to estimate long-run elasticity coefficients (Khan et al., 2019). FMOLS is non-parametric and offers more expectable parameters in small samples. It also can handle serial correlation and endogeneity issues in estimating coefficients in panel data (Khan et al., 2019).

In comparison, the DOLS is a parametric approach that directly represents the double-log model's elasticity coefficient (Bilgili et al., 2016). Compared to the OLS estimator, DOLS has less biasness in small samples using Monte Carlo simulations (Khan et al., 2019). (Pedroni, 1996) recommends techniques for estimating the coefficients used to calculate the long-run effects.

$$\hat{\beta}_{FMOLS} = \left(\sum_{i=1}^{N}\widehat{L_{22I}^{-1}}\sum_{t=1}^{T}(x_{it} - \bar{x}_i)^2\right)^{-1}\sum_{i=1}^{N}\hat{L}_{11i}^{-1}\hat{L}_{22i}^{-1}\left(\sum_{t=1}^{T}(x_{it} - \bar{x}_i)y_{it}^{*} - T\hat{\delta}_i\right) \tag{10}$$

In which

$$y_{it}^{*} = (y_{it} - \bar{y}_i) - \left(\frac{\hat{L}_{21i}}{\hat{L}_{22i}}\right)\Delta x_{it} + \left(\frac{\hat{L}_{21i} - \hat{L}_{22i}}{\hat{L}_{22i}}\right)\beta(x_{it} - \bar{x}_i) \tag{11}$$

And we denote $\hat{\delta}_i$ as

$$\hat{\delta}_i \equiv \hat{\Gamma}_{21i} + \hat{\Omega}_{21i}^{0} - \left(\frac{\hat{L}_{21i}}{\hat{L}_{22i}}\right)\left(\hat{\Gamma}_{221} + \hat{\Omega}_{22i}^{0}\right) \tag{12}$$

Where Ω refer to an asymptotic covariance matrix for long-run variance and Γ as dynamic covariance, L is a lower triangular matrix with partition calculation. Therefore, a DOLS estimator is used, which gets the following form:

$$y_{it} = \beta_i' x_{it} + \sum_{j=-q}^{q}\zeta_{ij}\Delta x_{i,t+j} + \gamma_{1i} D_{1i} + \varepsilon_{it} \tag{13}$$

TABLE 2 Cross-sectional dependency test.

Variables	Statistic	*p*-value	Abs (corr)
CO_2	49.123***	0.000	0.662
TI	4.422***	0.000	0.069
IQ	28.829***	0.000	0.421
TOP	43.209***	0.001	0.667
ECO	5.043***	0.000	0.109
GDP	5.935***	0.000	0.029

Note: The symbol *** indicates the significance level at 1%.

3.3.7 Dumitrescu and Hurlin (DH) non-causality test

The causality test indicates the direction of causal flow among all research variables, which is technical to confirm the predictable result (Yang et al., 2021). Recently developing Dumitrescu and Hurlin's (2012) non-causality test can handle cross-sectional correlation than the conventional Granger causality test (Granger, 1969).

D-H non-causal test is defined as

$$Y_{it} = \alpha_i + \sum_{k=1}^{K} \gamma_i^{(k)} Y_{it-k} + \sum_{k=1}^{K} \theta_i^{(k)} x_{it-k} + \varepsilon_{it} \tag{14}$$

where, $\alpha_i, \gamma_{i,} \theta_i,$ *and* ε_{it} respectively stand for intercept, coefficients, and residual term.

4 Results and discussions

Table 1 shows the descriptive statistics (i.e., mean value, standard deviation, maximum value, and minimum value) of all the selected variables. The mean value of the natural logarithm of carbon emissions is 1.089 and ranges between 1.514 and 2.975, with a standard deviation of 1.177. While our main explanatory variables technological innovation and institutional quality, have mean values are 9.306 and 1.102, with a standard deviation of 2.152 and 0.762, respectively. To eliminate heteroscedasticity, which could invalidate the empirical results, all the variables are treated logarithmically in this study.

4.1 Cross-sectional dependence and homogeneity tests

Empirical estimations of panel data necessitate several steps to identify appropriate methodologies. Checking the CSD issue in panel data analyses is the first step. Therefore, to determine the existence of CSD in the data, we employ the (Pesaran, 2004) tests. Table 2 demonstrates that the null hypothesis of no CSD is rejected because the *p*-values of each of the sampled variables are significant. This result is an indication of the presence of CSD. This suggests that error terms include unobserved common shocks across cross-sections due to economic integration.

TABLE 3 Slope heterogeneity test.

Test	Value	*p*-value
$\tilde{\Delta}$	15.451***	0.000
$\tilde{\Delta}_{adjusted}$	13.031***	0.000

Note: The symbols *** indicate the significance level at 1%.

TABLE 4 Unit root test.

Variable	CIPS		CADF	
	Level	First-difference	Level	First-difference
CO_2	−0.588	−3.717***	−0.992	−4.919***
TI	−1.382	−3.302***	−0.725	−12.511***
IQ	−1.129	−3.499***	−1.441	−8.341***
TOP	−0.426	−2.221***	−1.334	−7.572***
ECO	−0.998	−2.721***	−1.258	−9.120***
GDP	−1.592	−3.079***	−4.102	−19.869***

Note: The symbols *** and * indicate the significance level at 1% and 5%, respectively.

Additionally, APEC members engage in various moves to integrate their economies and advance trade while emphasizing. Thus, one nation's economic reforms and regulatory changes impact the neighbouring nations and regions. Table 3 shows the slope homogeneity results, which suggest that the slope homogeneity hypothesis is rejected and slope heterogeneity in the panels is confirmed.

4.2 Panel unit root test

After determining the presence of CD and heterogeneous slope in panel data, the next stage in the econometric analysis is to examine the stations of the variables in question. Because most economical series are found to follow unit root processes. Consequently, this non-stationary data produces inconsistent and misleading findings (Ahmad S et al., 2022). So to examine the series' stationarity, this study employs the CIPS and CADF proposed by Pesaran (2007), called the second-generation panel unit root test. Because in the presence of CSD, the CIPS and CADF unit root test is the most suitable option, which deals with CSD issues (Pesaran, 2007). Table 4 displays the results of panel stationary tests in both level and first difference forms. The CIPS and CADF test findings show that all factors become stationary following the first difference, demonstrating that all components are integrated at I (1).

4.3 Westerlund panel cointegration test

The cointegration test is carried out as the next step in the econometric analysis procedure to observe the series' long-run relationship. Because the CSD tests recommended using the second-generation panel cointegration test, we use the

TABLE 5 Westerlund cointegration test results.

Test	Value	*Z*-value	*p*-values
G_t	−2.644***	−3.029	0.001
G_a	−10.499	−1.211	0.110
P_t	14.282***	−3.921	0.000
P_a	−11.973***	−5.098	0.000

Note: The symbols *** and ** indicate the significance level at 1% and 5%, respectively.

Westerlund cointegration test in this research. The results of the Westerlund cointegration tests are shown in Table 5, which shows that the *p* values of Gt, Pt, and Pa are statistically significant at a 1% level. It rejects the null hypothesis of no cointegration. It demonstrates that the panel data in this study has a strong relationship and supports the existence of a long-run cointegration association among CO_2 and TI, IQ, GDP, TOP, and ECO inside the APEC countries. Therefore, in light of this, these variables are employed in assessing long-term relations.

4.4 Results of long-run estimate

Following the use of several diagnostic tests, they verify the existence of heterogeneity, cross-dependency, stationarity, and long-run relationships between the variables. Therefore, we investigated the long-term impact of technological innovation, institutional quality, trade openness, energy consumption, and economic growth on CO_2 emissions employing the Augmented Mean Group (AMG) and the CCEMG methods. Table 6 shows the outcomes of AMG and CCEMG estimation approaches, demonstrating that only two variables (Technological innovation and Institutional quality) are essential in lowering CO_2 emissions and improving environmental sustainability. On the other hand, energy consumption, trade openness, and GDP lead to increased CO_2 emissions and decreased environmental sustainability in APEC nations.

Technological innovation is a vital variable that influences environmental quality. Table 6 presents empirical evidence of a substantially detrimental link among technological innovation and CO_2 emissions. This highlights that environmentally friendly technological innovation supports APEC nations in reducing carbon emissions and enhancing the quality of the environment. The coefficients are 0.157 and 0.235 for AMG and CCEMG, respectively. More precisely, for AMG and CCEMG, a 1% rise in technological innovation reduces carbon dioxide emissions by 0.157% and 0.235%, respectively. Therefore, with the gradual innovation in environmental-related technologies, we can anticipate lower harmful emissions in APEC economies. These results are consistence with the existing finding (Ibrahiem, 2020; Khan et al., 2020; Obobisa et al., 2022a).

We also find a significant negative relationship between institutional quality and CO_2 emissions. This suggests that improving the quality of institutions decreases carbon dioxide emissions. More specifically, Table 6 shows that a 1% rise in institutional quality reduces Carbon dioxide emission by 0.139% and 0.082% for AMG and CCEMG, respectively. More precisely, the results reported in Table 6 show that a 1% increase in institutional quality causes reduced CO_2 emissions by 0.139% for AMG and 0.082% for CCEMG, respectively. This finding is a theoretically expected result for institutional quality prospects. It can be explained by the fact that better institutional quality is forecast to enhance environmental sustainability. Because greater political stability, higher government effectiveness, better control over corruption, and the role of law increase awareness and understanding of environmental concerns among countries' residents, thus encouraging more stringent environmental legislation (Danish and Ulucak, 2020). Environmental pollution is reduced due to increased public awareness and the proper implementation of environmental regulation laws (Danish and Ulucak, 2020). Better institutional quality not only promotes economic freedom and market economies but also represents the rule of law and respect for human life while also advancing environmental quality (Danish and Ulucak, 2020). Hence, more well-organized and strong institutions help promote innovation in environmental-related technologies, encourage the adaptation of renewable energy skills, and properly implant energy regulations. These empirical findings align with the previous studies (Bhattacharya et al., 2017; Salman et al., 2019a; Danish and Ulucak, 2020), all of which found institutional quality decreases CO_2 emissions. In contrast, its results contradict (Hassan et al., 2020a; Obobisa et al., 2022b).

TABLE 6 AMG test results.

Variables =	AMG coefficient	*p*-value	CCEMG coefficient	*p*-value
TI	−0.157**	0.060	−0.235***	0.000
IQ	−0.139***	0.000	−0.082***	0.019
TOP	0.370***	0.022	0.261***	0.001
ECO	0.045**	0.017	0.159**	0.061
GDP	0.918***	0.019	0.390***	0.041
Constant	−7.430***	0.248	−2.680***	0.388
Wald	49.23***		33.13	
RMSE (sigma)	0.066		0.032	

Note: The symbols *** and ** indicate the significance level at 1% and 5%, respectively.

TABLE 7 Robustness test.

Variables	FMOLS		DOLS	
	Coefficient	*p*-values	Coefficient	*p*-values
TI	−0.291***	0.063	−0.214***	0.001
IQ	−0.282***	0.096	−0.397***	0.085
TOP	0.123**	0.060	0.063**	0.037
ECO	0.147***	0.002	0.128***	0.005
GDP	0.419***	0.080	0.569***	0.103

Note: The symbols *** and ** indicate the significance level at 1% and 5%, respectively.

Moreover, trade openness has a significant positive impact on CO_2 emissions and this result confirmed the pollution haven hypothesis that trade openness leads to environmental degradation. More precisely, an increase of 1% in trade openness can significantly increase CO_2 emissions by 0.370% for AGM and 0.261% for CCEMG, respectively. This outcome aligns with earlier studies of Dauda et al. (2021), Dou et al. (2021), and Sarkodie and Strezov (2019).

Additionally, the energy consumption coefficient positively relates to CO_2 emissions, which validates the energy-led CO_2 assumption. This shows that a 1% rise in energy usage will probably enhance carbon emissions by 0.045% and 0.159% for AGM and CCEMG, respectively, in the long run. This outcome is consistent with the previous literature of (Lawson, 2020; Islam et al., 2021; Musah et al., 2021). Most APEC nations have maintained their rise through large-scale manufacturing and infrastructure projects and developing an economic instruments over the years. This enhances the use of energy consumption, which leads to CO_2 emissions.

Furthermore, economic growth is significantly positive and affects CO_2 emissions. More precisely, the results demonstrate that a 1% rise in GDP is linked to 0.918% and 0.390% CO_2 emissions. These findings demonstrate that rising economic activity in APEC nations will increase greenhouse gas pollution. Many recent studies support the outcome of this study (Teng et al., 2021; Obobisa et al., 2022c). APEC countries have witnessed rapid globalization and significant economic trends, such as industries and manufacturing activities that rely heavily on fossil fuel energy. Therefore, it will have a negative impact on the environment.

The results of the FMOLS and DOLS models are shown in Table 7 as robustness. These results align with the AMG and CCEMG estimation approaches in Table 5. FMOLS and DOLS coefficients are numerically distinct from those estimated by AMG and CCEMG. Overall, the FMOLS and DOLS outcomes further endorse the study variables' positive and negative impacts. Therefore, FMOLS and DOLS findings are more effective in robustness.

4.5 Results of panel causality

Finally, using the Dumitrescu and Hurlin (2012) D-H panel causality test, this research determines whether variables are bidirectional or unidirectional. This method is a superior form of the Granger non-causality test for panel data consisting of two statistics, i.e., Wbar and Zbar (Saud et al., 2019). The Wbar statistics describe the average test statistics, while the Zbar statistics show the standard normal distribution (Dumitrescu and Hurlin, 2012). Furthermore, the direction of causality assists policymakers in APEC nations in regulating appropriate economic and environmental policies. Table 8 summarises the results of the D-H panel causality test. We find that the unidirectional causality runs from trade openness, energy consumption to CO_2 emission and bidirectional causality relationships are between technological innovation, institutional quality, GDP, CO_2 emission. Overall, incorporating the D-H panel causality test results with long-term parameter estimation, we determine that increasing technological innovation and institutional quality can decrease environmental degradation in APEC countries.

TABLE 8 Dumitrescu-Hurlin panel causality tests.

Null hypothesis	W-stat.	Zbar-stat.	Prob.	Conclusion
TI does not homogeneously cause CO_2	7.415***	3.589	0.000	TI ↔ CO_2
CO_2 does not homogeneously cause TI	5.315**	2.070	0.000	
IQ does not homogeneously cause CO_2	6.142**	2.732	0.004	FI ↔ CO_2
CO_2 does not homogeneously cause IQ	17.982***	11.001	0.003	
TOP does not homogeneously cause CO_2	5.348***	2.028	0.036	RE → CO_2
CO_2 does not homogeneously cause TOP	9.729	5.443	2.001	
ECO does not homogeneously cause CO_2	3.839***	3.187	0.000	EG → CO_2
CO_2 does not homogeneously cause ECO	1.892	1.582	0.113	
GDP does not homogeneously cause CO_2	3.046***	5.201	0.000	GDP ↔CO_2
CO_2 does not homogeneously cause GDP	2.511***	2.654	0.006	

The symbol **** indicates the significance levels at 1%.

5 Conclusion and policy implications

This study examines the role of innovation in environmental-related technologies and institutional quality to drive environmental sustainability in APEC countries from 2004–2018. APEC nations are responsible for approximately 60% of global GDP and 48% of global trade. They have enhanced regulatory reform, improved corporate governance, transformed the public sector, and strengthened the legal infrastructure in recent years to keep economic growth and boost economic internationalization. Consequently, APEC countries account for six of the top ten polluted countries. However, APEC nations have recently reduced tariffs on environmental goods to encourage clean technologies and greener growth throughout the region. In this respect, the empirical findings from this research provide critical guidance and assistance for governments and lawmakers in implementing better environmental regulation strategies in the chosen region.

This research employs advanced econometric methods to investigate the connections among the variables. Pesaran's CD test is initially used to prove the presence of cross-sectional dependence in panel data. The variables' stationary characteristics are examined using second-generation panel unit root tests CIPS and CADF. Besides, the Westerlund and Edgerton (2007) cointegration test is used to resolve heterogeneity and examine long-run equilibrium. The AMG and CCEMG modeling techniques are employed as the main model, and FMOLS and DOLS are used to assess the model's robustness. Finally, the newly developed panel causality technique of Dumitrescu and Hurlin (2012) determines the causal direction between the variables examined.

The results show the following key finding. First, the cross-sectional dependence test reveals that APEC nations have significant interdependence because of the interaction of their institutional, economic, and technological relationships. Second, the AMG and CCEMG estimation approaches results to demonstrate that the CO_2 is responsive to innovation in environmental-related technologies and institutional quality changes with negative elasticities, trade openness, energy consumption, and GDP with positive elasticity. Additionally, a 1% rise in technological innovation and institutional quality reduces the CO_2 emission by 0.157%–0.235% and 0.082%–0.139%. In comparison, a 1% growth in trade openness, energy consumption, and GDP raises the CO_2 emission by 0.261%–0.370%, 0.045% to 0.159, and 0.390%–0.918%, respectively. Third, the D-H panel causality test findings show that unidirectional causality runs from trade openness and energy consumption to CO_2 emission. As compared to a bidirectional causality, relationships are between technological innovation, institutional quality, GDP, CO_2 emission.

According to the research findings of this study, the following policy implications are suggested for all countries. First, environmental-related technology innovation and institutional quality can reduce carbon dioxide emissions, a generally accepted indicator of sustainable development. Therefore, extensive investment in environmental technology innovations, enhancement in institutional environment quality, and prudent economic activity management can help reduce CO_2 emissions in APEC countries. Second, considering theoretical predictions and research findings on the significance of institutions, APEC countries' policy directions should concentrate on improving the institutional structure.

On the other hand, institutional reforms are essential for APEC countries to reduce carbon dioxide emissions and achieve climate targets. However, the growing influence of social media and communication technologies has also increased public awareness of environmental risks and the need for a clean and healthy environment. Finally, increased energy use and economic expansion also contribute to CO_2 in the atmosphere. To increase their commitment to sustainable economic growth and reduce their dependence on fossil fuels, APEC countries should take more concrete actions. This can be done by incorporating clean, low-carbon energy sources into APEC's long-term sustainable development efforts and providing monetary support for using renewable energy.

The limitation of this study is that only APEC countries are considered in this research. Therefore, some results may not be appropriate for other countries. Therefore, in the future, we will examine the moderating effects of green finance and financial globalization on environmental sustainability in a broader sample that includes developed and developing countries and other macroeconomic variables that will affect this relationship.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: The data relevant to this research is publicly available from the World Development Indicators and IMF.

Author contributions

MS conceptualized and designed the study and collected and analyzed the data. IH contributed to the critical review and editing of the manuscript. ÖI contributed to the formal analysis and drafted the manuscript. KR contributed to the study design and data analysis. IM contributed to collecting and analyzing the data.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Appendix

TABLE A1 Variable measurement and source of data.

Variable	Symbol	Measurement	Source
Carbon emissions	CO_2	Metric tons *per capita*	WDI
Technological innovation	TI	Patent applications (resident + non-resident)	WDI
Institutional Quality	IQ.	PCA WGI	WDI
Trade Openness	TOP	Trade (% of GDP)	WDI
Energy consumption	ECO	Energy consumption	IEA
Economic growth	GDP	GDP *per capita* (constant 2010$)	WDI