



Analyzing the impacts of renewable energy, patents, and trade on carbon emissions—evidence from the novel method of MMQR

Umra Waris¹ · Usman Mehmood² · Salman Tariq³

Received: 4 February 2023 / Accepted: 6 November 2023 / Published online: 16 November 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Achieving sustainable development necessitates proactive measures to mitigate the economy's negative impact on environmental standards. A new empirical association between renewable energy patent innovation and net international trade on carbon emissions in ASEAN countries from 1990 to 2021 is presented, along with its significance. Using present panel data techniques, this study investigates the connections between these factors. Second-generation cointegration and unit root tests, as well as a novel method of Moments Quantile Regression, are used in the econometric procedure. Compared to standard quantile regression, this method is more resistant to outliers and provides an asymmetric relationship between the variables. The findings show that trade increases carbon emissions in countries with medium to high emissions, that patent innovation contributes to increasing emissions, and that renewable energy mitigates carbon emissions in countries with low to medium emerging economies. Our results are consistent with other specifications, including quantile regression canay (Canay 2011), fully modified, dynamic, and fixed effect regressions, proving the EKC hypothesis. These countries need to prioritize greener products and adopt advanced manufacturing technologies to reduce carbon emissions from consumption. However, as prosperity increases, it also leads to higher consumption-based carbon emissions, worsening ecological damage in the region. Implementing policies like trade synchronization and increasing investment in patent innovations are proposed in this study to lower the current level of carbon emissions.

Keywords International net trade · Patent innovation · Consumption-based emissions of CO₂ · Consumption of renewable energy · EKC hypotheses · MMQR approach · ASEAN countries

Responsible Editor: Roula Inglesi-Lotz

✉ Umra Waris
umrawaris@gmail.com
Usman Mehmood
usmanmehmood.umt@gmail.com
Salman Tariq
salman.spssc@pu.edu.pk

- ¹ Department of Economics and Quantitative Methods, HSM, University of Management and Technology, Lahore, Pakistan
- ² Department of Political Science, University of Management and Technology, Lahore, Pakistan
- ³ Remote Sensing, GIS and Climatic Research Lab (National Centre of GIS and Space Applications), Department of Space Science, University of the Punjab, New-Campus, Lahore, Pakistan

Introduction

Human-caused climate change is wreaking havoc on the atmosphere and society worldwide (IPCC 2022). The burning of fossil fuels for energy has led to a continuous increase in CO₂ emissions over the past century. The Belt and Road Initiative (BRI) is an ambitious plan aimed at promoting regional development, restructuring economic activity, enhancing connectivity, and redistributing power among nations. It involves strengthening regional institutions, facilitating open trade, and developing physical and virtual infrastructure (Beeson 2018). The BRI connects the Asia-Pacific and Western European regions through a comprehensive network spanning Eurasia, linking over 65 countries. These areas contribute significantly to global GDP, trade, population, CO₂ emissions, land area, and energy consumption (Du and Zhang 2018; Fan et al. 2019).

Global industrialization and economic development have driven a sharp rise in energy consumption, resulting

in a major global challenge: climate change (Shahzad et al. 2021a; Hu et al. 2022). To address this issue, the international community, under the Paris Agreement, acknowledges the vulnerability of all countries and urges governments to take extraordinary measures through their nationally decided contributions (NDCs) to protect the environment (Baptista et al. 2022). At its 26th Conference of the Parties (COP 26), the international community committed to cutting emissions of CO₂ worldwide by half from their 2010 levels by 2020 (Smil 2022). The most recent data points to a few likely culprits for ecological decline and many mitigation options for lowering greenhouse gas emissions. For instance, non-renewable energy use, transportation, tourism, and FDI (Zhuang et al. 2023) are all acknowledged as significant contributors to environmental degradation, so are economic and financial growth, the exploitation of natural capital (Miao et al. 2022), and fast industrialization (Du et al. 2019).

Nevertheless, recent studies have identified some significant determinants as the countermeasures or remedies to oversee CO₂, including financial sector development, energy from renewable sources, technology for information and communication, green innovation (Ramzan et al. 2022), digital or international trade, and technological advancement (Alvarado et al. 2021). Several causes have been identified for the simultaneous economic business rise and energy consumption observed in recent years (Fareed et al. 2021). However, trade diversification is cited as a critical component in reducing GHG emissions (Jiang et al. 2022a). Similar to green innovation, investing money in research and development (R&D) activities to increase energy efficiency is seen as a viable way to reduce greenhouse gas emissions (GHGs) (Sun et al. 2022a) and enhance long-term global environmental quality. Moreover, renewable energy is a valuable, cost-effective alternative to address the world's energy needs (Sun et al. 2022b).

Achieving environmental sustainability is hindered by economic factors that harm the environment. Renewable energy and technology offer potential solutions, but their economic impact requires further investigation. This study focuses on analyzing the effects of net commerce, patent applications and residents, and renewable energy use on consumption-based CO₂ emissions in ASEAN countries from 1990 to 2021.

The ASEAN, comprising countries like Singapore, Malaysia, Vietnam, Thailand, Indonesia, and the Philippines, is poised to become a significant part of the global economy by 2030. The energy sector is a major contributor to global CO₂ equivalent emissions, representing 68% of the total. Notably, fossil fuels and coal account for 45% of these emissions (IEA 2021). ASEAN heavily relies on non-renewable energy sources, which poses a grave environmental risk due to emissions from fossil fuels. The region's energy demands are set to rise by 80% between 2013 and

2035. Notably, urbanization plays a significant role, potentially accounting for up to 70% of global carbon dioxide emissions resulting from energy use (Nathaniel and Khan 2020). Over 600 million people lived in ASEAN in 2012, and several member states are rapidly becoming urbanized (Wang et al. 2016).

GDP growth in the region has averaged 5.5% per year over the past three decades, according to a study by Ahmed et al. (2017). In ASEAN countries, overexploitation of fossil fuels has been linked to environmental degradation, which has in turn been linked to recent catastrophic disasters (Gyamfi et al. 2022; Rosenzweig et al. 2010). In the past, the region focused on economic development, and climate change concerns were primarily ignored (especially in Singapore). ASEAN is the world's third-highest emitter due to its lack of investment in energy technology and reliance on fossil fuels (Ahmed et al. 2017; Helm et al. 2012). In the twenty-first century, Asia's developing nations have borne the burden of economic growth, contributing \$2.6 trillion to global GDP and helping to propel the region's designation as the "Asian Century." As of now, ASEAN is a sizable economic bloc (FocusEconomics 2018); growth in this region is expected to continue (Das and Lin 2018; Nasir et al. 2019).

Economic expansion cannot occur without trade (Can et al. 2021). Trade, economic activity, technological advancements, and the size of businesses are all factors that affect energy use and emissions. Increases in international trade should lead to economic expansion, while energy use and emissions are influenced by these factors (Shahbaz et al. 2015). The energy demands of commerce and manufacturing are directly correlated with international trade, as well as the transportation of manufactured items. Industrialized nations can sell their developing counterpart's energy-saving production equipment, allowing for greater output with less input (technique effect) (Nasreen and Anwar 2014). Agriculture is the backbone of developing nations, and changes in product variety and energy levels are needed to transition to the industrial age (composition effect) (Shahbaz et al. 2015). These three routes affect CO₂ and energy emissions. At this point, the current research looks into whether or not ASEAN's net trade strategy positively impacts environmental quality.

International organizations prioritize social and environmental welfare over economic growth, with export-oriented economies mainly responsible for CO₂ emissions due to their use of non-renewable energy (Ali et al. 2022). Emissions of CO₂ are primarily caused by public and private use on a global scale (Li et al. 2021). Exports increase GDP and CO₂ emissions, but imports of energy-intensive products undermine efforts to reduce emissions (Jiang et al. 2022b). To establish a sustainable environment, the International Monetary Fund (IMF) and the World Bank have advised that energy product dealers construct net trade portfolios

(Jiang et al. 2022a). In addition, using energy from renewable sources and sophisticated technology in export goods production contributes to reducing the economy's emissions of CO₂ (Jiang et al. 2022b). Exchanging energy-intensive goods between nations, such as iron, cement, and refined petroleum, increases global energy demand and forces companies to rely on non-renewable power sources, increasing carbon emissions. This is a major contributor to global warming (Can et al. 2021).

The connection between economic development and its effect on the natural world has become increasingly important in recent years. Innovation promotes alternative energy to cut down on emissions of CO₂, but developments may lead to increased emissions. Systematic studies have been conducted to quantify the extent to which Kaya Identity contributes to emission reductions. To this end, many nations have signed environmental treaties like the Paris Agreement, the Kyoto Protocol, and the UNFCCC. Scientists, engineers, and academics have developed environmentally friendly technologies, come up with novel ideas, and filed patents on them (Li and Lin 2017; Liu and Guan 2016). Recent studies have found that different countries' historical settings and national contexts have different effects on sustainable development (Ibrahim and Vo 2021; Latif et al. 2022; Tze San et al. 2022; Yu et al. 2022b; Zhao et al. 2021). The rate at which patents are sought is an indicator of technical progress. Investigating whether or not ASEAN's patent strategy improves environmental quality is a primary goal of this study.

To lessen pollution and better the environment, scientists have studied what makes a difference in emissions. Many studies have found that expanding economies are among the leading causes of international trade (Muhammad et al. 2020; Ren et al. 2014); usage of energy from renewable sources (Mahmood et al. 2019; Shahbaz et al. 2013); pollution (Cai et al. 2018; Dong et al. 2018; Mardani et al. 2019; Saboori et al. 2012); urban growth (Fang et al. 2020; Lin et al. 2017); and population (Begum et al. 2015; Zhang et al. 2018).

This study fills several gaps in the literature by analyzing the effects of the ASEAN trade mix on the environment. It also highlights the importance of diversifying imports to environmental sustainability. Therefore, the overall net trade impact was determined by using net trade (goods and services). Furthermore, the study overestimated the emissions of ASEAN exporting economies since it used emissions based on ultimate demand for goods and services rather than on production. Overall, this research aims to evaluate the impact of net trade, patent applications, energy from renewable sources, and GDP in selecting ASEAN economies on consumption-based emissions of CO₂ reductions. Multiple-moment quantile regression (MMQR) is a recently developed estimate that connects predictor variables to quantiles of the criterion variable and is robust against

outliers, normalcy, heterogeneity, and endogeneity Machado and Silva (2019). Third, this study intends to employ the MMQR technique developed by (Machado and Silva 2019) to evaluate the significance of the EKC, which postulates a U-shaped relationship between economic growth and environmental factors. For MMQR robustness, two-step quantile regression of Canay (2011), FE-OLS, FMOLS, and DOLS are used. These findings provide a unified national strategy for environmental sustainability. These results backed the importance of a country's net trade, patent applications, energy from renewable sources, and GDP in achieving environmental sustainability.

The study sections present empirical findings that support the hypothesized relationship between variables, discuss econometrics' structure and data resources, and discuss the results of the study. Recommendations are made based on the findings discussed.

Literature review

Today, more than ever, it is essential to take measures to preserve our planet, and a wealth of studies has identified the root causes of environmental deterioration. In spite of the fact that trade specialization is a significant contributor to greenhouse gas emissions, more research needs to focus on the potential role of global net trade as a remedy. This study examines the relationships between global net trade, innovation, and the adoption of energy from renewable sources in ASEAN countries, all of which may serve as early warning indicators of environmental degradation. The economies of the ASEAN countries are among the world's fastest-growing; therefore, they are expected to contribute significantly to the global economy. There are four parts to assessing initial investigations, each looking at past attempts to assess variable connections.

Net trade nexus with consumption-based carbon emissions

Increased economic growth can be achieved in large part through international trade. However, economies based on specialized trade tend to cause environmental harm (Li et al. 2021). Most research has focused on how trade openness, import, and export impact trade volume (Fareed et al. 2021; Jiang et al. 2022a; Sharma et al. 2022). Although few studies have looked at trade composition as a proxy for pollution mitigation in international business, it is increasingly understood that global trade plays a vital role in reducing pollution. There have been conflicting results from studies examining how export diversification affects greenhouse gas emissions. The evidence suggests that increasing opportunities for export is a powerful tool for reducing environmental

impact. From 1990 to 2017, Shahzad et al. (2021b) assessed the climatic impacts of G-7 and E-7 nations' export diversification and energy resource usage. The estimates of the FGLS and FMOLS tests investigated how both economies' export diversification policies considerably increased interest in energy from renewable sources and decreased environmental destruction. According to an MMQR study by Rehman et al. (2021), export diversification in the fastest-growing Asian countries leads to decreased GHG emissions. The results for the BRICS and the top complex economies were similar in two studies by Sharma et al. (2021) and Wang et al. (2021). Researchers looked at how export variety impacted capacity utilization.

A Fourier quantile causality test indicates that the growth of Indonesia's export base from 1965 to 2014 led to both a higher load capacity factor and improved environmental quality. In Indonesia, a Fourier quantile causality test between 1965 and 2014 found that increased export variety increased the load capacity factor and improved environmental quality. Similar research by Ali et al. (2022) using the STIRPAT model finds a negative correlation between export diversification and India's ecological footprint between 1965 and 2017. This negative link is warranted since services exports account for a sizable portion of the Indian export basket (Li et al. 2021). It was found that extending China's export options helped the country's efforts to become carbon neutral. The effect of diversified imports and exports on the carbon footprints of 17 APEC countries is analyzed by Jiang et al. (2022b). Products with a high energy footprint are those that are imported. The fact that exports and ecological footprints are negatively correlated suggests that energy from renewable sources is being used in place of fossil fuels in the diverse manufacturing in these countries. Synchronization of trade is recommended.

On the contrary, a few studies have highlighted trade's negative impact and claimed that expanding exports increases emissions of CO₂. It has been argued that export diversification positively affected carbon emissions in 37 OECD countries between 1970 and 2019 (Iqbal et al. 2021). That these nations are shipping the same goods to more destinations is evidence that they are attempting to diversify their export markets. Because of this, emissions of CO₂ are rising (Can et al. 2021). Use panel data from newly industrialized countries to underline trade's composition influence. In newly industrialized countries, export diversification increases emissions of CO₂. Results show that industrialization concentrates exports.

Indonesia, Vietnam, and Malaysia export industries require large amounts of energy for farming and manufacturing (Nathaniel and Khan 2020). According to Rajão et al. (2020), deforestation in Brazil and Argentina is facilitated by EU-MERCOSUR trade. High resource use is linked to MERCOSUR nations' trade with the EU in the meat

industry, and these countries are also significant contributors to environmental challenges (Heyl et al. 2021). This study tests the following null hypothesis based on the conflicting evidence linking international trade and emissions of CO₂:

H_0 : Environmental degradation is accelerated by international trade.

Patent innovation nexus with emissions of CO₂

An increase in overall energy consumption and consequently in emissions of CO₂ can result from innovation, a significant driver of economic growth. This is one-way research results into the innovation-pollution nexus vary across nations and periods. With the help of panel data spanning 1990–2016, Dauda et al. (2021) verified EKC's hypothesis that many African countries displayed an inverse correlation between innovation and emissions of CO₂. Dauda et al. (2021) used panel data from a number of selected African countries from 1990 to 2016 to study the relationship between innovation and emissions of CO₂. From 1992 to 2014, Töbelmann and Wendler (2020) analyzed the impact of environmental innovation on CO₂ emissions across the EU-27. Using the generalized method of moments (GMM) in a dynamic panel, they find that the impact of innovation varies from country to country, with more variability seen in less developed nations.

In addition, they discovered that environmental innovation affects lowering carbon dioxide emissions, but that innovative activity as a whole still needs to improve. Using panel data from 1996 to 2012, Du et al. (2019) find that economies with income below the limit benefit relatively little from green technology's ability to reduce emissions of CO₂, while economies with income above the limit benefit significantly more (Razzaq et al. 2021a). Researchers in the European Union (EU), United States (US), and China (China) analyzed the effect of innovation on carbon dioxide (CO₂) emissions from 1990 to 2013. Researchers have found that spending money on R&D helps developed nations reduce their CO₂ output, but less developed nations see different results (Fernández Fernández et al. 2018). A variety of factors in each country should affect the environment differently. For 15 significant economies between 1992 and 2012, Yan et al. (2017) looked into the benefits of low-carbon technologies. "Clean" technologies decrease emissions, in contrast to "grey" ones that increase them. Additional analysis reveals that not all innovations have the same effect on CO₂ output. The research of Hu et al. (2022) and Tao et al. (2021) demonstrates that not all innovations have the same effect on greenhouse gas emissions. As a result, many scientists have investigated whether technological progress is influencing global warming. Research by Razzaq et al. (2021b) found that the impact of green technology innovation on polluted

environments in countries with high per capita incomes is small. Singapore's rapid expansion has high ecological costs, and green innovation technology sustained economic growth with the lowest costs, as Meirun et al. (2021) noted. Lin and Ma (2022) point out that investing heavily in green technology innovation and undertaking complex industrial restructuring is necessary. According to Lingyan et al. (2022), green technology does little to prevent significant carbon dioxide emissions. According to Razzaq et al. (2021b), this is true for the BRICS countries. Two studies by Qin et al. (2021) and Xu et al. (2021) confirmed the growing effect of green innovation in China and the G7 countries on emission reductions; because of the mixed results, the authors of this study proposed a null hypothesis regarding the impact of the patent invention on emissions of CO₂.

H_1 : Patent inventions deflate the quality of the environment.

Energy from renewable sources nexus with emissions of CO₂

The worldwide level of greenhouse gas emissions continues to rise despite the many steps made to control environmental damage. In recent years, scientists have been trying to find ways to lessen environmental damage without stifling economic development. Evidence from the current literature overwhelmingly suggests that moving to energy from renewable sources is the most effective way to boost environmental quality. However, the strength of this evidence varies greatly depending on factors like the sample countries, the selected period, and the choice of practical technique (Jiang et al. 2022b). Jiang et al. (2022b) emphasized the significance of using energy from renewable sources to help members of the Asian Pacific Economic Cooperation (APEC) lessen their environmental impact. Using energy from renewable sources results in a larger ecological footprint when multiple countries' goods are imported using FMOLS and DOLS. The impact on the environment can be reduced if the range of exports is broadened. Ansari et al. (2021) and Dogan et al. (2020) cite OECD countries as examples of consumption of highly renewable energy, suggesting that doing so improves energy efficiency and ecological sustainability.

To achieve the sustainable development goals of the G-7 and E-7 economies, Shahzad et al. (2021a) used the FGLS and FMOLS methods to assess the effect of energy from renewable sources on product diversification from 1990 to 2017. These findings prove that these nations' plans to diversify their exports will lead to a greater demand for energy from renewable sources and a consequent reduction in environmental impacts (Ramzan et al. 2022). Since the industrial sector is responsible for a disproportionate amount of pollution, it is concluded that increasing the use of energy from

renewable sources in the industrial sector is the best hope for achieving environmental sustainability in developing economies. With pollution as a primary concern, Sun et al. (2022b) look into how the adoption of energy from renewable sources has impacted pollution levels in the world's ten most polluting countries. Researchers found that energy from renewable sources was beneficial in both low- and high-pollution settings. Miao et al. (2022) also looked at the impact of renewable energy on developing countries' carbon footprint from 1990 to 2018. Their findings, in contrast to the previous research, advocate for energy from renewable sources regardless of pollution levels.

On the other hand, Fareed et al. (2021) examine the effect of regulating renewable energy sources on emissions of CO₂ in the context of severe pollution in Indonesia. Numerous studies have recognized the short-term role of energy from renewable source consumption for emissions of CO₂, including Sun et al. (2022b) for the BRICS, Sun et al. (2022c) for the MENA, Rehman et al. (2021) for the Asian nations, and Iqbal et al. (2021) for OECD countries. The study's null hypothesis is constructed from such pieces of evidence.

H_1 : Energy from renewable sources accelerates consumption-based emissions of CO₂.

Economic development nexus with environmental quality

In the context of both economic growth and climatic change, the EKC hypothesis has been the subject of extensive research. Balsalobre-Lorente et al. (2021a) used the environmental Kuznets curve (EKC) to investigate how changes in energy technology impact the vacation choices of residents of the EU-5. Both the EKC and the pollution haven hypotheses anticipate the existence of a region with the shape of an inverted U (since higher FDI inflows increase emissions of CO₂). Scientists believe that using energy from renewable sources and technological advancements in the energy sector can help reduce emissions of CO₂ from aviation. From 1995 to 2015, Balsalobre-Lorente et al. (2021b) examined the efficacy of the low carbon development hypothesis and the EKC framework in those countries of Spain, Italy, Greece, and Portugal. The econometric tests validated EKC's arguments. There was a correlation between urbanization and the extinction of species.

When it comes to emissions of CO₂, GDP growth, corruption, renewable energy, international trade, and GDP growth, Leitão (2021a) compares Portugal, Spain, Italy, Ireland, and Greece. According to the findings, increased emissions of CO₂ are the result of corrupt practices and rising prosperity. Assuming the international community embraces energy from renewable sources and increases its

level of international trade, the environment may be saved. Leitão (2021b) looked at changes in Portugal's GDP per capita, consumption of energy, and carbon dioxide emissions between 1970 and 2016. His revelations suggested that heightened commercial activity was the driving force behind environmental progress. Consumption of energy, emissions of carbon dioxide, economic growth, and globalization in South Asian countries were studied by Anser et al. (2021) using the EKC paradigm from 1985 to 2019. It was discovered that rising energy consumption is proportional to GDP expansion. Balsalobre-Lorente et al. (2022) analyzed various macroeconomic variables, including FDI, GDP growth, industrialization, energy consumption, and emissions of CO₂, for the BRICS countries between 1990 and 2014. Because of this discrepancy, the EKC and pollution refuge hypotheses are supported by the fact that emissions of CO₂ decrease with urbanization but increase with energy use. Carbon Emissions, Urbanization, Foreign Direct Investment, Economic Structure and Energy from Renewable Sources: a dynamic relation analysis from 1990 to 2019 broadened the dialogue about environmental performance in the PIIGS countries. These results lend credence to the Kuznets curve and the pollution haven hypothesis. The effect of economic complexity on emissions of CO₂ was studied by Doğan et al. (2022). After the introduction of a fee to offset environmental damage, emissions of CO₂, energy use, and resource stress were all found to decrease. The Group of Seven has also approved the concept of the EKC. Jahanger et al. (2022) analyzed the ecological footprints of developing countries from 1990 to 2016 by factoring in macroeconomic variables. Many African, Latin American, and Caribbean countries support the EKC theory, but many Asian countries do not. These scraps of evidence support the study's null hypothesis.

H_2 : The EKC relation exists in the ASEAN countries

Methodology

Data information

This research aims to use renewable energy consumption, international trade, and patent innovation as proxies for emissions of CO₂ due to human consumption. Additionally, GDP was used because the study followed the EKC hypothesis. With resemblance and the existence of transactional spillover among the areas of research, this theory is able to recognize the developmental influence of policy instruments (Aziz et al. 2020; Chien et al. 2021; Suki et al. 2020). The sample of this study includes six ASEAN countries chosen based on data availability: Malaysia, Singapore, Thailand, Indonesia, Vietnam, and the Philippines. These nations' panel data were collected from 1990 to 2021 to incorporate the variable's relationships. The data and its origin are fully explained in Table 1.

Theoretical framework

The preceding section provides the theoretical underpinning of the estimators and the projected ASEAN bloc findings. The preceding section provides the theoretical underpinning of the estimators and the expected contribution of the specific ASEAN bloc to highly significant CO₂ (Jiang et al. 2022b). Most of the studies in “Net trade nexus with consumption-based carbon emissions” acknowledge that international trade is a good strategy for reducing GHG emissions. To figure out how net trade affects emissions of CO₂, it is essential to look at the quality of the goods that are traded (Zhang et al. 2022). Global trade minimizes trade risk and enhances environmental quality by using environmentally products and industrial technology (Rehman et al. 2021; Shahzad et al. 2021b; Wang et al. 2020). If the trading portfolio includes energy-intensive items, emissions of CO₂ may rise (Can et al. 2021; Iqbal et al. 2021; Khan et al. 2021). Consequently, this relationship's estimated coefficient might be either positive

Table 1 Summary of target variables

Abbreviation	Target variables	Instruments measurements	Positioning	Source
CO ₂	Consumption-based emissions of CO ₂	Emissions of CO ₂ from energy	Endogenous variable	BP
T	International net trade	Net trade in goods and services (BoP, current US\$)	Focus variable	WDI
PT	Patent innovation	Patent applications, residents	Focus variable	WDI
RE	Energy from renewable sources Consumption	Energy from renewable sources consumption (% of total final energy consumption)	Focus variable	WDI
GDP	Economic growth	GDP per capita (constant 2015 US\$)	Control variable	WDI
SQGDP	EKC hypothesis	Quadratic term of GDP	Control variable	Derived

British petroleum or Global Atlas (BP) and World development indicators (WDI)

$\beta_2 = \frac{d(CO_2)}{dT} > 0$ or harmful $\beta_2 = \frac{d(CO_2)}{dT} < 0$. Patent innovation promotes eco-friendliness by investing in R&D, which increases manufacturing capacity and energy consumption (Hu et al. 2022; Tao et al. 2021). Additionally, patent development boosts the economy at a lower environmental cost than technological improvement (J. Chen et al. 2022; Shao et al. 2021). However, according to specific research, patent invention considerably reduces emissions of CO₂ only for developed countries (Du et al. 2019). Similarly, in nations with high levels of human capital (Lin and Ma 2022) and pollutants (Sun et al. 2022a; Sun et al. 2022b), patent innovation is a more effective cure. Thus, the estimated coefficient of this association might be either negative $\beta_3 = \frac{d(CO_2)}{d(PT)} < 0$ and positive $\beta_3 = \frac{d(CO_2)}{d(PT)} > 0$ or both. With the details discussed in “Energy from renewable sources nexus with emissions of CO₂”, renewable energy consumption is projected to be negative $\beta_4 = \frac{d(CO_2)}{d(RE)} < 0$, which takes energy from renewable sources as an alternative to fossil fuel use to reduce emissions of CO₂. However, regarding consumption-based carbon emissions, economic growth and EKC are expected to have positive $\beta_5 = \frac{d(CO_2)}{d(GDP)} > 0$ and negative $\beta_5 = \frac{d(CO_2)}{d(GDP)} < 0$ coefficient values. Therefore, the study of this relationship is required from the standpoint of ASEAN states’ SDG-oriented legislation; thus, this association must be depicted mathematically. As a result, the regression equation is created:

$$CO_{2it} = \beta_i + \beta_{1it}T_{it} + \beta_{2it}PT_{it} + \beta_{3it}RE_{it} + \beta_{4it}GDP_{it} + \beta_{5it}SQGDP_{it} + \mu_{it} \quad (1)$$

where the “*i*” is the ASEAN cross-section (CRS), and “*t*” indicates the time component from 1990 to 2021. Moreover, β_{it} represents the country-specific fixed impact, and μ_{it} is the error correction term in the model.

Cross-sectional dependence and unit root tests

Unknown factors may distort accurate parameters and lower the usefulness of panel data, resulting in cross-sectional dependence (CD). For example, Phillips and Sul (2003). Pesaran (2004)’s creation of the CD test. Fictitious results may be produced by avoiding CD in panel data. To begin the empirical part of the study, we will first apply the CD test developed by Pesaran (2015) to all cross-sectional units to infer the presence of CD. To do so, this study employs Pesaran’s (Pesaran 2007) cross-section augmented Dickey-Fuller (CADF) and cross-section Im, Pesaran, and Shin (CIPS) tests. Asymptotic properties of the concept allow for reliable panel unit root tests to be performed without

needing (*N*). The CADF and CIPS checks produce reliable information on the integration sequence of a series.

Technique for panel cointegration

The error correction-based (ECM) cointegration test was created by Westerlund (2007) and takes into account the CSD and slope heterogeneity issues. It does not heavily rely on prior knowledge regarding the integration orders of the series that tolerate different solidity ranks of the regressors. The long-run cointegration tests can be repeated numerous times using this method, which tends to be a discretionary bootstrap procedure. Two mean-group tests (Gt and Ga) and two-panel tests (Pt and Pa) form the foundation of this method.

Heterogenous panel estimators

The present research drew on five different methodologies well-established for panel studies. In the face of heterogeneity, quantile regression Canay (2011), FMOLS, FE-OLS, and DOLS emerge as the most reliable and consistent methods for producing results. When all methods yield the same findings, the goal of using multiple approaches has been achieved, guaranteeing internal reliability. In the presence of auto-correlation with a fixed lag and a fixed CD test threshold, the FE-OLS method still produces reliable results (Le et al. 2020; Pedroni 2004). It is based on Driscoll and Kraay (1998) standard errors. The average and the cointegration equilibrium are different across cross-sections in panel data. Therefore, Pedroni (2004) developed FM-OLS, which keeps a “heterogeneous serial correlation of the error processes” across the whole panel dataset (including an intercept for each cross-section). For panel calculations, DOLS is preferable to FE-OLS and FMOLS, which employ Monte Carlo simulations in small samples, as proposed by Kao and Chiang (2001). Increasing lead-lagged differentials is one way in which D-OLS handles endogeneity effectively.

Consistency and asymptotic normality of the parameter estimates are two desirable qualities of Canay (2011) two-step quantile regression approach. It enables a more robust estimate in the case of endogeneity or sample selection bias. This method addresses the issue of endogeneity and offers the capability to account for unobserved individual variations across different countries, as outlined by Ali 2023 and Li et al. (2021) in their study. The process involves two main steps. In the initial step, a fixed-effects model is employed to estimate the individual fixed effects (α_i). Subsequently, a new dependent variable, free of individual fixed effects, is derived using the equation ($\hat{y}_{it} = y_{it} - \hat{\alpha}_i$). In the second step, this new variable, \hat{y}_{it} , serves as the dependent variable in a standard quantile regression equation, following

the approach described by Yan et al. (2020). Therefore, our econometric specification is as follows:

$$Q_T(\text{CO}_{2it}) = \beta_i + \beta_{1it}T_{it} + \beta_{2it}PT_{it} + \beta_{3it}RE_{it} + \beta_{4it}GDP_{it} + \beta_{5it}SQGDP_{it} + \mu_{it} \quad (2)$$

The regression parameters of the T distribution point are denoted as Q_T , fixed individual effects are represented as β_i , and countries and years are denoted as i and t , respectively. (β_{it}), where $i = 1$ to 6 denotes the elasticities that require estimation.

As previously noted, to implement the quantile regression method proposed by Canay (2011), we begin by conducting the fixed effects regression for the fundamental Eq. 1 in order to derive a new dependent variable as follows:

$$(\widehat{CO}_{2it}) = (CO_{2it}) - \hat{\beta}_i \quad (3)$$

Equation (\widehat{CO}_{2it}) is now devoid of unobserved individual effects ($\hat{\beta}_i$), allowing us to proceed to the second phase. Following the elimination of the fixed effects from Eq. (2), the standard quantile regression can be executed as follows:

$$\min_q \sum_{k=1}^K \sum_{t=1}^T \sum_{i=1}^N w_k \rho_{Tk}(\text{CO}_{2it} - (\beta_{1it}T_{it} + \beta_{2it}PT_{it} + \beta_{3it}RE_{it} + \beta_{4it}GDP_{it} + \beta_{5it}SQGDP_{it})) \quad (4)$$

The estimators verify MMQR's results and shield them from the unit root and endogeneity distortions in parameter estimation.

Methods of moments quantile regression

The aforementioned techniques all estimate linear relationships between variables by averaging the variables, ignoring the conditional distribution of the variables (Sarkodie and Strezov 2019). Koenker and Hallock (2001) introduced a method that evaluates the influence of the averages of the relevant response variable on the coefficients of the quantile asymmetries of the criterion variable. If your data is affected by possible outliers, this method will hold up better than most (An et al. 2021). It may provide robust findings even when conditional means have no or minimal influence (Binder and Coad 2011). Inaccurate distribution of the criterion variable arises because quantile regression calculations cannot avoid crossing sections for different percentile levels.

In addition, a novel estimation strategy called "Method of Moments Quantile Regression" (MMQR) was used in this study; it was introduced by Machado and Silva (2019) and uses a fixed effects approach. Despite being the least sensitive to outliers, quantile regression fails to pick up on the heterogeneity that quietly persists across all of the cross-sections in a set of panel data. Unlike traditional quantile regressions, the MMQR allows "conditional heterogeneous

covariance effects" to influence and accomplish the goals via dependent variable extracts across the entire data distribution by Koenker (2004) and Canay (2011), assessed by shifting the mean values around. When parameters are endogenous and specific individual effects classify the dataset, MMQR has more credibility. When dealing with a non-linear model, this method is robust as well. In ecological research, data from many sources, such as satellite images, climate prediction models, and historical records, are commonly employed. However, there may be limitations in data availability or data quality that might affect the accuracy and dependability of both qualitative and quantitative data used in MMQR studies.

The MMQR is preferable to other non-linear estimating methods because it can incorporate a non-linear model. This is in contrast to methods like "Non-linear Autoregressive Distributed Lag (NARDL)," which explains non-linear features exogenously by not selecting benchmark values from the data as it remains fixed to zero (Shin et al. 2014). Since the criteria variable parameters are adaptive to the distribution's conditions, this method provides asymmetry based on location. Developing asymmetrical connections, or non-linear relationships, that allow MMQR to overcome endogeneity and heterogeneity problems makes the model more realistic and stable (An et al. 2021). In contrast, it provides non-crossing, intuitive structural quantiles. The quantile evaluations that depend on a scale for a specific location, $Q_T(T|X)$, are described as:

$$h8Y_{it} = \alpha_i + X'_{it}\beta + (\delta_i + Z'_{it}\gamma)U_{it} \quad (5)$$

From Eq. (5), the probability $P\{\delta_i + Z'_{it}\gamma > 0\} = 1$. ($\alpha, \beta, \delta, \gamma$) are estimated based on the parameters (α_i, δ_i), $i = 1, \dots, n$, which represents the individuals I fixed effects, Z presents k -vectors of fractions of X obtained using transformations differentiable with section 1 as shown:

$$Z_l = Z_l(X), l = 1, \dots, k \quad (6)$$

Moreover, X_{it} is allocated independently distributed for any specific individual (i) for a specific period (t), U_{it} is parallel to X_{it} , and its moments and associated criteria, as explained by Machado and Santos Silva, are estimated to ensure their fulfillment (Machado and Silva 2019). Hence, modify Eq. (5) after deriving as:

$$Q_T(T|X_{it}) = (\alpha_i + \delta_i q(T)) + X'_{it}\beta + Z'_{it}\gamma q \quad (7)$$

From Eq. (7), X'_{it} shows the regressors variables' vector, in which T, PT, RE, GDP , and $SQGDP$ are included, whereas CO_2 is the endogenous parameter, and its respective distribution Y'_{it} is obtainable by $Q_T(T|X_{it})$, which is the framework of the quantiles, which is exposed to independent locational distribution X_{it} for a specific individual (i)

over a while (t). Furthermore, (T) denotes the quantile fixed effects, which are represented by a scalar estimated coefficient that is derived as $(\alpha_i(T) = \alpha_i + \delta_i q(T))$

Remember that when OLS is used, and a result is obtained from fixed effects, adjusting the intercept does not reflect the individual’s influence. There is a time bound on the parameters, and it is understood that heterogeneity effects will vary across structures’ quantiles at a distribution determined by the criterion variable ($C02$). However, $q(T)$ is the functional form of sample quantile (T -th); it is derived by optimizing as shown below:

$$\min_q \sum_i \sum_t \rho_T(R_{it} - (\delta_i + Z'_{it}\gamma)q) \tag{8}$$

According to Eq. (8), the checking function is described as

$$\rho_T(A) = (T - 1)AI\{A \leq 0\} + TAI\{A > 0\}. \tag{9}$$

Empirical results and discussion

Summary of statistical characteristics

Table 2 shows the descriptive statistics, which indicate that all components are not normally distributed according to the Jarque-Bera test. The table below also displays the means and standard deviations for each factor.

Assessment of interdependence

In order to avoid completely erroneous findings, the cross-sectional dependence (CD) problem must be fixed, as it has the potential to generate fictitious results (Tao et al. 2021). To check if CD is present in all cross-sectional units to the same degree at the beginning of the empirical part of the study, we employ the CD test of Pesaran (2015). Table 3

Table 2 Summary of statistical characteristics

Vari-ables	Mean	Std. Dev.	Maximum	Minimum	Jarque-Bera
CO_{2t}	167.26	118.97	613.15	17.53	132.70*
T_t	1.27 e ¹⁰	2.67 e ¹⁰	1.25 e ¹¹	- 3.96 e ¹⁰	180.86*
PT_t	598.06	551.15	3093	22	74.71*
RE_t	21.07	21.39	76.08	0.19	17.29*
GDP_t	16,597.79	19,961.17	66,176.39	662.79	37.42*
$SQG-DP_t$	6.72 e ⁰⁸	1.12 e ⁰⁹	4.38 e ⁰⁹	439,290.2	109.75*

p -values are enclosed in parentheses

*Significance level at 1%, respectively.

shows that there is no CD in the consumption of energy from renewable sources, and all other variables (CO_2 , temperature, precipitation, GDP, and the EKC term) reject the null hypothesis of “no cross-sectional dependence” at the 1% significance level, indicating the presence of CD among the chosen ASEAN countries.

Another major issue in interdependent panel data is SLP-HTG, which is studied using a test developed by Pesaran and Yamagata (2008). Table 4 displays statistically significant evidence for the SLP-HTG in the ASEAN criminal data, as the null hypothesis “the slope coefficients are homogenous” was rejected at the 1% level. The result is a significant variance in each independent variable’s slope weight (SLP-HTG).

The prevalence of these issues implies that second-generation unit root tests are applied since the first-generation unit root tests are insufficient (Meng et al. 2022; Rehman et al. 2021).

Assessment of unit root

The CIP and CADS results of the empirical tests of a unit root to solve this problem and generate reliable coefficient estimates are shown in Table 5. The results show that all variables are stationary at the mixed level, I(0) or I(1). The findings demonstrate that at the first differences, CO_2 , T , PT , and RE reject the null hypothesis of “unit root existence,” although GDP and its quadratic term are stationary at their level. These inconsistent results urge the study to use the cointegration tests (Banerjee and Carrion-i-Silvestre 2017; Westerlund and Edgerton 2008).

Table 3 Tends of cross-sectional dependence analysis

Variables	Pesaran-CD Test	P -value	Corr
CO_{2t}	20.53	0.000	0.937
T_t	0.79	0.000	0.036
PT_t	15.44	0.000	0.705
RE_t	1.21	0.228	0.055
GDP_t	21.52	0.000	0.982
$SQGD P_t$	21.48	0.000	0.981

Table 4 Testing for slope heterogeneity

		Pesaran and Yamagata (2008)	
		Delta	p value
		13.049	0.000
adj		14.763	0.000

Table 5 Trends of unit root test

Variables	CIPS		CADS	
	I(0)	I(1)	I(0)	I(1)
CO_{2t}	-0.991	-3.595a	-1.422	-3.060a
T_t	-1.557	-4.134a	-1.744	-3.421a
PT_t	-2.148	-5.519a	-1.454	-3.482a
RE_t	-1.844	-4.962a	-1.877	-3.921a
GDP_t	-2.772a	-	-2.423a	-
$SQGDP_t$	-3.094a	-	-2.384a	-

P-values are enclosed in parentheses. a, b, c explain the significance level at 1%, 5%, and 10%, respectively

Assessment of cointegration

Table 6 results clarify that there is significant evidence against the null hypothesis of “no cointegration,” which is supported by the cointegration test. It indicates that variables are long-term cointegrated. After the verification of the long-run relationship, proceed to long-run elasticities estimations.

Furthermore, it is critical to emphasize that our model has a CD problem. To remove potential size distortions in the presence of CD, the panel estimation approach must integrate approaches that are robust to the effects of CD. In order to comply, the study applies a series of heterogeneous panel estimate approaches (Canay (2011), FM-OLS, FE-OLS, D-OLS, MMQR) that deal with these challenges efficiently.

Panel estimations

The outcomes of the estimator’s quantile regression Canay (2011), FMOLS, FEOLS, and DOLS are shown in Tables 7 and 8. Almost identical trends, statistical significance, and average coefficient sizes can be seen across all estimators. This demonstrates that the results from the aforementioned four models are reliable. When assessing nations with differing degrees of trade openness, the coefficients associated with net international trade display a notable escalation in consumption-based CO₂ emissions, demonstrating statistical significance at the 1% level within the DOLS and Canay (2011) quantile model. However, it is noteworthy that this linkage loses significance in the final two quantiles, namely,

Table 6 Panel cointegration (Westerlund 2007)

Statistics	Value	Z-value	p value	Robust p value
Gt	-2.368	0.716	0.063	0.030
Ga	-6.953	2.384	0.991	0.090
Pt	-5.291	0.483	0.685	0.370
Pa	-5.519	1.704	0.056	0.070

Table 7 Robustness check

Variables	FM-OLS	FE-OLS	D-OLS
T_t	$2.41e^{-10}$	$-2.79e^{-11}$	$1.26e^{-09a}$
PT_t	.067a	0.013a	0.036b
RE_t	-4.101a	-4.531a	-3.508a
GDP_t	0.016a	0.004a	0.009b
$SQGDP_t$	$-1.70e^{-07a}$	$-3.09e^{-08a}$	$-1.04e^{-07a}$

a and b → explain the significance level at 1% and 5%, respectively

the 80th and 90th, indicating a less influential role of trade openness in those specific quantiles. The findings indicate that the alternative hypothesis is accepted; a growing influence on CO₂ emissions can be attributed to the vast and intense margins of the overall products. It was primarily in the 1980s that trade liberalization boosted emerging nations’ economies by allowing their companies to sell their wares on a global scale. However, emerging nations need to increase their energy consumption to diversify their exports. Increasing exports necessitates transporting more goods, which consumes more resources and depletes more ecosystems (Muhammad et al. 2020). The results, which are consistent with the FEOLS models, show that a 1% increase in trade would lead to a 2% decrease in emissions of CO₂. It proves that during the studied period, net trade agreements aided in lowering emissions. In a recent cross-country analysis, EFTA, ASEAN, and MERCOSUR favored reducing emissions of CO₂, while NAFTA’s impact was less clear and may have even slightly increased emission growth (Abler and Pick 1993; Balogh and Mizik 2021). Also, EFTA nations significantly influenced shrinkage, followed by MERCOSUR and ASEAN members (Balogh 2022).

In Table 7, the rejection of the null hypotheses by patent innovation reveals that there is a correlation between the number of patents filed by domestic inventors and the amount of carbon dioxide released into the atmosphere. The analysis reveals a rise in CO₂ emissions by 0.067%, 0.013%, and 0.036% in the FMOLS, FEOLS, and DOLS models. Furthermore, across all quantiles except the first, an increase of one percentage point in innovation is correlated with heightened CO₂ emissions. These results affirm that advancing levels of innovation are linked to an increase in environmental harm. Research by Chen and Lee (2020) found that technological progress has no bearing on the state of the planet’s ecosystems. Innovation may increase resource productivity, its diminishing marginal value, and the prospect of increased resource consumption due to expanding economies of scale threatens to undermine environmental sustainability (Newell 2009; Yu et al. 2022a). Developing countries have a more significant influence on emissions of CO₂ from innovation than developed countries. The findings show that in ASEAN nations with low levels of financial

Table 8 Canay (2011) Robustness check

Variables	Canay (2011) Quantiles								
	$Q_{.10}$	$Q_{.20}$	$Q_{.30}$	$Q_{.40}$	$Q_{.50}$	$Q_{.60}$	$Q_{.70}$	$Q_{.80}$	$Q_{.90}$
T_t	$3.36e^{-10*}$	$7.95 e^{-10*}$	$4.46e^{-10*}$	$3.46e^{-10*}$	$3.51e^{-10*}$	$4.72 e^{-10*}$	$4.56e^{-10*}$	$3.98e^{-10}$	$1.65 e^{-10}$
PT_t	$- 0.001*$	$0.065*$	$0.111*$	$0.117*$	$0.145*$	$0.151*$	$0.167*$	$0.155*$	$0.294*$
RE_t	$- 1.246*$	$- 1.141*$	$- 1.110*$	$- 1.268*$	$- 1.055*$	$- 0.428*$	$1.261*$	$3.003*$	$5.732*$
GDP_t	$- 0.003*$	$- 0.002*$	$- 0.002*$	$- 0.002*$	0.002	$- 0.001$	0.001	0.001	$0.005*$
$SQGDP_t$	$6.99e^{-08*}$	$1.90e^{-08*}$	$6.17e^{-09}$	$4.44 e^{-09}$	$- 8.11e^{-09}$	$- 1.64e^{-08}$	$- 4.83e^{-08*}$	$- 5.14e^{-08}$	$- 1.54 e^{-08a}$

*Significance level at 5%

development, the coefficient estimate of innovation is statistically more significant.

Over the assessment period, countries in the ASEAN were found to have a significant inverse relationship between energy from renewable source consumption and emissions of CO₂ from consumers, supporting the alternative hypothesis. The escalation in the utilization of renewable energy sources results in a decrease of annual carbon emissions by 4.101%, 4.531%, and 3.508%, respectively, attributable to the negative coefficient. This inverse relationship is further substantiated by the findings in the initial six quantiles of Canay (2011). The increased use of energy from renewable sources as opposed to fossil fuels is mainly responsible for the decrease in emissions of CO₂. Sun et al. (2022b) and Iqbal et al. (2021) made similar discoveries for BRICS and OECD nations, respectively.

Table 7 demonstrates a meaningful influence of GDP growth on CO₂ emissions, underscoring its significance in this context. Furthermore, the negative coefficient associated with GDP2 in this table aligns with the postulates of the environmental Kuznets curve (EKC) hypothesis, suggesting a potential inverse relationship. Additionally, the confirmation of the EKC hypothesis across the 50th, 70th, 80th, and 90th quantiles in Canay (2011) further consolidates this understanding, as depicted in Table 8. According to the results, once a person’s income rises above a certain point, the negative effect of income on emissions begins to cancel itself out, suggesting that a higher income significantly decreases CO₂. This inverted U-shaped relationship

shows that high energy consumption during the early stages of an economy is linked to environmental damage. Indeed, rapid expansion in the advanced stages of economic development supports carbon-cutting measures. This result is similar to those obtained by Farhani et al. (2014) for 10 MENA countries, Apergis and Ozturk (2015) for 14 Asian countries, Higón et al. (2017) for under-developing nations, and Ulucak et al. (2020) for BRICS economies. In contrast, Osabuohien et al. (2014) found that EKC was not at play in non-oil-producing economies, and Pal and Mitra (2017) found the same thing about China and India.

Results of “method of moments quantile regression”

Table 9 demonstrates that MMQR can be used with panel estimates to yield even deeper insights. MMQR investigates exogenous factors and critical determinants of long-term development in ASEAN nations. The net trade has a positive and significant impact on emissions at all quantiles, which means that the null hypothesis is rejected. In contrast, the 10th quantile does not perform appreciably in emissions of CO₂. Quantile-interquartile scaling of heterogeneous coefficients in international trade, the emissions of CO₂ intensity go from $6.78e^{-10}$ to $1.68e^{-09}$. The results suggest that increased trade is likely harmful to the environment (Li et al. 2021; Shahzad et al. 2020; Wang et al. 2021).

The statistics reveal significant and heterogeneous effects in the context of patent innovation from the 30th to the 90th quantiles (excluding the 80th), indicating that it rejects the

Table 9 Panel quantile estimation-MMQR

Variables	Location	Scale	Quantile								
			10th	20th	30th	40th	50th	60th	70th	80th	90th
T_t	$1.20e^{-09*}$	$1.80e^{-10}$	$6.78e^{-10}$	$7.76e^{-10*}$	$8.99e^{-10*}$	$1.01e^{-09*}$	$1.10e^{-09*}$	$1.16e^{-09*}$	$1.26e^{-09*}$	$1.43e^{-09*}$	$1.68e^{-09*}$
PT_t	$0.139*$	$0.055*$	$- 0.022$	0.008	$0.046*$	$0.081*$	$0.108*$	$0.126*$	$0.158*$	0.212	$0.287*$
RE_t	$- 0.144*$	$0.413*$	$- 1.214*$	$- 0.988*$	$- 0.706*$	$- 0.442$	$- 0.244$	$- 0.109$	0.126	0.522	1.08
GDP_t	$- 0.005*$	$0.002*$	$- 0.008*$	$- 0.008*$	$- 0.007*$	$- 0.006*$	$- 0.005*$	$- 0.005*$	$- 0.004$	$- 0.003$	$- 0.001$
$SQGDP_t$	$2.43e^{-08*}$	$- 4.04e^{-08*}$	$1.42e^{-07*}$	$1.20e^{-07*}$	$9.20e^{-08*}$	$6.61e^{-08*}$	$4.68e^{-08}$	$3.36e^{-08}$	$1.05e^{-08}$	$- 2.83e^{-08*}$	$- 8.28e^{-08}$

*Significance level at 5%

null hypothesis that innovations do not affect CO₂. The coefficients show a positive relationship between patent invention and emissions of CO₂, and this relationship strengthens as one moves from lower to higher quantiles. Increasing innovation by 1% indicates a 0.01 to 0.29% increase in emissions of CO₂. The maximum value of the innovation's coefficient shows that the environment deteriorates from the 30th to the 90th quantile. Negative, insignificant heterogeneous coefficients at the 10th quantile show that innovations have reduced emissions of CO₂ by 0.02%, while there is no change at the 90th quantile. In contrast, Tao et al. (2021) found that green innovation was critical in meeting the carbon emissions mitigation target, even when controlling for other macroeconomic factors.

Moreover, Table 9 demonstrates that in the 10th to 60th quantiles, energy from renewable sources has a negative and inconsistent influence on emissions of CO₂ in ASEAN economies, with just the first three quantiles having a significant influence on CO₂ emissions. The strategy of reducing emissions of CO₂ while preserving the environment is referred to as energy from renewable sources, according to the 30th coefficient value. Furthermore, the generation of carbon-free electricity, expansion of the renewable energy sector, developments in technology, governmental assistance, and decentralized energy production all contribute to the reduction of CO₂ emissions from the 70th to 100th quantiles. Energy users in these quantiles have a substantial opportunity to support global efforts to address climate change and lower greenhouse gas emissions by switching to renewable energy sources. Similar outcomes are expected (Fuinhas et al. 2017; Nathaniel and Iheonu 2019).

Table 9 shows results for economic growth at different quantiles; GDP is negatively significant for the first 60th quantiles. At the same time, its square term is only essential for the first 40th and 80th quantiles, remaining negligible for the low and high quantiles. It revealed that EKC hypotheses are not present in this case. This association supported the findings of Shittu et al. (2021).

Conclusion and policy recommendation

The dire state of environmental sustainability is the direct result of rapid economic growth and the excessive use of fossil fuels. Numerous strategies have been proposed to address the mounting crisis brought on by emissions of greenhouse gases. However, trade and innovation have yet to receive sufficient attention from policymakers for emerging economies, especially the ASEAN members. The goal of this study was to analyze the impact of net international trade, patent innovation, and renewable energy consumption on the decline of ASEAN countries' CO₂ emissions from consumption from 1990 to 2021. In order to assess how much of an impact

export diversification has had on reducing CO₂ emissions in ASEAN countries, this study uses the net trade index. This study addresses the significance of trade in the composition of products and services, expanding upon previous research that has focused on the importance of trade in terms of volume for achieving economic sustainability. This is achieved by employing a state-of-the-art technique, the method of moments quantile regression, recently proposed by Machado and Silva (2019). Compared to traditional panel quantile regression, multi-mode quantile regression (MMQR) provides a more precise explanation of the association between variables across quantile distributions. The estimates produced by this method are highly accurate, and the strategy is highly resilient to outliers. Furthermore, we employed complementary methods, including Canay (2011) quantile regression, FE-OLS, FM-OLS, and D-OLS, to generate credible results.

The CD, SLP-HTG, unit root, and serial correlation tests were used to address the panel data problem before estimating the empirical results. The study emphasizes the environmental impact of extensive trade by pointing out that higher trade openness is associated with higher CO₂ emissions, especially in lower quantiles. The positive correlation between innovation, as measured by patents, and emissions across the majority of quantiles emphasizes the environmental effects of technological advancement. In contrast, lower CO₂ emissions are linked to higher renewable energy consumption in the ASEAN region, highlighting the sustainability of renewables. The study supports the environmental Kuznets curve, which postulates that economic growth can initially increase emissions but later help to lower them. In essence, the complex relationship between economic growth and environmental factors is illustrated by the fact that globalization, innovation, and GDP growth are all associated with higher CO₂ emissions, whereas renewable energy use and GDP squared are associated with lower emissions.

The multi-quantile quantitative ranking (MMQR) test results show significant differences between quantiles. Findings indicated that both increased international trade and patent innovation positively impacted CO₂ emissions. According to the results, higher environmental standards tend to follow on the heels of a rise in international trade and creative endeavors. The use of renewable energy tends to promote environmental preservation, but its negative impact is most significant at the lowest three quantiles of energy consumption. The MMQR GDP estimate coefficient was largest at the lowest quantile and smallest at the highest quantile. This suggests that the effect of a decrease in GDP on CO₂ emissions begins to attenuate after the median quantiles (5–10). The evidence also disproves international trade improves environmental sustainability is consistent, the lowest estimate of the four.

The study uses data to conclude that promoting renewable energy and increasing international trade can contribute to

environmental sustainability and strengthen the relationship between innovation and consumption. These policy suggestions for emerging markets like those in ASEAN directly result from this analysis. In order to encourage energy efficiency in a number of areas, including manufacturing, transportation, and infrastructure, ASEAN nations have also enacted rules. This includes establishing energy efficiency legislation, promoting energy-efficient devices, and providing incentives for energy-saving behaviors. Trade and patent breakthroughs have caused an increase in CO₂ emissions; hence, it is necessary to promote renewable energy sources like solar, wind, hydropower, and geothermal energy which have been a priority for several ASEAN countries. Governments have put in place policies, such as feed-in tariffs, tax incentives, and regulatory frameworks, to promote the creation and application of renewable energy technologies. Some ASEAN member nations have investigated or implemented cap-and-trade or other carbon pricing mechanisms into place. These regulations put a cost on carbon emissions, giving people financial incentives to lessen their carbon footprint.

There needs to be congruence between ASEAN's trade patterns and its economic, environmental, and energy policies. Since the current supply of renewable energy is insufficient to meet the energy demand, industries like cement, iron, oil refineries, and heavy engineering must rely on fossil fuels. Because of the impossibility of a sudden transition, ASEAN countries must adopt energy mix strategies to increase trade diversification. Good trade policy reform is also required to lessen the demand for carbon-intensive imports. However, that is only possible once the goods are organized into meaningful categories. It is crucial that products that use much energy be replaced with ones that use less energy because the sudden disappearance of high-energy-consumption products could cause economic pressure and create new jobs. The economies of the member states of ASEAN are stable. In light of this, they should streamline investing in environmentally friendly technologies and cutting-edge manufacturing processes. Funding from private sources can be difficult, but public-private partnerships can help greatly.

Limitations and future study suggestions

There are caveats to this study. In particular, the researchers relied solely on a linear model to assess how much of an effect net trade has on consumption-based carbon emissions. Non-linear analysis methods, such as the ARDL quantile-based regression analysis, could be used in future studies to understand the relationship better. New drivers, such as financial inclusion and digitalization, are mentioned in the report. However, load capacity factor and ecological footprint are emphasized to halt environmental degradation. If desired, research can be broadened to incorporate the other MINT fields and the G20 economies.

Author contribution Umra Waris conducted the analysis and wrote the paper. Usman Mehmood and Salman Tariq conceptualize the work and analyze the data.

Data availability Not required.

Declarations

Ethical approval Not required.

Consent to participate All authors participated in this research.

Consent for publication Not applicable.

Competing interests The authors declare that they have no competing interests.

References

- Abler DG, Pick D (1993) NAFTA, agriculture, and the environment in Mexico. *Am J Agric Econ* 75(3):794–798. <https://doi.org/10.2307/1243594>
- Ahmed K, Bhattacharya M, Shaikh Z, Ramzan M, Ozturk I (2017) Emission intensive growth and trade in the era of the Association of Southeast Asian Nations (ASEAN) integration: an empirical investigation from ASEAN-8. *J Clean Prod* 154:530–540. <https://doi.org/10.1016/j.jclepro.2017.04.008>
- Ali IMA (2023) Income inequality and environmental degradation in middle-income countries: a test of two competing hypotheses. *Soc Indic Res* 166(2):299–321. <https://doi.org/10.1007/s11205-023-03068-y>
- Ali S, Can M, Shah MI, Jiang J, Ahmed Z, Murshed M (2022) Exploring the linkage between export diversification and ecological footprint: evidence from advanced time series estimation techniques. *Environ Sci Pollut Res* 29(25):38395–38409. <https://doi.org/10.1007/s11356-022-18622-3>
- Alvarado R, Ortiz C, Jiménez N, Ochoa-Jiménez D, Tillaguango B (2021) Ecological footprint, air quality, and research and development: the role of agriculture and international trade. *J Clean Prod* 288:125589. <https://doi.org/10.1016/j.jclepro.2020.125589>
- An H, Razaq A, Haseeb M, Mihardjo LWW (2021) The role of technology innovation and people's connectivity in testing environmental Kuznets curve and pollution heaven hypotheses across the Belt and Road host countries: new evidence from method of moments quantile regression. *Environ Sci Pollut Res* 28(5):5254–5270. <https://doi.org/10.1007/s11356-020-10775-3>
- Ansari MA, Haider S, Masood T (2021) Do renewable energy and globalization enhance ecological footprint: an analysis of top renewable energy countries? *Environ Sci Pollut Res* 28(6):6719–6732. <https://doi.org/10.1007/s11356-020-10786-0>
- Anser MK, Usman M, Godil DI, Shabbir MS, Sharif A, Tabash MI, Lopez LB (2021) Correction to: Does globalization affect the green economy and environment? The relationship between energy consumption, carbon dioxide emissions, and economic growth. *Environ Sci Pollut Res* 28(37):51119–51119. <https://doi.org/10.1007/s11356-021-15192-8>
- Apergis N, Ozturk I (2015) Testing environmental Kuznets curve hypothesis in Asian countries. *Ecol Indic* 52:16–22. <https://doi.org/10.1016/j.ecolind.2014.11.026>
- Aziz N, Mihardjo LW, Sharif A, Jermisittiparsert K (2020) The role of tourism and renewable energy in testing the environmental Kuznets curve in the BRICS countries: fresh evidence

- from methods of moments quantile regression. *Environ Sci Pollut Res* 27(31):39427–39441. <https://doi.org/10.1007/s11356-020-10011-y>
- Balogh JM (2022) The impacts of agricultural development and trade on CO₂ emissions? Evidence from the non-European Union countries. *Environ Sci Pol* 137:99–108. <https://doi.org/10.1016/j.envsci.2022.08.012>
- Balogh JM, Mizik T (2021) Trade–climate nexus: a systematic review of the literature. *Economies* 9(3):99. <https://doi.org/10.3390/economies9030099>
- Balsalobre-Lorente D, Driha OM, Halkos G, Mishra S (2022) Influence of growth and urbanization on CO₂ emissions: The moderating effect of foreign direct investment on energy use in BRICS. *Sustain Dev* 30(1):227–240. <https://doi.org/10.1002/sd.2240>
- Balsalobre-Lorente D, Driha OM, Leitão NC, Murshed M (2021a) The carbon dioxide neutralizing effect of energy innovation on international tourism in EU-5 countries under the prism of the EKC hypothesis. *J Environ Manag* 298:113513. <https://doi.org/10.1016/j.jenvman.2021.113513>
- Balsalobre-Lorente D, Leitão NC, Bekun FV (2021b) Fresh validation of the low carbon development hypothesis under the EKC scheme in Portugal, Italy, Greece, and Spain. *Energies* 14(1):250. <https://doi.org/10.3390/en14010250>
- Banerjee A, Carrion-i-Silvestre JL (2017) Testing for panel cointegration using common correlated effects estimators. *J Time Ser Anal* 38(4):610–636. <https://doi.org/10.1111/jtsa.12234>
- Baptista LB, Schaeffer R, van Soest HL, Fragkos P, Rochedo PRR, van Vuuren D, Dewi RG, Iyer G, Jiang K, Kannavou M, Macaluso N, Oshiro K, Park C, Reedman LJ, Safonov G, Shekhar S, Siagian U, Surana K, Qimin C (2022) Good practice policies to bridge the emissions gap in key countries. *Glob Environ Chang* 73:102472. <https://doi.org/10.1016/j.gloenvcha.2022.102472>
- Beeson M (2018) Geoeconomics with Chinese characteristics: the BRI and China's evolving grand strategy. *Econ Politic Stud* 6(3):240–256. <https://doi.org/10.1080/20954816.2018.1498988>
- Begum RA, Sohag K, Abdullah SMS, Jaafar M (2015) CO₂ emissions, energy consumption, economic and population growth in Malaysia. *Renew Sust Energ Rev* 41:594–601. <https://doi.org/10.1016/j.rser.2014.07.205>
- Binder M, Coad A (2011) From Average Joe's happiness to Miserable Jane and Cheerful John: using quantile regressions to analyze the full subjective well-being distribution. *J Econ Behav Organ* 79(3):275–290. <https://doi.org/10.1016/j.jebo.2011.02.005>
- Cai Y, Sam CY, Chang T (2018) Nexus between clean energy consumption, economic growth and CO₂ emissions. *J Clean Prod* 182:1001–1011. <https://doi.org/10.1016/j.jclepro.2018.02.035>
- Can M, Ahmad M, Khan Z (2021) The impact of export composition on environment and energy demand: evidence from newly industrialized countries. *Environ Sci Pollut Res* 28(25):33599–33612. <https://doi.org/10.1007/s11356-021-13084-5>
- Canay IA (2011) A simple approach to quantile regression for panel data. *Econ J* 14(3):368–386. <https://doi.org/10.1111/j.1368-423X.2011.00349.x>
- Chen J, Hu X, Razi U, Rexhepi G (2022) The sustainable potential of efficient air-transportation industry and green innovation in realising environmental sustainability in G7 countries. *Econ Res-Ekonomska Istraživanja* 35(1):3814–3835. <https://doi.org/10.1080/1331677X.2021.2004190>
- Chen Y, Lee C-C (2020) Does technological innovation reduce CO₂ emissions? Cross-country evidence. *J Clean Prod* 263:121550. <https://doi.org/10.1016/j.jclepro.2020.121550>
- Chien F, Anwar A, Hsu C-C, Sharif A, Razzaq A, Sinha A (2021) The role of information and communication technology in encountering environmental degradation: proposing an SDG framework for the BRICS countries. *Technol Soc* 65:101587. <https://doi.org/10.1016/j.techsoc.2021.101587>
- Das K, Lin D-Y (2018) ASEAN states have fared well. now, to continue doing so. McKinsey & Company Home, McKinsey Global Institute. <https://www.mckinsey.com/mgi/overview/in-the-news/asean-states-have-fared-well-now-to-continue>. Accessed 6 Jan 2023
- Dauda L, Long X, Mensah CN, Salman M, Boamah KB, Ampon-Wireko S, Kofi Dogbe CS (2021) Innovation, trade openness and CO₂ emissions in selected countries in Africa. *J Clean Prod* 281:125143. <https://doi.org/10.1016/j.jclepro.2020.125143>
- Doğan B, Chu LK, Ghosh S, Diep Truong HH, Balsalobre-Lorente D (2022) How environmental taxes and carbon emissions are related in the G7 economies? *Renew Energy* 187:645–656. <https://doi.org/10.1016/j.renene.2022.01.077>
- Dogan E, Ulucak R, Kocak E, Isik C (2020) The use of ecological footprint in estimating the environmental Kuznets curve hypothesis for BRICST by considering cross-section dependence and heterogeneity. *Sci Total Environ* 723:138063. <https://doi.org/10.1016/j.scitotenv.2020.138063>
- Dong K, Hochman G, Zhang Y, Sun R, Li H, Liao H (2018) CO₂ emissions, economic and population growth, and renewable energy: empirical evidence across regions. *Energy Econ* 75:180–192. <https://doi.org/10.1016/j.eneco.2018.08.017>
- Driscoll JC, Kraay AC (1998) Consistent covariance matrix estimation with spatially dependent panel data. *Rev Econ Stat* 80(4):549–560. <https://doi.org/10.1162/003465398557825>
- Du J, Zhang Y (2018) Does One Belt One Road initiative promote Chinese overseas direct investment? *China Econ Rev* 47:189–205. <https://doi.org/10.1016/j.chieco.2017.05.010>
- Du K, Li P, Yan Z (2019) Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technol Forecast Soc Chang* 146:297–303. <https://doi.org/10.1016/j.techfore.2019.06.010>
- Fan J-L, Da Y-B, Wan S-L, Zhang M, Cao Z, Wang Y, Zhang X (2019) Determinants of carbon emissions in 'Belt and Road initiative' countries: a production technology perspective. *Appl Energy* 239:268–279. <https://doi.org/10.1016/j.apenergy.2019.01.201>
- Fang Z, Gao X, Sun C (2020) Do financial development, urbanization and trade affect environmental quality? Evidence from China. *J Clean Prod* 259:120892. <https://doi.org/10.1016/j.jclepro.2020.120892>
- Fareed Z, Salem S, Adebayo TS, Pata UK, Shahzad F (2021) Role of export diversification and renewable energy on the load capacity factor in Indonesia: a Fourier quantile causality approach. *Front Environ Sci* 9. <https://doi.org/10.3389/fenvs.2021.770152>
- Farhani S, Mrizak S, Chaibi A, Rault C (2014) The environmental Kuznets curve and sustainability: a panel data analysis. *Energy Policy* 71:189–198. <https://doi.org/10.1016/j.enpol.2014.04.030>
- Fernández Fernández Y, Fernández López MA, Olmedillas Blanco B (2018) Innovation for sustainability: the impact of R&D spending on CO₂ emissions. *J Clean Prod* 172:3459–3467. <https://doi.org/10.1016/j.jclepro.2017.11.001>
- Focus Economics (2018) Economic forecasts from the world's leading economists, economic snapshot for ASEAN. <https://www.focus-economics.com/regions/asean>. Accessed 6 Jan 2023
- Fuinhas JA, Marques AC, Koengkan M (2017) Are renewable energy policies upsetting carbon dioxide emissions? The case of Latin America countries. *Environ Sci Pollut Res* 24(17):15044–15054. <https://doi.org/10.1007/s11356-017-9109-z>
- Gyamfi BA, Onifade ST, Nwani C, Bekun FV (2022) Accounting for the combined impacts of natural resources rent, income level, and energy consumption on environmental quality of G7 economies: a panel quantile regression approach. *Environ Sci Pollut Res* 29(2):2806–2818. <https://doi.org/10.1007/s11356-021-15756-8>
- Helm D, Hepburn C, Ruta G (2012) Trade, climate change, and the political game theory of border carbon adjustments. *Oxf Rev*

- Econ Policy 28(2):368–394. <https://doi.org/10.1093/oxrep/grs013>
- Heyl K, Ekardt F, Roos P, Stubenrauch J, Garske B (2021) Free trade, environment, agriculture, and plurilateral treaties: the ambivalent example of Mercosur, CETA, and the EU–Vietnam Free Trade Agreement. *Sustainability* 13(6):3153. <https://doi.org/10.3390/su13063153>
- Higón DA, Gholami R, Shirazi F (2017) ICT and environmental sustainability: a global perspective. *Telematics Inform* 34(4):85–95. <https://doi.org/10.1016/j.tele.2017.01.001>
- Hu J, Xu J, Tong L, Razi U (2022) The dynamic role of film and drama industry, green innovation towards the sustainable environment in China: fresh insight from NARDL approach. *Econ Res-Ekonomika Istraživanja* 35(1):5292–5309. <https://doi.org/10.1080/1331677X.2022.2026239>
- Ibrahim M, Vo XV (2021) Exploring the relationships among innovation, financial sector development, and environmental pollution in selected industrialized countries. *J Environ Manag* 284:112057. <https://doi.org/10.1016/j.jenvman.2021.112057>
- IEA (2021) CO2 emissions from fuel combustion. <https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer>. Accessed 6 Jan 2023
- IPCC (2022) Climate change 2022 impacts, adaptation and vulnerability summary for policymakers. Contribution of working group II to the sixth assessment Report of the intergovernmental panel on climate change
- Iqbal N, Abbasi KR, Shinwari R, Guangcai W, Ahmad M, Tang K (2021) Does exports diversification and environmental innovation achieve carbon neutrality target of OECD economies? *J Environ Manag* 291:112648. <https://doi.org/10.1016/j.jenvman.2021.112648>
- Jahanger A, Usman M, Murshed M, Mahmood H, Balsalobre-Lorente D (2022) The linkages between natural resources, human capital, globalization, economic growth, financial development, and ecological footprint: the moderating role of technological innovations. *Res Policy* 76:102569. <https://doi.org/10.1016/j.resoupol.2022.102569>
- Jiang G, Alvarado R, Murshed M, Tillaguango B, Toledo E, Méndez P, Isik C (2022a) Effect of agricultural employment and export diversification index on environmental pollution: building the agenda towards sustainability. *Sustainability* 14(2):677. <https://doi.org/10.3390/su14020677>
- Jiang S, Mentel G, Shahzadi I, ben Jebli, M., & Iqbal, N. (2022b) Renewable energy, trade diversification and environmental footprints: evidence for Asia-Pacific Economic Cooperation (APEC). *Renew Energy* 187:874–886. <https://doi.org/10.1016/j.renene.2021.12.134>
- Kao C, Chiang M-H (2001) On the estimation and inference of a cointegrated regression in panel data (pp. 179–222). [https://doi.org/10.1016/S0731-9053\(00\)15007-8](https://doi.org/10.1016/S0731-9053(00)15007-8)
- Khan Z, Murshed M, Dong K, Yang S (2021) The roles of export diversification and composite country risks in carbon emissions abatement: evidence from the signatories of the regional comprehensive economic partnership agreement. *Appl Econ* 53(41):4769–4787. <https://doi.org/10.1080/00036846.2021.1907289>
- Koenker R (2004) Quantile regression for longitudinal data. *J Multivar Anal* 91(1):74–89. <https://doi.org/10.1016/j.jmva.2004.05.006>
- Koenker R, Hallock KF (2001) Quantile regression. *J Econ Perspect* 15(4):143–156. <https://doi.org/10.1257/jep.15.4.143>
- Latif B, Gunarathne N, Gaskin J, Ong TS, Ali M (2022) Environmental corporate social responsibility and pro-environmental behavior: the effect of green shared vision and personal ties. *Resour Conserv Recycl* 186:106572. <https://doi.org/10.1016/j.resconrec.2022.106572>
- Le T-H, Le H-C, Taghizadeh-Hesary F (2020) Does financial inclusion impact CO2 emissions? Evidence from Asia. *Financ Res Lett* 34:101451. <https://doi.org/10.1016/j.frl.2020.101451>
- Leitão NC (2021a) Testing the role of trade on carbon dioxide emissions in Portugal. *Economies* 9(1):22. <https://doi.org/10.3390/economies9010022>
- Leitão NC (2021b) The effects of corruption, renewable energy, trade and CO2 emissions. *Economies* 9(2):62. <https://doi.org/10.3390/economies9020062>
- Li K, Lin B (2017) An application of a double bootstrap to investigate the effects of technological progress on total-factor energy consumption performance in China. *Energy* 128:575–585. <https://doi.org/10.1016/j.energy.2017.04.044>
- Li M, Ahmad M, Fareed Z, Hassan T, Kirikkaleli D (2021) Role of trade openness, export diversification, and renewable electricity output in realizing carbon neutrality dream of China. *J Environ Manag* 297:113419. <https://doi.org/10.1016/j.jenvman.2021.113419>
- Li W, Elheddad M, Doytch N (2021) The impact of innovation on environmental quality: evidence for the non-linear relationship of patents and CO2 emissions in China. *J Environ Manag* 292:112781. <https://doi.org/10.1016/j.jenvman.2021.112781>
- Lin B, Ma R (2022) Green technology innovations, urban innovation environment and CO2 emission reduction in China: fresh evidence from a partially linear functional-coefficient panel model. *Technol Forecast Soc Chang* 176:121434. <https://doi.org/10.1016/j.techfore.2021.121434>
- Lin S, Wang S, Marinova D, Zhao D, Hong J (2017) Impacts of urbanization and real economic development on CO2 emissions in non-high income countries: empirical research based on the extended STIRPAT model. *J Clean Prod* 166:952–966. <https://doi.org/10.1016/j.jclepro.2017.08.107>
- Lingyan M, Zhao Z, Malik HA, Razzaq A, An H, Hassan M (2022) Asymmetric impact of fiscal decentralization and environmental innovation on carbon emissions: evidence from highly decentralized countries. *Energy Environ* 33(4):752–782. <https://doi.org/10.1177/0958305X211018453>
- Liu N, Guan J (2016) Policy and innovation: nanoenergy technology in the USA and China. *Energy Policy* 91:220–232. <https://doi.org/10.1016/j.enpol.2016.01.020>
- Machado JAF, Silva JMCS (2019) Quantiles via moments. *J Econ* 213(1):145–173. <https://doi.org/10.1016/j.jeconom.2019.04.009>
- Mahmood N, Wang Z, Hassan ST (2019) Renewable energy, economic growth, human capital, and CO2 emission: an empirical analysis. *Environ Sci Pollut Res* 26(20):20619–20630. <https://doi.org/10.1007/s11356-019-05387-5>
- Mardani A, Streimikiene D, Cavallaro F, Loganathan N, Khoshnoudi M (2019) Carbon dioxide (CO2) emissions and economic growth: a systematic review of two decades of research from 1995 to 2017. *Sci Total Environ* 649:31–49. <https://doi.org/10.1016/j.scitotenv.2018.08.229>
- Meirun T, Mihardjo LW, Haseeb M, Khan SAR, Jermstittiparsert K (2021) The dynamics effect of green technology innovation on economic growth and CO2 emission in Singapore: new evidence from bootstrap ARDL approach. *Environ Sci Pollut Res* 28(4):4184–4194. <https://doi.org/10.1007/s11356-020-10760-w>
- Meng Y, Wu H, Wang Y, Duan Y (2022) International trade diversification, green innovation, and consumption-based carbon emissions: the role of renewable energy for sustainable development in BRICST countries. *Renew Energy* 198:1243–1253. <https://doi.org/10.1016/j.renene.2022.08.045>
- Miao Y, Razzaq A, Adebayo TS, Awosusi AA (2022) Do renewable energy consumption and financial globalisation contribute to ecological sustainability in newly industrialized countries?

- Renew Energy 187:688–697. <https://doi.org/10.1016/j.renene.2022.01.073>
- Muhammad S, Long X, Salman M, Dauda L (2020) Effect of urbanization and international trade on CO2 emissions across 65 belt and road initiative countries. *Energy* 196:117102. <https://doi.org/10.1016/j.energy.2020.117102>
- Nasir MA, Duc Huynh TL, Xuan Tram HT (2019) Role of financial development, economic growth & foreign direct investment in driving climate change: A case of emerging ASEAN. *J Environ Manage* 242:131–141. <https://doi.org/10.1016/j.jenvman.2019.03.112>
- Nasreen S, Anwar S (2014) The causal relationship between trade openness, economic growth, and energy consumption: a panel data analysis of Asian countries. *Energy Policy* 69:82–91. <https://doi.org/10.1016/j.enpol.2014.02.009>
- Nathaniel S, Khan SAR (2020) The nexus between urbanization, renewable energy, trade, and ecological footprint in ASEAN countries. *J Clean Prod* 272:122709. <https://doi.org/10.1016/j.jclepro.2020.122709>
- Nathaniel SP, Iheonu CO (2019) Carbon dioxide abatement in Africa: the role of renewable and non-renewable energy consumption. *Sci Total Environ* 679:337–345. <https://doi.org/10.1016/j.scitotenv.2019.05.011>
- Newell RG (2009) Literature review of recent trends and future prospects for innovation in climate change mitigation. Paris: OECD Environ Working Papers 9:51
- Osabuohien ES, Efobi UR, Gitau CMW (2014) Beyond the environmental Kuznets curve in Africa: evidence from panel cointegration. *J Environ Policy Plan* 16(4):517–538. <https://doi.org/10.1080/1523908X.2013.867802>
- Pal D, Mitra SK (2017) The environmental Kuznets curve for carbon dioxide in India and China: growth and pollution at a crossroads. *J Policy Model* 39(2):371–385. <https://doi.org/10.1016/j.jpmod.2017.03.005>
- Pedroni P (2004) Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Econometr Theory* 20(03). <https://doi.org/10.1017/S0266466604203073>
- Pesaran MH (2004) General diagnostic tests for cross section dependence in panels
- Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. *J Appl Econ* 22(2):265–312. <https://doi.org/10.1002/jae.951>
- Pesaran MH (2015) Testing weak cross-sectional dependence in large panels. *Econ Rev* 34(6–10):1089–1117. <https://doi.org/10.1080/07474938.2014.956623>
- Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. *J Econ* 142(1):50–93. <https://doi.org/10.1016/j.jecon.2007.05.010>
- Phillips PCB, Sul D (2003) Dynamic panel estimation and homogeneity testing under cross-section dependence. *Econ J* 6(1):217–259. <https://doi.org/10.1111/1368-423X.00108>
- Qin L, Kirikkaleli D, Hou Y, Miao X, Tufail M (2021) Carbon neutrality target for G7 economies: examining the role of environmental policy, green innovation, and composite risk index. *J Environ Manag* 295:113119. <https://doi.org/10.1016/j.jenvman.2021.113119>
- Rajão R, Soares-Filho B, Nunes F, Börner J, Machado L, Assis D, Oliveira A, Pinto L, Ribeiro V, Rausch L, Gibbs H, Figueira D (2020) The rotten apples of Brazil's agribusiness. *Science* 369(6501):246–248. <https://doi.org/10.1126/science.aba6646>
- Ramzan M, Raza SA, Usman M, Sharma GD, Iqbal HA (2022) Environmental cost of non-renewable energy and economic progress: do ICT and financial development mitigate some burden? *J Clean Prod* 333:130066. <https://doi.org/10.1016/j.jclepro.2021.130066>
- Razzaq A, Sharif A, Ahmad P, Jermisittiparsert K (2021a) Asymmetric role of tourism development and technology innovation on carbon dioxide emission reduction in the Chinese economy: fresh insights from <sc>QARDL</sc> approach. *Sustain Dev* 29(1):176–193. <https://doi.org/10.1002/sd.2139>
- Razzaq A, Wang Y, Chupradit S, Suksatan W, Shahzad F (2021b) Asymmetric inter-linkages between green technology innovation and consumption-based carbon emissions in BRICS countries using quantile-on-quantile framework. *Technol Soc* 66:101656. <https://doi.org/10.1016/j.techsoc.2021.101656>
- Rehman MA, Fareed Z, Salem S, Kanwal A, Pata UK (2021) Do diversified export, agriculture, and cleaner energy consumption induce atmospheric pollution in Asia? Application of Method of Moments Quantile Regression. *Front Environ Sci*, 9. <https://doi.org/10.3389/fenvs.2021.781097>
- Ren S, Yuan B, Ma X, Chen X (2014) International trade, FDI (foreign direct investment) and embodied CO2 emissions: a case study of China's industrial sectors. *China Econ Rev* 28:123–134. <https://doi.org/10.1016/j.chieco.2014.01.003>
- Rosenzweig C, Solecki W, Hammer SA, Mehrotra S (2010) Cities lead the way in climate-change action. *Nature* 467(7318):909–911. <https://doi.org/10.1038/467909a>
- Saboori B, Sulaiman J, Mohd S (2012) Economic growth and CO2 emissions in Malaysia: a cointegration analysis of the environmental Kuznets curve. *Energy Policy* 51:184–191. <https://doi.org/10.1016/j.enpol.2012.08.065>
- Sarkodie SA, Strezov V (2019) Effect of foreign direct investments, economic development, and energy consumption on greenhouse gas emissions in developing countries. *Sci Total Environ* 646:862–871. <https://doi.org/10.1016/j.scitotenv.2018.07.365>
- Shahbaz M, Hye QMA, Tiwari AK, Leitão NC (2013) Economic growth, energy consumption, financial development, international trade and CO2 emissions in Indonesia. *Renew Sust Energy Rev* 25:109–121. <https://doi.org/10.1016/j.rser.2013.04.009>
- Shahbaz M, Loganathan N, Sbia R, Afza T (2015) The effect of urbanization, affluence and trade openness on energy consumption: a time series analysis in Malaysia. *Renew Sust Energy Rev* 47:683–693. <https://doi.org/10.1016/j.rser.2015.03.044>
- Shahzad U, Doğan B, Sinha A, Fareed Z (2021a) Does export product diversification help to reduce energy demand: exploring the contextual evidences from the newly industrialized countries. *Energy* 214:118881. <https://doi.org/10.1016/j.energy.2020.118881>
- Shahzad U, Ferraz D, Doğan B, Aparecida do Nascimento Rebelatto D (2020) Export product diversification and CO2 emissions: contextual evidences from developing and developed economies. *J Clean Prod* 276:124146. <https://doi.org/10.1016/j.jclepro.2020.124146>
- Shahzad U, Lv Y, Doğan B, Xia W (2021b) Unveiling the heterogeneous impacts of export product diversification on renewable energy consumption: New evidence from G-7 and E-7 countries. *Renew Energy* 164:1457–1470. <https://doi.org/10.1016/j.renene.2020.10.143>
- Shao X, Zhong Y, Liu W, Li RYM (2021) Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries? Evidence from advance panel estimations. *J Environ Manag* 296:113189. <https://doi.org/10.1016/j.jenvman.2021.113189>
- Sharma R, Shahbaz M, Kautish P, Vo XV (2022) Diversified imports as catalysts for ecological footprint: examining the BRICS experience. *Environ Dev Sustain* <https://doi.org/10.1007/s10668-022-02177-x>
- Sharma R, Sinha A, Kautish P (2021) Examining the nexus between export diversification and environmental pollution: evidence from BRICS nations. *Environ Sci Pollut Res* 28(43):61732–61747. <https://doi.org/10.1007/s11356-021-14889-0>

- Shin Y, Yu B, Greenwood-Nimmo M (2014) Modelling asymmetric cointegration and dynamic multipliers in a non-linear ARDL framework. In *Festschrift in Honor of Peter Schmidt* (pp. 281–314). Springer, New York. https://doi.org/10.1007/978-1-4899-8008-3_9
- Shittu W, Adedoyin FF, Shah MI, Musibau HO (2021) An investigation of the nexus between natural resources, environmental performance, energy security and environmental degradation: evidence from Asia. *Res Policy* 73:102227. <https://doi.org/10.1016/j.resourpol.2021.102227>
- Smil V (2022) Decarbonization algebra: the COP26 calls for impossibly steep cuts in carbon emissions: numbers don't lie. *IEEE Spectr* 59(2):20–21. <https://doi.org/10.1109/MSPEC.2022.9706399>
- Suki NM, Sharif A, Afshan S, Suki NM (2020) Revisiting the environmental Kuznets curve in Malaysia: the role of globalization in sustainable environment. *J Clean Prod* 264:121669. <https://doi.org/10.1016/j.jclepro.2020.121669>
- Sun Y, Anwar A, Razzaq A, Liang X, Siddique M (2022a) Asymmetric role of renewable energy, green innovation, and globalization in deriving environmental sustainability: Evidence from top-10 polluted countries. *Renew Energy* 185:280–290. <https://doi.org/10.1016/j.renene.2021.12.038>
- Sun Y, Bao Q, Siao-Yun W, ul Islam M, Razzaq A (2022b) Renewable energy transition and environmental sustainability through economic complexity in BRICS countries: fresh insights from novel method of moments quantile regression. *Renew Energy* 184:1165–1176. <https://doi.org/10.1016/j.renene.2021.12.003>
- Sun Y, Li H, Andlib Z, Genie MG (2022c) How do renewable energy and urbanization cause carbon emissions? Evidence from advanced panel estimation techniques. *Renew Energy* 185:996–1005. <https://doi.org/10.1016/j.renene.2021.12.112>
- Tao R, Umar M, Naseer A, Razi U (2021) The dynamic effect of eco-innovation and environmental taxes on carbon neutrality target in emerging seven (E7) economies. *J Environ Manag* 299:113525. <https://doi.org/10.1016/j.jenvman.2021.113525>
- Töbelmann D, Wendler T (2020) The impact of environmental innovation on carbon dioxide emissions. *J Clean Prod* 244:118787. <https://doi.org/10.1016/j.jclepro.2019.118787>
- Tze San O, Latif B, di Vaio A (2022) GEO and sustainable performance: the moderating role of GTD and environmental consciousness. *J Intellect Cap* 23(7):38–67. <https://doi.org/10.1108/JIC-10-2021-0290>
- Ulucak R, Danish, Khan SU (2020) Does information and communication technology affect CO mitigation under the pathway of sustainable development during the mode of globalization? *Sustain Dev* 28(4):857–867. <https://doi.org/10.1002/sd.2041>
- Wang L, Chang H-L, Rizvi SKA, Sari A (2020) Are eco-innovation and export diversification mutually exclusive to control carbon emissions in G-7 countries? *J Environ Manag* 270:110829. <https://doi.org/10.1016/j.jenvman.2020.110829>
- Wang Y, Chen L, Kubota J (2016) The relationship between urbanization, energy use and carbon emissions: evidence from a panel of Association of Southeast Asian Nations (ASEAN) countries. *J Clean Prod* 112:1368–1374. <https://doi.org/10.1016/j.jclepro.2015.06.041>
- Wang Z, Ben Jebli M, Madaleno M, Doğan B, Shahzad U (2021) Does export product quality and renewable energy induce carbon dioxide emissions: evidence from leading complex and renewable energy economies. *Renew Energy* 171:360–370. <https://doi.org/10.1016/j.renene.2021.02.066>
- Westerlund J (2007) Testing for error correction in panel data. *Oxf Bull Econ Stat* 69(6):709–748. <https://doi.org/10.1111/j.1468-0084.2007.00477.x>
- Westerlund J, Edgerton DL (2008) A simple test for cointegration in dependent panels with structural breaks*. *Oxf Bull Econ Stat* 70(5):665–704. <https://doi.org/10.1111/j.1468-0084.2008.00513.x>
- Xu L, Fan M, Yang L, Shao S (2021) Heterogeneous green innovations and carbon emission performance: evidence at China's city level. *Energy Econ* 99:105269. <https://doi.org/10.1016/j.eneco.2021.105269>
- Yan D, Ren X, Kong Y, Ye B, Liao Z (2020) The heterogeneous effects of socioeconomic determinants on PM2.5 concentrations using a two-step panel quantile regression. *Appl Energy* 272:115246. <https://doi.org/10.1016/j.apenergy.2020.115246>
- Yan Z, Yi L, Du K, Yang Z (2017) Impacts of low-carbon innovation and its heterogeneous components on CO2 emissions. *Sustainability* 9(4):548. <https://doi.org/10.3390/su9040548>
- Yu D, Soh W, Amin Noordin BA, Dato Haji Yahya MH, Latif B (2022a) The impact of innovation on CO2 emissions: the threshold effect of financial development. *Front Environ Sci* 10. <https://doi.org/10.3389/fenvs.2022.980267>
- Yu D, Tao S, Hanan A, Ong TS, Latif B, Ali M (2022b) Fostering green innovation adoption through green dynamic capability: the moderating role of environmental dynamism and big data analytic capability. *Int J Environ Res Public Health* 19(16):10336. <https://doi.org/10.3390/ijerph191610336>
- Zhang G, Zhang N, Liao W (2018) How do population and land urbanization affect CO2 emissions under gravity center change? A spatial econometric analysis. *J Clean Prod* 202:510–523. <https://doi.org/10.1016/j.jclepro.2018.08.146>
- Zhang R, Sharma R, Tan Z, Kautish P (2022) Do export diversification and stock market development drive carbon intensity? The role of renewable energy solutions in top carbon emitter countries. *Renew Energy* 185:1318–1328. <https://doi.org/10.1016/j.renene.2021.12.113>
- Zhao J, Shahbaz M, Dong X, Dong K (2021) How does financial risk affect global CO2 emissions? The role of technological innovation. *Technol Forecast Soc Chang* 168:120751. <https://doi.org/10.1016/j.techfore.2021.120751>
- Zhuang Y, Yang S, Razzaq A, Khan Z (2023) Environmental impact of infrastructure-led Chinese outward FDI, tourism development and technology innovation: a regional country analysis. *J Environ Plan Manag* 66(2):367–399. <https://doi.org/10.1080/09640568.2021.1989672>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.