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Relationship between economic growth, renewable energy use, technological innovation, and carbon emission toward achieving Malaysia's Paris agreement

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Abstract

Global climate change caused by greenhouse gases (GHGs), particularly carbon dioxide (CO_2) emissions, poses incomparable threats to the environment, development, and sustainability. This research investigates the potential of economic growth, renewable energy use, and technological innovation to achieve Malaysia's Paris Agreement by reducing CO_2 emissions. Time-series data from 1990 to 2019 were utilized applying the Dynamic Ordinary Least Squares (DOLS) method. The empirical findings show that the coefficient of economic growth is positive and significant with CO_2 emissions, indicating a 1% increase in economic growth is related to a 0.9% rise in CO_2 emissions. Furthermore, the coefficient of renewable energy use is negative and significant, which indicates that increasing renewable energy use by 1% is associated with CO_2 emissions reduction by 0.3% in the long run. In addition, increasing technological innovation lowers CO_2 emissions, implying that a 1% increase in the number of patent applications is linked to a 0.05% reduction of CO_2 emissions. The empirical findings reveal that increased renewable energy use and technological innovation can reduce Malaysia's carbon emission while economic growth deteriorates the environmental quality. Thus, effective implementation of policy measures to a low-carbon economy, promoting renewable energy use, and financing technological innovation could help to achieve Malaysia's Paris Agreement by reducing CO_2 emissions.

Keywords Climate change · CO_2 emissions · Economic growth · Renewable energy · Technological innovation · Malaysia

1 Introduction

Global climate change is a burning issue due to the atmospheric concentrations of GHGs dominated by CO_2 which is primarily emitted from human-induced events, such as the burning of fossil fuels and deforestation (Azmi and Tokai 2016; Magazzino 2017; Raihan et al. 2018, 2021; Jaafar et al. 2020; IPCC 2021). The continuous increase in CO_2 emissions is projected to have tremendous effects on the global climatic system resulting in catastrophic consequences that will impact all aspects of society (Singh 2016; Raihan et al. 2019; Begum et al. 2020; Sarkar et al. 2020). Therefore, reducing CO_2 emissions and increasing environmental quality became a worldwide concern to ensure sustainable development (Begum et al. 2015; Ibrahim 2018; Raihan and Said 2021). The Paris Agreement is a United Nations Framework Convention on Climate Change (UNFCCC) multilateral environmental agreement that seeks to improve the global response to climate change risks in the framework of sustainable development and poverty eradication

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initiatives. When Malaysia signed the Paris Agreement in 2016, it joined worldwide efforts to keep global warming far below 2 °C, to limit it to 1.5 °C. This also indicates that the country is dedicated to lowering national emissions and responding to the effects of climate change. Malaysia has pledged to reduce GHG emission intensity of GDP by 45% by 2030 compared to 2005 levels under the Paris Agreement. This includes a 35% unconditional basis and a 10% conditional basis contingent on developed nations providing climate financing, technological transfer, and capacity development. A significant issue emerging is how Malaysia can reduce CO_2 emissions, and this issue may be handled by examining the potential impacts of Malaysia's emission reduction components. Overall knowledge of Malaysia's potential to reduce emission is increasingly essential for policymakers to strike a balance between policies aimed at mitigating climate change and achieving sustainable development and executing both.

The concern for environmental sustainability and the development strategy primarily depends on whether the persistent economic growth produces environmental deterioration or if such growth is adequate to pay for the environmental cost of production or development process (Hitam and Borhan 2012). The environmental Kuznets curve (EKC) depicts an inverted *U*-shape relationship between economic growth and environmental degradation, in which environmental degradation rises with economic growth, peaks, and then declines when the economy reaches a critically high level of income (Grossman and Krueger 1991). As the economy grows, old and polluting technologies are phased out and replaced by newer, cleaner technology, increasing environmental quality (Saboori et al. 2012). Decoupling between economic development and environmental deterioration is aided by factors such as changes in output composition, the introduction of cleaner manufacturing technologies, environmental legislation, and environmental consciousness (Saboori et al. 2012). However, Malaysia's gross domestic product (GDP) in 2019 was USD365 billion, which ranked it 36th globally and 4th in Southeast Asia (World Bank 2021). According to Gan and Li (2008), Malaysia's GDP is anticipated to rise at a rate of 4.6% between 2004 and 2030, with real GDP reaching USD341.6 billion by 2030, up from USD107 billion in 2004. Thus, a key concern is whether Malaysia's increased economic development is aligned with improved environmental sustainability (emission reduction).

Moreover, the rising concern about global climate change has highlighted the significance of renewable energy (Irandoust 2016). The rapid depletion of fossil fuels and their severe environmental effects are gradually causing international economies to move to more sustainable renewable energy sources (Bhattacharya et al. 2017). The advantages of renewable energy minimize conventional energy use while preserving long-term global economic output (Paramati et al. 2017). The five major renewable energy sources are biomass, water (hydropower), the geothermal, wind, and solar. Compared to conventional energy, renewable energy is safe, clean, and abundant (Khan et al. 2017). Renewable energy is widely regarded as a carbon-free energy source with the potential to solve energy security and reduce emissions (Baek 2016). Renewable energy plays a critical part in meeting the global emission reduction goal of 50% by 2050 (IEA 2012; Paramati et al. 2017). The continual expansion in energy consumption in Malaysia has led to increased CO_2 emissions, as more than 90% of power generation relies on fossil fuels (Chachuli et al. 2021). Malaysia has been facing an increasing energy consumption demand over the past years due to urbanization and industrial development (Begum et al. 2017). However, Malaysia has a lot of resources that can be used to generate renewable energy (Chachuli et al. 2021). In addition, Malaysia has developed and implemented several policy tools to encourage renewable energy technology. Despite this, limited research has been conducted to investigate the link between renewable energy use and environmental degradation. Hence, it is crucial to analyze the potential of renewable energy use to reduce CO_2 emissions in Malaysia.

At present, technological advance is the most significant contributor to mitigating global climate change (Yang and Li 2017). The improvement of environmental legislation has resulted in a steady growth of direct environmental technologies to lower CO_2 emissions (Chen and Lee 2020). These innovations enable the rapid growth of new technological applications, resulting in increased energy efficiency and lower energy consumption. Furthermore, technological innovation plays a significant role in the economic restructuring and optimization process. It is changing conventional economic development from a production-driven mode to an innovation-driven mode aids in reducing CO_2 emissions generated by industrialization (Sohag et al. 2015). Malaysia's economic development has progressed to a new normal period. To some extent, technological innovation may help alter and upgrade Malaysia's industrial structure, and it is an important source of driving force for high-quality economic growth. For a long time, the Malaysian government has valued innovation activities, encouraging the rapid growth of enterprise scientific research activities, with technology innovation playing an increasingly significant role. Therefore, researching the influence of technological innovation on carbon emissions is critical both theoretically and practically for increasing Malaysia's economic growth and lowering carbon emissions.

The IPCC (2014) reported that population size, economic activity, lifestyle, energy consumption, land use patterns, technology, and inadequate climate policy are the primary drivers of GHG emissions. In this regard, several studies examined the nexus between CO_2 emissions and their determinants by using time-series data for Malaysia (Begum et al. 2015; Chin et al. 2018; Sarkar et al. 2019; Zhang et al. 2021). However, there is a scarcity of research exploring the dynamic impacts of emission reduction factors in Malaysia by using an econometric approach. Furthermore, a limited study investigates the potential of economic growth, renewable energy use, and technological innovation to reduce CO_2 emissions in Malaysia. To address this research gap, this study aims to examine the nexus among CO_2 emissions, economic growth, renewable energy use, and technological innovation in Malaysia by using the Dynamic Ordinary Least Squares (DOLS) approach. This study is significant because it contributes to the recent literature and policymaking in Malaysia in several directions. First, this research establishes the relationships between CO_2 emissions and emission reduction factors, revealing the potential impacts of economic growth, renewable energy use, and technological innovation on CO_2 emissions reduction in Malaysia. Second, it highlights the unique role of technological innovation, which is commonly not given too much attention when explaining the emission reduction factors. Next, several unit root tests and cointegration tests are employed to verify the precision of the results. Finally, the study's outcomes would provide further comprehensive and valuable insights to policymakers for designing effective policies related to climate change, low-carbon economy, promoting renewable energy use, financing technological advancement, and emission reduction in Malaysia.

2 Literature review

Over the last three decades, CO_2 emissions from energy consumption in Malaysia proliferated due to rapid population expansion, urbanization, and industrial development (Begum et al. 2020). Moreover, the Malaysian economy subsidizes petroleum prices (Abdullah et al. 2009), encouraging further energy use by accelerating economic growth. In line with energy demand, Malaysia is experiencing an increasing trend of CO_2 emissions. Figure 1 presents the annual trend of CO_2 emissions in Malaysia. Total CO_2 emissions in 1960 were about 568 Kilotons (kt) which increased gradually to 56,190 kt in 1990. Due to rapid industrialization, total CO_2 emissions in Malaysia increased drastically to 265,971 kt in 2019. From 1971 to 2019, Malaysia's average yearly increase rate of CO_2 emissions was 4.6%. Furthermore, Fig. 2 depicts the major sources of CO_2 emissions in Malaysia for 2014. Energy industries are the main culprit of CO_2 emissions in Malaysia, followed by transport, manufacturing, and cement production (MNRE 2018). Therefore, the country is highly concerned about the growing emission intensity, especially from the energy sector. Consequently, lowering CO_2 emissions has become a key priority in Malaysia to preserve environmental sustainability and mitigate the harmful effects of climate change.

Malaysia is the 4th biggest economy in Southeast Asia. The Malaysian economy is growing swiftly due to strong worldwide demand for electronics, rising demand for commodities such as oil and gas, an improved labor market, a pro-cyclical budget, and significant infrastructure expenditure. Since the 1970s, Malaysia's economy has been among the world's fastest-growing (Begum et al. 2020). Malaysia transitioned from a resource-based economy in the 1970s to a multi-sector economy in the 1990s, focusing on manufacturing and services (Begum et al. 2020). During the periods 1970–1980 and 1980–1990, Malaysia's economy grew at an average rate of 7.7% and 5.8%, respectively. Malaysia has seen significant economic growth during the previous thirty years. From 1990 to 2019, the average rate of economic growth was about 6.5%. Figure 3 presents the annual trend of economic growth in Malaysia. GDP in Malaysia was nearly RM40 billion in 1960, which increased to RM1.42 trillion in 2019. The services sector grew at the fastest rate, accounting for 57.7% of GDP, followed by the manufacturing (22.3%) and agriculture sectors (8.2%) (DOSM 2020). Primary industries like crude oil, palm oil, tin, rubber, and their production and export have made significant contributions to the country's socioeconomic growth. Malaysia's

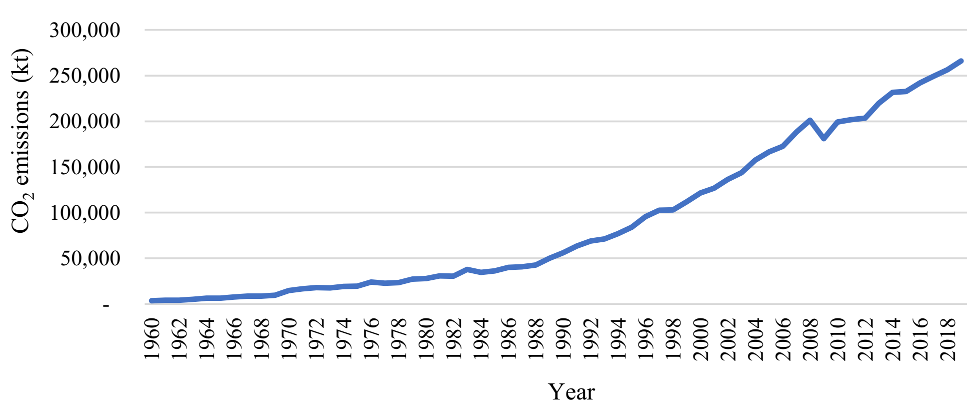

Fig. 1 Annual trend of CO_2 emissions in Malaysia Source: World Bank (2021)

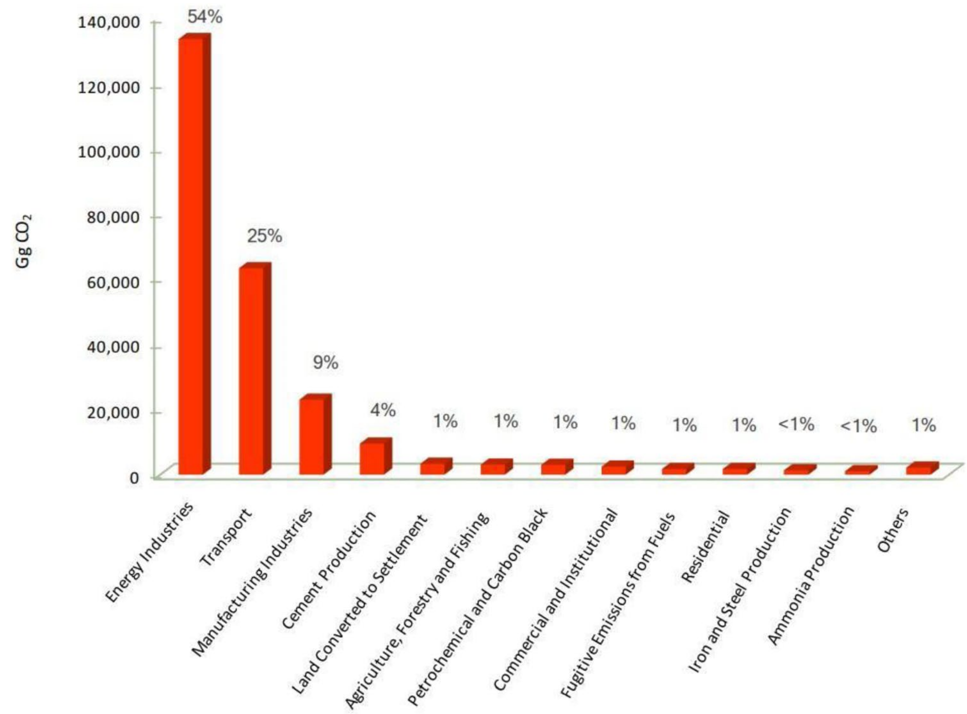

Fig. 2 The major sources of CO_2 emissions in Malaysia for 2014 Source: MNRE (2018)

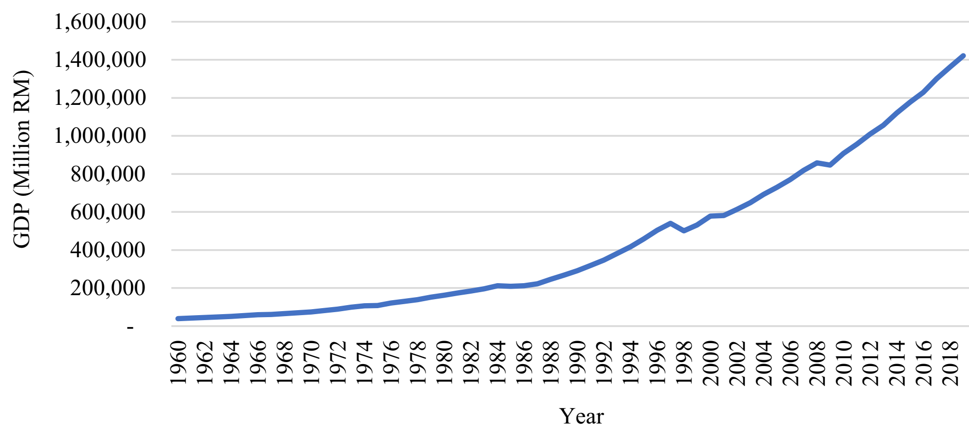

Fig. 3 Annual trend of economic growth in Malaysia Source: World Bank (2021)

economic development has only slowed since 1990, in 1998, due to the Asian financial crisis, and then again in 2008 and 2009, amid the global economic downturn (Begum et al. 2020).

Numerous studies have been carried out to determine the link between environmental and economic activities for various countries. For example, Adebayo (2021a) for Japan, Ali et al. (2017) for Singapore, Adebayo and Kalmaz (2021) for Egypt, Ahmed et al. (2019) for China, Adebayo and Akinsola (2021) for Thailand, Kirikkaleli and Kalmaz (2020) for Turkey, Adebayo and Odugbesan (2021) for South Africa, Bouznit and Pablo-Romero (2016) for Algeria, Adebayo (2020) for Mexico, Akbota and Baek (2018) for Kazakhstan, Adebayo (2021b) for Indonesia, Vo et al. (2019) for ASEAN countries, Wang et al. (2020) for G7 countries, Teng et al. (2020) for OECD countries, Pao and Tsai (2010) for BRIC countries, and Al-Mulali (2011) for MENA countries. In the Malaysian economy, however, several studies have discovered the environmental Kuznets curve (EKC), which indicates that increasing economic growth improves environmental quality (Hossain 2011; Saboori et al. 2012; Hitam and Borhan 2012; Begum et al. 2015; Bekhet and Othman 2017; Azam et al. 2018; Sharif et al. 2020; Zhang et al. 2021). According to Panayotou (2000), economic development is not necessary for environmental devastation, but policies and institutions must address the issues.

The growing concern about global warming, GHGs emissions, and rising fossil fuel prices suggests that achieving energy sustainability would likely result in a cleaner environment. Renewable energy offers several advantages over traditional energy. They come from natural resources and may be renewed regularly. Renewable energy, moreover, has a low environmental effect since it creates little or no waste products like CO_2 and other pollutants. Hence, it may offer a solution to global warming and energy security (Sebri and Ben-Salha 2014). However, renewable energy not only reduces CO_2 emissions but also contributes to increased economic prosperity. Furthermore, renewable energy reduces dependency on imported fossil fuel energy and increases the availability of reliable electricity (Sebri and Ben-Salha 2014). As a result, many countries began to transition away from fossil fuels and toward more renewable energy sources (Aziz et al. 2020; Liu et al. 2021). Global renewable energy usage has increased by more than 60%, from 353 million tons of oil equivalent (Mtoe) in 1995 to 579 Mtoe in 2014 (Liu et al. 2021). Furthermore, renewable energy accounted for approximately 70% of net increased global power capacity in 2017, with a new investment of 279.8 billion USD. Thus, renewable energy use appears to have a significant global impact on achieving the Paris Agreement's and Sustainable Development Goals' goals.

However, Malaysia has abundant renewable energy resources, such as forest residues, oil palm biomass, mill residues, hydropower, solar thermal, solar photovoltaic, municipal waste, rice husk, and landfill gas (Sulaiman et al. 2013). In 2001, Malaysia's government designated renewable energy as the country's fifth fuel source as part of the country's efforts to secure long-term energy supply and satisfy the country's rising demand. Since then, work on developing the legal, regulatory, and financial framework has begun to meet the renewable energy generation objectives that have been set (Chachuli et al. 2021). The annual trend of renewable energy use in Malaysia is presented in Fig. 4. In 1990, renewable energy accounted for about 12% of the total final energy consumption, but by 2010, that figure had dropped to under 4%. However, since 2010, with the adoption of several policy programs, Malaysia's renewable energy use has steadily increased, reaching 6% of total final energy use in 2018.

Several studies reported that CO_2 emissions could be reduced by increasing renewable energy use by using econometric approaches. Liu (2020) reported that renewable energy use would reduce CO_2 emissions in China. Baek (2016) reported that using renewable energy reduces CO_2 emissions in the United States. Bölük and Mert (2015) highlighted the potential of renewable energy sources in reducing emissions in Turkey. Sugiawan and Managi (2016) reported that boosting renewable energy use in Indonesia might reduce CO_2 emissions. Danish et al. (2017) and Waheed et al. (2018) reported that renewable energy has a major role in lowering CO_2 emissions in Pakistan. Jebli and Youssef (2015) reported that increasing renewable energy usage in Tunisia decreases CO_2 emissions. Al-Mulali et al. (2016) reported that renewable energy reduces CO_2 emissions in Kenya. Sharif et al. (2020) found a strong negative relationship between renewable energy use and environmental deterioration in China, the USA, Japan, Canada, Brazil, South Korea, and Germany. Dogan and Seker (2016) reported that increases in renewable energy consumption reduce carbon emissions in the top renewable energy countries. Khan et al. (2017) reported that increasing renewable energy consumption is good for the environment and reduces the use of traditional energy sources in Europe. For 25 African nations, Zoundi (2017) found that renewable energy hurt CO_2 emissions. Irandoust (2016) reported that renewable energy increases environmental well-being in Nordic nations. Paramati et al. (2017) reported that renewable energy usage significantly decreases CO_2 emissions in G20 nations. Liu et al. (2017) suggest that economic growth and renewable energy negatively influence CO_2 emissions in the BRICS. Furthermore, according to Dong et al. (2017), renewable energy might serve as a cleaner alternative for other fossil fuels, resulting in considerable CO_2 emissions reductions for the BRICS countries. Shafiei and Salim (2014), Bilgili et al. (2016), and Jebli et al. (2016) reported that renewable

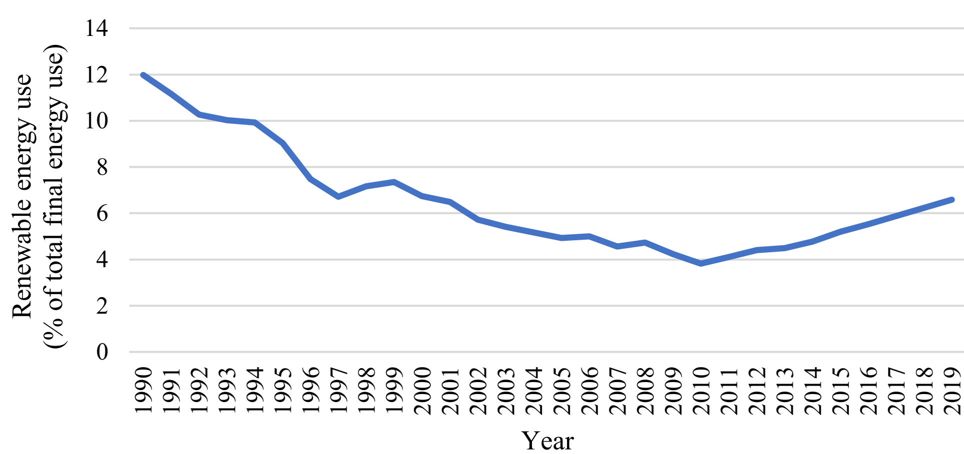

Fig. 4 Annual trend of renewable energy use in Malaysia Source: World Bank (2021)

energy consumption reduces CO_2 emissions in OECD countries. Ito (2017) reported that renewable energy contributes to emissions reductions in 42 developing nations. Bhattacharya et al. (2017) reported that the increased use of renewable energy has a considerable negative impact on CO_2 emissions in 85 developed and developing economies throughout the world. Zhang and Liu (2019) reported that the expansion of renewable energy helps improve the environment in Asian countries. However, there are limited studies in Malaysia to explore the potential of renewable energy use to reduce environmental degradation. Sulaiman et al. (2013) reported the potential of renewable energy to assure the sustainability of power supply and limit CO_2 emissions in Malaysia.

Furthermore, technological innovation is critical for increasing energy efficiency. Advanced technologies enable the economy to achieve a certain amount of production while consuming less energy (Sohag et al. 2015). In addition, technical progress allows the economy to transition from depletable to renewable energy sources to fulfill energy demands. As a result, technological innovations cut energy consumption and CO_2 emissions from the burning of fossil fuels. With the rapid economic expansion, Malaysia has seen a lot of technical innovation. Figure 5 depicts the trend of technological innovation in Malaysia (as assessed by the number of patents). Following a surge in patent applications in 1997, Malaysia's patent application submissions began to decline in 2007. Figure 5 indicates that the number of patents rose dramatically between 1985 and 2019, suggesting considerable technical innovation occurred in Malaysia. Thus, it is essential to track the dynamic effects of technology advancement on CO_2 emissions.

According to the endogenous economic growth hypothesis, increased research and development (R&D) spending can enhance economic production efficiency and resource usage efficiency. However, the impact of technology advancements on environmental quality, particularly CO_2 emissions, remains unknown (Chen and Lee 2020). According to Kumar and Managi (2009), technological innovation lowered CO_2 emissions in rich countries while increasing CO_2 emissions in most developing countries. According to Chen and Lee (2020), technical innovation in high-income nations efficiently decreases CO_2 emissions and is thus considered environmentally beneficial green technology innovation. Several studies have shown that technological innovation reduces CO_2 emissions. According to Ahmed and Ozturk (2018), Zhang et al. (2019), Khan et al. (2019), and Shahbaz et al. (2020), China's technological innovation efficiency have a significant positive impact on environmental performance. According to Ang (2008), CO_2 emissions in China are adversely connected to research intensity, technology transfer, and the economy's ability to absorb foreign technology. Lin and Zhu (2019) also claim that renewable energy-driven innovation in China decreases carbon dioxide emissions. Rahman et al. (2019) reported that the adoption of clean technology by international businesses might enhance environmental quality in Pakistan by lowering carbon emissions. Ahmed et al. (2016) reported that technological innovation improves environmental quality by reducing CO_2 emissions in 24 European nations. According to Churchill et al. (2019), technical advancements in G7 nations improve environmental quality. Ganda (2019) reported that clean energy consumption and R&D spending assist OECD nations in reducing CO_2 emissions. It is now commonly acknowledged that technical advancements play a significant role in lowering GHG emissions while maintaining economic growth; as a result, any improved understanding of the process of technological innovation is likely to expand our knowledge of mitigation options (Bosetti et al. 2008). Despite this hopeful development, the mechanisms of knowledge accumulation remain a mystery, and the true potential of technological innovation is yet unknown.

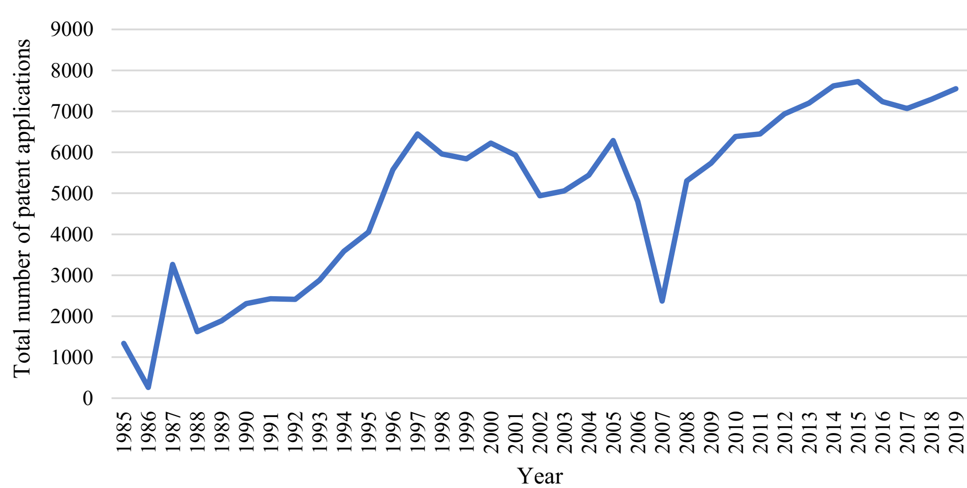

Fig. 5 Annual trend of the number of patent applications representing technological innovation in Malaysia

3 Methodology

3.1 Study design and settings

3.1.1 Data

This study provides an empirical analysis of the dynamic impacts of economic growth, renewable energy use, and technological innovation on CO_2 emissions in Malaysia by employing the dynamic ordinary least squared (DOLS) approach of cointegration by Pesaran and Shin (1995) and Pesaran et al. (2001). Time-series data from 1990 to 2019 for Malaysia were obtained from the World Development Indicator (WDI) dataset. This research considers CO_2 emissions as the dependent variable while economic growth, renewable energy use, and technological innovation as explanatory variables. This study measures CO_2 emissions as kilotons (kt), economic growth as GDP (constant local currency unit), renewable energy use as the percentage of total final energy use, and technological innovation as the total number of patent applications (residents and non-residents). It ought to be noted that technological innovation refers to a country's industrial and commercial organizations' interest in finding new technology, which can be measured using a quantitative metric such as the number of patents (Tang and Tan 2013). Patenting activities may be used as a proxy for technological innovation since green patents are the codified form of technology. Growth in patent applications indicates that industries and private groups are interested in utilizing new and green technology (Fei et al. 2014). Lastly, the variables are transformed into a logarithm to ensure that data are normally distributed. The variables with their logarithmic forms, measurement units, and data sources are presented in Table 1.

3.1.2 Empirical model

Theoretically, CO_2 emission is associated with income. Assuming the market clearing condition, where CO_2 emissions equal economic growth, the following function is written within the framework of the standard Marshallian demand (Friedman 1949) function at time *t* as:

$$\mathrm{CO}_{2_t} = f(\mathrm{GDP}_t), \tag{1}$$

$\mathrm{CO}_{2t} = f\left(\mathrm{GDP}_t; \mathrm{RNE}_t; \mathrm{TI}_t\right)$, where, CO_{2t} is the CO_2 emissions at time *t*, and GDP_t is the economic growth at time *t*.

Furthermore, this study intends to estimate the influence of renewable energy use on CO_2 emissions. Hence, Eq. (1) can be as follows:

$$\mathrm{CO}_{2t} = f\left(\mathrm{GDP}_t; \mathrm{RNE}_t\right), \tag{2}$$

where RNE_t is the renewable energy use at time t.

Based on the discussion in the introduction section, technological innovation can influence energy use in many ways; therefore, this study considers technological innovation in the model. Sohag et al. (2015) revealed that technological innovation is a crucial factor in spurring economic growth by accelerating factor productivity and ensuring energy efficiency. This study focuses on whether technological innovation reduces CO_2 emissions. This research measures technological innovation as the total number of patent applications following the empirical studies of Ang (2008); Madsen et al. (2010); Tang and Tan (2013); Bonilla et al. (2014); Fei et al. (2014); Sohag et al. (2015); Ahmed et al. (2016); Fan and Hossain (2018); Wu et al. (2018); and Villanthenkodath and Mahalik (2020). Therefore, it could be assumed that the parameter of the partial change in CO_2 emissions due to changes in technology should be negative.

The present study used the following economic functions to determine the interaction between CO_2 emissions, economic growth, fossil fuel energy use, renewable energy use, and technological innovation:

$$\mathrm{CO}_{2t} = f\left(\mathrm{GDP}_t; \mathrm{RNE}_t; \mathrm{TI}_t\right), \tag{3}$$

where TI_t is the number of patent applications at time t.

The next equation depicts the empirical model:

$$\mathrm{CO}_{2t} = \tau_0 + \tau_1 \mathrm{GDP}_t + \tau_2 \mathrm{RNE}_t + \tau_3 \mathrm{TI}_t, \tag{4}$$

Equation (4) is further expanded as the econometric model in the following form:

$$CO_{2t} = \tau_0 + \tau_1 \mathrm{GDP}_t + \tau_2 \mathrm{RNE}_t + \tau_3 \mathrm{TI}_t + \varepsilon_t, \tag{5}$$

where τ_0 and ε_t stand for intercept and error term, respectively. In addition, τ_1, τ_2, and τ_3 denote the coefficients.

Moreover, Eq. (6) shows the logarithmic arrangement of Eq. (5):

Table 1 Variables with their logarithmic forms, units, and data sources

Variables	Description	Logarithmic forms	Units	Sources
CO_2	CO_2 emissions	LCO_2	Kilotons (kt)	WDI
GDP	Economic growth	LGDP	Ringgit Malaysia (RM)	WDI
RNE	Renewable energy use	LRNE	% of total final energy use	WDI
TI	Technological innovation	LTI	Number of patent applications	WDI

$$LCO_{2t} = \tau_0 + \tau_1 \mathrm{LGDP}_t + \tau_2 \mathrm{LRNE}_t + \tau_3 \mathrm{LTI}_t + \varepsilon_t, \quad (6)$$

where $\mathrm{LCO2}_t$ is the logarithmic form of CO_2 emissions at time t, LGDP_t is the logarithmic form of economic growth at time t, LRNE_t is the logarithmic form of renewable energy use at time t, and LTI_t is the logarithmic form of technological innovation at time t.

3.1.3 Flow chart of the analysis

The flow chart of the analysis techniques employed in the present study to explore the dynamic interaction of economic growth, renewable energy use, and technological innovation on CO_2 emissions in Malaysia is depicted in Fig. 6.

3.2 Stationarity techniques for data

Conducting a unit root test is essential to avoid erroneous regression. It verifies that variables included in regression are stationary by differencing them and using the stationary processes in estimating the equation of interest (Mahadeva and Robinson 2004). The unit root test was used in this study to ensure that no variables violated the sequence of integration and to justify using the DOLS approach over traditional cointegration techniques. The obligation to determine the order of integration before investigating cointegration among the variables is recognized in the empirical literature. According to some studies, it is critical to use more than one unit root test to evaluate the integration order of the series since unit root tests have different potency depending on the sample size (Saboori et al. 2017; Adebayo et al. 2021). Therefore, we applied the Augmented Dickey-Fuller (ADF) test introduced by Dickey and Fuller (1979), Dickey-Fuller generalized least squares (DF–GLS) test suggested by Elliott et al. (1992), and Phillips-Perron (*P–P*) test proposed by Phillips and Perron (1988) to detect the autoregressive unit root.

3.3 DOLS cointegration test

This research utilized DOLS, an extended equation of ordinary least squares estimation, to evaluate the time-series

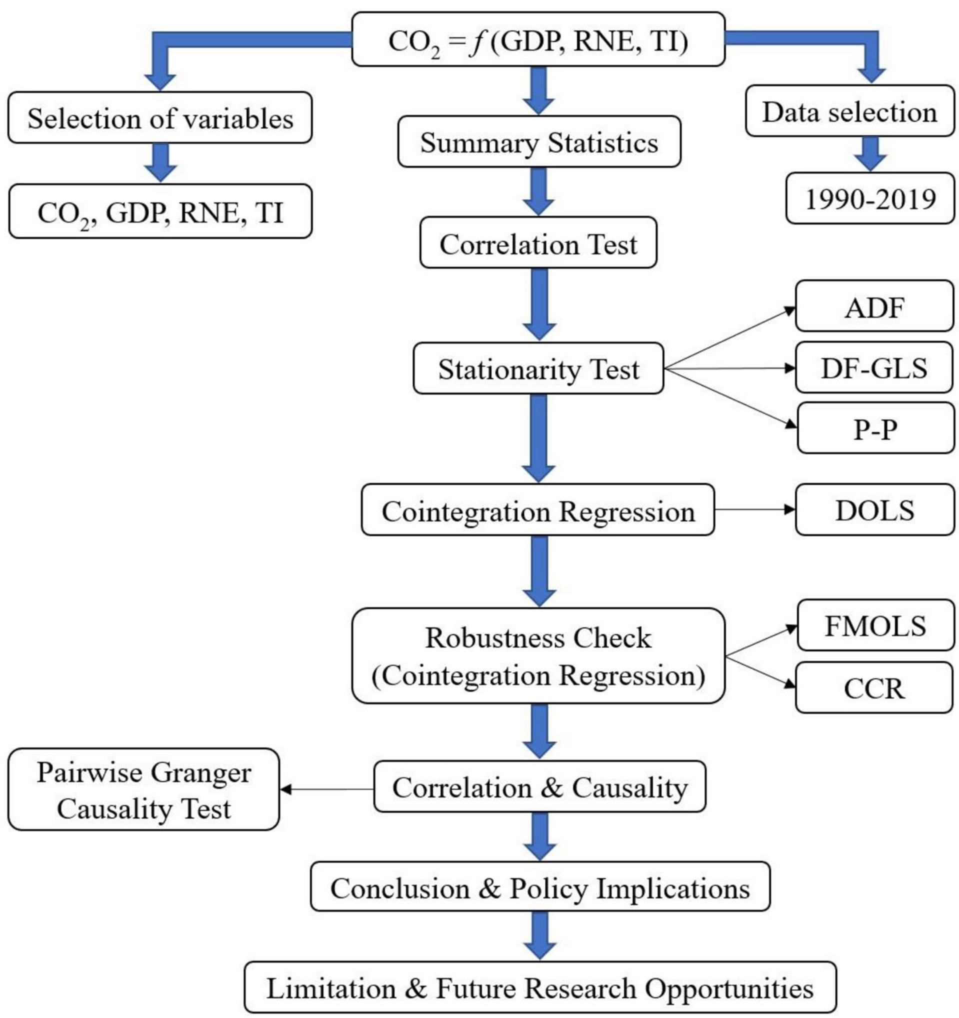

Fig. 6 Flow chart of the analysis techniques employed in the present study

data. It contains explanatory factors and leads and lags of their initial difference terms to regulate endogeneity and to calculate the standard deviations using a covariance matrix of errors resistant to serial correlation. The inclusion of the different terms' leads and lags confirms that the error term is orthogonalized. The standard deviations of the DOLS estimators provide a valid test for the statistical significance of the variables because they have a normal asymptotic distribution (Wang 2012). When a mixed order of integration occurs, the DOLS approach effectively allows individual variables in the cointegrated outline to be integrated by estimating the dependent variable on explanatory variables in levels, leads, and lags.

The DOLS estimation's main advantage is the mixed order integration of individual variables in the cointegrated outline. For example, in DOLS estimation, one of I(1) variables was regressed against other variables, some of which were I(1) variables with leads (p) and lags (− p) of the first difference. In comparison, others were I(0) variables with a constant term (Alcantara and Padilla 2009). As a result of aggregating the leads and lags among explanatory variables, this estimate solves slight sample bias, endogeneity, and auto correlation issues (Stock and Watson 1993). The DOLS test by the present study is depicted as follows in Eq. (7):

$$\begin{aligned}\Delta LCO2_t = {} & \tau_0 + \tau_1 LCO2_{t-1} + \tau_2 LGDP_{t-1} + \tau_3 LRNE_{t-1} + \tau_4 LTI_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LCO2_{t-i} \\ & + \sum_{i=1}^{q} \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LRNE_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LTI_{t-i} + \varepsilon_t,\end{aligned} \tag{7}$$

where Δ is the first difference operator and q is the optimum lag length in Eq. (7).

3.4 Cointegration regression to check the robustness of DOLS estimation

We employed the fully modified OLS (FMOLS) proposed by Hansen and Phillips (1990) and Park's (1992) Canonical Cointegrating Regression (CCR) to ensure the robustness of DOLS outcomes. The FMOLS approach modifies least squares to account for serial correlation repercussions and endogeneity in the independent variables caused by the existence of cointegrating interaction. Polynomial regression of deterministic variables, stationary error, and integrated processes were all made easier. The errors can be connected serially, and the regressors can be endogenous. The FMOLS method is capable of estimating non-stationary I(1) data where it can use standard regression techniques (OLS) of the non-stationary (unit root) data to add to the problem of spurious regressions. Moreover, the CCR technique entails data transformation using only the stationary component of a cointegrating model. After such data transformation, a cointegrating link provided by the cointegrating model will stay unaffected. In a cointegrating model, the CCR transformation makes the error term uncorrelated with regressors at zero frequency. Consequently, the CCR approach produces asymptotically efficient estimators and asymptotic chi-square tests that are free from nuisance parameters. By analyzing the influence of serial correlation, asymptotic coherence can be obtained using FMOLS and CCR approaches. Therefore, long-term elasticity is assessed in this research by utilizing FMOLS and CCR estimators using Eq. (7).

3.5 Pairwise Granger causality

The present research intends to capture the causal effects between the variables. Therefore, we utilize the pairwise linear Granger causality test proposed by Granger (1969) to examine if there is a causal association between the variables. Granger causality is a statistical concept of causation based on a prediction that has several advantages over other time-series research approaches (Winterhalder et al. 2005) and is therefore used in this study. If a time-series Y can help predict the future of another time-series X, then Y "Granger-causes" X. The time series of these two variables have data length T, denoting their values at time t by X_t and Y_t (t = 1,2,…,T), respectively. However, X_t and Y_t can be modeled by a bivariate autoregressive model:

$$X_t = \sum_{l=1}^{p} \left(a_{11,l} X_{t-l} + a_{12,l} Y_{t-l} \right) + \varepsilon_t, \tag{8}$$

$$Y_t = \sum_{l=1}^{p} \left(a_{21,l} X_{t-l} + a_{22,l} Y_{t-l} \right) + \xi_t, \tag{9}$$

where p is the model order, $a_{ij,l}$ (i,j = 1,2) are coefficients of the model, and ε_t and ξ_t represent residuals. Ordinary least squares can estimate the coefficients, and the Granger causality between X and Y can be detected by F tests (Tam and Chang 2013).

Table 2 Summary statistics of the variables

Variables	LCO2	LGDP	LRNE	LTI
Mean	11.87185	27.27076	1.820436	8.552015
Median	11.99460	27.29024	1.757384	8.680641
Maximum	12.49114	27.98270	2.483284	8.952476
Minimum	10.93649	26.39816	1.340000	7.742836
Std. Dev	0.467520	0.449577	0.318560	0.381797
Skewness	− 0.476756	− 0.193111	0.562669	− 0.105425
Kurtosis	1.984539	2.060428	2.291031	2.627306
Jarque–Bera	2.425434	1.289954	2.211281	2.116429
Probability	0.297388	0.524675	0.330999	0.046971
Sum	356.1556	818.1227	54.61307	256.5604
Sum Sq. Dev	6.338665	5.861458	2.942936	4.227299
Observations	30	30	30	30

Table 3 The results of the correlation analysis

	LCO2	LGDP	LRNE	LTI
LCO2	1.000000	0.987623	− 0.851639	0.747026
LGDP	0.987623	1.000000	− 0.782246	0.765253
LRNE	− 0.851639	− 0.782246	1.000000	− 0.638969
LTI	0.747026	0.765253	− 0.638969	1.000000

4 Empirical Findings

4.1 Summary statistics

The outcomes of the summary measures amid variables are shown in Table 2 together with the statistical estimates of different normality tests (skewness, probability, kurtosis, and Jarque–Bera) used. Each variable includes 30 observations of time-series data from 1990 to 2019 for Malaysia. The values of skewness by the variables are close to zero, implying that all the variables adhere to normality. Furthermore, the research employed kurtosis to evaluate if the series is light-tailed or heavy-tailed compared to a normal distribution. The empirical findings indicate that all the series are platykurtic as their values are less than three. In addition, the Jarque–Bera probability results reveal that all the parameters are normal. The unit root test for stationarity of the variables and further analysis of the DOLS estimation is based on these statistics.

4.2 Correlation between the variables

Correlation analysis to test for linear relationships between the variables is presented in Table 3. The results reveal that all the variables are correlated to one another. LCO_2, LGDP, and LTI indicate a robust and positive correlation, which implies that when the value of one variable increases, the value of the other variable also tends to increase and vice versa. However, LRNE shows a negative correlation with LCO_2, LGDP, and LTI, which reveals that when the value of renewable energy use increases, the other variable's value tends to decrease and vice versa.

4.3 Results of unit root tests

This study used the Augmented Dickey–Fuller (ADF), Dickey–Fuller generalized least squares (DF–GLS), and Phillips–Perron (*P–P*) unit root tests to check the data stationarity. The outcomes of the unit root tests by ADF, DF–GLS, and *P–P* are presented in Table 4. The findings of unit root tests show that LCO_2, LRNE, and LTI were found stationary at the level and remained stationary after taking the first difference in ADF and P-P tests. In contrast, they have been found non-stationary at the level and become stationary after taking the first difference in the DF-GLS test. In addition, LGDP was found non-stationary at the level but became stationary at the first difference in ADF and DF-GLS tests, while it has been found stationary at the level and remained stationary after taking the first difference in the *P–P* test. Hence, the occurrence of mixed orders integration for variables estimated by the ADF, DF-GLS, and *P–P* tests justify using the DOLS method.

4.4 DOLS outcomes

The outcomes of the DOLS estimated by using Eq. (7) are presented in Table 5. When other variables are held constant,

Table 4 The results of unit root tests

Logarithmic form of the variables		LCO_2	LGDP	LRNE	LTI
ADF	Log levels	− 2.8348**	0.5494	− 2.6898*	− 2.3364**
	Log first difference	− 5.1480***	− 3.9483***	− 3.2911**	− 5.9553***
DF-GLS	Log levels	− 0.1546	0.8857	− 1.1396	− 1.4943
	Log first difference	− 4.3382***	− 2.1431**	− 3.2830***	− 6.0676***
P-P	Log levels	− 7.2492***	− 1.9162**	− 2.4589**	− 2.2483**
	Log first difference	− 5.1561***	− 4.8207***	− 3.2911***	− 6.2034***

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively

Table 5 The outcomes of DOLS: dependent variable LCO2

Variables	Coefficient	Standard Error	*t*-Statistic	*p*-value
LGDP	0.875461***	0.037598	23.28499	0.0000
LRNE	– 0.296109***	0.035668	– 8.301767	0.0000
LTI	– 0.052112	0.030482	– 1.709600	0.1094
C	– 10.97381***	0.997077	11.00598	0.0000
R^2	0.997033			
Adjusted R^2	0.994491			
Standard error of the estimate	0.044519			
Long run variance	0.000531			
F-statistic	1104.454			
Prob (F-statistic)	0.000000			
Root mean square error (RMSE)	0.040560			

***, **, and * signify significance at the 1%, 5%, and 10% levels, respectively

the estimated coefficient of LGDP is positive and significant at a 1% level, implying that a 1% rise in economic growth would result in a 0.86% increase in CO_2 emissions. This finding reveals that economic development triggers environmental degradation in the long run. Furthermore, the estimated coefficient of renewable energy use is negative and significant at a 1% level, indicating that increased use of renewable energy by 1% is associated with reducing CO_2 emission by 0.3% in the long run. This reveals the emission reduction potential by expanding the use of renewable energy in Malaysia. In addition, the estimated long-run coefficient of technological innovation is negative, implying that a 1% increase in technical innovation results in a 0.05% reduction in CO_2 emissions. The DOLS results demonstrate that increased renewable energy use and technological innovation improve the environment by reducing carbon emission while economic growth deteriorates the environmental quality in Malaysia.

Moreover, it is noteworthy that the signs of the estimated coefficients are consistent both theoretically and practically. We also used a variety of diagnostic tests to assess the goodness of fit of our estimated model. First, the R^2 and adjusted R^2 values are 0.9970 and 0.9945, respectively, suggesting that the estimated regression model fits quite well. This means that the independent variables may account for 99% of the dependent variable's change variation. Second, the F- statistic indicates that the dependent and independent variables support the estimated DOLS regression. The F-statistic has a p-value of 0.0000, indicating that the model's linear relationship is statistically significant. Third, the root mean square error (RMSE) score is 0.0406 (near 0) and non-negative, indicating that the DOLS model's outputs are a near-perfect match to the data.

4.5 Robustness check

We utilized the FMOLS and CCR estimators to verify the consistency of DOLS estimation. The FMOLS and CCR estimation results for the model are presented in Table 6 and Table 7. The outcomes of FMOLS and CCR estimation provide evidence of the robustness of the DOLS estimation. The FMOLS and CCR estimation results confirmed the positive coefficient of economic growth, which is significant at a 1% level. Furthermore, both FMOLS and CCR estimation outcomes verified the negative coefficient of renewable energy use at a 1% level of significance. The results from FMOLS and CCR estimation further validate the inverse association between technological innovation

Table 6 The results of FMOLS: dependent variable LCO2

Variables	Coefficient	Standard Error	*t*-Statistic	*p*-value
LGDP	0.894965***	0.033479	26.73231	0.0000
LRNE	– 0.298103***	0.040099	– 7.434088	0.0000
LTI	– 0.042413	0.032486	– 1.305562	0.2036
C	– 11.62634***	0.848212	– 13.70688	0.0000
R^2	0.990817			
Adjusted R^2	0.989716			
Standard error of the estimate	0.044674			
Long run variance	0.001767			

***, **, and * signify significance at the 1%, 5%, and 10% levels, respectively and CO_2 emissions. Hence, it can be stated that economic growth increases CO_2 emissions in Malaysia while renewable energy use and technological innovation help to reduce CO_2 emissions. The outcomes of the FMOLS and CCR are duly in line with the findings from DOLS outcomes. The R^2 and adjusted R^2 values from FMOLS and CCR estimation reflect the model's goodness of fit.

4.6 Diagnostic inspection

We performed normality, heteroscedasticity, and serial correlation analysis to verify the intensity of the cointegration valuation. Table 8 shows the diagnostic test results. The model indicates normality and nonexistence of autocorrelation and heteroscedasticity. In addition, we employed the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMQ) test to check the stability of the model. The CUSUM and CUSUMQ plots at a 5% significance level are presented in Fig. 7. The values of the residuals are represented by blue lines, while the confidence levels are represented by red lines. At a 5% significance level, the calculated results show that the studied residuals' values remain within the lines of confidence, which confirms the model's stability.

4.7 Pairwise granger causality

The relationship between the variables indicates that there is the existence of Granger causality, which the F-statistic determines. The summary of pairwise Granger causality is presented in Table 9 including the causality direction between the variables, such as, left to right (→), right to left (←), and no causality (≠). The pairwise Granger causality

Table 7 The results of CCR: dependent variable LCO_2

Variables	Coefficient	Standard Error	*t*-Statistic	*p*-value
LGDP	0.903899***	0.040059	22.56420	0.0000
LRNE	− 0.288821***	0.045213	− 6.388004	0.0000
LTI	− 0.044472	0.031445	− 1.414289	0.1696
C	− 11.86808***	1.051169	− 11.29037	0.0000
R^2	0.990701			
Adjusted R^2	0.989585			
Standard error of the estimate	0.044957			
Long run variance	0.001767			

***, **, and * signify significance at the 1%, 5%, and 10% levels, respectively

Table 8 The results of diagnostic tests

Diagnostic tests	Coefficient	*p*-value	Decision
Jarque–Bera test	2.072585	0.0176	Residuals are normally distributed
Breusch–Godfrey LM test	47.97189	0.0000	No serial correlation exits
Breusch–Pagan–Godfrey test	14.42781	0.0000	No heteroscedasticity exists

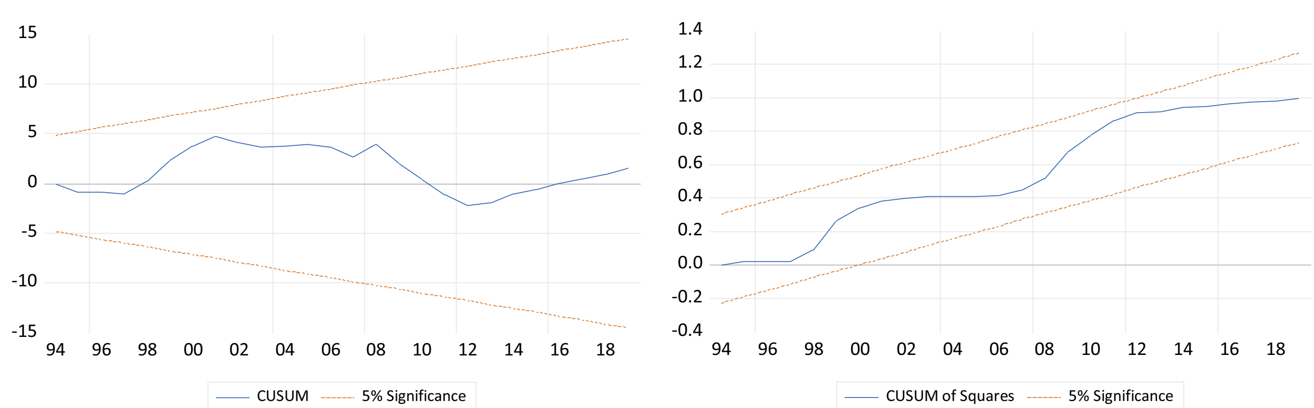

Fig. 7 Plot of CUSUM and CUSUMQ (critical bounds at 5% significance level)

Table 9 The results of pairwise Granger causality test

Null Hypothesis	*F*-statistic	Decision on N-Hypothesis	Causality Direction
LGDP does not granger cause LCO_2	0.56655**	Reject	LGDP→LCO_2
LCO_2 does not granger cause LGDP	0.47761	Accept	
LRNE does not granger cause LCO_2	0.00237	Accept	LRNE≠LCO_2
LCO_2 does not granger cause LRNE	2.36021	Accept	
LTI does not granger cause LCO_2	0.05415	Accept	LTI≠LCO_2
LCO_2 does not granger cause LTI	2.22135	Accept	
LRNE does not granger cause LGDP	1.12833	Accept	LRNE←LGDP
LGDP does not granger cause LRNE	3.82443*	Reject	
LTI does not granger cause LGDP	2.70189	Accept	LTI←LGDP
LGDP does not granger cause LTI	3.19184*	Reject	
LTI does not granger cause LRNE	1.55544*	Reject	LTI→LRNE
LRNE does not granger cause LTI	0.40424	Accept	

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively

test results reveal unidirectional causality from LGDP to LCO_2, LGDP to LRNE, and LGDP to TI, due to statistical significance leading to the rejection of the null hypothesis. This indicates that economic growth causes CO_2 emissions, economic growth causes renewable energy use, economic growth causes technological innovation, and technological innovation causes renewable energy use in Malaysia. The results suggest that economic prosperity can stimulate the increase in renewable energy use and technological innovation. Economic growth is critical for expanding the renewable energy sector because it provides the resources needed to study and develop renewable energy technologies and infrastructure. However, the pairwise Granger causality test indicates no causal relationship of CO_2 emissions with renewable energy use and technological innovation. Figure 8 presents the causality between the examined variables.

5 Discussion

The present study investigates the interconnection between economic growth and environmental pollution for the case of Malaysia, and the empirical results showed that economic development exerts a positive and significant impact on CO_2 emissions in the long run. The outcome indicates that a decrease in environmental sustainability accompanies an increase in economic growth. The fact that fossil fuels, which produce both environmental damage and economic growth, are the major sources for industry and agriculture in Malaysia causes the positive influence of economic expansion on CO_2 emissions (Begum et al. 2020). Since industrial growth is linked to infrastructure expansion, trade creation, and economic capitalization, which favorably impact investment and company production, increasing oil consumption,

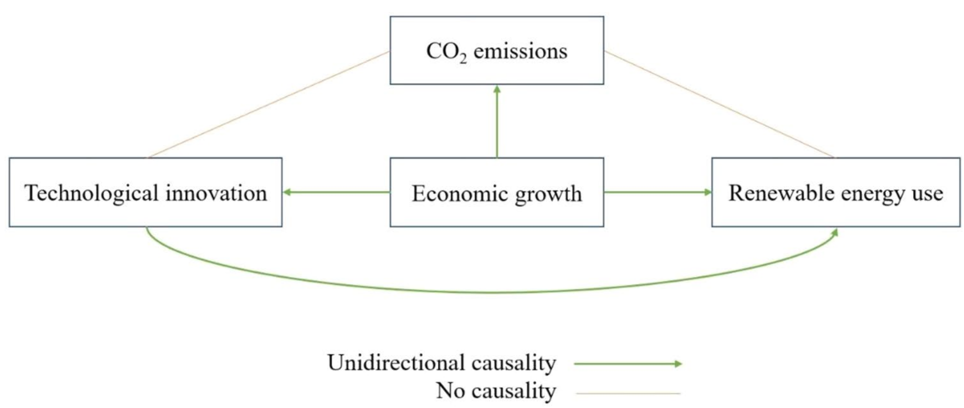

Fig. 8 Granger causality between the examined variables Source: World Bank (2021)

emissions have begun to rise in Malaysia (Adebayo and Odugbesan 2021). Furthermore, fundamental economic shifts, such as moving from rural to industrial activities, are primarily responsible for this effect. Malaysia's economy is currently moving to the services sector, which consumes a lot of energy. Furthermore, faster economic expansion implies more rapid urbanization and higher energy consumption, both of which increase CO_2 emissions owing to the misuse or misallocation of non-renewable energy sources (Begum et al. 2017). According to Adebayo and Akinsola (2021), rising economic growth is associated with greater environmental pollution. It adds to more societal demands being satisfied through consumption and development activities, resulting in more pollution, waste, and environmental deterioration. Thus, economic activities appear acceptable for environmental protection and development rather than constituting a danger to long-term environmental quality (Wang et al. 2020). Malaysia's most pressing task is to promote economic development while lowering CO_2 emissions (CO_2 accounted for three-quarters of GHG emissions). Hence, unless the economy significantly converts to employing low-carbon technology for manufacturing products and services, the capacity to reach a 45% decrease in emission intensity may be jeopardized (Zhang et al. 2021). Solid policies and methods to minimize reliance on fossil fuel supplies, energy intensity, and CO_2 emissions are required to achieve sustainable development.

This study attempts to examine the possibilities of renewable energy resources in Malaysia for lowering GHG emissions. According to our empirical result, renewable energy usage appears to have a critical role in lowering CO_2 emissions in Malaysia. The estimates demonstrate that renewable energy consumption has a negative and significant impact on CO_2 emissions, implying that increasing renewable energy sources in the total energy mix can help Malaysia reduce CO_2 emissions. The findings are consistent with Sulaiman et al. (2013); Shafiei and Salim (2014); Jebli and Youssef (2015); Bölük and Mert (2015); Al-Mulali et al. (2016); Baek (2016); Bilgili et al. (2016); Irandoust (2016); Jebli et al. (2016); Dogan and Seker (2016); Sugiawan and Managi (2016); Bhattacharya et al. (2017); Danish et al. (2017); Dong et al. (2017); Ito (2017); Liu et al. (2017); Paramati et al. (2017); Khan et al. (2017); Zoundi (2017); Waheed et al. (2018); Zhang and Liu (2019); Liu (2021); and Sharif et al. (2020) suggest that renewable energy leads to environmental improvements. In addition, Chachuli et al. (2021) reported that renewable energy development for power generation had a beneficial environmental impact on Malaysia. CO_2 emissions are falling in tandem with the country's renewable energy growth. Malaysia effectively decreased up to 0.16% of CO_2 emissions from renewable energy generation by 2.77 million tonnes over seven years during the renewable energy policy transition from 2012 to 2018 (Chachuli et al. 2021).

Malaysia has many green energy sources that can be developed such as solar, hydro, wind, geothermal, tidal waves, biomass, and biodiesel. Solar energy has been one of the rising green technologies in the renewable energy industry for Malaysia. Solar energy is an elegant means of producing electricity directly from the sun, without the concern for fuel supply or environmental impact. It is renewable, clean, and does not emit pollutants in the process of electricity generation. Practically, solar power devices can be designed for a variety of applications or operational requirements, either centralized or distributed power generation. Malaysia, located in the wet and humid tropics, with a hot climate coupled with temperature averages of 25 °C, is favorable for the development of solar energy. According to the report documented by the Ministry of Energy, Water and Communications, an installation of the solar photovoltaic system in Malaysia would produce energy of about 900–1400 kWh per year, and the areas located in the Northern and Eastern regions demonstrate the highest potential for solar energy application. The most significant project is the Green Energy Office (GEO) building, an administration-cum-research office integrated with photovoltaics panels to provide electricity for the building uses, during the peak daylight hours.

Hydroelectricity is a renewable energy source contributing 6% to the world energy supply, and 2.8% of Malaysia's total electricity requirements. With a fair amount of sunshine, and a high rainfall rate well distributed throughout the year, Malaysia poses an ideal and substantial potential for hydropower generation. The hydropower potential in Malaysia is estimated at 29,000 MW, with 85% located in East Malaysia; however, only 2000-MW of the resource has been fully utilized. This is basically due to the high capital investment required for its development. Furthermore, wind energy is a green power technology with minimal environmental impact that has significant potential to promote the building of tourist resort islands in the long term (Foo 2015). However, the current utilization of wind energy in Malaysia is limited and depends on the availability of wind resources that varies with location. Moreover, ocean energy is another promising renewable energy source available in Malaysia that can be harnessed into the form of ocean current, waves, tides, thermal difference, and salinity gradient. East Malaysia has a great potential for tidal energy extraction, with total electricity of 14.5 GWh/year. This implementation could save natural gas and avoid the emission of 4.5 million tons of GHG per year. Furthermore, Malaysia has been seriously considered nuclear potential as a stable base for power generation. Despite its prominent role to serve as a clean and valuable source of energy, its wide-scale development is retarded by the high capital cost. In addition, green hydrogen is beginning to attract more attention from both policymakers and investors because of its long-term sustainability.

Moreover, about 60% of the total land area in Malaysia is still being forested, while 15% is applied for agriculture activities. The expansion of the palm oil industry is expected to generate huge quantities of biomass wastes that are planning to use as a potential source of renewable energy. Due to the huge volume of oil palm availability, palm biomass exerts high green potential as an indigenous, affordable, and clean source of energy for system heating or power generation. Additionally, Malaysia holds a large volume of wood biomass, with only 60–65% of the residues having been harvested for energy. Furthermore, with a significant portion of organic compounds, a high potential energy resource, known as landfill gas (biogas) is naturally produced in Malaysia from the anaerobic degradation at waste management facilities. This gas can be used for power generation, transportation, and cooking. Moreover, being the world's largest producer and exporter of oil palm, Malaysia emerged as one of the pioneers in the palm biodiesel industry. The current installed biodiesel production capacity is about 10.2 million tons and there are several active biodiesel plants to be installed, expected to commence another commercial production of 1.49 million (Foo 2015). The development of bioethanol is another efficient and new idea for the Malaysian fuel industry. Among the numerous types of renewable energy, ethanol derived from biomass, or second-generation bioethanol, is currently the most advanced environmentally friendly biofuel, which offers greater promise in replacing fossil fuels as it does not compete with the human food supply. Malaysian oil palm empty fruit bunches are being used for bioethanol production since 2015, substituting about 2% of the Malaysian petrol consumption. Since the country is bestowed with abundant agricultural resources, palm-based bioethanol with high viability in transportation systems is still the main focus of practical interest.

However, Malaysia's average percentage of renewable energy in overall primary energy use is only about 6%, which is lower than the worldwide average of 18% (World Bank 2021). The lower levels of renewable energy consumption in Malaysia could not significantly promote economic growth and emission reduction. As a result of the growing global environmental consciousness, it is essential to shift Malaysia's energy balance to renewables to enable sustainable energy sources and build an environmentally healthy ecosystem. Infrastructure concerns and institutional and administrative structures may provide a barrier to renewable energy implementation. The presence of these impediments can either prohibit the implementation or result in higher-than-expected expenses. Moreover, due to monopsony power and knowledge asymmetries, as well as financial and technical constraints, Malaysia's renewable energy market is not effective. Hence, overcoming these roadblocks is critical to adopting renewable energy (Bhattacharya et al. 2017). However, the Malaysian government aimed to increase renewable energy's contribution to the national energy mix to 20% by 2025. This policy has initiated programs to expand the national accessibility of renewable energy (Chachuli et al. 2021). The Malaysian government is now working on the Renewable Energy Transition Roadmap, aiming to achieve a national objective of 25% renewable energy by strengthening existing renewable energy programs and examining new techniques for scaling up renewable energy projects (Chachuli et al. 2021). The new renewable energy target will maintain the country's energy supply continuity and lessen the environmental burden caused by the country's excessive reliance on the fossil-fuel-based energy system.

Our study reveals the unidirectional causality from economic growth and technological innovation to renewable energy use, indicating that economic growth and modern technologies cause renewable energy use. Azlina et al. (2014) support our finding, discovering unidirectional causality running from economic growth to renewable energy consumption in Malaysia. Economic growth stimulates modern technologies to increase the use of more renewable energy sources. Instead, the government's comprehensive renewable energy promotion plan has elevated the renewable energy industry to a vital economic sector, contributing significantly to the country's socioeconomic and long-term progress. Furthermore, the development of renewable energy has made significant contributions to climate change mitigation, the energy sector, banking and finance, and, most significantly, people's well-being through creating jobs, affordability, and a cleaner environment (Chachuli et al. 2021). Malaysia plans to increase the share of renewable energy in its installed capacity to 31% in 2025 and 40% in 2035 under its power generation plan. Continuous economic expansion is likely to stimulate the supply of renewable energy by providing the resources needed to study and develop renewable energy technologies and infrastructure, resulting in a reduction in CO_2 emissions in Malaysia.

Moreover, we explore the potential of technological innovation to reduce environmental degradation in Malaysia. The empirical finding indicates that an increased number of patent applications can lead to a decline in CO_2 emissions. This means that using clean technologies in the manufacturing process might help to enhance Malaysia's environmental quality. Most researchers believe that technological innovation will help reduce CO_2 emissions and improve environmental quality (Ang 2008, Yang and Li 2017; Chen and Lee 2020). Our result is aligned with the findings from Ang (2008); Ahmed et al. (2016); Ahmed and Ozturk (2018); Khan et al. (2019); Rahman et al. (2019); Shahbaz et al. (2020); Churchill et al. (2019); and Ganda (2019); and Zhang et al. (2019) who reported that technological innovations promote environmental quality. However, our study outcome indicates that the emission reduction potential of technological innovation is not as much of renewable energy use. This indicates that Malaysia is not paying adequate attention to developing low-carbon technology innovation. Ali et al. (2016) reported that technological advancement has an environmentally friendly impact on pollution reduction. Malaysia's target to reduce carbon emissions by 45% by 2030 can be met through transformative green growth and green technology adoption. Green technologies can help Malaysia achieve its strategic goal of pursuing green growth for sustainability and resilience. As we move toward an era where there is a greater awareness of the need for sustainable and environmentally friendly behaviors, the discussion over the role that patent applications should play in mitigating climate change is becoming more intense. While pursuing development, patents on green technologies ensure that the environment is always protected and conserved for current and future generations (Ridzuan and Chew 2018).

However, the impact of technological innovation to reduce CO_2 emissions is still in its early stage in Malaysia and will take the time to show some more outstanding results in this regard. New technologies must be developed through research and patent applications to soften the link between carbon emissions and environmental sustainability to achieve the emission reduction target. Part of this endeavor is the development of technology that enables more efficient energy usage, and it will likely play a significant role in any future stabilization strategy. New technology, such as hybrid cars, provides substantial energy savings while maintaining the same level of service. Air conditioning systems that are more energy-efficient would save a lot of money while maintaining the same level of comfort (Bosetti et al. 2008). Our study reveals the unidirectional causality from economic growth to technological innovation, which indicates that economic growth accelerates technological innovation. As a country's income rises, it can invest more in R&D and adopt more efficient technology. More efficient technologies decrease the use of natural resources and pollutants and trash generated as by-products, resulting in a cleaner environment. For example, if adequate environmental management systems are in place to ensure proper waste disposal, more investment in R&D is expected to improve environmental quality.

Malaysia's government submitted its Intended Nationally Determined Contributions (INDC) in January 2016. Malaysia intends to reduce its GHG emissions intensity of GDP by 45% by 2030 relative to the emissions intensity of GDP in 2005. This consists of 35% on an unconditional basis and a further 10% is the condition upon receipt of climate finance, technology transfer, and capacity building from developed countries. The low-carbon Malaysia research is one of the outcomes emerging from the development of the Low Carbon Society Scenarios for Asian Regions project conducted by the Low Carbon Asia Research Group. The group assembles some 50 researchers from multidisciplinary backgrounds from Malaysia and Japan to create a low-carbon future for Asia, beginning with developing the Iskandar Malaysia Low Carbon Society Blueprint. In Malaysia, the potential of reducing the energy and GHG emission was focused on renewables and energy efficiency in the power, industry, commercial, and residential sectors. The Institute of Energy Economics, Japan (IEEJ) compared its outlook for Malaysia with the country's INDC. IEEJ's outlook has two scenarios. The reference scenario assumes changes based on the historical development of energy supply–demand and moderate policy prospects, while the advanced technology scenario assumes the application of stronger and ambitious energy-environment policies and corresponding technologies. However, Malaysia's unconditional INDC is almost the same as or slightly better than the IEEJ's reference scenario. Since 2016, when Malaysia submitted the INDC, advanced technology such as artificial intelligence and the internet of things has been developing rapidly. For the transport sector, electric vehicles are drawing much attention, and connected cars or autonomous vehicles are just becoming available. Compared with the intensity of GDP, which is the INDC, the GDP growth rate exceeds the GHG emission growth rate, so the GHG/GDP ratio is expected to decline. Nevertheless, the total amount of GHG emissions would steadily increase. If Malaysia were willing to set itself even more ambitious targets, aggressive measures are required in the energy and the transport sectors that account for large proportions of GHG emissions. The outcome of the present study indicates that the transfer of clean technologies from the developed countries to Malaysia could help to reduce CO_2 emissions and improve environmental quality in Malaysia.

6 Conclusion and policy implications

6.1 Conclusion

This study investigates the potential of economic growth, renewable energy use, and technological innovation to achieve Malaysia's Paris Agreement by reducing carbon emissions. Time-series data over the period 1990 to 2019 have been used to examine the dynamic impacts of the variables. The current study utilized ADF, DF-GLS, and P-P unit root tests to capture the integration order of the series. The DOLS estimator was employed to capture the long-run impacts of economic growth, renewable energy use, and technological innovation on CO_2 emissions in Malaysia. We employed the FMOLS and CCR test as a robustness check to the DOLS estimation. In addition, a pairwise Granger causality test was used to explore the causal relationship between the study variables. The empirical findings indicate that increased renewable energy use and technological innovation improve the environmental quality in Malaysia whereas economic growth has an adverse impact on environmental degradation in the long run. From a Malaysian perspective, our findings shed new light on the effects of renewable energy use and technological innovation on environmental quality. The policy recommendation is drawn following the study outcomes to a low-carbon economy, promote renewable energy use, and finance technological innovation to ensure emission reduction in Malaysia.

6.2 Policy implications

Malaysia is completely dedicated to being a significant player in the worldwide transition to a low-carbon and eventually carbon-free society, with the aim of reaching this goal by 2050. Various initiatives to stimulate green growth would be implemented in conjunction with Malaysia's 2050 carbon neutrality goal. Our research suggests that the policymakers in Malaysia prepare an environmental policy that reduces CO_2 emissions without jeopardizing economic growth. To avoid pollution at the source, the "pollute first, then treat" strategy might be altered, and the economic development mode at the expense of the environment could be transformed. In this respect, we recommend the government assist markets by building a robust legislative framework that generates long-term value for emission reductions and continually promotes innovative technologies that lead to a less carbon-intensive economy. The Malaysian government may potentially implement carbon capture and storage technology to reduce CO_2 emissions from fossil fuel consumption in power generation and industries. Furthermore, economic development is highly emission-intensive, and increased energy consumption and CO_2 emissions are frequently associated with economic growth. Renewable energy sources are becoming more important in manufacturing processes as technology improves and the desire for environmental sustainability intensifies. Thus, fostering the economic transition to renewables is critical for reducing the environmental pressures caused by economic development. Policymakers could also encourage and promote the growth of renewable energy companies and technology. These measures will help the economy increase the percentage of renewable energy consumption in overall energy consumption by displacing CO_2-intensive conventional energy sources. Finally, we propose that institutional alignment is required to encourage renewable energy consumption across economic activities and assure long-term economic growth.

Our findings imply that the Malaysian government could create and execute effective support policies to encourage investment in new renewable energy technology to achieve a consistent and sustained increase in renewable energy consumption. The government might invest in renewable energy projects through public–private partnerships. Policymakers could support renewable energy technological progress by emphasizing renewable energy's significant impact on Malaysia's energy sector. To raise public awareness of renewable energy and environmental preservation, regulatory regulations might be established. Furthermore, increasing the share of renewable energy in overall energy usage will long-term impact CO_2 emissions reduction and industrialization. Therefore, the Malaysian government may enhance the amount of renewable energy in the country's energy mix by investing in renewable energy infrastructure, lowering renewable energy costs, and maximizing renewable energy efficiency. Due to emission control, greenhouse gas, and fossil fuel exploitation methods, greater use of renewable energy to replace fossil fuels reduces adverse environmental and ecological consequences. Appropriate and far-reaching actions in renewable energy generation must be made to prevent climate change and guarantee that Malaysia's energy consumption is sustainable. New coal-fired power facilities would not be built by the government. In addition, many gas power facilities in Peninsular Malaysia would be used to replace coal-fired power plants, resulting in cleaner electricity generation. To assist environmentally friendly transportation measures, the Malaysian government would prioritize the development of the energy-efficient automobile manufacturing business.

Moreover, through enhancing energy efficiency and technological innovation, CO_2 emissions may be decreased. Malaysia has possibilities across various sectors to achieve its goal of a 40% decrease in emissions intensity as a percentage of GDP. However, many mitigation measures are constrained by the cost and applicability of suitable technology. The cost of producing renewable energy is still greater than that of conventional energy. Thus, the Malaysian government might invest more in scientific research and development to improve energy efficiency and lower the cost of renewable energy. Furthermore, technical innovation is crucial for high-quality economic development. Malaysia could encourage the transition from a resource and energy-driven economy to an innovation-driven economy to minimize energy consumption. Therefore, Malaysia may invest more in low-carbon technology research and development to reduce emissions from manufacturing processes and support long-term economic growth. The government may perhaps enhance funding for businesses doing technological innovation research linked to energy conservation and emission reduction and encourage firms to develop low-carbon technology vigorously. Malaysia could investigate the sources of pollutants and employ more targeted technical advances to enhance environmental conditions. Hence, the Malaysian government might increase its collaboration with universities and scientific research institutes to boost the efficiency of technological innovation, mainly environmentally green technology breakthroughs. In trade and partnership with high-income nations, environmentally friendly technical innovation may be fostered as well.

Furthermore, the use of green technologies can be a way to solve the climate change problem by offering consumers to lead a healthier lifestyle such as alternative energy resources, energy stores, management technologies, recycling and waste technologies, and the disposal of greenhouse gases. Creative implementation of green technologies in business may impact the social aspect, the economy, and the environment. The government might invest in green technology innovation and environmental protection to enhance environmental disposal and product development skills. Malaysia may perhaps continue to develop green environmental protection technology, increase bilateral collaboration, and establish a win–win scenario in the environmental protection area. Additionally, the government might encourage the commercialization of patents and the conversion of patents into productivity and innovation, particularly in climate-friendly and renewable energy-related technology. When upgrading technological innovation levels, Malaysia may consider the influence on the environment and guide the development of environmentally friendly technologies. At the same time, environmental protection concerns might be explored in more depth with other high-technology nations for economic, political, and social globalization, and their respective technical advantages could be leveraged to foster collaborative technological innovation transformation. Malaysia may perhaps pay special attention to the benefits of political globalization and work closely with other nations to directly replicate and use innovative technology.

6.3 Limitations and future research opportunities

Although the current study yielded substantial empirical findings in the case of Malaysia, our analysis has some flaws that might be addressed in future research. One of the critical drawbacks of our analysis is the unavailability of the data related to renewable energy use and technological innovation beyond the period of study, which limits the power of the econometric techniques used. However, this study has examined the dynamic impacts of economic growth, renewable energy use, and technological innovation on CO_2 emissions in Malaysia. Further studies can explore the potential of other determinants of emission reduction, such as increasing forested areas, recycling products, reducing water and electricity use, changing food habits to organic food, etc. Furthermore, this study utilized CO_2 as an indicator for environmental degradation from GHGs emissions. More research could be done utilizing CO_2 equivalency and consumption-based carbon emissions as a proxy for environmental deterioration, as well as other emissions indicators, including nitrous oxide (N_2O), sulfur dioxide (SO_2), methane (CH_4), and other short-lived climate forces (SLCF). The reduction of SLCF leads to immediate health benefits and better air quality for city populations. Nevertheless, CO_2 emission is regarded as a proxy for environmental pollution in this study, which is not the only cause of declining environmental quality. Future research might investigate more environmental pollution indicators, such as water pollution and land pollution.

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Data availability All data generated or analyzed during this study are available here: https://databank.worldbank.org/source/world-development-indicators.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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