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Research article

How does technological innovation moderate the environmental impacts of economic growth, natural resource rents and trade openness?

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ABSTRACT

The objective of this study is to unravel the linear impacts of economic growth, technological innovation, natural resource rents and trade openness on carbon emissions in Malaysia during 1980–2021. It also unveils the moderating role of technological innovation on the impacts of economic growth, natural resource rents and trade openness on carbon emissions. It further analyses the nonlinear relationship between technological innovation and carbon emissions. It estimates the parameters with the Autoregressive Distributed Lag model technique. The results of the linear model reveal that economic growth, natural resource rents and trade openness contributes to carbon emissions while technological innovation mitigates carbon emissions. The disaggregated analysis of natural resource rents indicates that oil rents, natural gas rents and coal rents intensify carbon emissions while mineral rents and forest rents do not contribute to carbon emissions. The disaggregated analysis of trade openness shows that exports worsen carbon emissions while imports have tenuous effect. The disaggregated analysis of technological innovation indicates that innovation by non-residents mitigate carbon emissions while innovation by residents do not alleviate carbon emissions. Moreover, evidence from the interaction model reveals that technological innovation can favourably mitigate the adverse impacts of economic growth and trade openness on carbon emissions albeit it cannot alleviate the impact of natural resource rents on carbon emissions. Besides, the nonlinear model indicates a U-shaped relationship between technological innovation and carbon emissions. Unlike previous studies that typically focused on the direct impacts of these variables, this study unravels the impacts of the disaggregated components as well as provides insights into the moderating and nonlinear effects of technological innovation on carbon emissions. The implication of this study is that efforts to achieve a carbon-neutral economy should consider the direct and indirect impacts of economic growth, technological innovation, natural resource rents and trade openness. It is recommended for Malaysia to encourage technological innovation in her quest to abate the adverse environmental impacts of economic activities.

1. Introduction

Carbon dioxide emissions are considered as the primary drivers of environmental degradation, climate change and global warming. According to the Intergovernmental Panel on Climate Change (IPCC) Report (2021), greenhouse gases emissions from human activities such as burning of fossil fuels, industrial pollution and deforestation constitute the principal causes of about 1.1 °C rise in global warming from the pre-industrial level. The globe may experience 1.5 °C increase in global warming in the next two decades if there are no swift and wide-ranging efforts to mitigate greenhouse gases emissions (IPCC Report, 2021). The threat posed by global warming to the human ecosystem has emerged as one of the greatest environmental concerns attracting the attention of scholars and policymakers in recent years. An attempt to abate the mounting level of global carbon emissions should initially analyse the main causes of the emissions with a view to proffering policy options to ensuring carbon-neutral economy. Some of the human activities that can influence the level of carbon dioxide emissions are economic growth,

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natural resource extraction, trade openness and technological innovation.

Economic growth can contribute to carbon emissions if the economic activities rely on fossil fuels (e.g., natural gas, coal, oil) as sources of energy rather than obtaining energy from renewable resources (e.g., wind power, solar energy, hydro power). Besides, the use of pollution-intensive methods of production, transportation and processing of products can release carbon emissions into the atmosphere. In this regard, some studies have shown that economic growth contributes to carbon emissions (Chen et al., 2023; Khan et al., 2020) albeit other views exist (Aladejare, 2022; Bosah et al., 2023). For instance, Ehigiamusoe and Lean (2019) reported that economic growth mitigates carbon emissions in high-income countries albeit it contributes to carbon emissions in middle- and low-income countries. Economic growth may not aggravate carbon emissions if productive activities adopt clean energy, and energy-efficient techniques to stimulate output growth (Alvarado and Toledo, 2017; Bosah et al., 2023). Powanga and Kwakwa (2024) argued that higher income enables firms and individuals to acquire gadgets and equipment that are friendly to the environment thereby switching to environmental-friendly behaviour.

Though natural resource rents can play a fundamental role in the economic development of a country (especially in developing economies), the extraction or exploitation of natural resources can have detrimental consequences on the environment (Aladejare, 2022). For instance, the extraction of non-renewable natural resources such as natural gas, crude oil and other mineral resources can intensify carbon emissions. In this regard, a strand of the empirical literature revealed that natural resource rents contribute to carbon emissions (Bekun et al., 2019; Chen et al., 2023; Danish et al., 2019; Lin et al., 2024; Shen et al., 2021). However, another strand of the literature argued that natural resource rents can mitigate carbon emissions if natural resource extraction uses advanced technologies with proper and efficient management (Balsalobre-Lorente et al., 2018; Luqman, 2024). This implies that the impact of natural resources rents on carbon emissions depends on whether the processes of natural resource extraction are environmental-friendly.

The expansion of global trade occasioned by the adoption of trade liberalization policy in many countries had resulted in rapid economic growth, which could have ramifications for carbon emissions. Over the past decades, though the wave of trade expansion has significantly contributed to the rapid development of the global economy, the level of carbon emissions has also intensified. This worrisome trend has prompted some scholars to investigate the impact of trade openness on carbon emissions, and the empirical outcomes has been mixed. For instance, a strand of the empirical literature argued that trade openness contributes to carbon emissions (Luqman, 2024; Vural, 2020). Trade openness can aggravate carbon emissions if it boosts energy consumption as well as the importation of pollution-intensive goods or products. Through trade, advanced countries with stricter environmental protection standards can move their pollution-intensive corporations to developing countries that have less stringent environmental policies to reduce production costs. However, another strand of the literature posited that trade openness can mitigate carbon emissions if it allows the transfer of advanced and energy-efficient technologies (Ehigiamusoe, 2023; Le et al., 2016).

Technological innovation can influence carbon emissions if it enhances green productivity, energy efficiency and the development of clean energy resources. (e.g., wind power, solar energy, hydro power). In other words, technological innovation can engender new or modified processes, practices or systems that ensure low- or neutral-carbon economy. In this regard, some studies have posited that technological innovation mitigates carbon emissions (Meirun et al., 2021; Zhao et al., 2024). Nonetheless, other studies have opined that technological innovation cannot reduce carbon emissions (Appiah et al., 2023; Raiser et al., 2017). They argued that the measures of technological innovation need lapses of time to attain their full mitigating-effects on carbon emissions (Alvarez-Herranz et al., 2017). Besides, the relationship between technological innovation and carbon emissions could depend on the country's levels of technological innovation, economic development, and carbon emissions (Du et al., 2019; Chen and Lee, 2020; Toebelmann and Wendler, 2020), which emphasizes the need for a country-specific analysis to enhance policy decision-making.

Apart from the direct impact, technological innovation can moderate the impact of economic growth, natural resource rents and trade openness on carbon emissions. For instance, some studies have argued that technological innovation is a significant driver of economic growth (Acheampong et al., 2022; He et al., 2023); technological innovation can mitigate carbon emissions (Meirun et al., 2021; Zhao et al., 2024); and economic growth can influence carbon emissions (Chen et al., 2023; Khan et al., 2020). Hence, there is a possibility that technological innovation could moderate the impact of economic growth on carbon emissions, an issue that has not been empirically determined. Similarly, though some studies have posited that natural resource rents influence carbon emissions (Hussain et al., 2020; Shen et al., 2021), the empirical literature on the moderating role of technological innovation on the impact of natural resource rents on carbon emissions is still scanty (Zhao et al., 2024). Furthermore, technological innovation and trade openness have a dynamic relationship. For instance, Tachie et al. (2020) opined that trade openness is one of the channels through which technology and globalization can be transferred from one country to another, while Ibrahim et al. (2024) posited that trade openness enhances technological innovation. Nevertheless, it is not clear whether technological innovation can moderate the impact of trade openness on carbon emissions. Our study intends to fill these research gaps.

Besides the indirect impacts of technological innovation on carbon emissions, the relationship between technological innovation and carbon emissions could be nonlinear (i.e., U-shaped or inverted U-shaped). Essentially, an inverted U-shaped implies that at the early stage, technological innovation contributes to carbon emissions, but after a certain turning point is attained, an increase in technological innovation will alleviate carbon emissions. On the contrary, a U-shaped relationship implies that at the early stage, technological innovation alleviates carbon emissions, but after a certain threshold level is reached, a further rise in technological innovation will contribute to carbon emissions. The scanty literature on the nonlinear relationship between technological innovation and carbon emissions mainly focused on OECD countries while developing countries have been neglected (Appiah et al., 2023; Mensah et al., 2018). Hence, it is essential to provide insights into this issue in a developing country such as Malaysia with a view to assisting policy formulation.

The motivation for choosing Malaysia is due to the high level of carbon dioxide emissions amid rising economic activities in recent years, which is now worrisome to policymakers. The attainment of carbon-neutral economy is now a priority in the country's development agenda. According to the World Development Indicators (2024), carbon dioxide emissions rose from 2.04 to 7.38 metric tons per capita during the 1980–2021 period. Moreover, Malaysia's ranking in Environmental Performance Index (EPI) has plummeted in recent years stressing the need to urgently improve environmental quality (Environmental Performance Index Report, 2024). According to the IPCC Report (2021), efforts to mitigate greenhouse gases emissions should unravel the inderlying drivers of carbon dioxide emissions (e.g. economic activities) and tackle them. For instance, Malaysia's real GDP per capita (i.e., a measure of economic activities) rose from US$3159.7 to US$10,605.6 while trade openness rose from 112.5% to 134% of GDP during the period (World Development Indicators, 2024). The number of technological innovations rose from 1337 to 7534 patent applications, whereas the natural resource rents declined from 37.7% to 6.92% of GDP during the period (World Development Indicators, 2024). Given the trends in these variables and the dearth of empirical literature on these issues in Malaysia, it is necessary to empirically analyse how these variables influence carbon emissions. Unlike previous studies, this study is significant because it provides insights into the direct and indirect environmental impacts of economic growth, natural resources rents, trade openness and technological innovation in Malysia. It also shows the environmental impacts of the components of these variables, as well as the non-linear relationship between technological innovation and carbon emissions in Malaysia.

Therefore, the specific objectives of this study are: (i) to examine the impacts of economic growth, natural resource rents, technological innovation and trade openness on carbon emissions in Malaysia; (ii) to unravel the moderating role of technological innovation on the impacts of economic growth, natural resource rents and trade openness on carbon emissions in Malaysia; (iii) to unveil the non-linear impact of technological innovation on carbon emissions in Malaysia.

This paper makes the following contributions to the literature: First, this paper reveals the direct impacts of economic growth, technological innovation, natural resource rents and trade openness on carbon emissions in a developing country. It represents an innovative idea that further disaggregates these variables into their components parts and shows how these different components influence carbon emissions. For instance, it disaggregates technological innovation (proxy by patent applications) into innovation by residents and innovation by non-residents. The latter are the patent applications filed by foreign individuals and organizations with the Malaysia's patent office or via the procedure specified by the Patent Cooperation Treaty for exclusive rights for invention. Conversely, innovation by residents are the patent applications filed by Malaysia citizens. Since a patent offers protection to an invention (i.e., a new technical solution to a specific problem) and owner of invention (residents or non-residents) for a given period, the status of the owner of patient could have different impacts on carbon emissions.

Our study also disaggregates natural resource rents into oil rents, natural gas rents, mineral rents, coal rents and forest rents. Specifically, mineral rents refer to the differences between the production cost of minerals (e.g., gold, tin, lead, iron, zinc, copper, silver, nickel, phosphate, bauxite) and the production value at global prices. Natural gas rents refer to the difference between the production cost and production value of natural gas at regional prices, while coal rents are the variations in the production cost and the value of coal production at world prices. Oil rents refer to the difference between the production cost and the value of crude oil production at regional prices, while forest rents are the roundwood harvest multiply by the regional rental rate and prices. These components of natural resource rents could have different effects on carbon emissions, which necessitate this investigation. Most previous study typically focused on the aggregated data of natural resource rents (i.e., differences between average production cost and prices of commodities – oil, natural gas, coal, mineral, forest-) without analysing the environmental impact of the components. Furthermore, since international trade consists of imports and exports of goods and services, our study also provides insights into the effects of imports (i.e., value of merchandise and market services received from other countries) and exports (i.e., value of market services and goods provided to other countries) on carbon emissions. This is fundamental because imports and exports could have different ramifications for carbon emissions. The disaggregated approach used in this study represents a novel idea in the empirical literature, and the empirical outcomes will aid policy formulation.

Second, unlike past studies that typically focused on the direct effects of these variables on carbon emissions, our study unravels the moderating role of technological innovation on the impact of economic growth, natural resource rents and trade openness on carbon emissions. This is fundamental since technological innovation has dynamic relationships with economic growth, natural resource rents and trade openness (He et al., 2023; Ibrahim et al., 2024). This analysis enables us to unveil the marginal effects of economic growth, natural resource rent and trade openness on carbon emissions at various level of technological innovation. In other words, our analysis allows us to show how a simultaneous rise in economic growth and technological innovation; natural resource rent and technological innovation; as well as trade openness and technological innovation influence carbon emissions. To the best of our knowledge, these issues have not been empirically unraveled.

Third, the relationship between technological innovation and carbon emissions could be nonlinear, an issue that has not received much empirical investigation. Our empirical strategy enables us to show whether the relationship between technological innovation and carbon emissions is a U-shaped or an inverted U-shaped. The empirical outcomes of this investigation will provide insights into the turning point beyond which the impact of technological innovation on carbon emissions changes. This will guide policymakers on how to ensure the optimum level of technological development that can ensure a carbon-neutral economy. Finally, to obtain robust empirical outcome that are useful for policy formulation, our empirical strategy addresses some economic and econometric issues such as autocorrelation, heteroskedasticity and structural breaks.

Apart from this introduction, this paper is structured as follows: Section 2 reviews the related literature; Section 3 presents the methodology; Section 4 contains the empirical outcomes; Section 5 presents the discussion and policy implications; and Section 6 concludes with some remarks.

2. Literature review

Some studies have investigated the impacts of economic growth, natural resources rents, trade openness and technological innovation on carbon emissions albeit the empirical outcomes are mixed (Bekun et al., 2019; Chen and Lee, 2020). For instance, Bekun et al. (2019) examined the impacts of economic growth and natural resource rents on carbon emissions in 16-EU nations and revealed that economic growth and natural resource rents aggravate carbon emissions. They argued that overdependence on natural resources rents will contribute to carbon emissions if a country ignores conservation and management practices. Danish et al. (2019) analyzed the impacts of economic growth and natural resource rents on carbon emissions in BRICS and showed that natural resource rents do not contribute to carbon emissions. But the country-specific analysis indicated that natural resource rents intensify carbon emissions in South Africa but mitigate carbon emissions in Russia. They noted that excessive utilization of natural resources via agriculture, mining, deforestation can worsen carbon emissions.

Hussain et al. (2020) explored the impacts of economic growth, natural resource rents and trade openness on energy consumption and carbon emissions in 56 Belt and Road Initiative (BRI) nations. Evidence from the study indicated that economic growth, natural resource rents and trade openness increase both energy consumption and carbon emissions. Chen and Lee (2020) investigated the impact of technological innovation on carbon emissions in a panel of 96 countries and revealed that technological innovation has no significant mitigating impact on carbon emissions. But when the panel was split, the study revealed that technological innovation in high-technology, high-income and high-carbon emissions nations can mitigate carbon emissions in neighboring nations. The study added that globalization can enhance the mitigating effect of technological innovation on carbon emissions. In their analysis of BRICS, Khattak et al. (2020) reported that technological innovation increases carbon emissions. But the country-specific analysis indicated that technological innovation contributes to carbon emissions in India, China and South Africa albeit it mitigates carbon emissions in Brazil.

Vural (2020) analyzed the impact of economic growth and trade openness on carbon emissions in 8 African nations and reported that trade openness contributes to carbon emissions. In a provincial panel analysis of China, Shen et al. (2021) indicated that natural resource rents intensify carbon emissions while green investment mitigate carbon emissions. They suggested the need to strengthen the country's natural tax law and promote green investment to mitigate carbon emissions. Aladejare (2022) examined the impact of economic growth and the components of natural resource rents e.g., (mineral, oil and natural gas rents) on carbon emissions in 5 African countries. The results indicated that mineral rents and natural gas rents aggravate carbon emissions albeit oil rents and economic growth have no significant effect. Using a panel data of 38 developing countries, Chen et al. (2023) reported that economic growth and natural resource rents aggravate carbon emissions. They noted that geopolitical risk worsens the adverse impact of natural resource rents on carbon emissions. Adebayo et al. (2022) revealed that natural resource rents intensify carbon emissions while technological innovation alleviates carbon emissions in 10 nations. In a related study using data of BRICS, Adebayo et al. (2023) reported that economic growth heightens carbon emissions while natural resource rents and technological innovation abate carbon emissions. Bosah et al. (2023) noted that economic growth and natural resource rents mitigate carbon emissions in 159 nations, while Powanga and Kwakwa (2024) documented that economic growth alleviates carbon emissions in Kenya. However, Lin et al. (2024) revealed that natural resource rents contribute to carbon emissions in 36 nations. Luqman (2024) reported that economic growth and trade openness increase carbon emissions, while natural resources rents and technological innovation mitigate carbon emissions in China. Shahbaz et al. (2024) reported that natural gas rents intensify carbon emissions while coal rents and mineral rents have the opposite effects in 30 countries.

Apart from the linear impact of technological innovation on carbon emissions, technological innovation could have a moderating role on the impacts of some variables on carbon emissions. For instance, Adebayo et al. (2022) opined that technological innovation can ameliorate the adverse impact of natural resource rents on carbon emissions in 10 nations while Adebayo et al. (2023) indicated that technological innovation can mitigate the environmental impact of natural resource rents in BRICS. Adewale et al. (2024) indicated that the interaction term between technological innovation and financial development mitigates carbon emissions in BRICS. Zhao et al. (2024) also revealed that technological innovation can favourably moderates the effect of geopolitical risks and natural resource rents on carbon emissions in BRICS. However, the empirical literature on the moderating role of technological innovation on the impact of economic growth, natural resource rents and trade openness on carbon emissions is still scanty.

Besides the moderating role, the relationship between technological innovation and carbon emissions could be nonlinear. In this regard, some studies have examined the nonlinear nexus between technological innovation and carbon emissions albeit the empirical outcomes have been mixed (Appiah et al., 2023; Dauda et al., 2021). For instance, Dauda et al. (2021) showed that technological innovation and carbon emissions have an inverted U-shaped relationship in a panel of 9 African nations. But the country-specific analysis validated the inverted U-shaped nexus in Egypt, Mauritius, Morocco and South Africa whereas there was no evidence of nonlinearity in the remaining 5 countries. Similarly, Appiah et al. (2023) found no evidence of nonlinearity between technological innovation and carbon emissions in OECD nations. Hence, it is fundamental to determine this issue in a developing country.

Unlike previous studies that typically focused on the direct impacts of economic growth, technological innovation, natural resource rents and trade openness on carbon emissions (Hussain et al., 2020; Khattak et al., 2020; Luqman, 2024), our paper conducts the analysis at two levels. It unravels the environmental impacts of these variables, and thereafter unveils the environmental impacts of the disaggregated components of these variables. For instance, it disaggregates technological innovation into innovation by residents and innovation by non-residents; natural resource rents into oil rents, natural gas rents, mineral rents, coal rents and forest rents; as well as trade openness into exports and imports. The empirical outcomes of the disaggregated approach would provide greater insights for policy decision-making. Second, the few past studies that analyzed how technological innovation moderates the environmental impacts of some variables focused on BRICS or newly industrialized countries (Adebayo et al., 2023; Adewale et al., 2024; Zhao et al., 2024). Fundamentally, none of these papers comprehensively unravel the moderating role of technological innovation on the impacts of economic growth, natural resource rents and trade openness on carbon emissions. To the best of our knowledge, the marginal effects of economic growth, natural resource rent and trade openness on carbon emissions at various levels of technological innovation have not been empirically determined. Our study fills these research gaps using data from a developing country. Third, the empirical literature on the nonlinear impact of technological innovation on carbon emissions is still scanty (Appiah et al., 2023; Dauda et al., 2021), hence, it is fundamental to analyse this issue. This paper will show whether the relationship between technological innovation and carbon emissions is a U-shaped or an inverted U-shaped. This analysis can provide insights into the turning point beyond which the impact of technological innovation on carbon emissions changes. To obtain robust empirical outcome that are useful for policy formulation, our paper employs empirical techniques that can tackle autocorrelation, heteroskedasticity, endogeneity and structural breaks.

3. Methodology

3.1. Model specification

To unravel the impacts of economic growth (GDP), technological innovation (TEC), natural resource rents (NAT) and trade openness (TOP) on carbon emissions (CO2), this study employs the following model (Adebayo et al., 2023; Ahmad et al., 2020; Bosah et al., 2023):

$$CO2_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 TEC_t + \alpha_3 NAT_t + \alpha_4 TOP_t + \varepsilon_t, \tag{1}$$

To unravel the impacts of the components of these variables on carbon emissions, this study disaggregates technological innovation into innovation by residents and innovation by non-residents; disaggregates natural resource rents into oil, natural gas, mineral, coal and forest rents; as well as disaggregates trade openness into exports and imports (World Development Indicators, 2024).

Apart from the direct impact, technological innovation could moderate the impact of economic growth, natural resource rents and trade openness on carbon emissions (Adewale et al., 2024; Zhao et al., 2024). Therefore, this study interacts technological innovation with economic growth, natural resource rents and trade openness as follows:

$$CO2_t = \beta_0 + \beta_1 GDP_t + \beta_2 TEC_t + \beta_3 NAT_t + \beta_4 TOP_t + \beta_5 (GDP^*TEC_t) + \varepsilon_t \tag{2}$$

$$CO2_t = \phi_0 + \phi_1 GDP_t + \phi_2 TEC_t + \phi_3 NAT_t + \phi_4 TOP_t + \phi_5 (NAT^*TEC_t) + \varepsilon_t \tag{3}$$

$$CO2_t = \psi_0 + \psi_1 GDP_t + \psi_2 TEC_t + \psi_3 NAT_t + \psi_4 TOP_t + \psi_5 (TOP^*TEC_t) + \varepsilon_t \tag{4}$$

where GDP*TEC is the interaction term between economic growth and technological innovation, NAT*TEC = is the interaction term between natural resource rents and technological innovation, TOP*TEC is the interaction term between trade openness and technological innovation. All the variables are transformed into natural logarithm before analysis.

The marginal effects of economic growth, natural resources rents and trade openness on carbon emissions can be computed by taking the partial derivatives of Equations (2)–(4) with respect to economic growth, natural resources rents and trade openness as follows:

$$\frac{\partial CO2_t}{\partial GDP_t} = \beta_1 + \beta_5 TEC_t$$

$$\frac{\partial CO2_t}{\partial NAT_t} = \phi_3 + \phi_5 TEC_t$$

$$\frac{\partial CO2_t}{\partial TOP_t} = \psi_4 + \psi_5 TEC_t$$

Emphasis is on the sign and significance of the coefficients of the linear and interaction term. For instance, technological innovation mitigates the adverse impact of economic growth on carbon emissions if $\beta_1 > 0$ and $\beta_5 < 0$.Conversely, technological innovation cannot mitigate the adverse impact of economic growth on carbon emissions if $\beta_1 > 0$ and $\beta_5 > 0$, To capture the total effect, we compute that marginal effect of economic growth on carbon emissions at various levels of technological innovation. A negative marginal effect ($\beta_1 + \beta_5 TEC$) implies that greater economic growth and technological innovation will mitigate carbon emissions while a positive marginal effect implies the opposite.

To ascertain the existence of a nonlinear impact of technological innovation on carbon emissions, this study adds the square term of technological innovation (TEC^2) to the model (Appiah et al., 2023; Balsalobre-Lorente et al., 2021; Dauda et al., 2021):

$$CO2_t = \varpi_0 + \varpi_1 GDP_t + \varpi_2 TEC_t + \varpi_3 NAT_t + \varpi_4 TOP_t + \varpi_5 TEC_t^2 + \varepsilon_t \quad (5)$$

If $\varpi_2 < 0$ and $\varpi_5 > 0$, it suggests that technological innovation and carbon emissions have a U-shaped relationship, while $\varpi_2 > 0$ and $\varpi_5 < 0$, implies an inverted U-shaped relationship.

3.2. Justification of the variables in the model

Carbon dioxide emissions: The justification for focusing on carbon dioxide emissions is because carbon dioxide emissions (i.e., emissions from fossil fuels utilization, manufacturing of cement, consumption of solid, liquid, & gas fuels, including gas flaring) are often considered as the main greenhouse gases that intensify environmental degradation. global warming and climate change (Filonchyk et al., 2024). The 2021 Report of the Intergovernmental Panel on Climate Change (IPCC) noted that greenhouse gases emissions from human activities are the key drivers of roughly 1.1 °C rise in global warming from the pre-industrial level. The 21st century will continue to experience a rise in global surface temperature until substantial efforts are made to considerably reduce greenhouse gas emissions. Essentially, global warming constitutes a severe threat to human ecosystem, and it is considered as a worrisome environmental problem that policymakers need to tackle. The soaring carbon dioxide emissions will make the land and ocean carbon sinks less effective at reducing the accumulated atmospheric emissions, and the consequences of greenhouse gas emissions are irreversible in centuries (IPCC Report, 2021). Therefore, an attempt to abate human-induced global warming requires an empirical analysis of the main causes of carbon dioxide emissions in order to provide policy options that can ensure carbon-neutrality. This variable (i.e., carbon dioxide emissions) has also been used in some past studies (Acheampong et al., 2022; Balsalobre-Lorente et al., 2021; Dauda et al., 2021).

Economic growth can heighten carbon emissions if economic activities rely on burning fossil fuels (e.g., natural gas, coal, oil) rather than using clean energy (e.g., wind power, solar energy, hydro power). The utilization of emissions-intensive techniques of production, processing of products and transportation can release carbon emissions into the atmosphere (Chen et al., 2023; Khan et al., 2020). Nonetheless, economic growth will not contribute to carbon emissions if the productive activities utilize clean energy and energy-efficient techniques or enable individuals and firms to switch to environmental-friendly behaviour (Bosah et al., 2023; Powanga and Kwakwa, 2024). A priori, the coefficient of economic growth is expected to be positive.

Natural resource rents can contribute to carbon emissions if natural resource extraction uses emissions-intensive method instead of advanced technologies with proper and efficient management (Balsalobre-Lorente et al., 2018). The natural resource rents can stimulate economic development especially in developing nations, but the extraction or exploitation of natural resources can have detrimental consequences on the environment (Aladejare, 2022). More precisely, the extraction of natural gas, coal, crude oil, and other mineral resources can intensify carbon emissions (Bekun et al., 2019; Chen et al., 2023). A priori, the coefficient of natural resource rents could be positive or negative, depending on whether the processes of natural resource extraction are environmental-friendly.

Trade openness can aggravate carbon emissions if it boosts economic activities, energy consumption and the importation of emissions-intensive goods/services. The expansion of global trade had enhanced rapid economic growth, which could have ramifications for carbon emissions. Trade openness can intensify carbon emissions if it enables advanced countries with stricter environmental protection standards to relocate their emissions-intensive firms to developing nations that have less stringent environmental policies to reduce production costs. Nonetheless, trade openness will not contribute to carbon emissions if it provides opportunity to transfer advanced or clean and energy-efficient technologies from developed to developing nations (Le et al., 2016). A priori, the coefficient of trade openness could be positive or negative.

Technological innovation can affect carbon emissions if it boosts energy efficiency, green productivity, and clean energy resources. Technological innovation can engender new or modified processes, practices or systems that ensure low- or neutral-carbon economy (Meirun et al., 2021; Zhao et al., 2024). It can integrate less emissions technologies in the process of production, boost energy transition and encourage the development of environmental technologies (Adebayo et al., 2023). A priori, the coefficient of technological innovation is expected to be negative.

3.3. Data

This study uses annual data of Malaysia for 1980–2021. Data on carbon emissions, real GDP per capita, technological innovation, natural resource rents and trade openness were obtained from the World Development Indicators (2024).

3.4. Empirical strategy

This study employs that ARDL model proposed by Pesaran et al. (2001) which can determine the cointegration relationship between the variables via the bounds test. The justification for using the ARDL technique is that it can reveal both the long-run and short-run impacts of the independent variables on the dependent variables. Secondly, it can accommodate a model whose variables are mixed order of integration (i.e., stationary at level or stationary after first differenced). Thirdly, it allows for the selection of different lag orders for different variables. Fourthly, the ARDL method can produce robust results even in small samples. Finally, it can produce valid and unbiased estimates because it can deal with potential endogeneity and autocorrelation.

4. Empirical findings

4.1. Preliminary analysis

The descriptive statistics reported in Table 1 show the minimum, mean, and maximum values of the variables. They indicate wide variations among the variables, while the standard deviations reveal that the data are relatively dispersed around their means. Moreover, the correlation analysis displayed in the lower panel of Table 1 suggests that GDP, technological innovation, and trade openness have positive relationship with carbon emissions while natural resource rents have negative association with carbon emissions.

The unit root tests displayed in Table 2 reveals that some variables are stationary at level while some variables are stationary after first differenced. Hence, it is necessary to utilize an estimation technique (e.g., ARDL) that can handle a model with mixed order of integration.

Table 1
Descriptive statistics and correlations.

	CO_2	GDP	TEC	NAT	TOP
Mean	5.134	6614.2	4630.1	15.281	155.13
Maximum	7.719	11,114.5	7727.0	37.783	220.40
Minimum	2.040	3159.7	262.0	4.541	104.68
Std Dev.	1.995	2441.1	2333.1	8.369	36.513
CO_2	1				
GDP	0.957**	1			
TEC	0.899**	0.897**	1		
NAT	−0.903**	−0.884**	−0.889**		
TOP	0.336**	0.137**	0.343**	−0.418**	1

Notes: ** indicates significance at 5% level. CO_2 = carbon emissions, GDP = real GDP per capita.
TEC = technological innovation, NAT = natural resource rents, TOP = trade openness.

4.2. ARDL cointegration test and estimations

Table 3 shows that the F-statistic values of the bound test (i.e., 13.760, 19.001, 24.862, 22.273 and 5.472) are greater than the upper critical value (i.e., 3.490). Therefore, we reject the null hypothesis (i.e., no cointegration) and conclude that the variables have cointegration. The ARDL estimation results in Model 1 reveal that the long-run coefficients of GDP, natural resource rents and trade openness are positive and significant, suggesting that these variables increase carbon emissions. Specifically, holding other variables constant, one percent increase in GDP will intensify carbon emissions by 1.282 percentage points in the long-run, and 0.558 percentage points in the short-run. This finding is consistent with some previous studies (Chen et al., 2023; Ehigiamusoe and Lean, 2019; Khan et al., 2020). The economic and environmental implications of these results are that economic growth heightens carbon emissions in Malaysia. The plausible justification for these results is that economic activities release substantial carbon dioxide emissions into the atmosphere as well as rely on energy obtained from fossil fuels that are unfriendly to the environment. The continuous use of energy-inefficient and emissions-intensive techniques of production, processing and transportation in Malaysia will continue to deteriorate environmental quality. Economic growth can intensify carbon emissions by increasing the consumption of energy- or pollution-intensive goods and services (e.g., automobiles, electronic appliances).

Similarly, one percent increase in natural resource rents will raise carbon emissions by 0.215 percentage points in the long-run, and 0.093 percentage points in the short-run. Some previous studies such as Shen et al. (2021), Danish et al. (2019), Bekun et al. (2019), and Hussain et al. (2020) revealed that natural resource rents intensify carbon emissions in China, BRICS, EU-16 nations, and 56 Belt and Road nations, respectively. The economic and environmental implications of these results are that overdependence on natural resources can have a detrimental impact on the environment especially if management and conservation options are overlooked. Natural resource abundance in a country often produces an economic structure that is substantially skewed towards the

Table 2
Unit root tests.

Variables	Augmented Dickey Fuller		Phillips-Perron		Unit root with break test	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
CO_2	−2.217	−5.391***	−2.178	−5.393***	−4.891**	−6.679***
GDP	−1.163	5.415***	−1.134	−5.415***	−2.641	−6.570***
TEC	−2.501	−11.638***	−2.197	−14.949***	−6.567***	−14.646***
NAT	−1.639	−6.191***	−1.639	−7.236***	−2.723	−7.198***
TOP	−2.629*	−3.768***	−1.355	−3.808***	−3.772	−4.727**

Note: *** and ** indicate statistical significance at 1% and 5% levels, respectively, and a rejection of the null hypothesis of no unit root.

Table 3
ARDL cointegration test and estimations.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bound test	13.760***	19.001***	24.862***	22.273***	5.472***
GDP	1.282*** (0.116)	4.515*** (1.580)	1.053*** (0.071)	0.967*** (0.083)	1.197*** (0.071)
TEC	−0.013** (0.005)	3.715** (1.736)	−0.439** (0.198)	3.223*** (1.012)	−0.374** (0.164)
NAT	0.215*** (0.087)	0.179*** (0.057)	−1.551** (0.644)	0.280*** (0.047)	0.520*** (0.075)
TOP	0.451*** (0.065)	0.356** (0.141)	0.473*** (0.066)	5.798*** (1.648)	0.220*** (0.047)
GDP*TEC		−0.417** (0.195)			
NAT*TEC			0.209** (0.072)		
TOP*TEC				−0.605*** (0.193)	
TEC^2					0.042*** (0.011)
ECT_{t-1}	−0.435*** (0.084)	−0.727*** (0.086)	−0.830*** (0.087)	−0.768*** (0.087)	−1.030*** (0.194)
Δ GDP	0.558*** (0.101)	3.286*** (1.206)	0.839*** (0.093)	0.618*** (0.136)	0.971*** (0.180)
Δ TEC	−0.005 (0.015)	2.704** (1.300)	−0.579*** (0.161)	2.478** (0.690)	−0.607*** (0.179)
Δ NAT	0.093*** (0.031)	0.130*** (0.041)	−2.283*** (0.543)	0.215*** (0.042)	0.537*** (0.108)
Δ TOP	0.196*** (0.040)	0.259*** (0.104)	0.393*** (0.054)	4.043*** (1.102)	0.227*** (0.067)
Δ GDP*TEC		−0.298** (0.147)			
Δ NAT*TEC			0.256*** (0.063)		
Δ TOP*TEC				−0.460*** (0.132)	
Δ TEC^2					0.043*** (0.012)
Constant	−12.316*** (1.202)	−40.506*** (13.388)	−6.696** (2.587)	−38.135** (8.024)	−11.092*** (0.888)
R^2	0.995	0.997	0.998	0.999	0.998
Serial correlation	0.504 [0.608]	0.321 [0.730]	1.803 [0.219]	1.895 [0.198]	1.861 [0.189]
Heteroskedasticity	0.460 [0.832]	0.512 [0.905]	0.769 [0.708]	0.613 [0.838]	0.472 [0.946]
Normality	0.573 [0.750]	2.972 [0.226]	0.509 [0.775]	2.916 [0.285]	0.387 [0.823]
Ramsey RESET	0.808 [0.424]	2.046 [0.163]	1.625 [0.135]	0.526 [0.610]	0.374 [0.713]

Notes: ***, **and * indicate the statistical significance at the 1%, 5% and 10% levels, respectively. The values in bracket are standard errors while the values in squared bracket are the probability values of the diagnostic tests.

resource sector, and ultimately raise energy demand and carbon dioxide emissions. Such economic structure hinders diversification and investment in low carbon production technology (Chen et al., 2023). Heavy reliance on natural resource rents can lead to governance issues (e.g., mismanagement, corruption, weak institutions) that hinder effective implementation of environmental laws and regulations.

To unravel the impact of the components of natural resource rents on carbon emissions, this study disaggregates natural resource rents into oil rents, natural gas rents, coal rents, mineral rents and forest rents. The estimation results displayed in Appendix 1 indicate that oil rents, natural gas rents and coal rents have detrimental impact on carbon emissions, while mineral rents and forest rents do not contribute to carbon emissions. Precisely, one percent rise in oil rents, natural gas rents and coal rents will raise long-run carbon emissions by 0.098, 0.033 and 0.014 percentage points, respectively. Aladejare (2022) reported that natural gas rents aggravate carbon emissions in 5 African countries while Gyamfi and Adebayo (2023) revealed that natural gas rents and coal rents contribute to carbon emissions in E7 nations. Our empirical outcomes imply that the extractions of oil, natural gas and coal contribute to carbon dioxide emissions in Malaysia. The extractions of these natural resources do not adhere to environmental protection protocols that can safeguard the environment. The use of pollution-intensive and energy-inefficient techniques to extract oil, natural gas and coal heightens carbon dioxide emissions in Malaysia.

Furthermore, carbon emissions will rise by 0.451 percentage points in the long-run, and 0.196 percentage points in the short-run if trade openness increase by one percent. Some past studies have also reported that trade openness has a detrimental impact on carbon emissions (Luqman, 2024; Vural, 2020). The economic and environmental implications of these results are that trade openness is detrimental to environmental quality in Malaysia. The plausible justification for this empirical outcome is that trade openness in Malaysia provides the opportunity to increase the importation and exportation of goods and services. Trade openness aggravates carbon emissions because it can enable advanced countries with stricter environmental protection standards to relocate their emissions-intensive firms to developing nations that have less stringent environmental policies to reduce production costs. Besides, trade openness raises the level of carbon emissions in the country because it increases the importation of pollution-intensive products as well as the transfer of energy-intensive industries. It increases the export of goods and services, which raise domestic production via increase in scale of industries.

To trace the component of trade openness that contribute to carbon emissions, this study disaggregates trade openness into exports and imports (see Ahmed et al., 2019). The empirical outcomes (see Appendix 1) show that exports have a significant detrimental impact on carbon emissions while the impact of imports is tenuous. Ahmed et al. (2019) revealed that exports contribute to carbon emissions while imports have insignificant effect on carbon emissions in the long-run in 8 countries. Salman et al. (2019) also reported that exports worsen carbon emissions in 7 ASEAN countries. The outcome of our analysis implies that the export of goods and services increase the scale of industries and domestic production which ultimately raise the level of carbon dioxide emissions.

As for technological innovation, the estimation results show that the long-run coefficient of technological innovation is negative (albeit the short-run coefficient is insignificant), suggesting that technological innovation mitigates carbon emissions. Precisely, holding other variables constant, one percent rise in technological innovation will alleviate carbon emissions by 0.013 percentage points in the long-run. This finding agreed with some previous studies (Toebelmann and Wendler, 2020; Meirun et al., 2021; Zhao et al., 2024). The economic and environmental implications of these results are that technological innovation mitigates carbon emissions. The plausible justification for this finding is that technological innovation enhances energy efficiency, green productivity as well as the development of clean energy resources such as wind power, solar energy, hydro power, etc. which reduces carbon emissions. Moreover, technological innovation can produce novel or modified processes or systems that can ensure low-carbon economy.

To unravel the impacts of the components of technological innovation on carbon emissions, this study disaggregates technological innovation into innovation by residents and innovation by non-residents (see Khattak et al., 2020). The empirical results (see Appendix 1) indicate that innovation by non-residents mitigate carbon emissions while innovation by residents do not alleviate carbon emissions. Mensah et al. (2018) reported that innovation by residents contribute to carbon emissions in Denmark and Finland while innovation by non-residents alleviate carbon emissions in Korea, New Zealand, and United Kingdom. Our empirical outcomes imply that Malaysia can utilize innovation by non-residents to abate carbon emissions in the country. In Model 2, this study adds the interaction term between technological innovation and GDP to the model, which enables us to determine the moderating role of technological innovation on the impact of GDP on carbon emissions. The empirical outcomes reported in Model 2 (Table 3) indicate that the coefficient of GDP is significantly positive, while the coefficient of the interaction term is significantly negative in both long-run and short-run periods. This implies that technological innovation has a favorable moderating role on the impact of GDP on carbon emissions. In other words, technological innovation mitigates the adverse impact of GDP on carbon emissions in Malaysia. Countries that apply technological innovation in their economic activities will experience a reduction in carbon dioxide emissions.

To unveil the total impact of both technological innovation and GDP on carbon emissions, it is fundamental to compute the marginal effect of GDP on carbon emissions at various levels of technological innovation. The marginal effects of GDP on carbon emissions computed at the minimum, mean and maximum levels of technological innovation are 2.193, 1.078 and 0.781, respectively. Since the marginal effects are decreasing, it can be concluded that GDP contributes more to carbon emissions at a lower level of technological innovation compared to a higher level of technological innovation. For instance, when the level of technological innovation (i.e., total number of patents applications) was 262 in 1986 in Malaysia, an increase in GDP increases carbon emissions by 2.193 percentage points. However, when the level of technological innovation rose to 7727 in 2015, a rise in GDP will raise carbon emissions by only 0.781 percentage points. Adewale et al. (2024) indicated that the interaction term between technological innovation and financial development mitigates carbon emissions in BRICS.

Model 3 focuses on the interaction term between technological innovation and natural resource rents. The results displayed in Model 3 (Table 3) show that the coefficient of the interaction term is positive and significant, implying that technological innovation cannot mitigate the adverse impact of natural resource rents on carbon emissions. This outcome implies that the technological innovation in natural resource extraction in Malaysia is inadequate to offset the adverse environmental impact of natural resource rent. The marginal effects of natural resource rents on carbon emissions computed at the minimum, mean and maximum levels of technological innovation are −0.387, 0.171 and 0.320, respectively. This finding differs from Zhao et al. (2024) who reported that the interaction term between technological innovation and natural resource rent mitigates carbon emissions in BRICS.

In Model 4, this study adds the interaction term between technological innovation and trade openness to the model. The empirical evidence shown in Model 4 (Table 3) reveal that the coefficient of the interaction term is negative while the coefficient of trade openness remains positive. The economic and environmental implications of these results are that technological innovation has a favorable moderating role on the impact of trade openness on carbon emissions in Malaysia. The country can mitigate the detrimental impact of trade openness on carbon emissions by raising the level of technological innovation. The marginal effects of trade openness on carbon emissions computed at the minimum, mean and maximum levels of technological innovation are

2.429, 0.812 and 0.381, respectively. The decreasing trend in the marginal effects implies that trade openness contributes more to carbon emissions when the level of technological innovation is low.

In the non-linear model (Model 5), this study adds the squared term of technological innovation to the model, which allows us to unravel the existence of a monotonous, U-shaped or inverted U-shaped relationship between technological innovation and carbon emissions. The empirical evidence show that the squared term of technological innovation is positive while the linear term is negative, suggesting a U-shaped relationship between technological innovation and carbon emissions. The economic and environmental implications of these results are that technological innovation at the early stage alleviates carbon emissions, but after a certain threshold is reached, a further rise in technological innovation will contribute to carbon emissions. It can be inferred that the innovation curse hypothesis is established, which argued that greater technological innovation is certainly not continually better and may even worsen carbon emissions. Mensah et al. (2018) showed a U-shaped relationship between technological innovation and carbon emissions in Austria, Netherlands, and Turkey. Dauda et al. (2021) also showed a U-shaped relationship between technological innovation and carbon emissions in 9 African nations while Appiah et al. (2023) found no evidence of nonlinearity between technological innovation and carbon emissions in 26 OECD countries.

In all the models, the coefficient of the error correction term (ECT) is negative and significant, indicating the speed of adjustment of carbon emissions from short-run deviation to long-run equilibrium. The coefficient of determination (R^2) reveals that variations in the independent variables can explain a considerable proportion of the variations in carbon emissions.

4.3. Robustness checks

4.3.1. Diagnostic tests

To ascertain the robustness of the estimations, this study conducts some residual diagnostic tests to ensure that the models are free from serial correlation and heteroskedasticity. The results of the Breusch-Godfrey Serial Correlation LM test reported in the lower panel of Table 3 cannot reject the null hypothesis of no serial correlation (i.e., the p-values are insignificant at 5% level), indicating that the models are free from serial correlation. Similarly, the results of the Breusch-Pagan-Godfrey Heteroskedasticity test cannot reject the null hypothesis of homoskedasticity, implying that the model are free from heteroskedasticity. The Jarque-Bera test also indicate that the variables have normal distribution. As for the stability diagnostic tests, the Ramsey RESET test indicate that the functional form of the models is appropriate, and they have no omitted variable bias. Similarly, since the CUSUM and CUSUM of squares tests (see Appendix 2) lie within the confidence intervals throughout the sample period, we cannot reject the null hypothesis (i.e., the model is stable) at 5% significance level. This implies that the models are stable and reliable.

4.3.2. Structural breaks

To ascertain whether the estimation results are sensitive to the existence of structural breaks, this study conducts structural breaks test using the Bai and Perron (2003) test. The test found significant structural breaks in 1989 and 1999. To account for these structural breaks, this study adds two dummy variables to the model. The first dummy variable (SBK1) takes the value of 1 from the first break year (1985), and 0 otherwise whereas the second dummy variable (SBK2) takes the value of 1 from the second break year (1999), and 0 otherwise (Hashmi et al., 2020). The empirical outcomes of the models with structural break dummies displayed in Table 4 are similar to the results reported in Table 3 in terms of the coefficients' sign and significance, albeit the magnitude slightly differ. This implies that our estimation results are robust. Besides, the coefficients of the structural break dummies are insignificant, suggesting that structural breaks do not contribute to carbon emissions in Malaysia.

5. Discussion and policy implications

The empirical outcomes of this study can be summarized as follows: First, economic growth contributes to carbon emissions in Malaysia. This finding agreed with some past studies (Chen et al., 2023; Ehigiamusoe and Lean, 2019; Khan et al., 2020). Economic growth intensifies carbon emissions in Malaysia probably because economic activities rely on pollution-intensive method of production. For instance, in the last three decades, more than 90% of energy consumption in Malaysia are sourced from fossils fuels that contribute to carbon emissions (Word Development Indicators, 2024). The policy implication of this finding is that Malaysia can lower carbon emissions by embracing clean energy resources and strengthening her environmental regulatory system. The country should encourage research and development into renewable energy sources, while the stakeholders should be given incentives to adopt renewable energy in economic activities. The country's environmental protection policies and laws should be strictly implemented, while carbon taxes should be enforced to discourage emissions-intensive industries. The government should vigorously promote energy-saving or efficient and emissions-reduction technologies to mitigate carbon emissions.

Second. natural resource rents have detrimental impacts on carbon emissions in Malaysia. This finding is consistent with some studies (Bekun et al., 2019; Danish et al., 2019; Hussain et al., 2020; Shen et al., 2021). The plausible justification for this finding is that the extraction of natural resources in the country is still emissions-intensive. In other

Table 4
ARDL long-run estimations with structural breaks dummies.

	Model 1	Model 2	Model 3	Model 4	Model 5
Bound test	11.853***	8.560***	9.531***	20.866***	7.387***
GDP	1.043*** (0.139)	6.658*** (1.931)	0.940*** (0.127)	0.691*** (0.159)	1.147*** (0.071)
TEC	−0.012** (0.003)	6.056** (2.100)	−0.893** (0.398)	7.207** (2.414)	−0.712*** (0.125)
NAT	0.165*** (0.077)	0.106** (0.065)	−2.825** (1.324)	0.254** (0.091)	0.531*** (0.070)
TOP	0.306*** (0.084)	0.301** (0.157)	0.775*** (0.240)	1.256*** (0.395)	0.208*** (0.048)
GDP*TEC		−0.684** (0.236)			
NAT*TEC			0.331** (0.150)		
TOP*TEC				−1.381** (0.463)	
TEC^2					0.061*** (0.009)
SBK1	0.137 (0.074)	0.050 (0.152)	−0.049 (0.079)	−0.101 (0.156)	0.067 (0.040)
SBK2	0.089 (0.048)	−0.044 (0.079)	−0.185 (0.103)	−0.084 (0.073)	0.081 (0.031)
ECT_{t-1}	−0.466*** (0.088)	−0.820*** (0.187)	−0.594*** (0.125)	−0.617*** (0.087)	−1.042*** (0.151)
Constant	−9.542*** (1.484)	−58.802** (16.205)	−2.457 (4.868)	−7.001** (1.948)	−9.256*** (0.863)
R^2	0.995	0.998	0.998	0.999	0.998

Notes: ***, **and * indicate the statistical significance at the 1%, 5% and 10% levels, respectively. The values in bracket are standard errors. SBK1 and SBK2 are structural breaks dummies.

words, the exploitation of natural resources is not properly and efficiently managed with advanced technologies that are carbon-neutral. To unravel the impacts of the components of natural resource rents on carbon emissions, this study disaggregates natural resource rents into oil rents, natural gas rents, coal rents, mineral rents and forest rents. The analysis revealed that oil rents, natural gas rents and coal rents have detrimental impacts on carbon emissions, while mineral rents and forest rents do not contribute to carbon emissions. The policy implication is that Malaysia should adopt advanced and carbon-neutral techniques in the exploitation of these natural resources to ensure environmental sustainability. The country should also develop a strategy that will reduce reliance on the exploitation and utilization of natural resources (e.g., oil, natural gas, coal) that contribute to carbon emissions. In other words, the country should embrace conservative methods in natural resources exploration and exploitation. It should encourage research and development as well as increase the investment into alternative cleaner natural resources (e.g., solar power, wind power, hydropower).

Third, trade openness has adverse impact on carbon emissions in Malaysia. This finding agreed with some past studies (Luqman, 2024; Vural, 2020). The impact of trade openness on carbon emissions depends on whether the scale effect (i.e., increase in production and energy consumption because of trade), composition effect (i.e., re-assignment of traded resources or commodities) or technique effect (i.e., transfer of clean and energy-efficient technologies due to trade) dominate (Dauda et al., 2021). Trade openness can influence carbon emissions through exports and/or imports. Therefore, to trace the component of trade openness that contribute to carbon emissions, this study disaggregates trade openness into exports and imports. The findings show that exports contribute to carbon emissions while imports have tenuous impact. These findings are consistent with some previous studies (Ahmed et al., 2019; Salman et al., 2019). This suggests that trade liberalization comes at the cost of environmental quality in Malaysia. Hence, the policy implication is to change the pattern of trade openness and accelerate the transition to a low-carbon trade strategy. The Malaysian exports are dominated by processing trade products which are characterized by high input and emissions. Therefore, policymakers need to optimize the structure of exports to achieve trade transformation. This could be reflected in reducing exports of high energy-intensive products and imposing carbon taxes on the exportation of emissions-intensive products.

Fourth, technological innovation mitigates carbon emissions in Malaysia. This finding agreed with some previous studies (Toebelmann and Wendler, 2020; Meirun et al., 2021; Zhao et al., 2024). The plausible justification for this finding is that technological innovation enhances energy efficiency and green productivity which do not intensify carbon emissions. To unravel the impacts of the components of technological innovation on carbon emissions, this study disaggregates technological innovation into innovation by residents and innovation by non-residents. The analysis indicates that innovation by non-residents mitigate carbon emissions while innovation by residents do not alleviate carbon emissions. The policy implication is that Malaysia should intensify efforts to encourage technological innovation by adopting more incentive policies for innovation projects and environmental inventions. The country can adopt green technological development and increase the financial input for green technological innovation. It may be necessary to provide greater financial support for the research and development of the enterprises. Stakeholders should be encouraged to increase investment in high-tech research and development, especially technical support for new environmental protection industries as well as facilitate the green transformation of manufacturing industries.

Furthermore, the interaction model revealed that technological innovation has a favorable moderating role on the impact of economic growth on carbon emissions in Malaysia. This implies that a simultaneous increase in both technological innovation and economic growth will not contribute to carbon emissions. Essentially, the marginal effect of economic growth on carbon emissions declines as technological innovation increases. The policy implication is that Malaysia can deploy technological innovation to boost economic activities, which will have beneficial ramifications for the environment. This is fundamental since some studies have revealed that technological innovation enhances economic growth (Acheampong et al., 2022; He et al., 2023; Meirun et al., 2021). Malaysia should establish green criteria for government performance assessment by replacing high pollution-intensive government activities with low-carbon activities to safeguard environmental sustainability.

Similarly, this study indicates that technological innovation has a favorable moderating role on the impact of trade openness on carbon emissions in Malaysia. Essentially, the marginal effects of trade openness on carbon emissions decreases as technological innovation increases in Malaysia. Put differently, trade openness contributes more to carbon emissions when the level of technological innovation is low. Therefore, Malaysia should use trade openness as a veritable channel to ensure the transfer of carbon-neutral technologies from advanced countries.

This study also revealed that the interaction term between technological innovation and natural resource rents contribute to carbon emissions in Malaysia. In other words, technological innovation cannot mitigate the adverse impact of natural resource rents on carbon emissions. The plausible justification is that the exploitation or extraction of natural resources in Malaysia is not efficiently managed with advanced technology. Zhao et al. (2024) reported that the interaction term between technological innovation and natural resource rents mitigate carbon emissions in BRICS. The policy implication is that Malaysia should adopt the state-of the-art technologies in the extraction of natural resources with a view to attaining carbon-neutral economy.

Finally, the non-linear model reveals that technological innovation has a U-shaped relationship with carbon emissions in Malaysia. At the early stage, technological innovation reduces carbon emissions, but after a certain turning point, a further rise in technological innovation will contribute to carbon emissions. This finding agreed with some past studies (Dauda et al., 2021; Mensah et al., 2018). Our empirical outcome implies that the innovation curse hypothesis is confirmed, which argued that greater technological innovation is certainly not continually better and may even worsen carbon emissions. The policy implication is that Malaysia should consider the level (turning point) of technological innovation that optimize the mitigation of carbon emissions.

6. Conclusion

This study estimated a linear model to unravel the impacts of economic growth, technological innovation, natural resource rents and trade openness on carbon emissions in Malaysia. It also employed the interaction models to unveil the moderating role of technological innovation on the impacts of economic growth, natural resource rents and trade openness on carbon emissions in Malaysia. This analysis allows us to compute the marginal effects of these variables on carbon emissions at various level of technological innovation. Besides, it deploys the nonlinear model to unravel the nonlinear relationship between technological innovation and carbon emissions in Malaysia.

The empirical outcomes of the linear model suggest that economic growth, natural resource rents and trade openness contributes to carbon emissions while technological innovation mitigates carbon emissions in Malaysia. To trace the components of natural resource rents, trade openness and technological innovation the influence carbon emissions, this study disaggregated these variables into their components. The analysis of natural resource rents indicated that oil rents, natural gas rents and coal rents have detrimental impact on carbon emissions while mineral rents and forest rents do not contribute to carbon emissions. The analysis of trade openness revealed that exports have a significant detrimental impact on carbon emissions while the impact of imports is tenuous. The analysis of technological innovation showed that innovation by non-residents mitigate carbon emissions while innovation by residents do not alleviate carbon emissions.

The interaction model reveals that technological innovation can favourably mitigate the adverse impact of economic growth and trade openness on carbon emissions albeit it cannot alleviate the detrimental impact of natural resource rents on carbon emissions. Specifically, economic growth and trade openness have less adverse impact on carbon emissions at a higher level of technological innovation. The nonlinear model revealed a U-shaped relationship between technological innovation and carbon emissions. This implies that technological innovation at the early stage alleviates carbon emissions, but after a certain threshold is reached, a further rise in technological innovation will contribute to carbon emissions.

This study provides important policy implications for optimizing trade structures, environmental governance, and economic expansion. The practical significance lies in providing the foundation for policymakers to formulate policies on sustainable development. Based on the findings, the following policy options are recommended.

- Since economic growth intensifies carbon emissions in Malaysia, it is necessary to prioritize sustainable economic development by adopting green consumption and investment practices. The government should offer subsidies to firms using green technologies and deploy appropriate taxes (e.g., carbon taxes, environmental taxes) to discourage emissions-intensive and energy inefficient production techniques.
- The adverse environmental impact of natural resource rents in Malaysia emphasizes the need for the country to adopt advanced and low-carbon techniques in the exploitation of natural resources (especially oil, natural gas, and coal). The country should develop a strategy that will reduce reliance on the exploitation and utilization of natural resources that contribute to carbon emissions.
- Since trade openness has adverse impact on carbon emissions in Malaysia, the country should modify the pattern of trade and accelerate the transition to a low-carbon trade strategy. In the production of exports, the country should replace emissions-intensive and energy inefficient production methods with clean technologies.
- The mitigating impact of technological innovation on carbon emissions in Malaysia stressed the need for the country to encourage technological innovation through incentive policies. Greater financial supports are required for high-tech research and development that can facilitate green transformation of manufacturing industries.
- Since technological innovation mitigates the adverse environmental impact of economic growth and trade openness in Malaysia, the country should deploy technological innovation to boost economic activities and trade to ensure environmental sustainability. The inability of technological innovation to abate the environmental impact of natural resource rents stresses the need for the country to adopt clean and state-of the-art technologies in the extraction of natural resources (especially oil, natural gas, coal).
- The U-shaped relationship between technological innovation and carbon emissions in Malaysia confirmed the innovation curse hypothesis, which argued that greater technological innovation is certainly not continually better for carbon emissions. It may be necessary for the country to consider the level of technological innovation that can optimize carbon emissions mitigation.

This study has succeeded in unravelling the impacts of economic growth, technological innovation, natural resource rents and trade openness using linear, interaction and non-linear models. One of the limitations of this study is the inability of the study to compare these issues in developed and developing countries. Hence, it is recommended that future studies should compare the analysis in developed and developing countries fir greater insights.

CRediT authorship contribution statement

Kizito Uyi Ehigiamusoe: Writing – original draft, Data curation. **Eyup Dogan:** Supervision, Methodology. **Suresh Ramakrishnan:** Writing – original draft, Software. **Rima H. Binsaeed:** Writing – original draft.

Declaration of competing interest

There is no conflict of interest between the authors.

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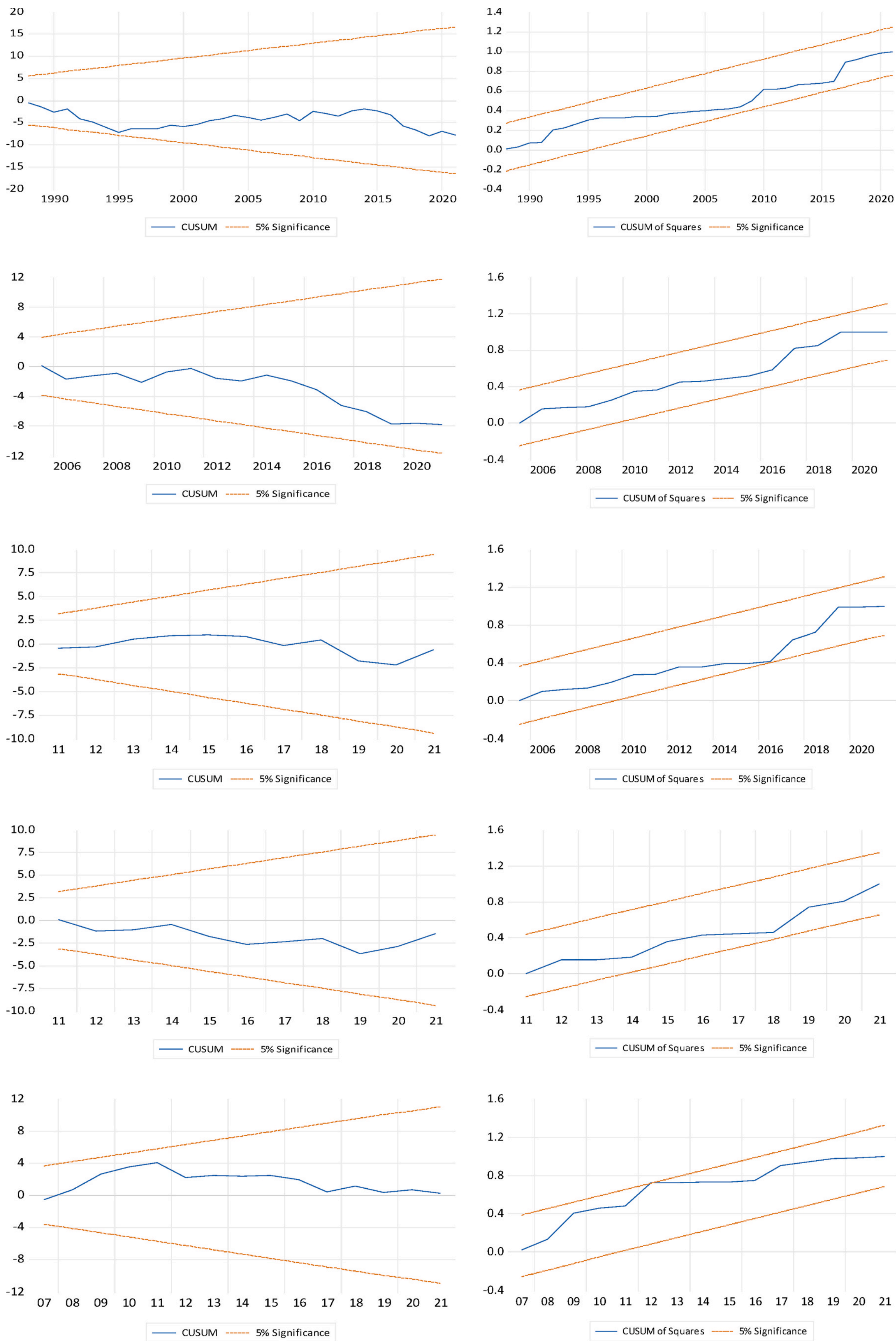
Appendix 1. ARDL long-run estimations with disaggregated variables

Bound test	12.756***	12.868***	23.906***	14.375***
GDP	0.785*** (0.128)	1.246*** (0.126)	0.828*** (0.074)	0.848*** (0.099)
TEC		−0.009 (0.035)	−0.001 (0.001)	
NAT	0.020 (0.069)	0.198** (0.093)		
TOP	0.547*** (0.056)		0.415*** (0.041)	
TECR	0.094*** (0.026)			−0.002 (0.014)
TECNR	−0.076** (0.034)			−0.021* (0.011)
EXP		0.291** (0.054)		0.286*** (0.082)
IMP		0.151* (0.101)		0.169* (0.086)
OIL			0.098*** (0.032)	0.070** (0.031)
GAS			0.033*** (0.011)	0.037** (0.021)
COAL			0.014** (0.007)	0.015** (0.006)
MINERAL			0.001 (0.009)	0.009 (0.008)
FOREST			−0.075** (0.027)	−0.093*** (0.026)
ECT_{t-1}	−0.767*** (0.123)	−0.442*** (0.102)	−0.984*** (0.098)	−1.157*** (0.146)
Constant	−7.869*** (1.202)	−11.651*** (1.351)	−7.754*** (0.670)	−7.496*** (0.908)
R^2	0.996	0.995	0.996	0.998

Notes: ***, **and * indicate the statistical significance at the 1%, 5% and 10% levels, respectively. The values in bracket are standard errors. TECR = technological innovation by residents, TECNR = technological innovation by non-residents, EXP = exports, IMP = imports, OIL = oil rents, GAS = natural gas rents, COAL = coal rents, MINERAL = mineral rents, FOREST = forest rents.

Appendix 2. Stability tests



Data availability

Data will be made available on request.

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