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Navigating the nexus: unraveling technological innovation, economic growth, trade openness, ICT, and CO_2 emissions through symmetric and asymmetric analysis

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In Malaysia's rapid economic growth and industrialization, environmental degradation and carbon emissions pose significant challenges. As urbanization continues to rise, there is a growing recognition of the imperative to tackle CO_2 emissions. Trade openness and globalization drive economic activity but also heighten environmental pressures, including CO_2 emissions from transportation and industry. Information communication technology (ICT) usage, shaped by infrastructure and regulations, can either improve energy efficiency or increase energy consumption. The study examines the impacts of economic growth (EG), trade openness (TON), technological innovation (TIN), and ICT on CO_2 emissions in Malaysia, using both symmetric and asymmetric methods from 1985 to 2021. While many studies have explored environmental degradation, focusing on CO_2 emissions and ecological footprint indicators, only a limited number have delved into the combined impact of sustainable EG, TON, ICT, and TIN on Malaysia's CO_2 emissions. Notably, these studies have often neglected the utilization of both symmetric and asymmetric methodologies. Hence, this study employed auto-regressive distributed lag (ARDL) and non-linear ARDL approaches to investigate the dynamic effects of the studied variables. The key findings from the symmetric analysis demonstrate that EG, TON, and ICT together take part in the increase of CO_2 emissions in both the short and long run. Particularly, technological innovation plays a significant role in reducing CO_2 emissions in the short term through the adoption of cleaner technologies. However, the results of the NARDL bound test reveal asymmetric long-term consequences of technological innovation, economic growth, and ICT on CO_2 emissions. The study underscores the need for CO_2 reduction policies in Malaysia, advocating for measures, such as incentivizing cleaner technologies and upgrading energy infrastructure. It also recommends implementing carbon pricing mechanisms for production and trade, alongside awareness campaigns to foster behavioral changes aimed at reducing emissions.

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Introduction

Climate change has evolved into an intensifying threat to sustainable development in recent decades, igniting a fervent global discourse (Destek & Sarkodie, 2019; Nathaniel & Khan, 2020). With the rise of environmental degradation casting a shadow on nations worldwide, the imperative of fostering sustainable growth has taken center stage, amplifying concerns regarding environmental limitations on progress and economic choices (Sun et al., 2020; Niinimäki et al., 2020). The increase in greenhouse gas emissions (GHGs) in recent decades has brought environmental pollutants to the forefront of global issues, representing a significant and critical concern (Dogan & Seker, 2016; Khan et al., 2017). Strikingly, despite the projected consequences of unchecked GHG emissions, they continue to surge unabated. This unrelenting trajectory has wielded considerable influence over environmental policy, enmeshed with the complexities of economic growth and CO_2 emissions. Given the pressing climate crisis, prioritizing sustainable economic growth has become paramount for economies worldwide (Azam et al., 2022). This emphasis is crucial, considering that achieving sustainable development remains unattainable until environmental sustainability is effectively established (Zafar et al., 2019). Notably, the surge in CO_2 emissions parallels the escalating use of fossil fuels, which is a consequence of the recent rapid expansion of modern industrial civilization (Bhui, 2021; Kanwal et al., 2022). These milestones comprise the establishment of the UNFCCC in 1992, the Tokyo Protocol in 1997, the significant Copenhagen Agreement of 2009, the China-USA Agreement of 2014, and the highly anticipated Paris Agreement set for 2015.

The Intergovernmental Panel on Climate Change (IPCC) underscores the pivotal role of innovation and technological advancement in curbing carbon emissions, emphasizing that the pace and scale of technological progress will shape future carbon reduction (Usman et al., 2021). Furthermore, information communication technology (ICT) plays a dual role: it is indispensable for industrialization, which impacts the environment and drives economic advancement (Khan and Qianli, 2017; Danish et al., 2018). While some researchers propose a robust and negative correlation between the expansion of the ICT sector and CO_2 emissions (Asongu et al., 2017; Danish, 2019; Haini, 2021), others assert its significance in monitoring, managing, and transitioning to a green economy amidst climate change (Usman et al., 2021). Despite its importance in mature economies, ICT's contribution to pollution remains uncertain. Notably, specific research points out that ICT can enhance environmental management and production processes, offering a potential avenue for environmental benefit (Heidari et al., 2019; Zhou et al., 2019; Awan et al., 2021).

Malaysia has set forth an ambitious goal to slash GHG emissions intensity by 45% by 2030, which includes an unconditional 35% reduction and a conditional 10% decrease. Committed to this trajectory, the 12th Malaysia Plan outlines a vision for carbon neutrality by 2050. Yet, without a proactive and comprehensive approach to climate change, Malaysia risks falling short of fulfilling its Nationally Determined Contributions (NDCs) within the Paris Agreement. To honor its commitments, Malaysia must preserve carbon sinks and expedite the transition from fossil fuel-based energy to renewable and alternative sources. However, the transformative shift from agriculture to industry between 1970 and 1980 significantly altered Malaysia's energy consumption dynamics, impacting its trajectory (Begum et al., 2015; Zhang et al., 2021). As the energy-intensive services sector gains prominence in Malaysia's GDP composition, achieving a 45% reduction in emission intensity remains a formidable challenge without a substantial pivot toward low-carbon technologies.

Within the empirical domain, numerous investigations have examined environmental degradation through the lens of CO_2 emissions and ecological footprint indicators (Hassan et al., 2023; Danish & Hassan, 2023; Li et al., 2023). However, only a limited number of studies have delved into the combined impact of sustainable economic growth (EG), trade openness (TON), technological innovation (TIN), and ICT on Malaysia's CO_2 emissions. Notably, these studies have often neglected to utilize both symmetric and asymmetric methodologies. This research targets to bridge this gap by closely studying the intricate relationship between sustainable EG, TON, TIN, ICT, and CO_2 emissions in Malaysia. Employing both auto-regressive distributed lag (ARDL) and non-linear ARDL approaches, this investigation provides a comprehensive exploration of this multifaceted relationship.

The research offers diverse fresh perspectives that significantly enhance our comprehension of environmental sustainability and economic progress in Malaysia. (I) By assessing the interplay of EG, TON, TIN, and ICT on CO_2 emissions, the study provides a holistic understanding of these factors' combined effects. This nuanced analysis offers insights into the intricate dependencies among these variables, contributing to a comprehensive view of their impact on emissions. (II) The study's discovery of technological innovation's potential to drive short-term reductions in CO_2 emissions through cleaner technologies offers a new perspective. This finding suggests opportunities for the Ministry of Science and Technology to develop environmentally conscious ICT frameworks, fostering sustainable development. (III) Identifying the unequal long-term effects of TIN, EG, and ICT on CO_2 emissions complicates our understanding of Malaysia's economic and technological context. This insight deepens our comprehension of the intricate connections within the country's developmental path. (IV) The study's identification of the connection between TIN and CO_2 emissions, distinguishing between positive and adverse advancements, adds a new dimension to the discourse on technology's environmental impact. This finding highlights the importance of aligning technological development with environmental sustainability goals. (V) The study's observation of the impact of ICT usage on CO_2 emissions, with escalating usage having a constructive influence while diminished usage correlates with adverse effects, sheds light on the critical role of digitalization in shaping environmental outcomes in Malaysia. This perspective offers valuable insights for policymakers and industry stakeholders. Finally, alongside its empirical findings, the study provides policy recommendations targeted at mitigating emissions and fostering sustainable development. These recommendations, such as supporting the integration of renewable energy and implementing financing mechanisms for green ICT, offer practical strategies for policymakers to tackle environmental challenges while promoting economic growth.

Literature review

Technological innovation and CO_2 emission. The technology effect is concerned with ongoing innovation and the deployment of new technologies, which encourage increased resource efficiency and productivity and lessen the harm that production activities cause to the environment (Wang et al., 2023). Cutting-edge technology is essential to an economy's ability to expand both environmentally and economically (Meirun et al., 2021; Wang et al., 2024). Scholars have extensively reconnoitred the impact of TIN on CO_2 emissions, attributing it to the increasing global capabilities in innovation (Zaho et al., 2021). The growing awareness among government officials and academics regarding TIN's potential to reduce CO_2 emissions has fueled ongoing technological advancements (Huang et al., 2020; Xie et al., 2021; Shan et al., 2021). Previous studies, such as those by Mensah et al. (2018), Lin and Zhu (2019), and Ganda (2019), have investigated the influence of patents on emissions as a proxy for technical advancement. However, it's worth noting that technical advancement has been associated with higher CO_2 emissions (Amin et al., 2020; Erdogan, 2021; Shahbaz et al., 2020). Conversely, renewable energy, TIN, and human capital have been found to inversely impact CO_2 emissions (Wang et al., 2021). Li et al. (2021) discovered a strong inverse correlation between technology innovation and CO_2 emissions in China. However, studies by Chen and Lee (2020) and Samargandi (2017) suggest that TIN does not necessarily have a negative impact on global CO_2 emissions. Decreased energy intensity, CO_2 emissions, EG, and TON have been linked to higher energy use due to technical development (Pata and Caglar, 2021; Adebayo et al., 2022;). Sharif et al. (2022) found a significant inverse correlation between these factors. Additionally, Wang et al. (2021) study noted a decline in Japan's energy density due to innovation spending. Long et al. (2018) and Erdogan (2021) contend that innovation in Chinese agriculture leads to a detrimental impact on carbon emissions. Lin and Xu (2020) underscore the significance of energy efficiency in curbing carbon emissions within China's central region. Wang et al. (2021) suggest that innovation's impact on emissions varies by industry, with the industrial sector strongly driving reduction. The expansion of patents and trademarks affects carbon emissions positively in affluent nations but negatively in underdeveloped countries (Demircan Cakar et al., 2021). Local research and development (R&D) and innovation in the energy sector contribute to carbon emissions reduction (Shahbaz et al., 2020). Liang et al. (2019) found a link between the number of patents and carbon emissions, indicating that a decrease in patent numbers might lead to a more sustainable environment.

Economic growth and CO_2 emission. Economic activity significantly influences CO_2 emissions, with specialized sectors generating more CO_2 per production unit often correlating with economic growth (Akhtar et al., 2023; Lin and Guan, 2023). Over time, the intertwining of economic expansion and CO_2 emissions leads to ecological harm as economies grow (Gao, 2023; Ahmad et al., 2023). Such growth yields negative outcomes, including reduced agricultural productivity, increased insecurity, disease prevalence, and poverty, largely attributed to climate change (FAO, 2019; Kogo et al., 2021; Fajobi et al., 2023). Ironically, the industries and agricultural sectors, which are particularly susceptible to climate change, are its primary contributors. A substantial 73% of GHG emissions arise from energy consumption linked to industrial and agricultural processes (World Resources Institute, 2020). Consequently, climate change hampers economic progress and prosperity, necessitating prompt mitigation strategies in these sectors. Economic growth and development notably shape environmental degradation and CO_2 emissions. As wealth per capita increases, environmental degradation tends to rise (Khan et al., 2022). Economic growth also influences long-term energy use and emissions (Ang, 2008), highlighting the interconnectedness among energy, the environment, and economic progress (Shang et al., 2023). Trade liberalization holds a dual impact on emissions: it can reduce them through methodological changes but potentially increase them due to the income-pollution relationship (Mahmood et al., 2019; Yang et al., 2020). Environmental considerations are vital for fostering sustainable economic development (Abbas et al., 2023). Strategic approaches are necessary to achieve equilibrium between growth and environmental conservation due to the complex interplay among economic expansion, CO_2 emissions, and environmental regulations.

Trade openness and CO_2 emission. The emergence of clean energy, predominantly driven by renewable sources, along with the continuous advancement of globalization and trade liberalization, has brought about significant structural shifts in energy, trade, economy, and society. This transition has been accompanied by the growth of service sectors and urbanization (Li et al., 2021). Trade openness has a growing positive impact on national economies, especially when considering the interdependence of financial systems, which boosts economic growth (Zhang et al., 2024; Ashiq et al., 2023). However, trade openness carries dual disadvantages: while it promotes economic growth, it also adversely affects the environment and climate (Zhang et al., 2023). The association between trade and carbon emissions remains debated, whether direct or indirect (Kolcava et al., 2019; Xie et al., 2020). Literature often focuses on trade's direct emission impact, potentially overlooking socio-economic factors (Vural, 2020). Trade's influence on emissions is notably influenced by Foreign Direct Investment (FDI) (Zubair et al., 2020). According to Usman et al. (2022), trade openness markedly deteriorates Pakistan's environmental quality. Prior studies yielded varied results, with trade openness shown to negatively affect the environment or contribute to pollution reduction (Wang and Zhang, 2021; Azam et al., 2022). Irfan et al. (2023) discovered a short-term equilibrium correlation between trade openness and carbon emissions in Sri Lanka, but no such correlation existed in the long term. They also observed that trade openness stimulates investment, thereby fostering economic growth. Jakada et al. (2023) unveiled the adverse indirect impacts of trade openness on CO_2 emissions in the long run, offset by positive direct effects in both the short and long terms. Mahmood et al. (2019) indicated that trade openness has asymmetric effects on CO_2 emissions, with different levels of openness yielding inconsistent and inconsequential outcomes.

ICT and CO_2 emission. The expanding role of ICT in the global GDP encompasses various industries. However, while it brings about favorable effects on economic growth, it also presents limitations in terms of resources and poses environmental difficulties (Jahanger and Usman, 2023; Saqib et al., 2024; Haldar et al., 2023). Technology and the environment have a complex interaction, as noted by Kumar et al. (2020). As a low-carbon enabler, ICT fosters ecological sustainability by boosting energy efficiency and curbing GHG emissions in sectors like power, transport, and construction (Abdollahbeigi & Salehi, 2020; Zafar et al., 2019; Tzeremes et al., 2023). In order to combat the effects of climate change and advance a green, circular economy, information and communication technology (ICT) is essential (Yang et al., 2023; Durán-Romero et al., 2020). Energy consumption, economic growth, population, and greenhouse gas emissions all increased in line with Malaysia's 25-year spike in internet users (Fakher et al., 2023). The ICT industry's share of GHG emissions grows due to environment-linked ICT component production (Villanthenkodath et al., 2022). Increased utilization of devices, such as computers, smartphones, and online connectivity, leads to heightened demand for energy, one of the main causes of environmental deterioration (Adebayo et al., 2022; Dedaj et al., 2022). There are significant environmental concerns due to the growing economy and increased energy usage, as evidenced by Hassan et al. (2023), Uzar (2020), Raihan and Tuspekova (2022). Pan & Dong (2023) illustrate that the growth of the Internet has the feasibility to decrease urban CO_2 emissions through the enhancement of industrial structures, the stimulation of eco-friendly innovation, and the reinforcement of environmental regulations. Additionally, the Internet can steer cities dependent on resource extraction toward a trajectory of low-carbon development.

Table 1 Source of data and variables.

Variables	Symbol	Description	Data sources
CO_2 emission	CO_2	Carbon emission per capita	WDI*
GDP per capita	EG	GDP per capita (constant at 2005)	WDI
Trade openness	TON	Sum of exports and imports	WDI
Mobile use	ICT	Mobile cellular subscriptions per 100 people	WDI
Technological Innovation	TIN	Total number of patent applications	WDI

*WDI world development indicators.

Research methods

ARDL and NARDL are considered advanced econometric techniques for analyzing time series data. These techniques are employed to represent and comprehend the dynamic interactions between variables, especially in the context of co-integration and long-run relationships among economic or time series variables. They are particularly useful in examining non-linear relationships, lagged effects, and short- and long-term dynamics in economic models.

Data origin and characteristics. In this research, an investigation was conducted into the enduring and immediate connections between CO_2 emissions, EG, TIN, TON, and ICT. This was carried out through the utilization of both the linear and non-linear ARDL approach. To fulfill the research objectives, time series data spanning from 1985 to 2021 were extracted from the World Development Indicator (WDI) dataset specifically for Malaysia (World Bank, 2022). Further insights regarding the data can be found in Table 1.

Model specifications. This research examined the enduring interactions among the variables of interest through the ARDL approach, pioneered by Pesaran et al. (2001). The methodology comprises the following key components: (i) Determining the optimal lag order for the model and using Ordinary Least Squares (OLS) to estimate the co-integration relationship. (ii) Applying the method developed by Johansen and Juselius, which is statistically robust irrespective of whether the variables are categorized as I(0), I(1), or mutually co-integrated. This indicates that a unit root test may not be required. (iii) When used with tiny and limited datasets, the ARDL technique is also acknowledged for its applicability and efficacy (Menegaki, 2019). (iv) As demonstrated by earlier research, it offers objective estimates over the long run, even in the presence of specific endogenous model regressors (Tuntivate, 1989; Pahlavani et al., 2005). (v) The method described allows for varied outcomes concerning short- and long-term impacts, facilitating a simultaneous evaluation of how each variable influences the others across different timeframes (Sikder et al., 2022). During the estimation process, a clear distinction between dependent and explanatory variables was established using the ARDL bounds testing approach. According to Wang and Wang (2018), the ARDL version of the VECM was subjected to the application of Eq. (2) in order to execute the phases for bound testing. There are theoretical links between EG, TIN, TON, ICT, and CO_2 emissions. Following the idea of market equilibrium, in which CO_2 emissions are in line with economic expansion and energy consumption, we use the Cobb Douglas production function to establish Eq. (1) (Biddle, 2012). This formula can be used to assess how TON, TIN, and ICT affect CO_2 emissions.

$$CO_2 = f\,(EG, TON, ICT, TIN) \tag{1}$$

This study has opted for the employment of the ARDL and NARDL bound test due to its adeptness in handling datasets with limited observations (Muhammad & Abdullahi, 2020). Furthermore, the bound test eliminates the necessity for variables to possess identical orders, requiring a fusion of integration at levels I (0) and first-order I (1). One important point, as highlighted by Alam and Hossain (2024), is that the bound test takes care of issues with serial correlation and variable endogeneity. It becomes necessary to include lags for the independent and dependent variables in order to properly construct the linear ARDL model. In cases where the dependent variable exhibits q lags and the independent variables feature r lags, the ensuing ARDL framework is established as follows:

$$CO2_t = \beta_0 + \sum_{i=1}^{q} \text{Б}_1 CO2_{t-i} + \sum_{i=0}^{r} \text{Б}_2 EG_{t-i} + \sum_{i=0}^{r} \text{Б}_3\, TON_{t-i} + \sum_{i=0}^{r} \text{Б}_4\, ICT_{t-i} + \sum_{i=0}^{r} \text{Б}_5 TIN_{t-i} + \varepsilon t \ldots\ldots\ldots \tag{2}$$

In this context, where rq stands for q values ranging from 1 to 5, representing the highest permissible number of lags for EG, TON, ICT, and TIN correspondingly. The formulation of the ARDL bound test is expressed through Eq. (3):

$$\Delta LCO2_t = \beta_0 + \sum_{i=1}^{q} \text{Б}_1 \Delta LCO2_{t-i} + \sum_{i=0}^{r} \text{Б}_2 \Delta LEG_{t-i} + \sum_{i=0}^{r} \text{Б}_3\, \Delta LTON_{t-i} + \sum_{i=0}^{r} \text{Б}_4\, \Delta ICT_{t-i} + \sum_{i=0}^{r} \text{Б}_5 \Delta LTIN_{t-i} + \vartheta_1 LCO2_{t-1} + \vartheta_2 LEGt - 1 + \vartheta_3 LTONt - 1 + + \vartheta_4 ICT_{t-1} + \vartheta_5 LTIN + \varepsilon t \ldots\ldots\ldots \tag{3}$$

The operator Δ represents the differencing operation, and L signifies the natural logarithm of the variables. Equation (3) encapsulates the short-term dynamics denoted by θi for i ranging from 1 to 5, as well as the long-term dynamics represented by Б1, Б2, Б3, Б4, and Б5. By employing a reduced form and an error correction model, the Eq. (3) can be expressed in a more succinct manner as follows:

$$\Delta LCO2_t = \beta_0 + \sum_{i=1}^{q} \text{Б}_1\, \Delta LC02_{t-i} + \sum_{i=0}^{q} \text{Б}_2\, \Delta LEG_{t-i} + \sum_{i=0}^{q} \text{Б}_3\, \Delta LTON_{t-i} + \sum_{i=0}^{q} \text{Б}_4\, \Delta ICT_{t-i} + \sum_{i=0}^{q} \text{Б}_5\, \Delta LTIN_{t-i} + \theta_i ECT_{t-1} + \varepsilon_t \ldots\ldots\ldots \tag{4}$$

The error correction term (ECT), whose coefficient is represented by the symbol θ, captures the long-term relationship between the variables and indicates how quickly changes towards the long-term equilibrium follow any disturbance to the system.

Non-linear ARDL model. A number of studies, such as Ramli et al. (2022), Ozturk and Ullah (2022), Sun et al. (2022) used a similar method for analysis. Shin et al. (2014) introduced a non-linear ARDL methodology, which is adopted in this study to investigate potential asymmetrical relationships among variables. This involves examining both positive and negative changes within the independent variable. This approach is taken because the conventional symmetric assumption regarding the linear impact of independent variables on the dependent variable is employed to establish the long-term relationship through co-integration testing. To assess this, the constructive separation of positive and negative shifts in EG, ICT, and TIN is conducted by generating two additional sets of series, following the methodology outlined by Qamruzzaman and Jianguo (2018). This process

Table 2 Synopsis of data.

	CO_2	EG	TON	ICT	TIN
Mean	11.684	8.777	5.073	2.578	8.352
Maximum	12.386	9.340	5.395	5.013	8.952
Minimum	10.497	8.126	4.650	−2.696	5.568
Std. dev.	0.603	0.356	0.216	2.576	0.689
Observations	36	36	36	36	36

Source: Authors' own computation.

leads to the formulation of the subsequent equations.

$$\left.\begin{aligned} LEG_t^+ &= \sum_{i=1}^{t} \Delta LEG_i^+ = \sum_{i=1}^{t} Max\left(\Delta LEG_i, 0\right) \\ LEG_t^- &= \sum_{i=1}^{t} \Delta LEG_i^- = \sum_{i=1}^{t} Min\left(\Delta LEG_i, 0\right) \end{aligned}\right\} \tag{5}$$

$$\left.\begin{aligned} ICT_t^+ &= \sum_{i=1}^{t} \Delta ICT_i^+ = \sum_{i=1}^{t} Max\left(\Delta ICT_i, 0\right) \\ ICT_t^- &= \sum_{i=1}^{t} \Delta ICT_i^- = \sum_{i=1}^{t} Min\left(\Delta ICT_i, 0\right) \end{aligned}\right\} \tag{6}$$

$$\left.\begin{aligned} LTIN_t^+ &= \sum_{i=1}^{t} \Delta LTIN_i^+ = \sum_{i=1}^{t} Max\left(\Delta LTIN_i, 0\right) \\ LTIN_t^- &= \sum_{i=1}^{t} \Delta LTIN_i^- = \sum_{i=1}^{t} Min\left(\Delta LTIN_i, 0\right) \end{aligned}\right\} \tag{7}$$

Equations (5), (6), and (7) are incorporated into Eq. (3) to constitute our NARDL model, which can be represented as:

$$\begin{aligned} \Delta LCO2_t = {} & \varphi_0 + \lambda_1 LCO2_{t-1} + \lambda_2^+ LEG_{t-1}^+ + \lambda_3^- LEG_{t-1}^- + \lambda_4 LTON_{t-1} \\ & + \lambda_5^+ ICT_{t-1}^+ + \lambda_6^- ICT_{t-1}^- + \lambda_7^+ LTIN_{t-1}^+ + \lambda_8^- LTIN_{t-1}^- \\ & + \sum_{i=1}^{q} \varphi_i \Delta LCO2_{t-i} + \sum_{i=0}^{q} (\varphi_i^+ \Delta LEG_{t-i}^+ + \varphi_i^- \Delta LEG_{t-i}^-) \\ & + \sum_{i=0}^{q} \varphi_i \Delta LTON_{t-i} + \sum_{i=0}^{q} (\varphi_i^+ \Delta ICT_{t-i}^+ + \varphi_i^- \Delta ICT_{t-i}^-) \\ & + \sum_{i=0}^{q} (\varphi_i^+ \Delta LTIN_{t-i}^+ + \varphi_i^- \Delta LTIN_{t-i}^-) + \mu_t \end{aligned} \tag{8}$$

In the equations provided above, the coefficients λ_1 to λ_8 represent the elasticity coefficients in the long run, while φi signifies the elasticity coefficients in the short run.

Results and discussions

Primary outcome. Before commencing any regression analysis, it is crucial to meticulously examine the fundamental characteristics of the variables and their correlations. Descriptive statistics concerning the primary variables are outlined in Table 2. The data highlights that ICT demonstrates the lowest mean value (2.578), while CO_2 emissions exhibit the highest mean value (11.684). In terms of standard deviation, the most pronounced volatility is observed in the information communication technology variable, indicating a higher degree of variability, while trade openness demonstrates the least volatility. All variables perform well in terms of standard deviation, as they all have values lower than their respective average values. This indicates that they are suitable for estimation purposes. The trends of endogenous variables are illustrated in Fig. 1. Most endogenous variables exhibit clear upward trajectories over time. However, the trade openness for carbon emissions showcases an irregular pattern, as depicted in Fig. 1.

Furthermore, our approach mandates a series of evaluations to ensure the appropriateness of implementing NARDL models, encompassing examinations, such as structural break and unit root tests. The outcome of the Chow structural break test yields an *F*-statistic of 0.41, which falls below the critical value at the 5% significance level (0.84). Notably, there are no indications of structural breaks evident within our dataset. This implies that significant changes with the potential to impact the empirical outcomes have not occurred. Table 3 shows the outcomes of the unit root test. Together, the Phillips-Perron (P-P) test (Phillips & Perron, 1988), the Augmented Dickey-Fuller's *t*-test (DF-GLS), and the Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1979) provide a range of insights into the idea of stationarity. To be more precise, CO_2 exhibits level stationarity in the ADF and P-P tests, whereas TIN exhibits level stationarity in the ADF and DF-GLS tests. The ADF, DF-GLS, and P-P tests consistently demonstrate the significance of the variables at the first difference. Given these outcomes signaling stationarity, our recommendation is to employ the ARDL econometric technique, which accommodates variables that are stationary both at the level and in their first differences.

The results related to the identification of co-integration, as displayed in Table 4, demonstrate a value of 7.939, exceeding the critical threshold of 5.914 set by Narayan (2005). Hence, at the 1% significance level, the null hypothesis is maintained. As a result, the measured co-integration results support the co-integration verification. But in order to thoroughly inspect the empirical association between the variables that are being examined, we can apply the NARDL test, which takes into account both favorable and adverse shocks.

Upon conducting the co-integration test, the subsequent step involves conducting both linearity and non-linearity tests. This aims to explore potential non-linearity within the data series. In this context, we have utilized the BDS test as suggested by Broock et al. (1996), with the null hypothesis stating "series are linearly dependent." The outcomes presented in Table 5 validate the significance of the series in every dimension, indicating that the variables exhibit non-linear dependence. Consequently, the appropriate approach entails the application of the non-linear ARDL test instead of the conventional ARDL test.

Estimation of linear ARDL model. Table 6 presents our empirical findings concerning the immediate and prolonged influences of independent variables on CO_2 emissions in Malaysia. The ARDL results demonstrate a noteworthy and positive correlation between economic growth and CO_2 emissions, both in the short and long term. This suggests that EG contributes to environmental deterioration over varying timeframes. These results align with earlier research by Kirikkaleli (2020) in China, Karaaslan, and Çamkaya (2022) in Turkey, Behera and Dash (2017) in developing countries with low to middle incomes, and Mikayilov et al. (2018) in Azerbaijan. Moreover, Mahmood et al. (2019) argue that economic growth accelerates environmental degradation earlier in the developmental stages, attributing CO_2 emissions to this growth. They found a strong positive correlation between TON and CO_2 emissions, which held true for both short and long durations. This aligns with the asymmetric impact of TON and FDI on carbon intensity as observed by Wang and Wang (2021). Additionally, there is a notable and positive relationship between ICT and CO_2 emissions, a trend also observed in research by Zhou et al. (2019) in China. Their research showed that the ICT sector does not have a good environmental impact when taking into account its projected carbon consequences, which are many times bigger than its direct effects. ICT creation and disposal, according to Haini (2021), Ishida (2015), and Williams (2011), cause environmental impact. Technological progress has a significantly

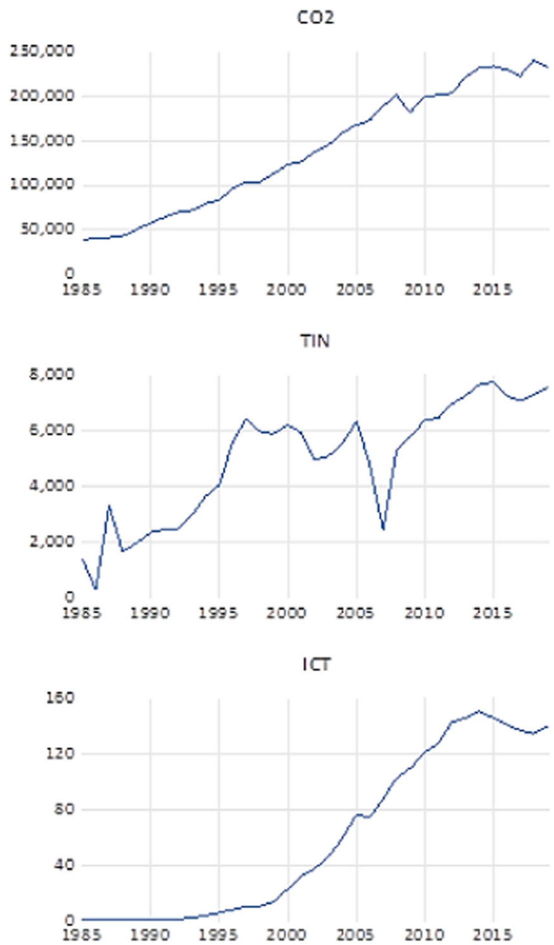

Fig. 1 Trend of the study variables. The figure depicts the trend of the study variables.

Table 3 ADF, DF-GLS, P-P unit root tests.

Log levels			Log 1st difference			
Variables	**ADF**	**DF-GLS**	**P-P**	**ADF**	**DF-GLS**	**P-P**
LCO_2	−4.103***	−0.813	−4.805***	−0.167	−4.752***	−4.937***
LEG	−0.940	1.206	−0.929	−5.263***	−4.205***	−5.257***
LTON	−1.413	−1.165	−1.687	−3.372**	−3.431***	−3.402**
ICT	−0.2080	−0.544	−0.035	−3.174**	−3.083***	−3.173**
LTIN	−2.904*	−2.279**	−2.611	−13.665***	−0.883***	−13.665***

"(***), (**), and (*) represent 1%, 5%, and 10% level of significance, respectively".
Source: Authors' own computation.

Table 4 Result of ARDL and Non-linear ARDL bounds test.

Equations	AIC lag	*F*-stat.	Decision
$FLCO_2(LCO_2$|LEG, LTON, ICT, LTIN)	4	7.939***	Co-integration
Asymptotic critical values, Narayan (2005)	***I*(0)**	***I*(1)**	
1%	4.394	5.914	
5%	3.178	4.450	
10%	2.638	3.772	

Source: Authors' own computation.
*** indicates significance at 1% level.

Table 5 Non-linearity BDS test statistic.

BDS statistic	Dimen ii	Dimen iii	Dimen iv	Dimen v	Dimen vi
LCO_2	0.205***	0.349***	0.450***	0.521***	0.572***
LEG	0.185***	0.185***	0.317***	0.413***	0.540***
LTON	0.155***	0.259***	0.324***	0.352***	0.364***
ICT	0.181***	0.295***	0.364***	0.402***	0.417***
LTIN	0.005	0.056***	0.111***	0.164***	0.207***

"*** represent 1% level of significance".
Source: Authors' own computation.

Table 6 Long-run and short-run ARDL results.

Variables	Coefficient	Std err.	*T*-stats [Prob]
Long run			
LEG	0.671***	0.176	3.798 [0.001]
LTON	0.755***	0.093	8.078 [0.000]
ICT	0.005***	0.001	7.535 [0.000]
LTIN	0.042	0.068	0.611 [0.547]
Short run			
ΔLEG	0.615***	0.142	4.328 [0.000]
ΔLTON	0.154*	0.076	2.011 [0.056]
ΔICT	0.002***	0.001	3.819 [0.000]
ΔLTIN	−0.042***	0.011	−3.917 [0.001]
ΔC	0.661***	0.093	7.094 {0.000]
ECM(−1)	−0.480***	0.070	−6.826 [0.000]
Diagnostic tests	***F*-statistic**	***P*-value**	
R-square	0.998		
χ^2 Serial correlation	0.348	0.206	
Adjusted *R*-square	0.997		
χ^2 Normality	0.043	0.978	
χ^2 Breuch-Pagan- Godfrey test	0.476	0.419	
χ^2 ARCH	0.862	0.857	
χ^2 Ramsey RESET	0.184	0.672	

"(***) and (*) represent 1% and 10% level of significance, respectively".
Source: Authors' own computation.

Table 7 Long-run and short-run NARDL results.

Variables			
Long run	**Coeff.**	***t*-statistic**	**Probability**
LEG_POS	1.278***	5.378	0.000
LEG_NEG	−0.353	−0.908	0.374
LTON	0.363**	2.186	0.041
ICT_POS	0.002*	1.790	0.088
ICT_NEG	0.010**	2.560	0.018
LTIN_POS	−0.123**	−2.154	0.044
LTIN_NEG	−0.056	−1.080	0.292
Short run			
D(LEG_POS)	0.920***	4.002	0.000
D(LEG_NEG)	−0.254	−0.878	0.390
D(LTON)	0.043	0.329	0.745
D(ICT_POS)	0.001*	1.792	0.088
D(ICT_NEG)	0.007**	2.471	0.022
D(LTIN_POS)	−0.004	−0.114	0.910
D(LTIN_POS(−1))	−0.029**	−2.184	0.041
D(LTIN_NEG)	−0.040	−1.049	0.306
ECM(−1)	−0.720***	−5.857	0.000
C	9.125**	10.836	0.000

	Diagn. tests	
Test	**Test-statistic**	**Prob.**
BGSC LM test	1.019	0.380
B-P-G Heteroscedasticity test	0.841	0.907
ARCH test (Heteroscedasticity)	0.484	0.501
Jarque-Bera test	0.104	0.948

"(***), (**), and (*) represent 1%, 5%, and 10% level of significance, respectively".
Source: Authors' own computation.

negative short-term effect on CO_2 emissions. The result aligns with the conclusions drawn in Zaho et al.'s 2021 study, which associated the rise in global innovation capabilities with the impact of TIN on CO_2 emissions. Scholars and public authorities are becoming more conscious of how technology innovation might help cut CO_2 emissions (Huang et al., 2020; Xie et al., 2021; Shan et al,. 2021).

Estimation of non-linear ARDL model. To assess the influence of favorable and adverse shifts in independent variables on dependent variables, the non-linear ARDL approach is employed, and the outcomes are exhibited in Table 7. At the outset, a positive and enduring alteration in EG establishes a direct and substantial correlation with CO_2 emissions in Malaysia. On the other hand, a negative alteration in economic growth (EG) results in outcomes that lack significance for both the short run and the long run. Over time, a complex interplay emerges between economic expansion and CO_2 emissions. It is noteworthy that EG and developments exert a discernible influence on environmental degradation and CO_2 emissions (Gao, 2023; Liu et al., 2022; Musa et al., 2023). The study emphasizes that both in the short and long term, a positive change in ICT has a significant and direct effect on CO_2 emissions. Subsequent research has also pointed out that ICT advancement plays a leading role in increasing CO_2 emissions, thereby exacerbating environmental challenges (Awad, 2022; Ramzan et al., 2022; Ebaidalla and Abusin, 2022). Awan et al. (2022) illustrated that long-term internet use upsurges CO_2 emissions in EU member states, particularly in those where green ICT use is still below ideal levels. Furthermore, as per Amari et al. (2022), the progress of ICT in sub-Saharan African nations has an adverse impact on environmental quality, contributing to a notable rise in CO_2 emissions linked to increased energy consumption and economic expansion. Similarly, Weili et al. (2022) demonstrated that productivity gains resulting from ICT advancement result in heightened energy utilization and consequent carbon dioxide emissions. Conversely, a decrease in ICT advancement has a considerable negative effect on CO_2 emissions in the long term. A number of studies have demonstrated an association between ICT development and lower CO_2 emissions in nations participating in the Belt and Road Initiative (BRI) (Danish, 2019); these countries also include the BRICS countries (Brazil, Russia, India, China, and South Africa) and other developing economies (Batool et al., 2022). Interregional commerce in ICT products has been demonstrated by Zhou et al. (2022) to increase energy consumption, carbon intensity, and carbon emissions, all of which have a detrimental effect on the environment. Thus, the relationship between ICT advancement and CO_2 emissions across different countries, as observed through empirical data or through the prism of economic theory, is contingent upon the relative strength of two opposing forces: a negative relationship attributable to increased energy efficiency and a positive correlation driven by the expansion of production scale. For both the short and long term, there is a negative correlation between CO_2 emissions and the positive change in technological innovation. A 1% increase in technological innovation results in a decrease of 0.123% in CO_2 emissions in the long run and 0.029% in the short run. The impact of technological advancements on CO_2 emissions is of utmost significance. By promoting technological innovation, countries can create avenues to devise more efficient strategies for addressing aspects that have adverse effects on environmental quality. This approach involves enhancing energy efficiency and decreasing energy consumption. Additionally, nations can leverage technological advancements to optimize the effectiveness of their existing energy sources. Furthermore, TIN can act as a crucial driver in promoting the development of new eco-friendly energy resources (Khattak et al., 2020; Ahmad & Zheng, 2021; Adebayo et al., 2023). However, it's recognized that not all TINs influence CO_2 emissions. Consequently, it becomes vital to spotlight innovations specifically geared toward improving energy efficiency and facilitating the transition to green energy sources. These targeted innovations can encourage the adoption of renewable energy while simultaneously reducing reliance on fossil fuels.

Numerous scholars, like Cheng et al. (2022) and Shahbaz et al. (2020), contend that technical innovation is essential to reducing CO_2 emissions. Cleaner technologies are incorporated into production processes and energy efficiency is increased as a result. Our conclusions about how technological innovation affects CO_2 emissions align with the results of other empirical studies (e.g., Rahman et al., 2022; Lin & Ma 2022). China's accomplishments in energy conservation and carbon reduction through increased technical innovation have been highlighted by Cheng et al. (2022). Notably, energy-focused technological initiatives in Brazil and China have led to significant reductions in carbon emissions. The consensus underlying this phenomenon is that technological innovation, particularly in the field of environmental technologies, is integral to addressing environmental challenges while simultaneously enhancing energy efficiency. The advancement of technologies geared towards environmental preservation directly curbs environmental degradation, such as by curbing waste disposal, underscoring the multifaceted role of technological innovation in safeguarding environmental quality. Moreover, TIN can additionally contribute to environmental enhancement by facilitating the progression of energy transition. Notably, as TIN fosters energy transition, it holds the potential to bolster the capacity for generating renewable energy. This anticipated outcome is poised to yield further improvements in environmental well-being. Furthermore, the statistically significant coefficient of ECM at a 1% level of significance indicates a substantial 72% annual adjustment for attaining long-term equilibrium.

Based on the results of diagnostic tests presented in the lower section of Table 7, the null hypothesis concerning homoscedasticity is rejected. This conclusion is supported by the non-significant chi-square values obtained from both the Breusch-Pagan-Godfrey heteroscedasticity test and the ARCH test. Additionally, we conducted the Jarque-Bera test to assess normality and detect the presence of serial correlation, alongside the Breusch-Godfrey Serial Correlation LM test. In both cases, the resulting probability chi-square values were statistically insignificant, affirming the model's conformity to normality and lack of serial correlation. To evaluate the dynamic stability of our model, we employed the CUSUM and CUSUMQ tests, following the methodology outlined by Brown et al. (2003). The graphical representations of these tests, as shown in Fig. 2, provide evidence of the model's overall stability.

Lastly, Fig. 3 shows how the explanatory variables (LGDP, ICT, and LTIN) were adjusted using NARDL multipliers to the new equilibrium equations after prior optimistic and adverse shocks. The thick and thin red-dotted lines demarcate an asymmetric pattern and delineate the essential boundaries, respectively. The solid black and black-dotted lines show how CO_2 adjusts asymmetrically to positive and negative shocks. The asymmetric relationship between GDP, ICT, and TIN with CO_2 is confirmed by the phase patterns in Fig. 3.

The results of the causality test. While we have analyzed both the short- and long-term impacts of regressors on the dependent variable, assessing the causal connection between variables is equally vital in formulating policy recommendations. We employed the Granger procedure within the VAR (Vector Autoregression) causality test to determine the symmetric causal relationship between variables. This decision was made because the asymmetric model only examines a restricted set of variables, rendering asymmetric causality inapplicable in such scenarios (Engle & Granger, 1987). The long-run feedback effects between CO_2, EG, TON, mobile subscriptions, and technical innovation are shown in Table 8's long-run causality results. At 5%, 1%, and 10% significant levels, respectively, there is evidence of

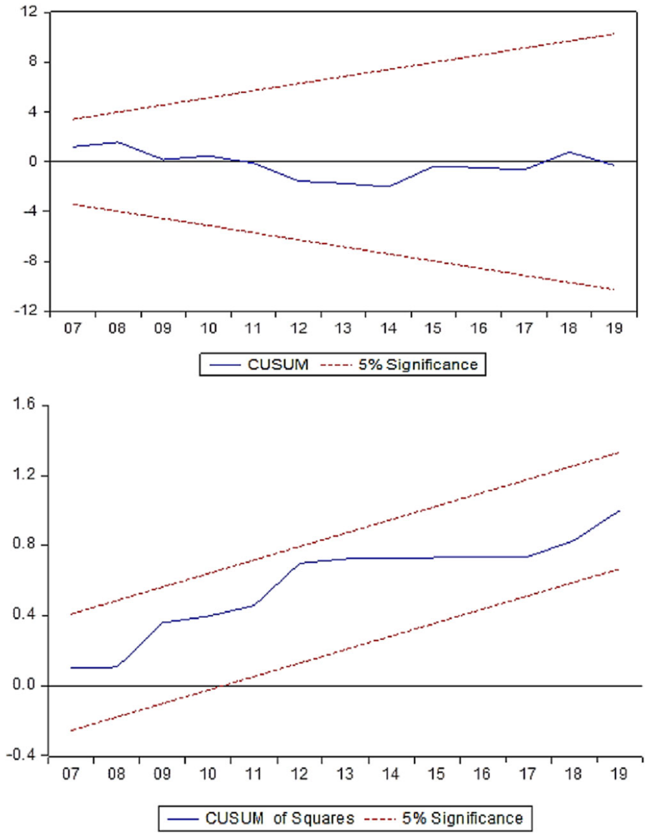

Fig. 2 The cumulative sum and sum square of recursive residuals plot. The figure exhibits the cumulative sum and sum square of recursive residuals plot.

bidirectional causality from technical innovation, TON to CO_2, TON to mobile subscriptions, which is consistent with the long-run and short-run findings. Furthermore, GDP Granger influences trade openness and technical innovation at significance levels of 1% and 5%, respectively. There is a unidirectional link between CO_2 and mobile subscriptions, as well as between mobile subscriptions and technological innovation, at a 1% level of relevance.

In addition, all explanatory factors and CO_2 emissions are tested for causal links using the Granger causality test. Table 9 provides a summary of the findings. These results demonstrate a one-way causal relationship between ICT and CO_2 emissions. Furthermore, there is evidence of bidirectional causality between CO_2 emissions and TON emissions as well as between TIN and CO_2 emissions.

Robustness analysis. By employing single-equation estimator methods, such as FMOLS, DOLS, and CCR, we were able to reinforce the validity of the long-term estimates obtained from the ARDL estimator. The FMOLS estimate operates under the assumption of a single co-integration and employs a semi-parametric correction to address estimation challenges arising from the long-term linkage between co-integration and stochastic issues. On the other hand, the CCR estimate, akin to FMOLS, addresses co-integration issues rather than making modifications to stationary data. The DOLS test's main advantages are that it removes endogeneity, minimizes sample size bias, and accounts for different order integration of variables in the co-integrated frame (Alcantara and Padilla, 2009). Table 10 displays the results of the FMOLS, DOLS, and CCR. It demonstrates that the

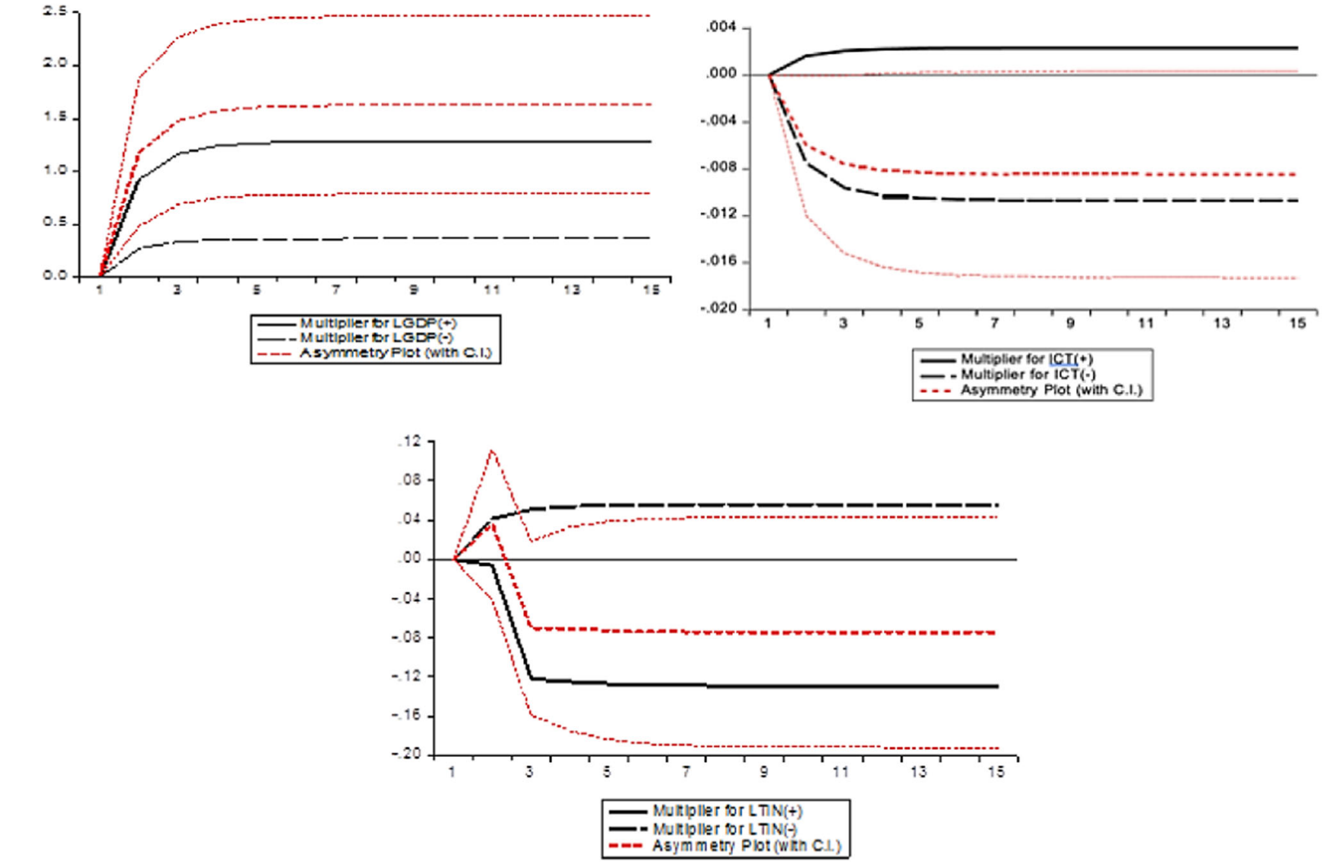

Fig. 3 The multipliers for GDP, ICT, LTIN. The figure depicts the multipliers for GDP, ICT, LTIN.

Table 8 Granger causality test results.

Direction of causality	*F*-statistics	*P*-value	Decision
LGDP → LCO_2	0.475	0.626	Do Not Reject Ho
LCO_2 → LGDP	0.675	0.517	Do Not Reject Ho
LTIN → LCO_2	4.623**	0.0184	Reject Ho
LCO_2 → LTIN	3.526**	0.0431	Reject Ho
ICT → LCO_2	0.765	0.474	Do Not Reject Ho
LCO_2 → ICT	2.526*	0.098	Reject Ho
LTON → LCO_2	4.150**	0.026	Reject Ho
LCO_2 → LTON	6.192***	0.005	Reject Ho
LTIN → LGDP	0.029	0.971	Do Not Reject Ho
LGDP → LTIN	5.499***	0.009	Reject Ho
ICT → LGDP	1.607	0.218	Do Not Reject Ho
LGDP → ICT	1.176	0.323	Do Not Reject Ho
LTON → LGDP	0.658	0.525	Do Not Reject Ho
LGDP → LTON	3.700**	0.037	Reject Ho
ICT → LTIN	2.605*	0.091	Reject Ho
LTIN → ICT	0.721	0.495	Do Not Reject Ho
LTON → LTIN	1.483	0.244	Do Not Reject Ho
LTIN → LTON	1.116	0.341	Do Not Reject Ho
LTON → ICT	3.267*	0.053	Reject Ho
ICT → LTON	6.304***	0.005	Reject Ho

"*** indicates significance at 1% level, ** indicates significance at 5% level, * indicates significance at 10% level".
Source: Authors' own computation.

long-run ARDL estimation results and GDP, TON, and ICT have comparable signs. The findings of FMOLS, DOLS, and CCR are also supported by the long-run results of non-linear ARDL for GDP, TON, ICT, and TIN.

Conclusion and policy implications

This study delves into the symmetrical and asymmetrical impacts of TIN, EG, TON, and ICT on CO_2 emissions in Malaysia spanning the period from 1985 to 2021. Our linear model's findings

Table 9 Granger causality test results.

Direction of causality	*F*-statistics	*P*-value	Decision
LEG → LCO_2	0.475	0.626	
LCO_2 → LEG	0.675	0.517	
LTIN → LCO_2	4.623**	0.0184	TIN ↔ CO_2
LCO_2 → LTIN	3.526**	0.0431	
ICT → LCO_2	0.765	0.474	
LCO_2 → ICT	2.526*	0.098	CO_2 → ICT
LTON → LCO_2	4.150**	0.026	TON ↔ CO_2
LCO_2 → LTON	6.192***	0.005	

"*** indicates significance at 1% level, ** indicates significance at 5% level, * indicates significance at 10% level".
Source: Authors' own computation.

Table 10 FMOLS, DOLS, and CCR estimation results.

Variables	Coeff.	Std. err.	*t*-stats	Prob.
Method: FMOLS				
LGDP	0.874***	0.089	9.815	0.000
LTON	0.777***	0.060	12.939	0.000
ICT	0.005***	0.001	10.468	0.000
LTIN	−0.025	0.022	−1.134	0.266
C	−0.021	0.561	−0.037	0.970
Method: DOLS				
LGDP	0.911***	0.242	3.756	0.001
LTON	0.645**	0.235	2.741	0.015
ICT	0.004**	0.001	2.895	0.011
LTIN	−0.017	0.054	−0.326	0.748
C	0.353	0.984	0.359	0.724
Method: CRR				
LGDP	0.873***	0.107	8.124	0.000
LTON	0.784***	0.070	11.195	0.000
ICT	0.004***	0.001	9.458	0.000
LTIN	−0.024	0.034	−0.714	0.481
C	−0.048	0.619	−0.077	0.938

*** indicate significance at 1% level, ** indicate significance at 5% level.
Source: Authors' own computation.

demonstrate how ICT, TON, and EG both temporarily and permanently cut CO_2 emissions. Technological advancement has a destructive and considerable immediate effect on carbon emissions. The NARDL study, on the other hand, demonstrates that ICT and CO_2 emission in Malaysia have a strong and dynamic asymmetrical connection over short and long durations. Both beneficial and poor consequences of ICT's positive and negative shock can be seen in Malaysia's carbon emissions. Technology advancement has the potential to provide a variety of positive effects, both now and in the future. Because it conserves energy, technological innovation lowers energy use and CO_2 emissions.

Furthermore, economic expansion has an optimistic and notable effect on carbon emissions. Economic expansion is directly related to energy use. A larger-scale transition from less energy-efficient to more energy-efficient technology may be required to satisfy Malaysia's objectives for CO_2 emission reduction and economic growth. This transition might be accelerated by implementing collaborative public-private initiatives and programs to encourage the development of renewable and energy-efficient technology. The findings of this study carry significant policy implications for Malaysia as a developing nation. Firstly, Malaysia can prioritize eco-friendly technology research and adoption to achieve short-term CO_2 emissions reduction through clean innovations. Secondly, for the long-term effects of TIN, EG, and ICT on emissions, a balanced approach to technological progress can be adopted. Encouraging cleaner technologies while mitigating the negative impacts of adverse changes can promote sustainable growth. Thirdly, leveraging ICT for emissions reduction emphasizes the importance of digitalization. Supporting digital infrastructure expansion and technology-driven solutions can enhance efficiency and reduce emissions. Fourthly, acknowledging EG's significant impact on emissions suggests aligning economic development with emission reduction strategies through cleaner production methods and green practices. Fifthly, recognizing the two-way causal link between trade openness and emissions emphasizes incorporating environmental considerations into trade policies. Malaysia can pursue sustainable trade practices for resource-efficient production and responsible consumption. Sixthly, a holistic approach integrating policies across sectors can address the interconnectedness of emission-contributing variables. Seventhly, facing challenges from adverse technological advancements and increasing emissions, implementing carbon pricing mechanisms and social campaigns for awareness can be considered. Eighthly, prioritizing the transition to low-carbon technologies through incentives for renewables, energy efficiency, and clean production methods can leverage TIN's potential. Ninthly, long-term policy planning can incorporate both immediate benefits and sustained environmental improvements.

Lastly, international collaboration can share best practices, technology, and knowledge exchange to accelerate sustainable development progress. However, this study has some limitations. Firstly, it focuses solely on employing both linear and non-linear ARDL methods. Future studies could explore alternative methodological approaches. Additionally, this research only examines the relationship among technological innovation, economic growth, trade openness, ICT, and CO_2 emissions within a single country through symmetric and asymmetric analysis. Future research could expand its scope by conducting cross-country comparisons, incorporating new variables, and extending the study period.

Data availability

World Bank Development Indicators (WDI): https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=MY
Malaysia Energy Statistics: https://www.st.gov.my/en/contents/files/download/116/Malaysia_Energy_Statistics_Handbook_20201.pdf.

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Author contributions
In the collaborative effort, Ha Junsheng and Yuning Mu focused on crafting the introduction and conclusion sections, whereas Muhammad Mehedi Masud took charge of the methodology and analysis components. Rulia Akhtar meticulously reviewed and thoroughly examined the entire text, providing valuable input to refine the manuscript. Abu Naser Mohammad Saif's role encompassed tasks related to literature review, manuscript editing, and overall formatting. K.M. Anwarul Islam and Nusrat Hafiz watched over the entire working procedure and provided significant feedback. All authors have examined the findings and approved the manuscript's final version.

Competing interests
The authors declare no competing interests.

Ethical approval
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This research does not involve human participants or animals.

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