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Decarbonizing Growth: The Role of Human Capital Development and Innovation in Malaysia's Pursuit of SDG 13

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ABSTRACT

This study investigates the impact of human capital development and technological innovation on environmental sustainability in Malaysia, as part of the Malaysian commitment to Sustainable Development Goal 13 (Climate Action). Using Autoregressive Distributed Lag (ARDL) model and time series data covering the period 1990-2022, the analysis explores the dynamic relationship between CO_2 emissions and major macroeconomic variables, namely economic growth, energy consumption, technological innovation, trade openness, foreign direct investment (FDI), quality of governance, education, and GINI coefficient. The empirical findings reveals that technological innovation and human capital development significantly contribute to long-run decline in CO_2 emission, hence emphasis their role in ensuring a sustainable low-carbon economy. On the other hand, FDI correlates with higher emissions, which gives relevance to pollution haven hypothesis in the Malaysian case. The study emphasis the need to invest in green technology, incorporate sustainability in the education system and tightening environmental standards in the foreign investments. Such policy steps are necessary to ensure that economic progress is no longer linked to environmental degradation and accelerate Malaysia's transition towards a climate-resilient future.

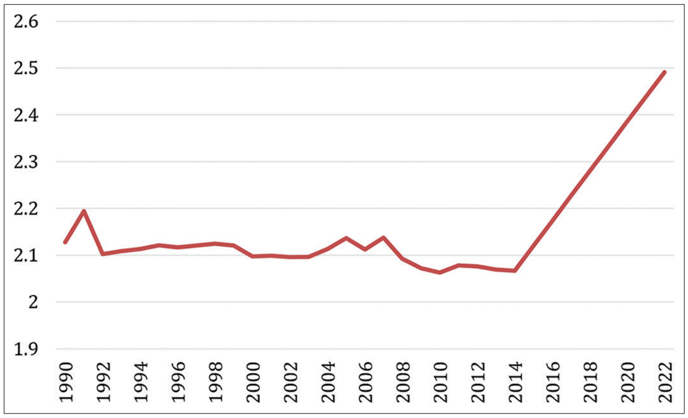
Keywords: Human Capital Development, Technological Innovation, Environmental Sustainability, CO_2 Emissions, Sustainable Development Goals (SDG 13)
JEL Classifications: Q52, Q56, O03, I2

1. INTRODUCTION

Environmental sustainability remains a critical global challenge as economies strive to balance industrial growth with carbon reduction efforts. Over the past three decades, global carbon dioxide (CO_2) emissions have risen exponentially and are expected to reach 41.6 billion metric tons in 2024 (James et al., 2024). In Malaysia, the rising trend of carbon emissions over the past decades (1990-2022) has been a major concern in the nation's effort to achieve sustainable development. The pursuit of the SDGs goals especially SDG13 (Climate Action) will be hindered if insufficient initiatives are taken to address the increasing trend of carbon emissions in Malaysia. Figure 1 clearly shows the increasing trend of the carbon emissions in Malaysia which demonstrated a sharp rise, especially during the more recent years of 2015-2022.

While developed economies have begun stabilizing emissions through technological advancements, many developing nations

Figure 1: Trend of carbon emissions in Malaysia year 1990-2022



continue to experience rising pollution levels due to rapid industrialization and energy consumption. The Environmental Kuznets Curve (EKC) hypothesis suggests that as economies grow, environmental degradation initially worsens before improving at higher income levels (Grossman and Krueger, 1995). However, recent research (You et al., 2024; Shabani, 2024; and Wang and Qu, 2024) challenges this assumption, arguing that technological innovation and human capital development play crucial roles in shaping environmental outcomes independent of economic growth. Given these complexities, there is a need to reassess traditional environmental models by incorporating additional economic and social dimensions that influence long-term sustainability, especially from a more localized perspective.

This study is particularly timely as Malaysia prepares to introduce carbon pricing and a potential Climate Change Act under the 12th Malaysia Plan (EPU, 2021). The country's ability to break free from carbon lock-in and achieve sustainable growth will depend on technological innovation, human capital investments, and effective policy interventions (Schuch et al., 2024). At the same time, Sustainable Development Goal 13 (SDG 13) – Climate Action is of critical importance to Malaysia, as the country faces increasing risks from climate change, extreme weather events, and environmental degradation. With Malaysia committed to reducing greenhouse gas emissions by 45% per GDP by 2030 and achieving net-zero emissions by 2050 (Rao et al., 2025), aligning economic policies with SDG 13 is essential for ensuring long-term resilience and environmental justice. By focusing on Malaysia, this research enhances our understanding of how emerging economies can balance economic development with environmental sustainability, offering policy insights for achieving long-term decarbonization while contributing to global climate goals.

Past studies have demonstrated that green technologies and ICT advancements significantly reduce carbon emissions by optimizing industrial energy use and reducing fossil fuel dependency (You et al., 2024; Saqib et al., 2024). For instance, in Belt and Road Initiative (BRI) economies, ICT and renewable energy consumption were found to have an inverse relationship with CO_2 emissions, suggesting that digital advancements can accelerate decarbonization efforts (You et al., 2024). Similarly, in BRICS countries, investments in green technology and economic complexity were shown to have long-term environmental benefits, further reinforcing the argument that innovation is a critical tool for sustainability (Feng et al., 2024). As an emerging country that was dependent on fossil fuels, Malaysia's effectiveness in driving long-term carbon reduction through innovation remains understudied, particularly in the presence of structural economic and social constraints.

Human capital, particularly through education and workforce skill development, is another crucial factor influencing environmental sustainability. Higher levels of education and environmental awareness encourage the adoption of energy-efficient practices and the transition to cleaner technologies (Dinda, 2004). Empirical evidence suggests that human capital enhances the effectiveness of renewable energy in reducing emissions, with studies showing that nations with higher human capital indices achieve greater reductions in carbon intensity (Shabani, 2024). In Malaysia, the expansion of the electrical and electronics sector, a major contributor to the country's exports, presents both an opportunity and a challenge, as its high energy intensity requires targeted policies to integrate energy-efficient manufacturing practices (Afroz et al., 2024). However, the relationship between human capital and carbon emissions remains complex, as Malaysia's current labor force composition and educational policies may not fully support a large-scale transition to low-carbon industries.

Additionally, most existing studies focus on either economic growth-environmental trade-offs or policy-driven climate strategies, without integrating the interactive effects of innovation and education on environmental quality (Afroz et al., 2024; Rao et al., 2025). This study fills this gap by empirically assessing the interconnected roles of innovation and human capital in Malaysia's decarbonization pathway, providing a comprehensive analysis of their short- and long-term impacts on carbon emissions. The novelty of this study lies in its integrated approach, combining insights from technological advancements, workforce development, and socio-economic factors to present a more holistic understanding of Malaysia's environmental sustainability trajectory. Besides that, this research contributes theoretically by building a new framework that explains the fundamentals of human capital development through education and new technological innovations in the nation's pursuit of SDGs, specifically SDG13.

Given Malaysia's continued dependence on fossil fuels, its rising energy intensity, and its commitment to carbon pricing and net-zero emissions (EPU, 2021; Rao et al., 2025), a deeper investigation is needed into how these factors interact to influence sustainability outcomes. This study aims to address these gaps by (1) examining whether innovation can serve as an alternative pathway to decarbonization beyond economic growth and (2) analyzing the combined effects of human capital and innovation on Malaysia's achievement of SDG 13 as reflected by its environmental quality. By doing so, it provides new insights into policy interventions that can ensure a just and sustainable low-carbon transition. By addressing these issues, the research contributes to both academic discourse and practical policy development, offering evidence-based recommendations for achieving Malaysia's net-zero emissions target while ensuring equitable economic growth. In addition, the empirical finding from this newly developed framework offered critical knowledge on how the current SDGs achievement has been translated through local actions and policies.

2. LITERATURE REVIEW

The intersection of economic development and environmental sustainability remains a critical area of research, particularly in the context of emerging economies seeking to balance growth with ecological responsibility. The Environmental Kuznets Curve (EKC) theory provides a foundation for the framework developed in gaining insight into this relationship, suggesting that environmental degradation initially intensifies with economic expansion but later declines as nations transition toward service-based economies, enact stricter regulations, and adopt cleaner technologies (Grossman and Krueger, 1995; Panayotou, 1993). While this model has been widely studied, its emphasis on economic growth as the primary determinant of environmental quality overlooks other significant influences, such as technological innovation and human capital development (Stern, 2004). Addressing these aspects can provide a more comprehensive understanding of sustainability dynamics.

A growing body of literature explores how innovation and human capital shape environmental outcomes. Technological advancements, particularly in energy efficiency and renewable energy, have been shown to mitigate pollution independent of economic growth (Porter and Van der Linde, 1995; You et al., 2024). Likewise, human capital—through education and workforce development—facilitates the adoption of green technologies and sustainable practices (Dinda, 2004; Wang et al., 2024). Despite these findings, research on Malaysia's carbon emissions and environmental policies has largely focused on the economic growth-energy consumption nexus (Mohamed et al., 2024; Afroz et al., 2024), with limited attention given to the interplay between innovation and human capital.

Therefore, this study aims to fill this gap by synthesizing existing research on Malaysia's decarbonization trajectory through a multidimensional approach. Specifically, it examines whether technological innovation can drive carbon reduction independently of economic growth and analyzes how human capital investments through education can influence the clean energy transition. By integrating these factors, this study offers a more holistic perspective on Malaysia's sustainability challenges and policy opportunities. The following sections will explore the theoretical review of underlying theories that formed the research framework, followed by an empirical review of key findings based on the existing literature.

2.1. Theoretical Review: Environmental Kuznets Curve (EKC)

The Environmental Kuznets Curve (EKC) hypothesis provides a foundational framework for understanding the relationship between economic growth and environmental quality. It suggests that environmental degradation initially worsens as income rises but eventually improves after reaching a certain development threshold (Grossman and Krueger, 1995). This relationship is often attributed to structural shifts from pollution-intensive industries to a service-based economy, stronger environmental regulations, and technological advancements (Panayotou, 1993). However, the EKC framework primarily focuses on economic growth as the main driver of environmental change, often placing less emphasis on other critical factors such as innovation and human capital (Stern, 2004). These factors play a key role in shaping environmental outcomes, yet their integration into environmental quality models remains an evolving area of research.

Technological innovation is widely recognized as a fundamental driver of environmental sustainability, as advancements in energy efficiency, cleaner production methods, and low-carbon technologies can mitigate pollution independent of income levels (Porter and Van der Linde, 1995). Similarly, human capital, reflected in education and skills, influences environmental quality by fostering awareness, promoting sustainable practices, and enabling the adoption of green technologies (Dinda, 2004). While EKC models provide a useful foundation, integrating these broader economic and social dimensions can offer a more comprehensive understanding of environmental quality dynamics. This study builds on existing theoretical frameworks by highlighting the importance of these variables, contributing to a more multidimensional approach to analyzing environmental sustainability.

2.2. Empirical Review

Empirical studies have increasingly investigated whether innovation can accelerate decarbonization, and how human capital contributes to sustainable energy transitions (Afroz et al., 2024; Rao et al., 2025). These studies provide valuable insights into the effectiveness of these factors across different economic and policy contexts. This section reviews the existing empirical evidence on how innovation and human capital influence carbon emissions, identifying key findings and gaps that motivate this study.

Innovation, particularly through green technologies, information and communication technology (ICT), and renewable energy advancements, plays a crucial role in reducing carbon emissions by improving energy efficiency and minimizing fossil fuel dependence. You et al. (2024) analyzed the relationship between ICT, renewable energy consumption (REC), and CO_2 emissions across 64 Belt and Road Initiative (BRI) economies and found that ICT adoption significantly reduces carbon emissions in the long run. However, their findings also suggest an inverted U-shaped relationship between ICT and CO_2 emissions, indicating that early-stage digitalization may lead to increased emissions due to rising energy demand, but as ICT becomes more efficient, it facilitates carbon reduction. A finding by Yun et al. (2025) has also indicated that the transformation of the industry structure that is more inclined towards the adoption of sustainable environment-friendly production has significant positive impacts on the environment. Similarly, Saqib et al. (2024) confirmed that eco-friendly ICT and environmental technologies contribute to lowering the carbon footprint in top-polluting economies, reinforcing the argument that technological advancements are key to sustainability efforts. Beyond ICT, green technological advancements have proven to be effective in mitigating environmental damage. Feng et al. (2024), in their study on BRICS countries, demonstrated that investments in green technology and renewable energy significantly reduce CO_2 emissions, supporting the notion that innovation is essential for long-term decarbonization. These findings suggest that for Malaysia to achieve a successful low-carbon transition, it must not only invest in clean technology but also develop policies that accelerate the adoption of innovation-driven carbon reduction strategies, ensuring that regulatory mechanisms, financial incentives, and skilled labor align with national decarbonization goals.

Human capital plays a crucial role in reducing carbon emissions by fostering the adoption of renewable energy, energy efficiency technologies, and sustainable industrial practices. Wang et al. (2024) highlight that countries with stronger human capital are more capable of integrating green technologies and reducing their ecological footprint, reinforcing the idea that education and workforce development are essential for achieving environmental sustainability. Similarly, Shabani (2024) finds that the effectiveness of renewable energy in reducing carbon emissions depends on human capital levels, with a threshold effect—when the human capital index surpasses a certain level, the impact of renewable energy on emissions reduction becomes significantly stronger. These findings suggest that countries with better-educated populations and a more skilled workforce can transition toward a low-carbon economy more effectively. Khan et al. (2024) further support this argument by showing that in G7 economies, research and development (R&D) investments in human capital significantly contribute to decarbonization efforts, proving that technology and skilled labor must work together to drive sustainability. The environmental degradation-education nexus in Malaysia was also analyzed by Yun (2021) shedding light on the need to design an education system that can promote the reduction of carbon emissions in the future.

The literature on carbon emissions in Malaysia has focused on the impact of energy consumption, renewable energy, and economic policies on environmental sustainability. Mohamed et al. (2024) investigate the Environmental Kuznets Curve (EKC) hypothesis in Malaysia, finding that while economic growth initially increases carbon emissions, renewable energy usage in power generation has the potential to mitigate environmental degradation in the long run. However, their findings also highlight that electricity intensity is a major driver of emissions, emphasizing Malaysia's reliance on fossil fuels for electricity generation. Similarly, Afroz et al. (2024) explore the role of economic complexity in emissions, concluding that Malaysia's heavy dependence on energy-intensive industries, particularly electrical and electronics manufacturing, significantly contributes to CO_2 emissions. Their study underscores the need for energy-efficient industrial practices and policies that encourage sustainable manufacturing.

In terms of climate policies, Rao et al. (2025) highlight the high social cost of carbon (SCC) in Malaysia, arguing that existing policies may not be sufficient to achieve the country's net-zero emissions target by 2050. Their study suggests that carbon pricing and conservation efforts, such as increasing protected forest areas, could help reduce Malaysia's SCC and support its environmental commitments. Additionally, Schuch et al. (2024) examine Malaysia's carbon lock-in problem, emphasizing that nearly 80% of the country's greenhouse gas (GHG) emissions come from fossil fuels, particularly coal and oil. They argue that Malaysia must implement structural energy reforms, decentralize political power in energy policymaking, and adopt green growth strategies to transition toward a low-carbon future. These studies collectively highlight that Malaysia's environmental sustainability depends on balancing economic growth, industrial transformation, and strong policy interventions to break fossil fuel dependency and reduce long-term carbon emissions.

While existing literature has extensively examined economic growth, energy consumption, and environmental degradation in Malaysia, significant gaps remain in understanding the interactive role of innovation and human capital in shaping carbon emissions. Studies such as Mohamed et al. (2024) and Afroz et al. (2024) validate the Environmental Kuznets Curve (EKC) hypothesis, demonstrating that Malaysia's industrialization has driven emissions growth, but renewable energy can help mitigate environmental degradation. However, these studies primarily focus on economic growth-environment trade-offs and sectoral energy consumption, without evaluating whether innovation can substitute economic growth as a key driver of decarbonization. Similarly, Yun et al. (2024) highlighted that the increasing utilization of green innovations will increase sustainability by enhancing the efficiency of production and avoiding resource wastage.

This study fills these gaps by taking a multidimensional approach to Malaysia's decarbonization pathway, integrating technological innovation and human capital development, into the environmental sustainability discourse. Unlike previous studies that isolate growth-environment linkages or policy-driven strategies, this research examines whether innovation can drive carbon reduction independently of economic growth and how human capital investments impact Malaysia's clean energy transition. The novelty of this study lies in its holistic framework, which combines technological advancements and workforce development to provide a more comprehensive understanding of Malaysia's transition toward a low-carbon economy. By doing so, it offers policy recommendations that balance economic development with sustainability, ensuring that Malaysia's net-zero targets are achieved through an inclusive and innovation-driven approach.

3. METHODOLOGY

This study investigates the role of human capital development through education, and the advancement of innovation and technology in supporting Malaysia's progress towards the Sustainable Development Goals (SDGs), with a specific focus on SDG 13: Climate Action. By integrating human capital and technological innovation into the empirical framework, a newly specified model was developed to assess the joint impact of these variables on environmental outcomes, particularly carbon dioxide (CO_2) emissions, over the period from 1990 to 2022.

The findings are expected to contribute to a deeper understanding of how education and innovation can serve as strategic levers for achieving the SDGs. Additionally, the empirical insights will offer valuable implications regarding the synergetic effects of education and innovation, which are fundamental for the realization of climate-related sustainability goals. The results will also serve as a guide for policymakers in formulating targeted interventions aimed at aligning economic development with environmental protection.

The conceptual foundation of the study is underpinned by several economic theories. First, the Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped relationship between environmental degradation and income per capita (Kaika and Zervas, 2013). In the early stages of economic growth, environmental degradation tends to increase; however, once a certain income threshold is reached, further growth leads to improved environmental outcomes as societies invest more in cleaner technologies and environmental regulations.

Second, the Pollution Haven Hypothesis (Copeland and Taylor, 2004) suggests that trade openness may result in increased foreign direct investment (FDI) in countries with laxer environmental regulations, thereby making them havens for pollution-intensive industries. This emphasizes the importance of including both trade openness and FDI as explanatory variables in the model, given their potential influence on domestic environmental conditions.

Third, Human Capital Theory posits that higher levels of education enhance individual capabilities, leading to more productive and innovative economies. From an environmental perspective, an educated population is more likely to develop and adopt cleaner technologies, contributing to reduced pollution and more sustainable economic growth (Sarwar et al., 2020).

To empirically analyze these relationships, the following log-linear model was employed:

$$LNCO^2_t = \beta_0 + \beta_1 LNGDP_t + \beta_2 LNEC_t + \beta_3 LNTECH_t + \beta_3 LNTO_t + \beta_4 LNFDI_t + \beta_5 LNQOG_t + \beta_6 LNHC_t + \beta_7 LNGINI_t + \mu_t \quad (1)$$

$LNCO^2_t$: Log of carbon dioxide emissions per capita (metric tons per capita), representing environmental degradation.

$LNGDP_t$: Log of GDP per capita (constant 2015 US$), capturing the level of economic development.

$LNEC_t$: Log of energy consumption (quadrillion BTUs), a direct measure of resource use and environmental pressure.

$LNTECH_t$: Log of patents registered per capita, serving as a proxy for technological innovation.

$LNTO_t$: Log of trade openness (measured as the ratio of total trade to GDP), representing integration with global markets.

$LNFDI_t$: Log of foreign direct investment, net inflows as a percentage of GDP.

$LNQOG_t$: Log of quality of governance, encompassing institutional effectiveness, regulatory quality, and rule of law.

$LNHC_t$: Log of secondary school enrolment rate (gross %), used as a proxy for human capital development.

$LNGINI_t$: Log of the GINI coefficient, representing income inequality.

In this time-series study, unit root tests such as Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) will first be conducted to ensure that the model is free from spurious regression problems. Next, the Auto-Regressive Distributed Lag (ARDL) Bound testing approach will be implemented when the variables in the model are found of mixed-order integration. Diagnostic tests will also be carried out to ensure that the findings are free from serial correlation, and heteroscedasticity issues and that the model is structurally stable. The Autoregressive Distributed Lag (ARDL) model is suitable to be used in examining cointegration relationships when variables are of a mix stationary at level (I(0)) and at the first difference (I(1)). It is essential, however, to ensure that none of the variables are integrated of order two or higher (I(2)). The ARDL approach is particularly ideal when analyzing datasets involving small sample sizes, making it well-suited for studies with limited data availability. According to Monte Carlo simulations by Pesaran et al. (2001), the ARDL method produces more reliable and accurate estimates compared to other alternative cointegration techniques in small sample analysis. Furthermore, the ARDL framework addresses the issue of endogeneity by treating all variables as potentially endogenous, thereby providing unbiased, consistent, and statistically valid estimates for both short-run dynamics and long-run equilibrium relationships. Accordingly, the econometric specification of the ARDL model is outlined in Equation (2).

$$\begin{aligned}\Delta LNCO2_t = {} & \beta_0 + \beta_1 LNGDP_{t-1} + \beta_2 LNEC_{t-1} + \beta_3 LNTECH_{t-1} \\ & + \beta_4 LNTO_{t-1} + \beta_5 LNFDI_{t-1} + \beta_6 LNQOG_{t-1} \\ & + \beta_7 LNHC_{t-1} + \beta_8 LNGINI_{t-1} + \sum_{i=0}^{k} \beta_6 \Delta LGDP_{t-i} \\ & + \sum_{i=0}^{k} \beta_7 \Delta LNEC_{t-i} + \sum_{i=0}^{k} \beta_8 \Delta LNTECH_{t-i} \\ & + \sum_{i=0}^{k} \beta_9 \Delta LNTO_{t-i} + \sum_{i=0}^{k} \beta_{10} \Delta LNFDI_{t-i} \\ & + \sum_{i=0}^{k} \beta_8 \Delta LNQOG_{t-i} + \sum_{i=0}^{k} \beta_9 \Delta LNHC_{t-i} \\ & + \sum_{i=0}^{k} \beta_{10} \Delta LNGINI_{t-i} + \varepsilon_t \end{aligned} \quad (2)$$

Where the symbol β_0 represents the intercept, Δ represents the difference operator and ε_t Represents the error term. The first part of the equation presents short-term variables, whereas the 2nd part of the equation indicates long-run variables.

3.1. Data Sources

The following Table 1 shows the sources of data:

4. ANALYSIS AND DISCUSSION

The analysis begins by testing the stationarity of each variable using two types of unit root tests: the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron (PP) test as shown in Table 2.

The unit root tests are first conducted at level, I(0), for both intercept and intercept with the trend, followed by testing at the first difference, I(1), under the same specifications. After completing the ADF tests, the procedure is repeated using a more robust PP test to confirm the stationarity properties of the variables. The unit root tests are essential to be performed to ensure that none of the variables are integrated at the second difference, I(2). The presence of second-order difference I(2) variables will render the ARDL approach to be ineffective. Hence, although the ARDL technique does not require pre-testing for unit roots, to avoid the ARDL model crashing in the presence of an integrated stochastic trend of I(2), a unit root test should be carried out the determine the number of unit roots in the series under consideration (Nkoro and Uko, 2016).

Based on the ADF results, the variables LNGDP, LNEC, LNFDI, LNQOG, and LNHC are found to be stationary at level, and these findings are consistent with the PP test results. At the first difference, all variables are found to be stationary, mostly at the 5% and 1% significance levels. Notably, the variable $LNCO_2$ is non-stationary under the ADF test but becomes stationary under the PP test with an intercept. Meanwhile, LNTECH is found to be non-stationary at both level and first difference, for both intercept and trend specifications, in both the ADF and PP tests.

Table 1: Data sources

Variable	Sources of Data
$LNCO_2$	World Development Indicators (WDI)
LNGDP	World Development Indicators (WDI)
LNEC	World Development Indicators (WDI)
LNTECH	World Development Indicators (WDI)
LNTO	World Development Indicators (WDI)
LNFDI	World Development Indicators (WDI)
LNQOG	International Country Risk Guide (ICRG)
LNHC	World Development Indicators (WDI)
LNGINI	World Inequality Database (WID)

In conclusion, the variables exhibit mixed orders of integration, some are stationary at level, while others become stationary at first difference. However, none of the variables are stationary at the second difference I(2). Therefore, the Autoregressive Distributed Lag (ARDL) approach is deemed appropriate to be used in cointegration analysis for this model.

To verify the existence of long-run cointegration, the bounds testing approach based on the F-statistics is employed. As shown in Table 3, the model is estimated to use a maximum lag length of 2 for both the dependent and independent variables, selected based on the Schwarz Information Criterion (SIC). With this lag structure, the computed F-statistic is 12.98, which exceeds the critical value for the upper bound at the 1% significance level. Therefore, the null hypothesis of no cointegration is rejected, confirming the presence of a long-run cointegrating relationship at the 1% significance level.

To ensure the robustness of the model, several diagnostic tests are conducted, namely, the serial correlation test, Ramsey RESET functional form test, normality test, Breusch-Pagan heteroscedasticity test, and stability tests (CUSUM and CUSUM of Squares). As presented in Table 4, the results indicate that the model passes all diagnostic checks, with P-values exceeding the 10% significance level for the first four tests. This suggests that the model is free from serial correlation, correctly specified in terms of functional form, normally distributed, and does not suffer from heteroscedasticity problem.

Furthermore, the results of both CUSUM and CUSUM of Squares tests as shown in Figure 2, clearly indicated the stability of the model as the line was found within the 10% significance critical bounds.

Table 2: ADF and PP unit root test

Level I(0)	ADF unit root		PP unit root	
	Intercept	Intercept and Trend	Intercept	Intercept and Trend
$LNCO_2$	1.799 (1)	0.858 (0)	1.894 (2)	1.130 (1)
LNGDP	−1.559 (0)	−3.299 (0)*	−1.646 (2)	−3.273 (3)*
LNEC	−3.973 (2)***	−2.338	−10.470 (31)***	−4.394 (31)***
LNTECH	0.063 (0)	−1.035 (0)	0.120 (1)	−1.035 (0)
LNTO	−0.788 (0)	−2.321 (0)	−0.900 (2)	−2.333 (8)
LNFDI	−5.121 (0)***	−5.423 (0)***	−5.118 (1)***	−5.420 (3)***
LNQOG	−2.825 (1)*	−3.001 (1)	−2.764 (1)*	−2.960 (4)
LNHC	−2.792 (0)*	−1.131 (0)	−2.969 (4)**	−1.027 (4)
LNGINI	−1.059 (1)	−1.465 (1)	−1.414 (2)	−3.051 (2)
First difference I(1)	**ADF unit root**		**PP unit root**	
	Intercept	**Intercept and trend**	**Intercept**	**Intercept and trend**
$LNCO_2$	−1.973 (1)	−6.832 (0)***	−4.735 (3)***	−6.491 (3)***
LNGDP	−4.586 (1)***	−4.628 (1)***	−5.117 (3)***	−5.083 (3)***
LNEC	−3.568 (1)**	−5.121 (1)***	−3.828 (5)***	−6.327 (26)***
LNTECH	−1.973 (0)	−1.877 (0)	−1.943 (1)	−1.864 (1)
LNTO	−4.791 (0)***	−4.862 (0)***	−4.802 (5)	−4.853 (8)***
LNFDI	−6.648 (1)***	−6.582 (1)***	−22.872 (30)***	−27.887 (25)***
LNQOG	−4.590 (0)***	−4.468 (0)***	−5.603 (9)***	−5.352 (9)***
LNHC	−4.861 (0)***	−5.709 (0)***	−4.852 (1)***	−5.808 (5)***
LNGINI	−9.514 (0)***	−9.365 (0)***	−9.514 (0)***	−9.365 (0)***

***, **, and * are 1%, 5%, and 10% of significant levels, respectively. The optimal lag length is selected automatically using the Schwarz Info Criteria (SIC) for the ADF test and the bandwidth is selected by using the Newey–West method for the PP unit root test

Next, the short-run dynamics of carbon dioxide (CO_2) emissions per capita were reported by the reparametrize Error Correction Model (ECM) as shown in Table 5. The ECM framework enables analysis of how various economic, institutional, and environmental factors influence CO_2 emissions in the immediate term, while also accounting for the system's adjustment back to long-run equilibrium. A key finding reported was the statistically significant and negative coefficient of the lagged CO_2 emissions term, indicating a strong correction mechanism. This implied that the deviations from the long-term equilibrium in CO_2 emissions are substantially corrected in the following period, reflecting system stability and a tendency for the variables to revert toward their long-run path after the short-run shocks.

Economic activities as proxied by the change in GDP per capita, show a significant negative effect on CO_2 emissions in the short run. This result was found to be aligned with the early phase of the Environmental Kuznets Curve (EKC) hypothesis, where income growth is associated with improved energy efficiency or shifts towards less carbon-intensive consumption and production patterns. Meanwhile, energy consumption as measured in quadrillion Btu, and its short-run change exhibited a positive and significant impact on emissions, indicating that higher energy use intensifies environmental pressure. This underscores the urgent need for cleaner and more efficient energy technologies. Technological innovation as represented by patent registrations per capita was found related to a decline in carbon emissions, highlighting its critical role in sustainable development. The result, therefore, was in consistent with earlier findings by Saqib et al. (2024) and Yun et al. (2025). However, the lagged innovation term shows a significant positive impact, which may reflect a transitional phase where initial technology adoption temporarily increases energy use before efficiency gains materialize. On the other hand, trade openness and its lag value were both found to positively affect the emissions. This suggested that the likely increased industrial activity and transportation could potentially be associated with greater trade flows, emphasizing the necessity of integrating environmental safeguards within trade policies.

Meanwhile, Foreign Direct Investment (FDI) as measured by the net inflows produced a mixed result instead. The current period inflows were found to increase emissions, possibly via pollution-haven effects, while the lagged FDI term reduces emissions instead, suggesting that cleaner technologies and green practice adoption could be introduced over time which in turn mitigate the environmental impacts. Governance quality, proxied by the Quality of Governance index, was found significantly negative with the emissions. Strong governance likely strengthens environmental regulations and promotes sustainable practices, thus, highlighting the importance of institutional effectiveness. Human capital, captured through secondary school enrolment rates, also exhibits a significant negative impact on emissions. Thus, indicating that higher educational attainment fosters environmental awareness and supports sustainable policies. The finding was in support to the earlier findings by Shabani (2024) and Khan et al. (2024)

Table 3: Detecting the presence of long-run cointegration based on F stat

Model	Max Lag	Lag order	F statistics
$LNCO_2$ =LNGDP, LNEC, LNTECH, LNTO, LNFDI, LNQOG, LNHC, LNGINI	(2,2)	(2, 1, 2, 2, 2, 2, 1, 2, 2)	12.983***
Critical Values for F stat		**Lower I(0)**	**Upper (1)**
10%		1.85	2.85
5%		2.11	3.15
1%		2.62	3.77

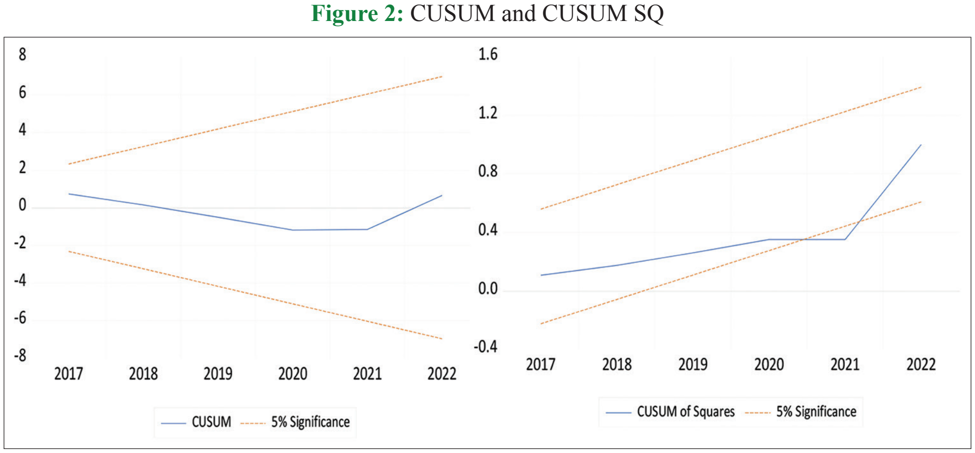
The critical values are based on Pesaran et al. (2001), case III: unrestricted intercept and no trend. k is a number of variables and it is equivalent to 5. *, **, and *** represent 10%, 5%, and 1% level of significance, respectively

Table 4: Diagnostic tests

Model	(A) Serial Correlation [P-value]	(B) Functional Form [P-value]	(C) Normality [P-value]	(D) Heteroscedasticity [P-value]
$LNCO_2$=LNGDP, LNEC LNTECH, LNTO, LNFDI, LNQOG, LNHC, LNGINI	2.458 [0.239]	0.339 [0.585]	0.148 [0.928]	1.823 [0.233]

** represents 5% significant levels. The diagnostic test performed as follows A. Lagrange multiplier test for residual serial correlation; B. Ramsey's RESET test using the square of the fitted values; C. Based on a test of skewness kurtosis of residuals; D. Based on the regression of squared fitted values

Figure 2: CUSUM and CUSUM SQ



that has similarly pointed out the significance of human capital development through education in emissions reduction. Income inequality, as measured by the GINI coefficient, positively influences emissions in the short run, possibly due to unequal access to clean technologies or overconsumption by higher income groups. This finding was in consistent with Ravallion et al. (2000) and Heerink et al. (2001) which suggested that greater inequality may reduce emissions, indicating a potential trade-off between social justice and environmental protection. The lagged inequality term is strongly negative, which may reflect the negative effects of redistributive policies in mitigating environmental harm over time. This in turn was in line with findings by Hao et al. (2016) and Baek & Gweisah (2013) demonstrating that higher income inequality exacerbates environmental degradation.

Finally, the error correction term (ECT) is negative and highly significant at -0.307, confirming a stable long-run equilibrium relationship. This indicates that approximately 30.7% of deviations from the long-run path are corrected within one period, demonstrating the model's robustness and the system's capacity to adjust rapidly aftershocks. In short, the significant negative term of the error correction term showed that convergence is achieved in the long run, thus, confirming the presence of a long-run relationship between the variables.

Next, the significant long-run determinants of CO_2 emissions as shown in Table 6 are imperative to be determined for shaping policies that foster environmental sustainability in the country.

Table 5: Short-run elasticities and error correction model (based on present lag)

Variables	Coefficient	t-stat	Prob
D(LNCO$_2$ (−1))	−0.619***	0.078	−7.856
D(LNGDP)	−0.084*	0.034	−2.414
D(LNEIA)	0.047*	0.023	2.003
D(LNEIA(−1))	0.061**	0.022	2.725
D(LNTECH)	−0.008***	0.001	−5.774
D(LNTECH(−1))	0.071***	0.004	14.448
D(LNTO)	−0.075***	0.018	−4.102
D(LNTO(−1))	0.124***	0.018	6.651
D(LNFDI)	0.020***	0.001	13.964
D(LNFDI(−1))	−0.004***	0.000	−5.463
D(LNQOG)	−0.147***	0.046	−3.181
D(LNHC)	−0.079***	0.011	−7.191
D(LNHC(−1))	−0.040***	0.009	−4.072
D(LNGINI)	0.152***	0.039	3.855
D(LNGINI(−1))	−0.572***	0.054	−10.470
ECT	−0.307***	0.017	−18.016

***, ** and * are 1%, 5% and 10% of significant levels, respectively

Table 6: Long run elasticities

Variables	Coefficient	Standard error	t-statistic
D(LNGDP)	−0.084	0.095	−0.883
D(LNEC)	0.047	0.076	0.628
D(LNTECH)	−0.008**	0.003	−2.376
D(LNTO)	−0.075	0.051	−1.480
D(LNFDI)	0.020**	0.008	2.466
D(LNQOG)	−0.147	0.133	−1.104
D(LNHC)	−0.079*	0.037	−2.143
D(LNGINI)	0.152	0.110	1.381

***, ** and * are 1%, 5% and 10% of significant levels, respectively

For the long-run relationship (Table 6), only three variables, technological innovation, foreign direct investment, and human capital were found to significantly influence CO_2 emissions, as evidenced by their statistical significance findings.

One of the significant findings reported was the significant role of technological innovation, which exhibits a statistically negative coefficient (-0.008) at the 5% level. This indicates that over time, advancements in technology contributed to the reduction in CO_2 emissions. This was in line with findings reported by Feng et al. (2024) and Yun et al. (2025) which indicated the improvement of environment was possible through new technological innovation. The result supported the hypothesis that the adoption of cleaner and more efficient technologies such as renewable energy systems, green manufacturing techniques, and digital efficiency tools plays a vital role in decoupling economic activities from environmental degradation. Thus, recognizing the sustained investment in R&D and green innovation as part of a critical long-term climate strategy.

Foreign direct investment was revealed to be another significant factor, with a statistically positive coefficient (0.020) reported at the 5% significance level. This implies that in the long run, the increased FDI was associated with higher CO_2 emissions. As such, the findings seem to be consistent with the pollution haven hypothesis (PHH), which suggests the likelihood of multinational firms relocating emission-intensive production to other host countries that have more lenient environmental regulations. This result shed light on the importance of the need to strengthen environmental governance and enforcement in ensuring that the FDI flows support sustainable development rather than exacerbate environmental harm.

Lastly, human capital reported a negative and significant coefficient (0.079) at the 10% level. This suggests that improvements in human capital through education and skills development contribute to lower CO_2 emissions in the long run. The result was in consistent with Wang et al. (2024) and Shabani (2024) shedding light on the importance of human capital development in fostering environment sustainability awareness. Educated populations are more likely to adopt eco-friendly practices, support green policies, and engage in innovation that prioritizes sustainability.

5. CONCLUSION AND POLICY RECOMMENDATIONS

In conclusion, this research closely examined how Malaysia through its human capital development and new technology innovation fosters sustainable development in its efforts to pursue the Sustainable Development Goals (SDGs), especially the Sustainable Development Goal 13 (SDG 13) of Climate Action. By employing the Autoregressive Distributed Lag (ARDL) model on data spanning 1990-2022, the analysis discovered the relationship between economic activities, innovation, education, governance, and environmental results. The findings evidently pointed out that education and skill development played a major key role in reducing emissions. In the long run, innovation as recorded by patent applications appeared to have a significant impact on the carbon emission and thus mitigating the environmental damage. In contrast, rising economic activity and energy consumption were found to significantly contribute to rising carbon emissions, exposing how the environmental issue has been linked to Malaysia's economic growth.

In addition, trade openness and foreign direct investment led to mixed results. The lack of strict regulations and environmental rules could potentially cause more harm to the environment as it provided loopholes for firms to employ less environmentally friendly technologies. Besides that, some of the unethical firms may even exploit and take advantage of the less stringent regulations enforcement simply dumping pollutants for profit gains but at the expense of the local ecosystems. As the Environmental Kuznets Curve hypothesis posited, the initial stages of rapid growth usually result in environmental damage, but once societies pass a specific income level, there will be a shift to better environmental quality. In short, the findings from this research have implied that both education and innovation are key to Malaysia's pursuit of the Sustainable Development Goals (SDGs), especially SDG 13 both in the short-run and long-run equilibrium. In Malaysia, efforts to address environmental issues have involved government agencies, local authorities, NGOs, academic institutions, and private sector partners working together in the efforts to integrate environmental sustainability goals into local and national development plans. Collaborating closely in establishing frameworks, regulations, and initiatives. One such example is the All-Party Parliamentary Group Malaysia on Sustainable Development Goals (APPGM-SDG Malaysia) which was launched in 2019 to support the implementation of the 2030 Agenda for Sustainable Development, covering social, economic, and environmental pillars.

Based on the empirical results, the study identifies the significance of human capital development as a decisive factor of CO_2 emission decrease. To realize this potential the government ought to invest more in secondary and tertiary education and specifically the integration of sustainability, environmental awareness as well as green technology and skills in the curricula. Diversifying and expanding vocational training and upskilling of the workforce in renewable energy, sustainable production, and environmental management will make sure that Malaysia develops a climate-neutral and innovation-friendly labour force. Such undertakings will not only contribute to the decarbonization ambitions of the country but also increase the general resilience and flexibility of the economy.

Technological innovation also has a leading role in the decarbonization of the economy in the long-run. In this regard, Malaysia ought to increase both the public and private spending on research and development (R&D) especially on clean energy, energy efficiency as well as low-carbon technologies. Creation of effective networks or collaboration among universities, research institutions, and industries will help in speeding up the process of developing and adopting sustainable technologies. The government can also provide special incentives in the form of tax exemptions, grants, and patent subsidies on eco-innovation as well as establishing an enabling environment through green entrepreneurship and technology improvement.

On the other hand, foreign direct investment (FDI) leads to the higher emission levels, which corresponds to the pollution haven hypothesis. Thus, policy changes are required, so that FDI can contribute to environmental and climate objectives of Malaysia. This will be through imposition of strict environmental impact assessment on foreign investments, incorporating environment-based clauses on investment agreements and promoting FDI in green and low-carbon sectors to ensure that the foreign investment plays a positive role in the sustainable development agenda of Malaysia.

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