The Asian Journal of Technology Management Vol. 17 No. 2 (2024): 108-121

An ARDL Modelling Approach to Assess the Dynamic Effects of Economic Development and CO_2 Emissions in Malaysia

Kee Zheng Ding[*12] **and Tze-Haw Chan**[1]
[1]Graduate School of Business, University Sains Malaysia, Penang, Malaysia
[2]School of Business and Management, Institut Teknologi Bandung, Indonesia

Abstract. *This research paper conducts a comprehensive analysis of the complex relationship between CO_2 emissions and economic factors, specifically investigating the Environmental Kuznets Curve (EKC) theory in Malaysia. Using data from 1991 to 2020, the study applies the Autoregressive Distributed Lag (ARDL) modelling approach developed by Pesaran et al. (2001). The results demonstrate a significant long-term connection between Gross Domestic Product (GDP), trade, and carbon emissions, indicating that economic development plays a crucial role in influencing Malaysia's carbon footprint. Additionally, the inclusion of institutional quality in the model adds another layer of complexity, highlighting the multifaceted nature of the relationship between economic progress and environmental outcomes. Furthermore, examining short-term dynamics using the ARDL model reveals diverse effects over time for variables such as renewable energy and institutional quality, providing a more nuanced understanding of these relationships. These detailed insights are essential for policymakers dealing with the challenges of promoting economic progress while ensuring environmental sustainability. The findings contribute to a deeper understanding of the interplay between economic variables and CO_2 emissions, offering valuable guidance for policymakers striving to strike a balance between economic growth and environmental conservation in Malaysia.*

Keywords: *Malaysia, autoregressive distributed lag (ardl) modelling, environmental kuznets curve (ekc), carbon dioxide (co_2) emissions, gross domestic product (gdp), renewable energy (ren), institutional quality (iq), trade (tr)*

1. Introduction

In our continuously evolving world, comprehending the intricate interplay between economic growth and environmental impact is of paramount importance. This paper delves into the Malaysian narrative, utilizing the Autoregressive Distributed Lag (ARDL) modeling technique to scrutinize how the country's financial trajectory influences its carbon footprint both in the short- and long-term.

Picture a world abuzz with discourse on climate change, with Malaysia, distinguished but its dynamic economy and commitment to environmental conservation, assuming a pivotal role. Particularly for nations like Malaysia, heavily reliant on fossil fuels for economic advancement, the ramifications of climate change are a pressing concern due to their profound effects on global food production, public health, and ecosystems (Shahbaz et al., 2020). Due to Malaysia's historical reliance on energy combustion, CO_2 emissions have exhibited a sustained upward trend, as illustrated in Figure 1 (Enerdata, 2023).

*Corresponding author. Email: k.z.ding97@gmail.com
Received: June 10th, 2024; Revised: July 10th, 2024; Accepted: August 5th, 2024
Doi: http://dx.doi.org/10.12695/ajtm.2024.17.2.3 Print ISSN: 1978-6956; Online ISSN: 2089-791X.

Published by Unit Research and Knowledge- School of Business and Management-Institut Teknologi Bandung
How to cite: *Ding, K. Z., & Chan, T.-H. An ARDL Modelling Approach to Assess the Dynamic Effects of Economic Development and CO2 Emissions in Malaysia. The Asian Journal of Technology Management (AJTM), 17(2), 108-121. https://doi.org/10.12695/ajtm.2024.17.2.3*

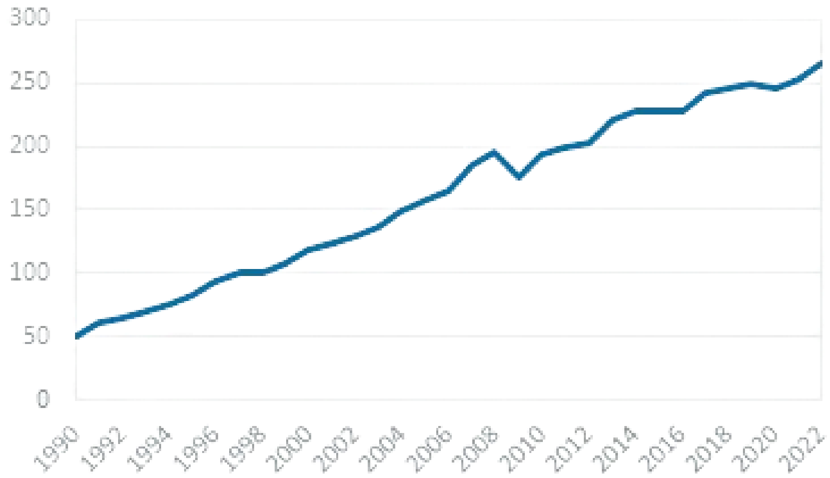


Figure 1
CO_2-ENERGY EMISSIONS (MtCO2)

This study focuses on finding the balance where economic growth meets sustainable living. The Environmental Kuznets Curve (EKC) hypothesis suggests that as a country becomes wealthier, its concern for the environment increases. But does this hold true for Malaysia? This is the key question we are aiming to answer.

We examine several key variables. GDP, the central economic indicator, measures the monetary value of all finished goods and services produced in a nation within a given period (Callen, 2019). Economists, governments, and corporations use it extensively to assess the state of national and international economies (Callen, 2019). Renewable energy consumption (REN) plays a role, as renewable energy has been shown to positively impact economic development (Le & Ozturk, 2020). IQ, as highlighted by Tashtamirov (2023), is essential for sustained economic development, particularly in cases like Russia, where poor institutional quality impedes growth.

Finally, trade (TR), which benefits nations through the trade of goods and services across borders, improves living standards and economic efficiency (McDonald, 2019). This study also explores the extent to which trade and renewable energy use contribute to variations in CO_2 emissions over time. Furthermore, we investigate whether IQ alters the conventional understanding of the Malaysian EKC. These variables are the foundation for understanding how Malaysia's economic progress impacts its carbon emissions.

By examining the relationships between trade, carbon emissions, renewable energy usage, IQ, and economic growth in Malaysia, this study aims to contribute to the literature. It analyzes annual data from 1981 to 2020 using an ARDL model, allowing for a detailed analysis of both short- and long-term dynamics. This research addresses a gap in the literature on the EKC theory in emerging nations by focusing on Malaysia and investigating whether its economic growth follows the EKC pattern. To determine the stationarity of the variables, unit root tests, such as the Augmented Dickey-Fuller (ADF) test, are employed. Cointegration is tested using the ARDL Bounds Test (refer to Equation (4)).

The results show a significant long-term correlation between GDP, trade, and carbon emissions, indicating that Malaysia's economic growth has a substantial impact on its carbon footprint. Specifically, the analysis reveals a 2.2548% increase in CO_2 emissions for every 1% increase in GDP, underscoring the challenge of balancing environmental sustainability with economic growth. Interestingly, the EKC hypothesis, which posits that higher IQ and economic growth lead to better environmental outcomes, is challenged by the finding that IQ has little effect on emissions. The positive relationship between emissions and renewable energy use may indicate inefficiencies or an insufficient replacement of non-renewable energy sources (refer to Equation (4)).

These findings suggest that policies focused solely on economic growth and institutional improvements may not be sufficient to achieve environmental sustainability in Malaysia. A multifaceted approach, including promoting renewable energy efficiency, implementing green technologies, and enhancing trade regulations, is necessary. The study highlights the need for tailored environmental policies specific to Malaysia's context, rather than relying on generalized economic theories like the EKC hypothesis. This research contributes to the broader discussion on sustainable development by providing empirical evidence from a developing country, offering valuable insights for policymakers seeking to balance economic and environmental protection (refer to Equation (4)). As climate change continues to dominate global discussions, Malaysia serves as a case study with important lessons. Acknowledging its reliance on non-renewable energy sources, Malaysia has been actively investigating ways to transition to more sustainable alternatives. The country introduced the National Green Technology Policy in 2009 and the National Renewable Energy Policy in 2010 (UNFCCC, 2020) to promote renewable energy use. As we face the dual challenge of economic growth and environmental preservation, Malaysia's experience offers valuable guidance for policymakers worldwide (refer to Equation (3)).

The remaining sections of the paper are structured as follows: the Literature Review discusses relevant studies, followed by the Methodology, which provides an overview of the approach used. The Findings and Discussion examine the empirical results, and the paper concludes with the Conclusion.

2. Literature Review / Hypothesis Development

The EKC hypothesis, introduced by Grossman and Krueger (1991), explores the relationship between economic growth and environmental degradation. It suggests that in the early stages of economic development, CO_2 emissions increase due to industrialization and intensified production activities, leading to environmental degradation. However, when a country reaches a certain level of wealth, a turning point occurs, and CO_2 emissions decline, resulting in improved environmental quality (as shown in Figure 2).

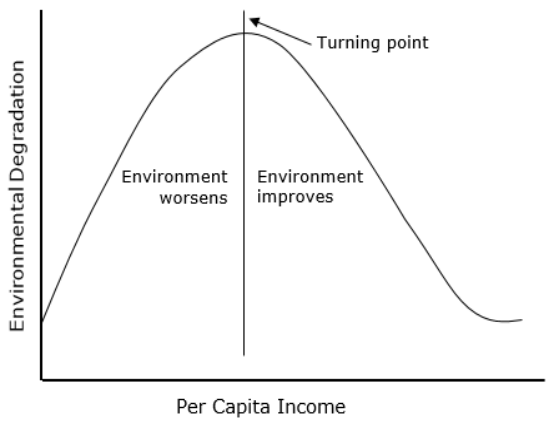


Figure 2
Environmental Kuznets Curve

Early studies, including those by Grossman and Krueger (1995), provided empirical support for the EKC hypothesis, especially regarding the link between GDP growth and environmental quality. Bartlett (1994) expanded this understanding by demonstrating an inverted U-shaped relationship between per-capita income and per-capita CO_2 emissions, indicating a turning point on the EKC curve.

Subsequent research has broadened the EKC framework. A global study by Rongrong et al. (2021), involving 147 countries, found that while economic growth significantly increases carbon emissions, economic structure can have a mitigated effect. For example, Holtz-Eakin & Selden (1995) and Mikayilov et al. (2018) suggest that the relationship is not as straightforward as initially assumed. Gill et al. (2018) also challenge the universality of the EKC hypothesis by highlighting the nuanced and complex relationships between environmental and economic development. These differing perspectives emphasize the need for a more comprehensive investigation into the factors influencing environmental outcomes.

CO_2 emissions and variables

Several studies have examined the relationship between CO_2 emissions and IQ. Farzanegan and Markwardt (2018) suggest that improving IQ in the Middle East and North America (MENA) region could help control CO_2 emissions. Le and Ozturk (2020) created an EKC-type model covering 74 emerging markets and developing economies (EMDEs) between 1990 and 2014. Solarin et al. (2017) emphasized the crucial role of IQ in reducing emissions of CO_2 in Ghana, finding a negative correlation between institutional quality and environmental degradation. Similarly, Shahzad et al. (2020) and Shahzad (2020) confirmed that lower IQ contributes to increased CO_2 emissions, corroborating earlier findings by Shah et al. (2019).

In East Africa, Namahoro et al. (2021) found a negative relationship between carbon dioxide emissions and renewable energy use. Their study highlighted the role of renewable energy in reducing the negative effects of energy consumption on the environment. In the European Union, Radmehr et al. (2021) showed that a 1% increase in renewable energy usage results in a 0.05% decrease in carbon emissions. Trade is another significant factor influencing COS2 emissions. According to the World Bank (2023), while trade promotes economic growth, it also risks accelerating environmental deterioration. In 2020, trade contributed to approximately 27.2% of global fuel-related CO_2 emissions. Conversely, trade can facilitate access to low-emission technology and products (World Bank, 2023), presenting a dual role in both mitigating and exacerbating environmental impacts (Ugur et al., 2018).

Heidari, Katircioglu, and Saeidpour (2015) used data from five ASEAN countries—Malaysia, Indonesia, the Philippines, Singapore, and Thailand—to argue for a nonlinear relationship between economic development, carbon emissions, and energy consumption. Their regression analysis showed that carbon emissions initially rise with GDP growth but eventually decline after reaching a peak. Similarly, Saboori and Sulaiman (2013) used ARDL panels to study the interaction between energy consumption, economic growth, and CO_2 emissions in the five ASEAN countries. Building on this, a study on eight ASEAN nations between 1994 and 2018 employed the ARDL panel approach to examine the short- and long-term effects of economic growth on CO_2 emissions.

In conclusion, understanding the complex relationships between trade, energy consumption, and CO_2 emissions is essential for Malaysia to address its environmental challenges and pursue sustainable development (World Bank, 2023). This research aims to shed light on these connections and offer policy recommendations to promote a more sustainable future for Malaysia (World Bank, 2023).

3. Methodology

Data

This research analyzes annual data from Malaysia spanning 1991 to 2020, focusing on key indicators: carbon dioxide emissions (CO_2), GDP, renewable energy consumption (REN), IQ, and trade (TR). Our data was primarily sourced from the World Bank dataset (2023), which provides comprehensive insights into these variables. In contrast to the extensive datasets available for developed countries, accessing relevant and accurate data for emerging economies in Southeast Asia, including Malaysia, presents challenges. To address data gaps in IQ, mean imputations were used, enhancing the accuracy and robustness of our analysis.

For measurement, CO_2 emissions are expressed in metric tons per-capita, GDP is measured as GDP per-capita (current US$), and renewable energy consumption is represented as a percentage of total final energy consumption. Trade is measured as the share of GDP {(export + import)/real GDP}. IQ is assessed using the Worldwide Governance Indicator (WGI), which includes metrics such as anti-corruption, governance effectiveness, political effectiveness, absence of violence, quality of regulation, rule of law, and accountability.

To ensure the stability of our analysis and simplify coefficient interpretation, all variables are converted to their natural logarithmic form.

ARDL Modeling

This study applies the ARDL model as proposed by Pesaran et al. (2001). The first step involves a bounds cointegration test within the ARDL model, producing the F-statistic. This statistic serves as a benchmark for determining whether a long-term cointegration relationship exists between the variables. We measure this relationship by comparing the F-statistic to the upper and lower critical values outlined by Pesaran et al. (2001). The null hypothesis of no cointegration relationship is rejected only if the F-statistic exceeds the upper bound, indicating a significant cointegration relationship.

One key advantage of the ARDL model is its flexibility in handling variables with different stationarity orders, as long as none are integrated at I(2). This flexibility allows for the inclusion of variables that are I(0) or I(1). Therefore, conducting a unit root test is essential to ensure no variables are I(2) before constructing the ARDL model. In this study, we argue that GDP, along with renewable energy consumption, trade and IQ, are key determinants of CO_2 emissions.
A specific model is integrated as follows:

where CO_2, GDP, REN, TR and IQ represent CO_2 emissions, GDP per-capita, renewable energy consumption, trade and institutional quality, respectively. All variables are expressed in natural logarithmic form. In this model, $\beta 0$ is the intercept, $\beta 1$, $\beta 2$, $\beta 3$, $\beta 4$ and $\beta 5$ represent the long-run elasticities, the subscripts t denotes time (years), and αt is the random disturbance term. Based on Equation (1), the ARDL-bound cointegration test model is developed as follows:

Here ε_t is the residual term, and Δ denotes the "first order" difference of the variables. n, q, r, p, k are the lag orders. The null hypothesis for the ARDL bounds test is that no long-term cointegration relationship between the variables exists, i.e., H0: α1= α2= α3= α4= α5= α6=0. The alternative hypothesis H0 is that such a relationship does exist: H1: α1= α2≠ α3≠ α4≠ α5≠ α6≠0. Once a long-run cointegration relationship is established, the ARDL model can be used to analyze the long-run and short-term effects. The long-run effects are modeled as follows:

The coefficient of the independent variables in Equation (4) is calculated according to the results of Equation (3). Among them, the coefficients of lnGDP, lnGDP"2", lnREN, lnTR, and lnIQ are as follows, respectively:

Finally, the ARDL model is modified into an error correction model (ECM) to capture short-term dynamics: where ECM_t is the error correction term. The coefficient δ of ECM_t indicates the speed of correction to the long-term relationship, which is expected to be negative.

Table 1
Descriptive Statistics

	lnCO2	lnGDP	lnIQ	lnREN	lnTR
Mean	1.7754	8.7184	-0.9453	1.3869	5.1193
Median	1.8619	8.6706	-0.9322	1.4434	5.1327
Maximum	2.0437	9.3176	-0.6496	2.0399	5.3955
Minimum	1.2845	7.9112	-1.4529	0.6729	4.7607
Std. Dev.	0.2393	0.4663	0.1692	0.3774	0.1908
Skewness	-0.7530	-0.0516	-1.0128	-0.0517	-0.2536
Kurtosis	2.3103	1.4869	4.5034	2.0061	1.7824
Jarque-Bera	3.4297	2.8753	7.9542	1.2481	2.1746
Probability	0.1800	0.2375	0.0187	0.5358	0.3371
N	30	30	30	30	30

Note. CO_2, GDP renewable energy use, trade, and IQ, respectively. ln indicates taking the natural logarithmic form for each variable.

4. Findings and Discussion

Findings

The National Institute of Standards and Technology (NIST, 2023) defines kurtosis as a measure of the tail behavior of a distribution. High kurtosis indicates strong tails or the presence of outliers, while low kurtosis suggests lighter tails or fewer outliers. The Jarque-Bera test, on the other hand, assesses normality by examining the skewness and kurtosis of the sample (NIST, 2015).

In statistical analysis, a standard distribution operates assumes a skewness of 0 and a kurtosis value of 3. The Jarque-Bera (JB) test is designed to evaluate normality based on these parameters. Under perfect conditions—zero skewness and a kurtosis equal to 3—the test statistic equals 0 (Polanitzer, 2021). A JB test p-value below 0.05 indicates a significant departure from normality (Nirajan, 2023).

The descriptive statistics in Table 1 show that the mean lnCO2 value of 1.7754 indicates a moderate level of CO_2 emissions, with a left-skewed distribution and strong potential outliers. In contrast, lnGDP has a mean value of 8.7184, indicating a relatively high GDP with a symmetrical distribution, lower kurtosis, and fewer extreme values. lnREN and lnTR show moderate average values of 1.3869 and 5.1193, respectively, with roughly symmetrically distributed. However, the lnIQ has a negative mean of -0.9453 and a negatively skewed distribution, concentrated at the upper end. The JB test suggests deviations from normality, particularly for lnIQ, where a p-value of 0.0187 indicates non-normality.

Table 2
Correlation between Variables

	lnCO2	lnGDP	lnIQ	lnREN	lnTR
lnCO2	1				
lnGDP	0.8993	1			
lnIQ	-0.0717	-0.1324	1		
lnREN	-0.6471	-0.4918	0.2047	1	
lnTR	-0.4185	-0.6997	0.0853	-0.1062	1

Note. Refer to Table 1 for a detailed description of variables.

Table 2 reveals a strong correlation between economic growth and increased carbon dioxide emissions (0.8993). lnCO2 shows a weak negative correlation with lnIQ (-0.0717), suggesting little relationship between carbon emissions and IQ. In contrast, lnREN displays a pronounced negative correlation with InCO2 (-0.6471), indicating that higher renewable energy consumption tends to reduce emissions. Similarly, InTR exhibits a moderate negative correlation with lnCO2 (-0.4185), implying a possible relationship between trade and lower emissions.

Figure 3
Individual Trend Charts for Variables, 1981-2020

The time series trends in Figure 3 show distinct patterns across the variables. lnCO2 has a recognizable upward trend, indicating rising carbon dioxide emissions. lnGDP shows a consistent upward trend, reflecting economic growth. lnIQ and InREN fluctuate without clear overall trends, while lnTR peaks in 2004 before gradually declining.

Table 3
ADF Unit root test results

Variables	ADF (P-values)		
	Intercept	Intercept and trend	None
Level			
lnCO2	-2.3372(0.1678)	-1.2568(0.8787)	2.4330(0.9951)
lnGDP	-1.3978(0.5695)	-1.7702(0.6929)	2.0034(0.9871)
InIQ	-3.2847(0.0251)**	-3.2203(0.1003)	-0.5962(0.4503)
lnREN	-1.5867(0.4760)	-0.6727(0.9655)	-0.4526(0.5097)
lnTR	0.3073(0.9741)	-1.6553(0.7450)	-1.3408(0.1622)
First differences			
lnCO2	-5.4948(0.0001)***	-3.8463(0.0331)**	-1.6480(0.0927)*
lnGDP	-4.6071(0.0010)***	-4.5697(0.0057)***	-4.2783(0.0001)***
InIQ	-3.4383(0.0200)**	-3.4551(0.0686)*	-3.5445(0.0011)***
lnREN	-3.1738(0.0325)**	-3.8187(0.0305)**	-3.2416(0.0022)***
lnTR	-3.5215(0.0148)**	-3.7488(0.0366)**	-3.5250(0.0010)***

*Note. ***, **, and * symbolize significance levels at 1%, 5%, and 10%, respectively. P-values are presented in parentheses ( ). Based on the Akaike info criterion, the default maximum lag is set at 7.*

The ARDL model, which allows for the inclusion of variables at various time lags, is used in this empirical analysis (Khan, Teng, & Khan, 2019). The optimal lag selection is determined using the AIC criterion, which is effective for small sample sizes (Acquah, 2010). The "first differences" section indicates that all variables become stationary after accounting for first differences, as shown by significant negative ADF statistics.

Table 4
ARDL Bounds Test Results

Test statistics	Value	k
F-statistics	83.2138***	4
Critical values		
Significance level	I(0) Bound	I(1) Bound
10%	2.2	3.09
5%	2.56	3.49
2.5%	2.88	3.87
1%	3.29	4.37

*Note. *** symbolizes significance levels at 1%.*

The F-statistic in Table 4 (83.2138) is significant at the 1% level, indicating a long-term relationship between the variables. The critical values for I(0) and I91) confirm the presence of cointegration. The coefficients in Table 5 show the expected changes in the dependent variable for a uniform change in the corresponding independent variables. For example, a 1% increase in GDP leads to a 2.2548% rise in CO_2 emissions. Positive coefficients for lnGDP, lnREN and lnTR suggest positive influences, while the negative coefficient for lnIQ implies a negative influence.

Table 5
ARDL Long-term Estimation Results

Variables	Coefficient	St. error	T-ratio (p-values)
lnGDP	2.2548	0.3813	5.9133**(0.0274)
lnIQ	-0.7379	0.2814	-2.6223(0.1198)
lnREN	1.0224	0.2273	4.4982**(0.0460)
lnTR	3.8294	0.6916	5.5367**(0.0311)
C	-39.7366	7.4916	-5.3042**(0.0338)

*Note. ***, **, and * symbolize significance levels at 1%, 5%, and 10%, respectively.*

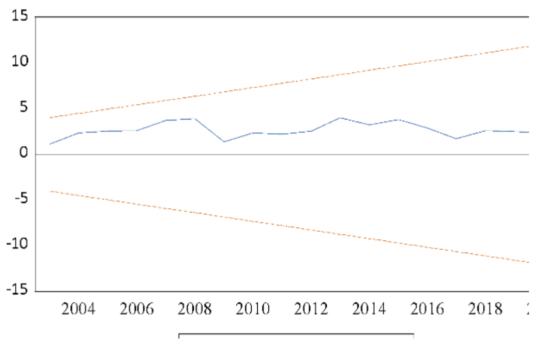
The significance of lnGDP p-value of 0.0274), lnREN (p-value of 0.0460), and lnTR (p-value of 0.0311) at the 1% level is particularly notable. However, lnIQ is not significant at the 10% level (p-values of 0.1198). The ECM in Table 6 reveals the short-term dynamics, showing the positive impact of past CO_2 emissions on current levels, and the mixed short-term impacts of GDP and renewable energy.

Table 6
ARDL Short - term Estimation Results

Variables	Coefficient	St. error	T-ratio (p-values)
△lnCO2(-1)	0.3862	0.0234	16.5213***(0.0036)
△lnCO2(-2)	0.7996	0.0249	32.0752***(0.0010)
△lnCO2(-3)	1.0446	0.0260	40.1513***(0.0006)
△lnGDP	0.5776	0.0102	56.5104***(0.0003)
△lnGDP(-1)	-0.2683	0.0111	-24.1184***(0.0017)
△lnGDP(-2)	-0.2714	0.0123	-22.0887***(0.0020)
△lnGDP(-3)	-0.2580	0.0089	-28.9189***(0.0012)
△lnIQ	0.1063	0.0039	27.2028***(0.0013)
△lnIQ(-1)	0.3577	0.0077	46.5830***(0.0005)
△lnIQ(-2)	0.3464	0.0084	41.1806***(0.0006)
△lnIQ(-3)	0.1679	0.0061	27.7378***(0.0013)
△lnREN	0.0079	0.0066	1.1997(0.3531)
△lnREN(-1)	-0.2422	0.0076	-31.8300***(0.0010)
△lnREN(-2)	0.0870	0.0060	14.5221***(0.0047)
△lnTR	0.9706	0.0241	40.3188***(0.0006)
△lnTR(-1)	-0.4760	0.0205	-23.2179***(0.0018)
△lnTR(-2)	-0.7122	0.0244	-29.1773***(0.0012)
△lnTR(-3)	-0.4754	0.0202	-23.5326***(0.0018)
ECT (-1)	-0.3919	0.0094	-41.8030***(0.0006)
Diagnostic Tests	F-statistic	P-value	
Breusch-Godfrey LM	2.3702	0.3667	
Breusch-Pagan-Godfrey	0.2824	0.9544	
ARCH	0.5391	0.4702	
Ramsey-RESET test	0.4936	0.6101	
JB	1.6600	0.4360	

*Note. ***, **, and * symbolize significance levels at 1%, 5%, and 10%, respectively.*

On the other hand, a series of diagnostic tests were performed in Table 6 to test the validity and consistency of the ARDL model. The Breusch-Godfrey LM test is used to check that the model has no serial correlation. The Breusch-Pagan-Godfrey test and the ARCH test show that the model has no heteroscedasticity problem, while JB indicates that the residuals are normally distributed. The Ramsey-RESET test of functional form confirms that the modeling is appropriate.



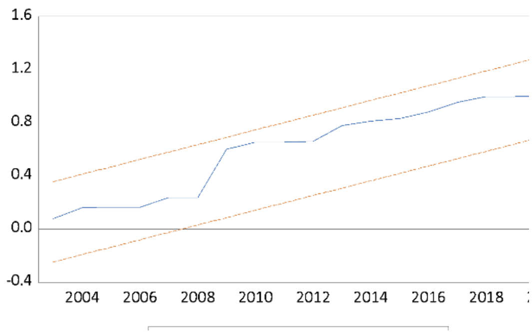


Figure 4
Plot of CUSUM and CUSUMQ Tests

In addition, Figure 2 shows that the fluctuations of both CUSUM and CUSUMQ do not exceed the limits within the sample period, indicating that the constructed ARDL model is stable.

Discussion

The empirical findings for Malaysia deviate from the expected EKC hypothesis, particularly with regard to lnIQ. The negative mean value of lnIQ and its lower probability (0.0187) raises concerns about the normality of the variable, challenging the notion that IQ improves with economic growth and supports environmental sustainability (Farzanegan & Markwardt, 2018; Solarin et al., 2017). This weak correlation between lnCO2 and lnIQ further suggests that IQ may not significantly reduce carbon emissions in Malaysia, aligning with opposing views from Holtz-Eakin & Selden (1995) and Mikayilov et al. (2018).

The lack of a significant relationship between emissions and IQ indicates that improving IQ and economic development alone may not be enough to achieve environmental sustainability. This finding resonates with Gill et al. (2018), who emphasized the complex relationships between environmental and economic development. Policymakers should reassess the framework in light of Malaysia's departure from the EKC hypothesis and focus on alternative strategies, such as promoting renewable energy and strengthening trade regulations (Namahoro et al., 2021; Radmehr et al., 2021; Ugur et al., 2018).

Although the long-term positive relationship between GDP growth and CO_2 emissions supports the initial phase of the EKC hypothesis, there is no evidence of a turning point where emissions decline as GDP continues to grow (Bartlett, 1994; Grossman & Krueger, 1991). The mixed results for renewable energy and trade, combined with the insignificant impact of IQ, suggest that other factors may influence the relationship between economic growth and environmental quality, as proposed by Rongrong et al. (2021). Therefore, the EKC hypothesis is not fully supported in this context, and Malaysia's experience does not confirm the hypothesis (refer to Equation (1)).

The long-term and short-term impacts of macroeconomic variables on CO_2 emissions provide critical insights for Malaysian policymakers. The 1% increase in GDP, associated with a 2.2548% rise in CO_2 emissions, suggests that sustainable economic growth should be promoted by integrating green technologies and encouraging energy efficiency, such as through tax incentives for green investments and subsidies for renewable energy projects. When the coefficient for InIQ is negative, its lack of statistical significance suggests that industrial efficiency improvements alone may not consistently reduce emissions (Shahzad, 2020; Shahzad et al., 2020). The surprising positive correlation between InREN and CO_2 emissions may be due to inefficiencies in replacing non-renewable sources, necessitating greater efficiency in renewable energy deployment (refer to Equation (2)).

In the short-term, past emissions have a significant path-dependence effect, indicating the importance of immediate measures to curb emissions, such as stricter regulations and incentives for low-carbon technologies. The negative coefficients for lagged GDP suggest that the initial positive impact of economic growth on emissions diminishes over time, emphasizing the need for long-term investments in sustainable practices. The error correction term indicates a moderate speed of adjustment towards long-term equilibrium, signaling that emission reduction strategies must be continuously monitored and updated. These insights allow policymakers to design targeted interventions that balance economic growth with environmental sustainability, helping Malaysia achieve its emission reduction goals (Heidari et al., 2015; Saboori & Sulaiman, 2013) (refer to Equation (2)).

5. Conclusions

In summary, this study employs the ARDL model to explore the dynamic interplay between economic variables and CO_2 emissions in Malaysia from 1991 to 2020, focusing on key indicators such as GDP, renewable energy consumption, IQ and trade. The findings highlight the complex relationship between economic development and environmental sustainability, providing valuable insights into the ongoing global discourse on climate change through the lens of Malaysia's economic development. The results show a significant long-term relationship between GDP, trade, carbon emissions, and renewable energy consumption, suggesting that economic development has a considerable impact on Malaysia’s carbon footprint. The inclusion of IQ in the model adds further complexity, reflecting the multifaceted relationship between financial development and environmental outcomes.

The study introduces the EKC hypothesis in the Malaysian context and questions whether the conventional wisdom—that environmental awareness increases with economic development—applies to the country. The positive long-term relationship between GDP and CO_2 emissions challenges the notion that economic growth inevitably leads to reduced environmental degradation. This highlights the uniqueness of Malaysia’s economic and environmental landscape. Additionally, the short-term dynamics revealed by the ARDL model illustrate the varied effects of renewable energy and IQ over time. These nuances are of critical for policymakers addressing the dual challenge of promoting economic development while ensuring environmental sustainability. The robustness of the ARDL model is supported by diagnostic tests and CUSUM/CUSUMQ charts, confirming the stability and reliability of the analytical framework.

However, this analysis acknowledges certain limitations, particularly in the context of the EKC hypothesis. Some significant factors, such as population growth, government regulations, and technological advancements, may not have been fully explored. Additionally, the historical scope and data sources may limit the findings, suggesting that future research using more recent and comprehensive data could provide a clearer picture of emerging trends (refer to Equation (6)).

To address these limitations and enhance the understanding of the factors influencing environmental sustainability in Malaysia, future research should consider a broader range of factors. Incorporating qualitative data and case studies could offer deeper insights into the intricate dynamics between environmental quality and economic development. Expanding the scope to include comparative studies with other countries could reveal shared or unique contextual elements affecting environmental outcomes. These findings should inform sustainable development strategies, recognizing the need for a flexible and comprehensive approach, rather than relying exclusively on traditional economic metrics (refer to Equation (6)).

Given the global imperative to balance economic prosperity and environmental well-being, Malaysia serves as an instructive case study. This research offers not only academic insights but also practical guidance for policymakers worldwide. Its significance extends beyond Malaysia, providing broader implications for countries seeking to navigate the delicate balance between economic development and environmental responsibility. Ultimately, this study serves as a roadmap for sustainable development, offering a blueprint for harmonizing economic growth with environmental stewardship across borders.

Declarations

Author contribution

All authors contributed equally as the main contributors of this paper. All authors read and approved the final paper.

Funding statement

The authors declare that this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing interest

The authors declare that they have no conflicts of interest to report regarding the present study.

References

Acquah, H. D.-G. (2010). Comparison of Akaike information criterion (AIC) and Bayesian information criterion (BIC) in selection of an asymmetric price relationship. *Journal of Development Agricultural Economics,* 2(1), 001-006.

Adebola Solarin, S., Al-Mulali, U., and Ozturk, I. (2017). Validating the Environmental Kuznets Curve Hypothesis in India and China: The Role of Hydroelectricity Consumption. Renew. *Sust. Energ. Rev.* 80, 1578–1587. doi:10.1016/j.rser.2017.07.028

ASEAN Secretary 2019, *ASEAN Economic Integration Brief, 06*, Available at: https://asean.org/wp-content/uploads/2021/08/AEIB_6th_Issue.pdf

Bartlett Aa (1994) reflections on sustainability, population growth, and the environment-revised. *popul environ* 16(1):5–35

Brad McDonald (2019) *International Trade: Commerce Among Nations, IMF.* Available at: https://www.imf.org/en/Publications/fandd/issues/Series/Back-to-Basics/Trade.

Farzanegan, M. R., and Markwardt, G. (2018). Development and Pollution in the Middle East and North Africa: Democracy Matters. *J. Pol. Model.* 40 (2), 350–374. doi:10.1016/j.jpolmod.2018.01.010

Grossman, G.M. And Krueger, A.B. (1991) environmental impacts of a North American Free Trade Agreement, Nber. doi:10.3386/w3914

Grossman Gm, Krueger Ab (1995) economic growth and the environment. *Q J Econ* 110:353–77. doi: 10.2307/2118443

Gill, A. R., Viswanathan, K. K., & Hassan, S. (2018). The Environmental Kuznets Curve (EKC) and the environmental problem of the day. *Renewable Sustainable Energy Reviews,* 81, 1636-1642. doi: 10.1016/j.rser.2017.05.247

Heidari, H, Katircioglu, ST, & Saeidpour, L 2015, 'Eco- ˘ nomic growth, CO2 emissions, and energy consumption in the five ASEAN countries', *International Journal of Electrical Power & Energy Systems,* 64, (785-791). doi: 10.1016/j.ijepes.2014.07.081.

Holtz-Eakin, D., & Selden, T. M. (1995). Stoking the fires? CO2 emissions and economic growth. *Journal of public economics*, 57(1), 85-101.

Khan, M. K., Teng, J.-Z., & Khan, M. I. (2019). Effect of energy consumption and economic growth on carbon dioxide emissions in Pakistan with dynamic ARDL simulations approach. *Environmental Science Pollution Research*, 26(23), 23480-23490.

Le, H. P., and Ozturk, I. (2020). The Impacts of Globalization, Financial Development, Government Expenditures, and Institutional Quality on CO2 Emissions in the Presence of Environmental Kuznets Curve. Environ. *Sci. Pollut. Res.* 27 (18), 22680–22697. doi:10.1007/s11356-020-08812-2.

Le, H. P., and Ozturk, I. (2020). The Impacts of Globalization, Financial Development, Government Expenditures, and Institutional Quality on CO2 Emissions in the Presence of Environmental Kuznets Curve. *Environ. Sci. Pollut. Res.* 27 (18), 22680–22697. doi:10.1007/s11356-020-08812-2.

Magomed Tashtamirov (2023) The role of institutions in Economic Development and . *Available at: https://www.shs-conferences.org/articles/shsconf/pdf/2023/21/shsconf_shcms2023_02005.pdf.*

Malaysia Energy Information. Enerdata. (2023). Available at: *https://www.enerdata.net/estore/energy-market/malaysia/*

Malaysia – UNFCCC (2020). Available at: https://unfccc.int/sites/default/files/resource/MALAYSIA_BUR3-UNFCCC_Submission.pdf

Mikayilov, J. I., Galeotti, M., & Hasanov, F. J. (2018). The impact of economic growth on CO2 emissions in Azerbaijan. *Journal of Cleaner Production,* 197, 1558-1572. doi: 10.1016/j.jclepro.2018.06.269

National Institute of Standards and Technology, NIST (2023) Jarque Bera Test. Available at: *https://www.itl.nist.gov/div898/software/dataplot/refman1/auxillar/jarqbera.htm*

National Institute of Standards and Technology, NIST (2015). measures of skewness and Kurtosis. Available at: *https://www.itl.nist.gov/div898/handbook/eda/section3/eda35b.htm*

Namahoro, JP, Wu, Q, Xiao, H, & Zhou, N 2021, 'The impact of renewable energy, economic and population growth on CO2 emissions in the East African region: Evidence from common correlated effect means group and asymmetric analysis', *Energies,* 14 (2), 312. doi: 10.3390/en14020312

Nirajan, K. (2023) Jarque-Bera test: Guide to testing normality with statistical accuracy, Data aspirant. Available at: *https://dataaspirant.com/jarque-bera-test/#:~:text=Use%20statistical%20software%20to%20calculate,rejected%2C%20indicati ng%20non%2Dnormality*

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of applied econometrics,* 16(3), 289-326. doi: 10.1002/jae.616

Polanitzer, R. (2021) Data science one on one-part 14: Normality testing and the jarque-bera test, Medium. Available at: *https://medium.com/@polanitzer/data-science-one-on-one-part-14-normality-testing-and-the-jarque-bera-test-701712e0b53b*

Radmehr, R, Rastegari, S, & Shayanmehr, S (2021). '*Renewable energy consumption, CO2 emissions, and economic growth Nexus: A simultaneity spatial modeling analysis of EU countries', Structural Change and Economic Dynamics*, 57, 13-27. doi: 10.1016/j.strueco.2021.01.006.

Rongrong Li, Qiang Wang, Yi Liu, Rui Jiang (2021). *per-capita carbon emissions in 147 countries: the effect of economic, energy, social, and trade structural changes, sustainable production and consumption*. doi: 10.1016/j.spc.2021.02.031

Saboori, B, & Sulaiman, J 2013b, 'Environmental degradation, economic growth and energy consumption: Evidence of the environmental Kuznets curve in Malaysia', *Energy Policy*, 60 (892-905). doi: 10.1016/j.enpol.2013.05.099

Shah, W. U. H., Yasmeen, R., and Padda, I. U. H. (2019). An Analysis between Financial Development, Institutions, and the Environment: a Global View. *Environ. Sci. Pollut. Res.* 26 (21), 21437–21449. doi: 10.1007/s11356-019-05450-1

Shahzad, U., Ferraz, D., Doğan, B., and Aparecida do Nascimento Rebelatto, D. (2020). Export Product Diversification and CO2 Emissions: Contextual Evidences from Developing and Developed Economies. *J. Clean. Prod.* 276, 124146. doi: 10.1016/j.jclepro.2020.124146

Shahzad, U. (2020). Environmental Taxes, Energy Consumption, and Environmental Quality: Theoretical Survey with Policy Implications. *Environ. Sci. Pollut. Res.* 27 (Issue 20), 24848–24862. doi: 10.1007/s11356-020-08349-4

Shahzad, U., Lv, Y., Doğan, B., and Xia, W. (2021). Unveiling the Heterogeneous Impacts of export Product Diversification on Renewable Energy Consumption: New Evidence from G-7 and E-7 Countries. *Renew. Energ.* 164, 1457–1470. doi: 10.1016/j.renene.2020.10.143

Ugur K. P. Et Al. (2018) *the influence of coal and noncarbohydrate energy consumption on CO2 emissions: revisiting the Environmental Kuznets Curve hypothesis for Turkey, energy.* doi: 10.1016/j.energy.2018.07.095

Tim Callen (2019) Gross Domestic Product: An Economy's All, IMF. Available at: *https://www.imf.org/en/Publications/fandd/issues/Series/Back-to-Basics/gross-domestic-product-GDP.*

World Bank (2023) - CO2 emissions (metric tons per capita). Available at: *https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?locations=MY*

World Bank (2023) - Control of Corruption: Estimate. Available at: *https://data.worldbank.org/indicator/CC.EST?locations=MY*

World Bank (2023) - Government effectiveness: Estimate. Available at: *https://data.worldbank.org/indicator/GE.EST?locations=MY*

World Bank (2023) - GDP per capita (current US$). *Available at: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD*

World Bank (2023) - Political stability and absence of violence/terrorism: Estimate. *Available at: https://data.worldbank.org/indicator/PV.EST?locations=MY*

World Bank (2023) - Regulatory quality: Estimate. *Available at: https://data.worldbank.org/indicator/RQ.EST?locations=MY*

World Bank (2023) - Renewable energy consumption (% of total final energy consumption). *Available at: https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS?locations=MY*

World Bank (2023) - Rule of law: Estimate. *Available at: https://data.worldbank.org/indicator/RL.EST?locations=MY*

World Bank (2023) - Trade (% of GDP). *Available at: https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS?locations=My*

World Bank (2023) - Voice and accountability: Estimate. *Available at: https://data.worldbank.org/indicator/VA.EST?locations=MY*