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Article

Green fiscal policy, carbon emissions, and environmental sustainability: Evidence from Malaysia

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Abstract: This study examined the impact of green fiscal policy on carbon emissions and environmental sustainability for Malaysia, by using time series data from 1988 to 2020. The study employs the Autoregressive Distributed Lag (ARDL) model and the Error Correction Model (ECM) to demonstrate both short-term and long-term relationships between carbon emissions per capita and environmental taxes, energy consumption, green technological innovations, population density, and real GDP per capita. This paper also observed an inverted U relationship between economic growth and carbon emissions, which backed the Environmental Kuznets Curve (EKC) hypothesis. The results reveal evidence supporting the Environmental Kuznets Curve (EKC) hypothesis, indicating an inverted U-shaped relationship between economic growth and carbon emissions. In the short run, environmental taxes, energy consumption, and population density significantly increase carbon emissions. In the long run, economic growth and population density remain significant determinants of emissions, while green technological innovation shows a delayed but positive contribution to environmental sustainability. The findings suggest that green fiscal policy can play an important role in supporting Malaysia's transition toward a low-carbon economy. However, stronger policy implementation, greater investment in green technology, and enhanced incentives for renewable energy adoption are necessary to achieve long-term environmental sustainability.

Keywords: environmental taxation; carbon emissions; environmental Kuznets curve; green technology innovation; environmental sustainability

1. Introduction

Being a fast-growing nation, Malaysia is investing significantly to ensure that sustainable environmental practices accompany economic growth and development. The rapid industrialisation and proliferation of energy use have driven carbon dioxide (CO2) emissions up, particularly in transportation and energy [1]. Guidelines from the Ministry of Environment and Water [2] indicated that carbon emissions increased in Malaysia from 2.48 metric tons per capita in 1988 to 7.59 metric tons per capita in 2020. There have been modest declines over the past couple of years, partly due to new green policies and incremental usage of renewable energy. However, these declines have not been enough to stabilise emission outputs. The current trends demonstrated evidence for more effective and deliberately targeted policies to combat environmental degradation [3].

In response to these challenges, the Malaysian government has initiated the practice of green fiscal policy as part of its eco-friendly policies in Malaysia. As a result, green budgetary policy is now implemented through carbon taxes, subsidies for renewable energy, and incentives provided through income taxes for the designation of green companies [4,5]. The above endeavours conform to the country's desire to

adhere to international accords that were triggered by the Paris Climate Agreement and the Kyoto Protocol. Even with the adoption of green fiscal policy tools, the country is faced with some limitations. The apparent values of green policy have been dampened by at least the implementation costs, an inadequate understanding of the long-term effect of greener environmental policy actions, and a comparatively low investment level in clean energy research, especially for small and medium-sized enterprises [6,7]. There are still challenges to overcome as Malaysia moves away from fossil fuels; from this perspective, coal dominates, as it produces the highest amount of greenhouse gas emissions [8].

In recent years, Malaysia has strengthened its commitment to green fiscal policy by integrating environmental sustainability into its national development agenda. Several initiatives have been introduced to encourage low-carbon development, including fiscal incentives for renewable energy investment, the Green Technology Financing Scheme (GTFS), tax incentives for energy-efficient technologies, and various programmes supporting green technology adoption. More recently, national policy frameworks such as the National Energy Transition Roadmap (NETR) and the National Energy Policy have further emphasised the role of fiscal instruments in facilitating the transition towards a low-carbon economy. Despite these policy efforts, Malaysia continues to face challenges in reducing carbon emissions due to its continued dependence on fossil fuels and increasing energy demand. Therefore, evaluating whether green fiscal policy has effectively contributed to carbon emission reduction is essential for assessing the effectiveness of existing policies and identifying areas for future policy improvement.

Other issues that need to be taken into consideration include the lack of empirical studies that analyse the impact of green fiscal policy on carbon emissions, energy consumption, and environmental sustainability in the Malaysian environment. Existing researches have been mostly concerned with developed countries, and there is still a lot to learn about the structure of Malaysian economy and its development level [9]. This means that it is uncertain whether international results are applicable to Malaysia. Lack of domestic evidence could also prevent reaching the goals related to the environmental sphere and Sustainable Development Goals (SDGs) [10]. Finally, it should also be noted that there are fears about economic consequences of green fiscal policies implementation [11].

Against this backdrop, this study aims to assess the effectiveness of green fiscal policy in Malaysia, with a specific focus on its impact on carbon emissions, energy use, and environmental sustainability. This research seeks to better understand the extent of fiscal measures including carbon pricing and incentives for green technologies to reduce emissions while promoting economic development. This is valuable information to determine the opportunity for Malaysia to transition justly and equitably to a low-carbon economy.

This study contributes to the existing literature in several important ways. First, unlike previous studies that primarily examine developed countries or cross-country panels, this research provides country-specific evidence for Malaysia, where the transition toward green fiscal policy remains relatively recent and the electricity sector continues to depend heavily on fossil fuels, particularly coal and natural gas. Consequently, the effectiveness of green fiscal instruments may differ considerably

from that observed in developed economies. Second, this study simultaneously examines the effects of environmental taxes, economic growth, energy consumption, green technological innovation, and population density within a unified ARDL-ECM framework, thereby providing a more comprehensive assessment of the determinants of carbon emissions. Third, by distinguishing between short-run and long-run effects, the study demonstrates that environmental fiscal instruments may generate immediate behavioural responses while requiring complementary policies to sustain long-term emission reductions. These findings provide evidence that is directly relevant for Malaysia's ongoing low-carbon transition and environmental policy reforms.

Despite the growing literature on green fiscal policy and environmental sustainability, limited studies have comprehensively examined the combined effects of economic growth, environmental taxes, energy consumption, population density, and green technological innovation on carbon emissions in Malaysia using the ARDL approach. Previous research conducted by other researchers may only cover one of the mentioned factors, or they have studied the topic through different countries other than Malaysia, limiting the relevance of their studies in the Malaysian policy context. The present study tries to fill this void by presenting new data for Malaysia during the period of 1988–2023. It makes a contribution to the existing literature by analysing the above-mentioned factors at once and testing the EKC hypothesis.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the data and methodology used in the analysis. Section 4 presents the empirical results and discussion. Section 5 concludes the study.

2. Literature review

This article develops its perspectives off the Environmental Kuznets Curve (EKC) theory which posits that in some countries, environmental degradation may worsen before it improves while income moves through its various stages of income [12,13]. This paper utilized this theory to determine the ability of green fiscal policies (carbon taxes and renewable energy subsidies) to alleviate the environmental degradation caused by economic growth in Malaysia [8,14]. The article examines the relationship between economic development, energy consumption and sustainability vis-a-vis the environment, but it also takes into account the influence of the population and other socioeconomic factors on the effectiveness of these fiscal policies [6].

Besides the Environmental Kuznets Curve (EKC), this study is also informed by the Pigouvian Tax Theory, which argues that environmental taxes can correct market failures by internalising the external costs of pollution. By increasing the cost of environmentally harmful activities, environmental taxes encourage firms and households to adopt cleaner production technologies, improve energy efficiency, and reduce carbon emissions. However, the effectiveness of such fiscal instruments may differ between the short run and the long run. While firms may respond immediately by reducing emissions to minimise tax liabilities, long-term effectiveness depends on continued policy enforcement, technological progress, and structural changes in the energy sector. Therefore, the impact of green fiscal policy is expected to evolve over time rather than remain constant.

Based on the above theoretical arguments, this study expects environmental taxes to reduce carbon emissions in the short run, while their long-run effectiveness depends on sustained policy implementation and technological progress. Energy consumption is expected to increase carbon emissions, whereas green technological innovation is expected to improve environmental sustainability. Furthermore, the Environmental Kuznets Curve hypothesis predicts an inverted U-shaped relationship between economic growth and carbon emissions.

Green fiscal policies, energy use, economic growth, population dynamics, technological innovations, and environmental degradation are interlinked concerns for both developed and developing nations. The implementation of green fiscal policy implementation in countries such as Brazil, member countries of the BRICS group, European Union, G7, and Malaysia signal a strengthening focus on sustaining the dual relationship of stimulating economic development while degrading the environment. Research suggests that green fiscal policy can succeed only if the quality of governing institutions, support for innovation and a focus on fiscal decentralisation are considered.

Several studies have subsequently demonstrated that varying fiscal approaches can lead to differing outcomes, conditioned by the quality of governance, but this has also been shown to be a very important policy factor. For example, Ya et al. [15] argued that investment in education and human capital was a priority for sustainable development progress in BRICS countries, where they encouraged well-defined policy investment to support human capital development. In contrast, Li & Xu [11] determined that government expenditure without well-defined environmental governance could lead to environmental degradation. Conversely, carbon taxes were shown by Zhao et al. [10] and Cheng et al. [16] to be efficient ways to dissipate carbon emissions, while considerably economic growth. Bai et al. [17] proposed new fiscal reforms that strike a balance between economic development, environmental concerns, and the post-pandemic context.

Building on the use of fiscal instruments, several scholars have conducted studies examining the role of incentives and subsidies in driving green economic transformation. For instance, Cui et al. [18] and Yuan et al. [19] recognised tax incentives and subsidies as crucial for supporting green growth in China, underlining their relevance in solving environmental challenges and driving country-wide economic transformation. In developed regions, Sharif et al. [20] discussed the contribution of ecological taxation and green technology in decreasing CO2 emissions in Nordic countries. Once again, Aydin & Bozatli [21] identified environmental taxes and green technology as playing a significant role in improving renewable energy uptake across OECD countries.

Beyond fiscal tools alone, there is an essential interaction between decentralisation and governance in relation to environmental outcomes. Xia et al. [22] identified fiscal decentralisation and country risk as factors that worsen energy poverty, but believed that factors such as growth, innovation, and renewables could mitigate the effects on energy poverty. Further evidence from Liu et al. [23], studying EU countries, showed that decentralisation produces positive outcomes for the environment only when district governance has strong institutions and targeted investment in renewable energy.

Shifting attention to the African continent, evidence stemming from the South African setting has shown that the local context typically yields different green results. Udeagha & Ngepah [24] and Udeagha & Breitenbach [9] demonstrated that fiscal decentralisation can support environmental sustainability, provided it is coupled with green innovation and governance, although this is limited across countries. In Malaysia, Ehigiamusoe et al. [6] observed that while both globalisation and information and communication technology (ICT) increased emissions, this was offset by the introduction of green fiscal policies. Their Malaysia analysis supported the EKC, which indicated that emissions initially increased with rising income but eventually declined. Every exhaustive analysis was provided for Malaysia's manufacturing sector, including Fernando & Hor [25] and Latif et al. [8], which demonstrated the speed efficiency of fiscal tools such as subsidies and energy usage in both firm categories, ensuring emissions constraints and improving energy efficiency in the industrial sector.

As researchers shifted their focus and attention to developed economies, policy coordination on regional and national levels became less controllable. For example, Zahra & Badeeb [26] concluded that fiscal decentralisation in their OECD countries sample aided environmental sustainability only if regional policies addressed local conditions. If the former is not the case, the uncertainty of particularly green investments can nullify fiscal-motivated environmentally friendly investments. Zhao et al. [10] found that decentralisation alleviated poverty in China, but it did not replace a working set of environmental regulations that guaranteed eco-fiscal responsibility; again, all of which pointed to the need for institutional support.

From a broader perspective, studies in the G7 context further reinforced the relevance of harmonised fiscal and environmental strategies. Miao et al. [27] emphasised the importance of robust fiscal policies and ecological management to foster sustainable economic growth and reduce environmental degradation. Similarly, in the same context, Bashir et al. [28] emphasised that taxing and government spending should always be accompanied by strict environmental legislation, especially regarding energy transitions. Further reinforcing this idea, Degirmenci & Yavuz [29] stated that environmental taxes and research and development (R&D) investment are essential for increasing renewable energy in the EU, adding the need for crucial investments in infrastructure to combat pollution.

Similarly, research in the BRICS nations shed light on the complexities of emerging markets, where energy transition firms were emerging. Ma et al. [30] described the role of renewable energy policies and incentives in science and technology in alleviating the degradation caused by fossil fuels. In their recommendations, they suggested green tax incentives and subsidies. These ideas were consistent with findings from Apergis & Ozturk [12], which supported the EKC hypothesis across 14 Asian countries. They found emissions rise with growth, but as income levels increased, emissions would eventually decline, provided there were sufficient and proactive institutional energy policies in place.

When it comes to fostering better resource efficiency, recent scholarship continued to endorse innovation-driven fiscal frameworks. Meng [13] stated that budgetary policy ought to direct taxes and rebates towards renewable energy, transitioning to a circular economy, and green technologies. Ahmad & Satrovic [14] examined the G7 and found that properly structured fiscal policies could compensate

for the environmental externality from economic openness, with innovation working to enhance sustainability. They mentioned that fiscal frameworks must facilitate investment in green technologies as a means of achieving growth aligned with environmental goals.

Building on the taxation discussion, studies from Africa and other developing nations highlighted the environmental costs of significantly underregulated natural resources exploitation. Erdogan [31] conducted research across Sub-Saharan Africa and found that natural resource rents (i.e., climate change) and resource-related variables (i.e., average population density, energy use) can be detrimental to the environment. The report emphasised the need for an appropriate policy framework to enhance environmental integrity. Similarly, Erdogan et al. [32] highlighted the importance of renewable energy investments in the G7 nations for achieving carbon neutrality. Their findings also emphasised that effective governance and institutional quality are crucial for mitigating ecological degradation, highlighting the need for clean energy transitions to be supported by robust institutional mechanisms for sustainable development.

In addition to fiscal policy alone, green finance has become increasingly recognised as an enabler of environmental improvements. For example, Hu et al. [33] examined China and found a link between green finance, technological innovation, CO2 reductions, and green fiscal policy. They underscored long-lived policies, which were better for sustainability for organisations than short-lived policies. Rahman & Alam [34] assessed Bangladesh, stating that although clean sources of energy are decreasing pollution, population growth, urbanisation, and per capita GDP were increasing CO2 emissions, and the role of demographic considerations to inform fiscal or energy planning is important.

In summary, previous studies have generally shown that green fiscal policies, including environmental taxes, green subsidies, and fiscal incentives, contribute to reducing carbon emissions and improving environmental sustainability. However, the empirical findings remain mixed, particularly between developed and developing economies. While studies conducted in developed countries consistently report significant long-run environmental benefits, evidence from developing countries suggests that the effectiveness of green fiscal policies depends on institutional quality, governance, energy structure, and the pace of green technology adoption.

Malaysia presents a unique case because the country remains highly dependent on fossil fuels despite increasing efforts to promote green fiscal policies and renewable energy development. Existing Malaysian studies have primarily focused on energy consumption, industrialisation, or renewable energy, with limited attention given to the effectiveness of green fiscal policy in reducing carbon emissions. Therefore, this study fills this gap by examining the short-run and long-run effects of environmental taxes, energy consumption, green technological innovation, population density, and economic growth on carbon emissions using the ARDL-ECM approach, thereby providing evidence that is directly relevant to Malaysia's environmental policy and sustainable development agenda.

3. Research methodology

The research investigates the effects of green fiscal policies on carbon emissions and environmental sustainability in Malaysia by employing the Autoregressive Distributed Lag (ARDL) model and the Error Correction Model (ECM). The ARDL model is most suitable for capturing the dynamic short-run and the long-run relationships between the variables of interest in this study. For example, Latif et al. [8] demonstrated that the ARDL model can accurately depict the dynamic relationship between carbon emission and energy consumption, making it particularly reasonable in this context. Conversely, the ECM is used to capture short-run adjustments to deviations from the long-run equilibrium. It explains the extent to which short-run changes in environmental and energy-related variables could fall within the long-run behaviour. Ahmad & Satrovic [14] commented that the ECM is appropriate for understanding short-run dynamics in the policy context, particularly environmental policy. The analysis involved 33 years of annual time-series data 1988–2020. **Table 1** presents the definitions of the variables and data sources used in this study.

Table 1. Variable definitions and data sources.

Variable	Type	Description	Relationship	Data sources
CO2	DV	Carbon emissions per capita (Metric tons)		World Bank
GDP	IV	Real GDP per capita (Constant USD, 2015)	+/-	World Bank
ET	IV	Environmental tax (% of GDP)	-	IMF
EC	IV	Energy consumption (BTU)	+/-	IEA
PD	IV	Population density (People per sq. km of land area)	+	World Bank
EP	IV	Environmental patents (% of total environmental technology patents)	-	OECD

The variables included in this study were selected based on both theoretical considerations and previous empirical literature on green fiscal policy and environmental sustainability. Environmental tax was used as the proxy for green fiscal policy because consistent annual data covering the study period were available for Malaysia. Energy consumption, economic growth, population density, and green technological innovation were included because they are widely recognised determinants of carbon emissions in the Environmental Kuznets Curve literature and have been extensively employed in previous environmental economics studies. Other potential variables, such as renewable energy subsidies and green public expenditure, were not included because consistent annual time-series data for the full study period were unavailable. Prior to model estimation, all variables were transformed into natural logarithms to reduce differences in scale and facilitate the interpretation of the estimated coefficients.

The empirical model employs GDP and GDP^2 to examine the Environmental Kuznets Curve (EKC) hypothesis which posits that economic growth and environmental degradation display a negative U-shaped form of relationship. To this end, the theory suggests carbon emissions will increase as the economy grows as a

result of industrialization, before decreasing again at higher values of income when technological improvements and environmental regulation become tighter.

The functional form of the model is expressed as:

$$\ln CO2 = f(\ln GDP, \ln GDP^2, \ln ET, \ln EC, \ln PD, \ln EP) \quad (1)$$

The corresponding empirical model is specified as:

$$\ln CO2_t = \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln GDP^2{}_t + \beta_3 \ln ET_t + \beta_4 \ln EC_t + \beta_5 \ln PD_t + \beta_6 \ln EP_t + \varepsilon_t \quad (2)$$

In Equation (3), LCO2 represents the natural logarithm of carbon emissions. A positive coefficient for LGDP and a negative coefficient for LGDP² would confirm the Environmental Kuznets Curve (EKC) hypothesis.

The ARDL bounds testing methodology, developed by Pesaran et al. [35] can be used to assess both the short-run and long-run relationships. The ARDL approach is appropriate for the present study because it accommodates variables integrated at different orders, I(0) and I(1), and is suitable for relatively small sample sizes. The optimal lag selection is made using the Schwarz Bayesian Criterion (SBC), and the model is estimated using the ordinary least squares (OLS) method.

The general form of the ARDL model is:

$$\begin{aligned} \Delta lnCO2_t = {} & \alpha_0 + \theta_1 \ln CO2_{(t-1)} + \theta_2 \ln GDP_{(t-1)} + \theta_3 (\Delta \ln \mathrm{GDP}_{t-1})^2 + \theta_4 \ln ET_{(t-1)} \\ & + \theta_5 \ln EC_{(t-1)} + \theta_6 \ln \mathrm{PD}_{(t-1)} + \theta_7 \ln EP_{(t-1)} + \sum_{i=1}^{n} \omega_1 \Delta \ln \mathrm{CO2}_{t-i} \\ & + \sum_{i=0}^{n} \omega_2 \Delta \ln \mathrm{GDP}_{t-i} + \sum_{i=0}^{n} \omega_3 (\Delta \ln \mathrm{GDP}_{t-i})^2 + \sum_{i=0}^{n} \omega_4 \Delta \ln ET_{t-i} \\ & + \sum_{i=0}^{n} \omega_5 \Delta lnEC_{t-i} + \sum_{i=0}^{n} \omega_6 \Delta \ln \mathrm{PD}_{t-i} + \sum_{i=0}^{n} \omega_7 \Delta \ln EP_{t-i} + \epsilon_t \end{aligned} \quad (3)$$

Where Δ symbolizes the first-difference operator, and ε_t is the stochastic error component. Each of the parameters θ_1 to θ_7 denotes long-run parameters, and the ω_1 to ω_7 are the short-run dynamic responses.

Once it is established that a long-run relationship exists, the error correction model (ECM) is defined to estimate the short-run dynamics and the speed of adjustment back to the long-run equilibrium:

$$\begin{aligned} \Delta \ln CO2_t = {} & \alpha_0 + \sum_{i=1}^{n} \omega_1 \Delta \ln \mathrm{CO2}_{t-i} + \sum_{i=0}^{n} \omega_2 \Delta \ln \mathrm{GDP}_{t-i} + \sum_{i=0}^{n} \omega_3 (\Delta \ln \mathrm{GDP}_{t-i})^2 \\ & + \sum_{i=0}^{n} \omega_4 \Delta \ln ET_{t-i} + \sum_{i=0}^{n} \omega_5 \Delta lnEC_{t-i} + \sum_{i=0}^{n} \omega_6 \Delta \ln \mathrm{PD}_{t-i} \\ & + \sum_{i=0}^{n} \omega_7 \Delta \ln EP_{t-i} + \lambda ECM_{t-1} + \epsilon_t \end{aligned} \quad (4)$$

The error correction term ECM_{t-i}, is defined as follows:

$$ECM_{t-i} = lnCO2_{t-1} - (\theta_1 \ln CO2_{(t-1)} + \theta_2 \ln GDP_{(t-1)} + \theta_3 (\Delta \ln \mathrm{GDP}_{t-1})^2 + \theta_4 \ln ET_{(t-1)} + \theta_5 \ln EC_{(t-1)} + \theta_6 \ln \mathrm{PD}_{(t-1)} + \theta_7 \ln EP_{(t-1)}) \quad (5)$$

The coefficient λ indicates, or is the speed at which the deviations from the long-run equilibrium are adjusted. A negative λ that is statistically significant suggests the presence of a stable equilibrium relationship.

4. Results and discussion

4.1. Descriptive analysis

Descriptive analysis was carried out for explaining the basic nature of the data in the research. It involves calculations such as mean, standard deviation, mean, median, skewness, and kurtosis. These statistics provide an initial impression of data distribution, variability, and relationships between variables. Skewness, for example, shows the direction of the distribution, either skewed to the left or right, while kurtosis measures the severity of the tail of the distribution, showing the existence of extreme values [36]. **Table 2** presents the descriptive statistics and correlation matrix of the variables used in this study.

Table 2. Descriptive statistics and correlation matrix.

Variable	**LC02**	**LGDP**	**LGDP²**	**LET**	**LEC**	**LPD**	**LEP**
Mean	1.7530	8.8493	78.3943	3.6841	6.8881	4.3220	6.5535
Median	1.8833	8.8543	78.3979	3.8712	6.9565	4.3422	6.6400
Maximum	2.0848	9.3160	86.7881	4.3438	7.2862	4.6362	7.3019
Minimum	0.9075	8.2424	67.9377	2.9957	6.0186	3.9342	4.9762
Std. Dev.	0.3244	0.2944	5.1866	0.5025	0.3603	0.2130	0.4722
Skewness	-1.0213	-0.2936	-0.2344	-0.0849	-1.0802	-0.2213	-1.1835
Kurtosis	3.0830	2.2881	2.2428	1.2264	3.3105	1.8241	5.3080
Correlation test							
LC02	1						
LGDP	0.9463	1					
LGDP²	0.9413	0.9998	1				
LET	-0.8679	-0.9202	-0.9228	1			
LEC	0.9794	0.9582	0.9534	-0.8509	1		
LPD	0.9477	0.9851	0.9854	-0.9477	0.9417	1	
LEP	0.2498	0.2941	0.2946	-0.2984	0.2647	0.2701	1

According to **Table 2**, the descriptive statistical analysis provides a general impression of the study variables, that is, LCO2, LGDP, LGDP², LET, LEC, LUR, and LEP. The mean and median values for most variables were nearly identical, indicating that the data distribution was relatively balanced. For example, LCO2 had a mean of 1.7530 and a median of 1.8833, indicating slight skewness in the data distribution. The standard deviation for the limited environmental tax (LET) was the highest (0.5022), indicating greater variation in the data compared to other variables.

The skewness values showed that LCO2 (-1.0213) and LEP (-1.1835) tended to be skewed to the left, while the kurtosis for LEP was the highest (5.3080), reflecting the presence of extreme values in the data.

From the correlation analysis, it can be observed that LCO2 and LGDP were strongly correlated (r = 0.9463), indicating that economic growth was closely linked with carbon emissions. Additionally, LEC was found to maintain a strong positive correlation with LCO2 (r = 0.9794), indicating that an increase in energy consumption was directly linked to increased carbon emissions. In contrast, LET had a negative correlation coefficient with LCO2 (-0.8679). This result showed that specific energy parameters may tend to lower carbon emissions. Finally, LEP exerted a lesser correlation with LCO2 (0.2498), showing that this component had a lesser impact on carbon emissions.

The trends of the study variables over the sample period are illustrated in **Figure 1**. The trends indicated that LCO2 increased from 1988 to 2023, in line with GDP [2]. This statistic showed that the rapid expansion of economic growth was accompanied by a corresponding increase in energy consumption, which in itself demonstrated a growing trend [1]. However, there were very few persistent declines in LCO2 during certain years, such as 1998 and 2020; this was likely due to economic crises that impacted industrial activity and energy consumption [3].

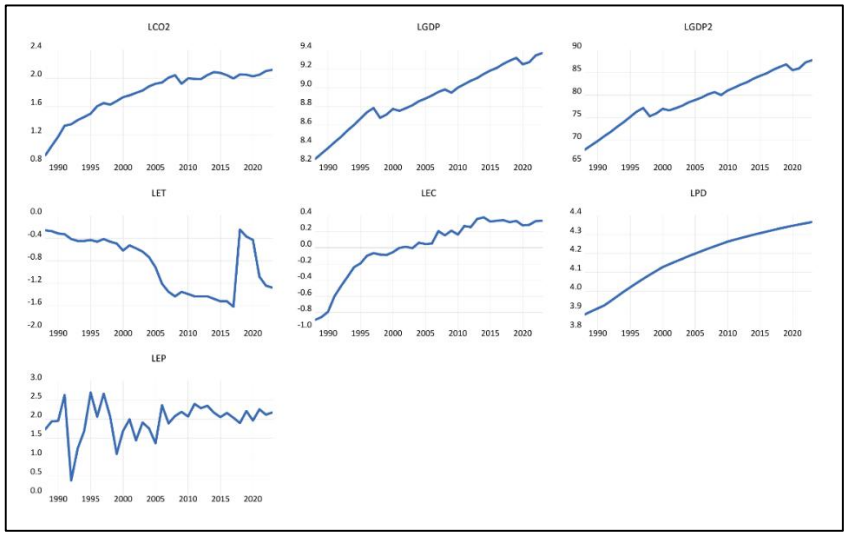


Figure 1. Variable trend.

Environmental taxes (LET) have been low as a percentage of GDP in regard to environmental considerations, reflecting the country's dependency on fossil fuels and unduly lax penalties on CO2 emissions [5]. The urbanized population (LUR) has continued to expand steadily, indicating the fast process of urbanization [6], while environmental patents (LEP) have tended toward variances, indicating that green technology innovation efforts were engaging in spurts in some instances [14].

The EKC described a trend suggesting that emissions will rise in the early stages of development due to energy use and industrialisation. After a specific income threshold was reached, carbon emissions were projected to decline as countries adopt green technology and implement stricter environmental policies [12]. This analysis supported the assumption that Malaysia is still in a period of growing carbon emissions;

however, with a firm green fiscal policy, the country can reach a level where carbon emissions begin to decline, as indicated in the EKC theory [13].

4.2. Unit root test

The unit root test is a crucial step in time series analysis, ensuring that the data is stationary. Non-stationary data can cause spurious regression problems, where seemingly significant relationships do not actually exist. Two tests widely used to test for stationarity are the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. the ADF test checks stationarity by using different lags to avoid the autocorrelation problem. At the same time, the PP test is more flexible and does not require precise lag specifications since it employs heteroskedasticity-robust standard errors [37]. These two tests are used to assess if a time series has a unit root. If it does, the data should be differenced to achieve stationarity. The results of the ADF and PP unit root tests are presented in **Table 3**.

Table 3. ADF unit root cause test and PP test results.

Variable	ADF test		PP test		Stationary
	Level	First difference	Level	First difference	
LC02	-2.6104	-5.1408***	-2.862	-6.9233***	I (1)
LGDP	-2.5602	-3.9022**	-2.5245	-4.7155***	I (1)
$LGDP^2$	-2.5466	-3.8966**	-2.5621	-4.6956***	I (1)
LET	-1.4334	-3.1348	-1.4312	-3.2228*	I (1)
LEC	-1.7054	-6.4906***	-1.6558	-6.4307***	I (1)
LPD	1.8094	-3.8241**	-0.1542	-2.254	I (1)
LEP	-4.035**	-5.3721***	-5.2772***	-25.5874***	I (0)

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

The indications were that most variables were not stationary at the level but became stationary with initial differencing, classed as I (1). For example, the variables LCO2, LGDP, $LGDP^2$, LET, LEC, and LPD were not significant at the level but became quite crucial after first differencing. This showed that these variables included a unit root at the level but became stationary after initial differencing, hence categorised as I (1). Conversely, the LEP variable was found to be stationary at the level, as the ADF and PP test statistics showed high significance at the 1% level without the need for additional differencing. Hence, these variables were categorised as I (0). This finding was crucial in time series analysis, as it confirmed the stationarity of variables at a lower frequency, thereby reducing the issue of spurious regression. Having the majority of them as I (1) while others were I (0), this model was well-suited for a cointegration test procedure, such as the ARDL Model to determine long-run associations among variables.

4.3. Lag optimal test

The optimal lag test is to determine the appropriate amount of lag in the econometric model. Lag refers to the time delay between the value of the independent variable and its effect on the dependent variable. Determining the appropriate lag is

important because too few lags can cause the model to be inadequate, while too many lags can cause overfitting problems, making the model less efficient [38].

Table 4 shows the results of the lag structure selection based on several criteria such as Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan-Quinn Criterion (HQ). Based on the table, the recommended lag is 2 because it has the lowest AIC, SC, and HQ values. In addition, the highest log-likelihood value (570.132) was also obtained at the 2nd lag. These results show that the use of the 2nd lag is most appropriate because it minimizes the error and improves the accuracy of the model estimation.

Table 4. Lag length criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	207.3401	NA	5.75E-15	-12.9252	-12.6014	-12.8196
1	504.9311	441.5868	6.77E-22	-28.9633	-26.3728*	-28.1189
2	570.132	67.30416*	4.06e-22*	-30.00852*	-25.1515	-28.4252*

4.4. ARDL bound test

The ARDL bounds test is among the tests used to examine the cointegration relationship among variables within a time series. The technique is ideal for use when there are mixed data integration levels (i.e., I (0) or I (1)). The borders test utilizes the *F*-statistic value to verify the long-run relationship among variables. This is contrasted with the upper (I (1)) and lower (I (0)) border values. If the *F*-statistic is greater than the upper bound, cointegration exists, while if it is less than the lower bound, there is no cointegration. The ARDL approach is more general since it enables the usage of different lag orders for all variables, thereby being ideal for intricate economic time series [35].

According to **Table 5**, the value of the computed *F*-statistic was 5.6397, which exceeded the upper boundary value in the 1% significance level (5.326). It indicated long-run relationships between the variables through a cointegrating relationship involving multiple economic aspects. The existence of a cointegration relationship in this particular model implies that the financial elements of GDP, energy consumption, environmental taxes, and green technology innovation also have long-run influences on carbon emissions in Malaysia. In summary, the results implied that the two variables exhibited a long-term trend together, as the EKC theory assumed, supporting the application of effective green fiscal policies, which would result in lower carbon emissions at higher levels of economic growth [13].

Table 5. ARDL bound test results.

Bounds testing to cointegration	
F-statistic	5.6397***
Cointegration	YES
ARDL	(2, 0, 0, 2, 2, 1, 2)
Maximum Lag	2
Significant Level	Critical Value

Table 5. (*Continued*).

Bounds testing to cointegration		
K= 6	Lower Bounds I (0)	Upper Bounds I (1)
10%	2.254	3.388
5%	2.685	3.96
1%	3.713	5.326

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

4.5. Error correction model (ECM) estimation

The ECM is a dynamic testing model that examines the relationships between variables in both the long run and the short run. The ECM advises that any changes in the short run potentially become a long-run equilibrium. This is enabled by the presence of an error correction term, which corrects the short-run deviation of the variables [35]. **Table 6** presents the evaluation of the long-run and short-run linkages between the independent variables and LCO2 using the ARDL Model. The factors, LGDP and LGDP², were significant at the 1% level, supporting the EKC hypothesis. It indicated that a 1% increase in LGDP would result in a 13.17% increase in carbon emissions. As economic growth continued to rise, the effect started to decline, with a 1% increase in LGDP² lowering carbon emissions by 0.75%. This means that economic growth during its initial stages leads to increased carbon emissions. After an income level is reached, the transition to green technology and stricter environmental policies reduces carbon emissions [12].

Table 6. Results of long-term and short-term ARDL estimates.

Dependent variable= LCO2		
Variable	Coefficient	Standard error
Long-term model		
LGDP	13.1683***	3.4693
$LGDP^2$	-0.7487***	0.1884
LET	0.0103	0.0518
LEC	0.1476	0.1511
LPD	1.6166***	0.2370
LEP	0.0280	0.0226
Constant	-64.6628***	15.2013
Short-term results		
D (LCO2 (-1))	0.2441**	0.1138
D (LET)	-0.1215*	0.0632
D (LET (-1))	-0.1567*	0.0767
D(LEC)	0.2704***	0.0868
D (LEC (-1))	0.2593***	0.0827
D (LPD)	21.7675*	2.5999
D (LEP)	0.0053	0.0084
D (LEP (-1))	-0.0269***	0.0088
CointEq (-1)*	-1.3395	0.1647

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

LPD was significant at the 1% level, where a 1% increase in population density resulted in a 1.62% increase in carbon emissions. Ehigiamusoe et al. [6] argued that densely populated regions are likely to record higher levels of carbon emissions because they experience greater energy demand, urban congestion, and increased industrial and transportation activities. Conversely, LET, LEC, and LEP were not statistically significant in the long run, indicating that environmental tax policy, energy consumption, and green technological innovation have not yet exerted a sustained influence on carbon emissions in Malaysia. One possible explanation is that environmental taxation in Malaysia remains relatively limited in scope and intensity, reducing its effectiveness in encouraging firms to undertake long-term investments in cleaner production technologies. Furthermore, Malaysia continues to rely heavily on fossil fuels, particularly coal and natural gas, for electricity generation, which weakens the long-run impact of environmental taxation on emission reduction.

Although renewable energy adoption has gradually increased, the pace of energy transition remains relatively slow, while the commercialization and widespread adoption of green technologies require considerable time before generating measurable environmental benefits. Similar challenges have been observed in several ASEAN economies, where carbon pricing mechanisms and renewable energy deployment are still developing compared with many advanced economies. Therefore, environmental taxation alone is unlikely to generate sustained emission reductions unless it is complemented by stronger regulatory enforcement, greater investment in renewable energy infrastructure, and continuous support for green technological innovation. These findings are consistent with [39], who argued that environmental policies and green innovations often require a longer implementation period before producing significant environmental improvements.

In the short run, D (LET) and D (LET (-1)) were significantly negative at the 10% level, indicating that a 1% increase in environmental taxes resulted in reductions of 0.12% and 0.16% in carbon emissions in the current and previous periods, respectively. Zahra & Badeeb [26] stated that environmental taxes can have an immediate effect in reducing carbon emissions due to increased production costs for industries that use fossil fuels. However, in the long term, the effect becomes insignificant, perhaps because companies adapt to this policy through increased energy efficiency or cost transfer to consumers, making the carbon reduction effect less [39]. Therefore, this highlights the need for additional regulatory mechanisms to ensure that the carbon tax continues to have long-term impact and is not limited to short-term effects alone.

However, the existence of the significant short-term effect from environmental taxation means that companies could act promptly upon the rise in the cost of production linked with fossil fuel consumption by decreasing pollution levels or altering their production processes. The lack of a significant long-term effect means that such changes might be temporary. Firms may gradually adapt through improved energy efficiency, technological adjustments, or by-passing additional costs to consumers. This interpretation is consistent with previous studies, which suggest that environmental taxation can produce immediate behavioural responses, whereas the long-term effect can be achieved only through effective policy enforcement and green investments [26,39].

Regarding energy consumption, D (LEC) and D (LEC (-1)) were statistically significant at the 1% level. In comparison, energy consumption increased by 1%, resulting in a 0.27% rise in carbon emissions for the current period and a 0.26% increase for the preceding period. Ahmad & Satrovic [14] confirmed that high dependence on fossil fuels remains a major contributor to carbon emissions, especially in developing countries that have not yet fully transitioned to clean energy. However, in the long term, the correlation was less significant, indicating that a gradual shift towards renewable energy and improved energy efficiency reduced the negative impact on carbon emissions [23]. This discovery highlights the need to speed up the shift to clean energy, making carbon reduction more effective in the long term.

The positive and large short-term impact of energy consumption illustrates Malaysia's continued reliance upon fossil fuel-based energy. As industries, transportation and electrical power generation remain reliant upon energy, an increase in energy consumption will result in an increase in carbon emissions. However, the lack of a long-term relationship could be indicative of the development of improved energy efficiency along with the adoption of additional renewable energy sources beginning to moderate the long-term relationship between energy consumption and emissions [23].

D (LPD) was significant at the 10% level, indicating that a 1% increase in population density resulted in a 21.77% increase in carbon emissions in the short term. Raihan & Tuspekova [1] noted that the sudden increase in population puts pressure on energy resources and urban infrastructure, leading to higher carbon emissions. However, these adverse effects can be reduced if the government promotes sustainable urban planning, green infrastructure development, and a more efficient public transport system [6]. This measure can reduce excessive energy consumption and ensure that population growth does not lead to an uncontrolled increase in carbon emissions.

Meanwhile, D (LEP (-1)) was significantly negative at the 1% level, indicating that a 1% increase in green technology innovation resulted in a 2.69% reduction in carbon emissions after a lag period. Liu et al. [23] argued that the impact of green technology innovation on reducing carbon emissions can only be observed after a specific period, as the application of green technology in the industrial and energy sectors requires substantial investments and complex structural changes. Abdullah & Ahmad [39] also noted that the primary challenges in implementing green technology are capital constraints and the limited transfer of technology from developed countries to developing countries. Therefore, these results underscore the need to ensure a more effective and widespread green innovation process in the energy and industry sectors to accelerate the benefits of reducing carbon emissions.

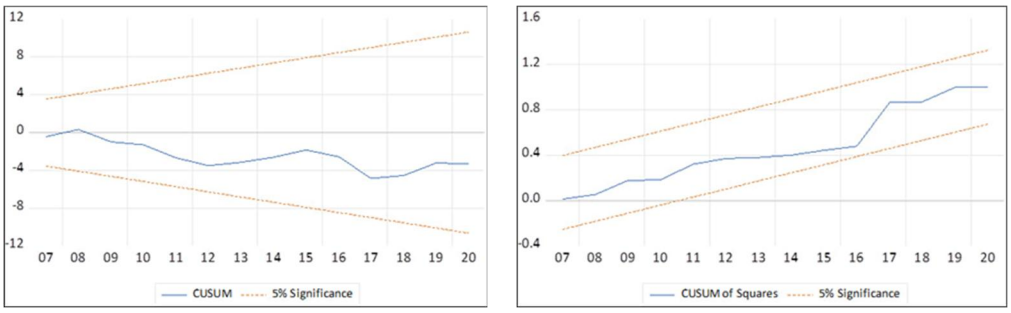
The delayed negative effect of green technological innovation highlights the time lag in the impact of the innovation process on emission reduction. It takes much effort in terms of financial investment, regulation, infrastructural preparedness, and adoption for green technologies to have an environmental impact. In this regard, the high lagged effect obtained in the research is in line with the claim that the contribution of technological innovation to sustainability is gradual [23,39].

Finally, the value of CointEq (-1) was statistically significant at the 1% level (-1.3395), indicating that the adjustment rate was substantial, whereby 133.95% of

short-run imbalances were eliminated in the subsequent period. This implied a significant adjustment rate to the long-run equilibrium. This finding emphasised the importance of hastening the transition to renewable energy and increasing incentives for green innovation. Besides, to ensure that carbon emission reduction is sustainable in the long-term equilibrium [23].

4.6. Diagnostic test

The ARDL diagnostic test process is a crucial step in validating the accuracy and reliability of a derived model. Several methods can be considered as part of the ARDL diagnostic test process, such as the autocorrelation test (Breusch-Godfrey Serial Correlation LM Test), the heteroskedasticity test (Breusch-Pagan-Godfrey Test), the model specification test (Ramsey RESET Test), and the model stability test (CUSUM and CUSUM2). The autocorrelation test is designed to check whether the residuals of the model are serially correlated, while the heteroskedasticity test shows whether the variance of the residuals is constant. The Ramsey RESET test indicates whether the model is well specified or whether omissions of relevant variables are to blame. Finally, the stability tests (CUSUM and CUSUM2) assess the stability of the model parameters over the study time period. If all of these conditions pass, the ARDL model becomes valid and acceptable for conducting econometric inferences [40]. The results for diagnostic checking were presented as **Table 7** and **Figure 2a, b**.



(a) **(b)**

Figure 2. Stability diagnostics of the ARDL model: **(a)** Cumulative Sum (CUSUM) test indicating the stability of the estimated coefficients over the sample period; **(b)** Cumulative Sum of Squares (CUSUMSQ) test showing the stability of the variance of the residuals over time.

Table 7. Diagnostic test results.

Diagnostic test	
$Normality$	2.3836
$Serial\ Correlation$	2.4580
$Heteroskedasticiti$	0.7962
$Ramsey$	0.4473
$CUSUM$	Stable
$CUSUM^2$	Stable

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

The normality test (2.3836) indicated that the data are approximately normally distributed, suggesting a balanced distribution of the data. The LM test (2.4580) stated that there was no autocorrelation problem in the data, ensuring the validity of the model estimates. Additionally, the non-significant heteroscedasticity test ($p = 0.7962$) indicated that the variance of the data was constant, thereby validating the model's results. The Ramsey test (0.4473) ensured that there were no specification errors in the model, showing that the model structure used was accurate and reliable. Additionally, the CUSUM and CUSUM² stability tests indicated that the model remained stable during the study period, meaning the relationship among the variables remained constant in the long run. As the diagnostic test results did not reveal any serious problems, the ARDL (2, 0, 0, 2, 2, 1, 2) model was sufficient to estimate the relationship between carbon emissions and economic and environmental factors with high accuracy, without encountering the risk of false regression or modelling failure.

5. Conclusion

This research investigated the relationship between fiscal policy, energy use, population density, economic growth, and carbon emissions in Malaysia using the ARDL model. Research findings validated the concept of the EKC, in which as an economy begins to expand, carbon emissions will rise, and eventually fall in later periods of expansion as more income supports cleaner technologies and environmental policies [12]. However, energy consumption in Malaysia remains tightly linked to, and directly responsible for, carbon emissions, indicating that Malaysia continues to rely heavily on fossil fuels. Unless a gradual transition to renewable energy occurs, emissions are likely to continue increasing.

In Malaysia, emissions are also influenced by population density, which contributes to emissions partly due to the lack of green infrastructure and inadequate public transportation. In the meantime, innovations in green technology are emerging, but the sector is still in the process of evolving [21]. Although Malaysia has begun to transition into green fiscal policies, this study highlighted that a transition into green budgetary policies can and should be bolder, with dedicated renewables initiatives, carbon taxes, and much higher investments into green technology that lead to long-term sustainability.

Reducing carbon emissions through effective green fiscal policy contributes not only to climate change mitigation but also to broader environmental sustainability by improving environmental quality, promoting cleaner energy systems, encouraging green technological innovation, and supporting Malaysia's long-term sustainable development objectives. Therefore, environmental sustainability should be viewed as a broader policy outcome achieved through the combined implementation of fiscal, technological, and energy transition policies.

Based on the empirical findings, several policy implications can be drawn. The first implication is that the positive effect of energy consumption on carbon emissions shows that Malaysia should speed up its process of shifting to green energies. Thus, governmental action is required to provide incentives for adopting new technologies and investing in solar, hydro, and wind energies in order to decrease the reliance on imported fossil fuels [7]. The second implication is related to the fact that although

environmental taxes were significant in the short run, their insignificant long-run effect suggests that the current environmental tax framework may not be strong enough to generate sustained emission reductions. This finding supports the introduction of a more transparent and enforceable carbon tax, together with complementary measures such as green investment incentives and stricter environmental enforcement [26]. A gradual or tiered carbon tax mechanism could be considered, whereby emission-intensive industries face progressively higher carbon pricing over time while allowing firms sufficient time to adopt cleaner production technologies.

In addition, the delayed effect of green technological innovation suggests that greater funding for research and development (R&D), increased technology transfer from developed countries, and cooperation between the public and private sectors will be required to accelerate the environmental benefits of innovation [21]. For the manufacturing sector, targeted fiscal incentives such as investment tax allowances, grants for energy-efficient technologies, and accelerated capital allowances for green equipment could encourage firms to adopt cleaner production processes. Meanwhile, in the power sector, renewable energy subsidies and continued investment in renewable energy infrastructure should complement environmental taxation to reduce dependence on coal and other fossil fuels while supporting Malaysia's long-term energy transition.

Finally, the considerable impact of population density on CO2 emissions underscores the significance of sustainable urban development policies. Such measures, including improved public transport, transit-oriented development, and more energy-efficient urban infrastructure, will help reduce emission pressures in high-density cities [6]. Taken together, these findings suggest that environmental taxation alone is unlikely to achieve long-term emission reductions. Instead, an integrated policy approach that combines carbon pricing, targeted sectoral incentives, renewable energy investment, and green technological innovation is more likely to support Malaysia's transition towards environmental sustainability.

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