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DO DEMOGRAPHIC FACTORS DRIVE CARBON EMISSIONS? EVIDENCE FROM MALAYSIA

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Abstract:

Malaysia's ongoing demographic transition, marked by changing population growth and rising life expectancy, has important implications for environmental sustainability, particularly carbon dioxide (CO_2) emissions. Despite continued economic development, managing CO_2 emissions remains a critical policy challenge in the country. This study investigates the impact of population growth and life expectancy on CO_2 emissions in Malaysia using the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) theory. Employing annual time-series data and the Autoregressive Distributed Lag (ARDL) approach, the findings reveal a long-run relationship between demographic factors and CO_2 emissions. The results indicate that population growth is negatively associated with CO_2 emissions, which may reflect Malaysia's shift toward an aging population with lower consumption intensity, as well as the effectiveness of environmental policies aimed at reducing emissions. In contrast, life expectancy is positively associated with CO_2 emissions, suggesting that longer lifespans contribute to greater cumulative energy use and environmental pressure over time. These findings highlight the complex role of demographic change in shaping environmental outcomes. From a policy perspective, efforts should focus on promoting sustainable consumption patterns, particularly among older populations, alongside strengthening green technology adoption and energy efficiency initiatives. Future research is recommended to incorporate age structure, gender-specific life expectancy, and sectoral emissions to provide a more comprehensive understanding of the demographic-environmental nexus in Malaysia.

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Introduction

Malaysia is currently experiencing significant demographic changes that have important implications for environmental sustainability, particularly CO_2 emissions. As of 2023, Malaysia's population reached approximately 33.4 million, with a growth rate of about 2.1%, although the long-term trend shows a gradual slowdown in population growth (DOSM, 2023). At the same time, life expectancy has steadily increased to around 76.7 years, reflecting improvements in healthcare, living standards, and overall socio-economic development (Ritchie, 2023). These demographic changes are occurring alongside Malaysia's continued economic growth and industrialization, which have contributed to rising energy consumption and CO_2 emissions. As a developing upper-middle-income country, Malaysia faces the dual challenge of sustaining economic progress while reducing environmental degradation, particularly greenhouse gas emissions that contribute to climate change (International Energy Agency, 2022).

These trends are closely linked to the concept of demographic transition, which describes the shift from high birth and death rates to lower fertility and mortality, accompanied by increasing life expectancy and an aging population (DOSM, 2023). Malaysia is currently entering a later stage of demographic transition, characterized by declining fertility rates and an increasing proportion of elderly individuals. This transition reflects structural changes in the economy, urbanization, and improved healthcare systems. However, such demographic shifts also have important environmental implications, as changes in population size, age structure, and consumption patterns can significantly influence CO_2 emissions. Understanding these dynamics is crucial for designing policies that align demographic development with environmental sustainability.

From a theoretical perspective, increases in population size are traditionally associated with higher environmental degradation, particularly through increased CO_2 emissions. A growing population leads to higher demand for energy, transportation, housing, and industrial production, which in turn increases fossil fuel consumption and emissions. Rapid population growth can also intensify urbanization and resource use, thereby increasing environmental pressure. Previous studies have indicated that population growth increases energy demand and consumption, leading to higher CO_2 emissions from increased economic and household activities (Wang et al., 2021; Shahbaz et al., 2022). In the Malaysian context, continued population growth, despite slowing rates, can still exert pressure on environmental resources, especially if accompanied by unsustainable consumption patterns and reliance on carbon-intensive energy sources (York, 2021).

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Similarly, rising life expectancy can increase CO_2 emissions by prolonging consumption over an individual's lifetime (Osei-Kusi et al., 2024). As people live longer, cumulative demand for energy, healthcare services, transportation, and residential resources increases, thereby elevating environmental pressure. Longer lifespans may also lead to shifts in consumption behavior, particularly among older populations, thereby influencing energy use patterns and emissions (Rjoub et al., 2021).

Although numerous studies have examined the determinants of CO_2 emissions in Malaysia, the existing literature has largely concentrated on conventional macroeconomic factors such as economic growth, energy consumption, trade openness, urbanization, and technological development. Most Malaysian studies investigating environmental degradation primarily employ aggregate population measures, without accounting for broader demographic transition dynamics, particularly population aging and rising life expectancy. For instance, previous studies in Malaysia mainly focused on the impacts of Gross Domestic Product (GDP) growth, industrialization, and energy use on CO_2 emissions. At the same time, demographic variables were often treated as secondary control variables rather than central explanatory factors (Nurgazina et al., 2021; Khan et al., 2021). As a result, limited attention has been given to how demographic changes associated with aging populations may influence long-term environmental sustainability in Malaysia.

To systematically analyze these relationships, this study adopts the STIRPAT model, which extends the traditional Impact, Population, Affluence, and Technology (IPAT) framework by allowing for empirical estimation of the impact of population-related factors on environmental degradation (Dietz & Rosa, 1994). This model is widely used in environmental studies for its flexibility in incorporating demographic variables, such as population size and life expectancy, thereby enabling a more comprehensive understanding of how demographic changes influence CO_2 emissions. The application of the STIRPAT framework in Malaysian environmental studies remains relatively limited in terms of incorporating demographic aging indicators. While the STIRPAT model has been widely applied internationally to analyze the impacts of population, affluence, and technology on environmental degradation, most Malaysian applications of the framework continue to rely on traditional variables and do not extend the model to capture the characteristics of the demographic transition (Shaari et al., 2024). Combining population growth and life expectancy as demographic variables within a single STIRPAT framework is particularly important because population growth captures the scale effect of human activities. In contrast, life expectancy reflects the environmental consequences of demographic aging and longer lifespans (Wang et al., 2021). The integration of these variables provides a more comprehensive understanding of the demographic–environment nexus, especially in countries undergoing demographic transition such as Malaysia.

The findings of this study are expected to provide policymakers with valuable insights for designing targeted policies. These evidence-based environmental policies account for demographic change. Specifically, the results can assist the Malaysian government in formulating strategies that promote sustainable consumption, improve energy efficiency, and address the environmental implications of an aging population. Furthermore, this study contributes to the growing body of literature by highlighting the nuanced relationship between demographic dynamics and environmental outcomes, thereby opening new avenues for future research. Subsequent studies could expand on this work by incorporating age structure, gender-specific life expectancy, and sectoral emissions, and by exploring alternative econometric approaches to deepen understanding of the relationship between demographic and environmental factors.

Literature Review

Population Size and CO_2 Emissions

Population size has long been regarded as one of the major determinants of environmental degradation, particularly CO_2 emissions. Numerous studies suggest that a larger population increases demand for energy, transportation, housing, industrial production, and natural resources, thereby intensifying environmental pressure. Recent studies continue to support this argument across different countries and regions. For instance, studies conducted in China and other developing economies reveal that population growth and urbanization contribute significantly to rising CO_2 emissions, driven by increased economic activity and energy consumption (Zhang et al., 2021). Similarly, Wang et al. (2021) identified that demographic expansion and changes in population structure exert substantial upward pressure on environmental degradation and CO_2 emissions.

A growing body of literature has also emphasized that the relationship between population size and CO_2 emissions may differ across economic structures, development levels, and environmental policies. In many developing countries, rapid population growth often accelerates urban expansion, industrialization, and infrastructure development, thereby increasing fossil fuel consumption and emissions. Hussain and Rehman (2021) reported that population growth positively affects CO_2 emissions due to increased energy use and economic activity. Likewise, studies focusing on European economies and global panel analyses indicate that larger population concentrations are associated with higher energy demand and environmental degradation. Additionally, Zarco-Soto et al. (2021) demonstrated that increasing city population size significantly raises energy consumption and CO_2 emissions in Spain. These findings support the argument that demographic pressure remains an important driver of carbon emissions, particularly in rapidly urbanizing economies.

In the context of Malaysia, the relationship between population size and CO_2 emissions has been discussed in several studies. Malaysia's continued population growth, urbanization, and industrial expansion have contributed to higher energy demand and environmental stress over the years (Nurgazina et al., 2021). Existing studies generally suggest that population growth is associated with greater environmental degradation due to rising transportation needs, electricity consumption, and residential emissions (Zhang et al., 2021). Nevertheless, some recent findings indicate that the effect of population growth on CO_2 emissions in Malaysia may not always be positive, particularly as the country undergoes a demographic transition toward an aging society and adopts stricter environmental policies (Redzwan & Ramli, 2024). Improvements in environmental awareness, the adoption of green technologies, and government mitigation strategies may reduce the environmental impact of population growth. Therefore, the Malaysian case presents an important context for examining how demographic changes influence CO_2 emissions.

Life Expectancy and CO_2 Emissions

Life expectancy has increasingly become an important demographic factor in explaining environmental degradation and CO_2 emissions. The existing literature suggests that rising life

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expectancy is commonly associated with higher CO_2 emissions due to prolonged consumption, increased healthcare demand, urbanization, and greater energy use (Szymańska, 2025; Shaari et al., 2024). In many developed and developing economies, improvements in healthcare systems, living standards, and economic development have contributed to longer lifespans, thereby increasing cumulative resource consumption and environmental pressure. A study by Osei-Kusi et al. (2024) determined that life expectancy, energy consumption, and CO_2 emissions are closely interconnected across regions, indicating that longer lifespans tend to intensify environmental degradation by increasing energy use and economic activity.

In rapidly developing economies, longer life expectancy is often associated with higher income levels, urbanization, and increased residential energy demand, all of which contribute to environmental degradation (Mahalik et al., 2023). Research by Saidmamatov et al. (2024) in the Aral Sea Basin demonstrated that CO_2 emissions and economic development significantly influence life expectancy while simultaneously increasing environmental pressure through greater resource utilization. Furthermore, environmental degradation and emissions are identified as negatively affecting public health and long-term sustainability, indicating a complex bidirectional relationship between environmental quality and longevity (Roy, 2024).

In the Malaysian context, the relationship between life expectancy and CO_2 emissions has attracted growing attention amid the country's ongoing demographic transition toward an aging society. Malaysia has experienced continuous improvements in healthcare services, living conditions, and economic growth, which have contributed to rising life expectancy. Nonetheless, rising longevity may also intensify environmental pressures through greater lifetime energy consumption, increased transportation demand, greater residential electricity use, and increased waste generation. According to Redzwan and Ramli (2024), CO_2 emissions and economic factors significantly influence life expectancy in Malaysia, highlighting the close interaction between environmental quality and demographic change. Additionally, studies of Association of Southeast Asian Nations (ASEAN) economies, including Malaysia, show that increases in life expectancy and economic expansion are associated with higher CO_2 emissions, despite increased adoption of green technologies. These findings suggest that Malaysia's aging population may pose additional environmental challenges in the future if sustainable consumption and low-carbon development policies are not strengthened.

Methodology

This research applies the STIRPAT framework to investigate how demographic changes, namely population growth and life expectancy, influence CO_2 emissions in Malaysia. Annual data spanning from 1985 to 2023 are employed to analyze the long-run association between the selected variables. The data utilized in this study were obtained from the World Bank and the Department of Statistics Malaysia (DOSM). The dependent variable in this study is total CO_2 emissions in Malaysia, including electricity and heat generation, transportation, manufacturing and construction, and agriculture and waste. The independent variables are demographic factors: total population size and total life expectancy. In contrast, the controlled variables include real GDP and the number of patents registered in Malaysia as proxies for technology. To ensure robust empirical analysis, several econometric techniques are implemented, starting with unit root tests to determine stationarity and then using the ARDL approach to examine cointegration relationships. In addition, the Fully Modified Ordinary Least Squares (FMOLS) method is applied to strengthen and validate the consistency of the estimated long-run results. Finally, the diagnostic test is performed to ensure that the estimated long- and short-run relationships are valid, reliable, and free from statistical error.

Empirical Model

One of the earliest theoretical frameworks explaining the relationship between demographic factors and environmental degradation is the IPAT model introduced by Paul R. Ehrlich and John Holdren in 1971. The IPAT model provides a foundational approach for identifying the determinants of environmental impact.

$$I = P \times A \times T.$$

In this framework, environmental impact (I) is influenced by population size (P), affluence (A), and technology (T). Environmental impact is commonly represented by indicators such as CO_2 emissions or natural resource depletion, while affluence is generally proxied by GDP. The model suggests that environmental degradation increases as population, economic activity, and technological intensity expand. Building upon the IPAT framework, the STIRPAT model was later developed by Thomas Dietz and Eugene Rosa in 1997. The STIRPAT model extends the original IPAT identity by transforming it into a stochastic, econometric form that enables empirical estimation and hypothesis testing across different settings. Unlike the IPAT framework, the STIRPAT model provides greater flexibility in empirical analysis by permitting the inclusion of additional independent variables and a stochastic error term. This flexibility makes the model highly suitable for demographic and environmental studies, such as demographic changes. Recent studies have increasingly employed the STIRPAT framework to examine the effects of population dynamics and socio-economic development on CO_2 emissions (Wang & Li, 2021; Liu et al., 2022). The following equation presents the STIRPAT model:

$$I_i = aP_i^b A_i^c T_i^d e_i.$$

The parameter a denotes the constant term, whereas b, c, and d capture the elasticities of population, affluence, and technology with respect to environmental impact. The error term, represented by e, accounts for unobserved or random factors not explicitly included in the model. According to Dietz and Rosa (1997), the regression-based structure of the STIRPAT model provides greater flexibility for examining how demographic and socio-economic factors contribute to environmental degradation beyond the conventional assumptions of the IPAT framework.

$$It = f(Pt, LEt, At, Tt).$$

This study extends the STIRPAT framework by incorporating demographic variables, namely population growth and life expectancy, into the environmental impact model for Malaysia. While the original STIRPAT model primarily emphasizes population size, affluence, and technology, this study broadens the framework by recognizing that the demographic transition and increasing longevity may independently affect CO_2 emissions (Liu et al., 2022; Muttarak, 2021). Population growth reflects the scale effect of human activities on the environment, whereas life expectancy captures the environmental implications of demographic aging, longer lifetimes, and increased resource consumption. The inclusion of life expectancy is particularly important in the Malaysian context, as the country is gradually transitioning to an aging society with rising longevity. Therefore, this study extends the conventional STIRPAT specification by integrating demographic transition indicators to capture better the evolving nexus between demographics and the environment in Malaysia.

Specifically, in this study, environmental impact (I) is represented by total CO_2 emissions as the dependent variable. Using aggregate CO_2 emissions enables a broader evaluation of environmental degradation by reflecting the overall level of emissions generated within the economy. This measurement approach provides deeper insight into the extent to which demographic changes contribute to variations in emissions across multiple sectors and activities.

The following model is formulated to investigate the effects of population growth and life expectancy on environmental degradation in Malaysia:

$$CO2_t = \beta_0 + \beta_1 POP_t + \beta_2 LE_t + \beta_3 GDP_t + \beta_4 TEC_t + \varepsilon_t.$$

In this specification, $CO2_t$represents total carbon dioxide emissions at the time t, while POP_t, denote the population growth in the period t. LE_t life expectancy in the period t. In addition, GDP_t captures gross domestic product per capita, and TEC_t measures technological progress based on the number of patent applications in period t. To ensure linearity and reduce heteroskedasticity, all variables are transformed to natural logarithms for the empirical analysis.

The hypothesis of this study is as follows:

H0: There is no significant relationship between population growth and CO_2 emissions.
H1: There is a significant relationship between population growth and CO_2 emissions.

H0: There is no significant relationship between life expectancy and CO_2 emissions.
H1: There is a significant relationship between life expectancy and CO_2 emissions.

Econometric Procedure

A unit root test is conducted to determine the stationarity of the variables as a preliminary step. The Augmented Dickey–Fuller (ADF) test is employed for this purpose. Subsequently, the study applies the ARDL approach to examine cointegration and short- and long-run relationships among the variables.

Unit Root Test

To examine the stationarity properties of the variables, this study first applies the ADF test as a preliminary analysis. The ADF procedure is an extended version of the conventional Dickey–Fuller unit root test and is widely utilized in time-series econometric studies. By incorporating lagged terms of the dependent variable, the test can address autocorrelation in the residuals. The general form of the unit root equation is expressed as follows:

$$\Delta Y_t = \beta_1 + \beta_{2t} + \delta Y_{t-1} + \alpha_i \sum \Delta Y_{t-1} + \varepsilon_t.$$

In the equation, $Y_t$denotes the variable under investigation, while Δrepresents the first-difference operator. The term $t$indicates the deterministic time trend, and εrefers to the white-noise error term with constant variance and zero mean. The coefficients β_1, β_2, δ, and $\alpha_i$are the parameters estimated within the model. Furthermore, the Akaike Information Criterion (AIC) is employed to identify the optimal lag length, k, for the analysis (Hirotugu Akaike, 1998). The ADF procedure is based on the following two hypotheses:

H0 = δ=0(Y_t is non-stationary)
H1 = δ≠0 (Y_t is stationary)

The null hypothesis (H_0) is rejected when the calculated t-statistic is more negative than the corresponding critical value. According to Damodar Gujarati (2003), failure to reject the null hypothesis, where $\delta = 0$, indicates the presence of a unit root in the series Y_t, implying that the variable is non-stationary.

Auto-Regressive Distributed Lag (ARDL) Modeling Approach

The ARDL technique is widely applied to examine cointegration among time-series variables. Although ARDL primarily serves as a modeling approach for analyzing both short- and long-run dynamics, it also integrates the bounds testing method introduced by M. Hashem Pesaran et al. (2001) to determine the presence of long-run equilibrium relationships among variables. This feature provides considerable flexibility, making the ARDL framework particularly suitable for time-series and cointegration analyses. Thus, the log-linear specification of this model is demonstrated in the following equation:

$$LnCO2_{Total,t} = \beta_0 + \sum_{i=1}^{p} \beta_1 \Delta LnPOP_{t-i} + \sum_{i=0}^{p} \beta_2 \Delta LnLE_{t-i} + \sum_{i=0}^{p} \beta_3 \Delta LnGDP_{t-i} + \sum_{i=0}^{p} \beta_4 \Delta LnTEC_{t-i} + \alpha_1 LnPOP_{t-1} + \alpha_2 LnLE_{t-1} + \alpha_3 LnGDP_{t-1} + \alpha_4 LnTEC_{t-1} + \varepsilon_t.$$

The analysis then proceeds with the estimation of the long-run model, followed by the short-run specification, to address the objectives of this study. In the error-correction framework, cointegration is confirmed when variables converge toward a long-run equilibrium, with the adjustment coefficient expected to be negative and statistically significant. The estimated model equations are presented as follows:

Results and Discussions

This section presents and discusses the study's empirical findings in detail. It begins with the results of unit root tests, which are used to determine the stationarity of the model's variables. The cointegration analysis proceeds as follows to assess the existence of a long-run equilibrium relationship among the variables. Subsequently, the long-run estimates derived from the ARDL model are examined to evaluate the sustained effects of the explanatory variables on CO_2 emissions. Finally, the section discusses the short-run dynamics using an error-correction model to capture the immediate adjustments and the speed of convergence toward the long-run equilibrium.

Unit Root Test

This study applies the ADF test to examine the stationarity of all variables included in the analysis. Prior to estimation, all variables are converted to natural logarithms to improve model linearity and ensure consistent variances. The unit root test is carried out at both level and first-difference forms, incorporating specifications with intercept and trend, as reported in Table 1. The optimal lag length is selected based on the AIC. The ADF results indicate that, at levels, the null hypothesis of a unit root cannot be rejected for all variables, suggesting non-stationarity. However, after taking first differences, all variables become stationary, leading to the rejection of the unit root hypothesis at the differenced form.

Table 1: ADF Unit Root Test

Variable	**Level**	**1st Difference**
	Intercept & trend	Intercept & trend
CO2	-1.405 [1]	-4.580 [1]***
	(0.843)	(0.004)
POP	0.719 [1]	-4.682 [1]***
	(1.000)	(0.003)
LE	-2.230 [1]	-6.405 [1]***
	(0.460)	(0.000)
GDP	-2.146 [1]	-5.334 [1]***
	(0.505)	(0.001]
TEC	-1.627 [1]	-7.292 [1]***
	(0.763)	(0.000)

Notes: The optimal lag is shown in the square brackets while the value in parentheses represents the p-value of the test. *** indicates 1% significance level.

As reported in Table 1, all key variables, including CO_2 emissions, population size (POP), life expectancy (LE), real GDP, and technology (TEC), are found to be stationary after first differencing, indicating that they are integrated of order one, *I(1)*. Importantly, none of the variables are stationary at level, *I(0)*. Given that all variables are integrated of the same order, and none are I(0), this supports proceeding with long-run estimation techniques for the long-run model specification.

Cointegration Test

Following the unit root test results, which confirm that all variables are integrated of order one, *I(1)*, and none are integrated of order two, *I(2)*, the analysis proceeds with the ARDL bounds testing approach to investigate the presence of a long-run equilibrium relationship among the variables. The condition that no variable is *I(2)* satisfies a key requirement for implementing the ARDL bounds testing procedure developed by Pesaran et al. (2001). In this study, the critical values are obtained from Narayan (2005), which are specifically designed for small sample applications. Additionally, the optimal lag length is selected using the AIC, which effectively balances model fit and parsimony while capturing the dynamic structure of the variables.

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Table 2: Bound Test for Cointegration

Test Statistics	**Model 1: CO2**	
F-statistics	44.593***	
k	7	
	Narayan (2005) critical values (k=4, n 39)	
Critical value	Lower bound	Upper bound
10%	2.169	3.306
5%	2.558	3.846
1%	3.468	5.057

Notes: The critical values for the lower *I(0)* and upper *I(1)* bounds are taken from Narayan (2005). *** indicate 1% and 5% significance levels.

The results of the ARDL bounds test, presented in Table 2, illustrate that the calculated F-statistics for all specified models are higher than the corresponding upper bound critical values. This provides strong statistical evidence to reject the null hypothesis of no cointegration. Accordingly, the findings confirm the existence of a long-run relationship between CO_2 emissions and the selected demographic and macroeconomic variables. These results further suggest that the variables tend to move together toward a stable long-run equilibrium, even though short-run fluctuations may arise due to structural adjustments or temporary shocks.

Long-run Model

Once cointegration is established, it indicates the presence of a stable long-run equilibrium among the variables, allowing for the estimation and interpretation of long-term coefficients. The long-run specification reflects the enduring effects of demographic factors, economic growth, and technological progress on total CO_2 emissions in Malaysia. Changes in population growth are associated with differences in consumption behaviors, labor market participation, housing requirements, and waste generation patterns. In addition, improvements in life expectancy may capture variations in health status, lifestyle choices, and socio-economic engagement, which can influence environmental pressures in distinct ways. The estimated long-run coefficients, therefore, help identify the demographic factors with the greatest impact on overall CO_2 emissions. To determine the optimal lag length for the ARDL model, the AIC was used, and the maximum lag of 1 yielded the lowest AIC. This lag length was selected because it minimizes information loss while providing the most parsimonious model.

Table 3: Long-run Effect of Population and Life Expectancy (ARDL)

Variables	Model 1: CO_2
C	7.461
	(0.599)
POP	-2.715**
	(0.0020)
LE	2.556
	(0.487)
GDP	1.777***
	(0.000)
TEC	0.109
	(0.184)

Notes: The lag length is chosen based on the Akaike Information Criterion (AIC). ***, ** indicate significance at 1% and 5%, respectively. Figures in the parentheses represent the p-value of the test.

Findings in Table 3 revealed that POP exhibits a negative, statistically significant relationship with CO_2 emissions, contradicting the initially expected positive association. This result implies that population growth is associated with reduced CO_2 emissions, indicating an inverse relationship between the two variables. Specifically, a 1% rise in population size leads to a 2.72% decrease in CO_2 emissions. This is an interesting finding, as in Malaysia population growth results in a reduction in CO_2 emissions. The negative relationship between population growth and CO_2 emissions in Malaysia may be explained by the country's ongoing demographic transition toward an aging population. Although population growth is traditionally associated with greater environmental degradation due to increased energy demand and consumption, recent demographic changes in Malaysia suggest a more complex relationship. Malaysia is gradually becoming an aging society as fertility rates decline and the elderly population grows. According to the DOSM, Malaysia is expected to become an aging nation by 2040, with a growing share of the population aged 60 years and above (Yunus, 2024). This demographic transition may alter overall consumption patterns, labor force participation, transportation use, and household energy demand, thereby moderating the growth of carbon emissions despite population growth.

Furthermore, older populations generally exhibit lower levels of industrial productivity, mobility, and consumption compared to younger working-age populations, which may contribute to lower energy demand and reduced emissions. For instance, Li et al. (2024) argued that aging populations influence environmental sustainability by reducing labour supply and changing social consumption patterns, thereby reducing carbon-intensive activities. Similarly, Wang et al. (2022) identified that population aging redefines the relationships among economic growth, energy consumption, and carbon emissions in Organisation for Economic Co-operation and Development (OECD) countries, suggesting that aging can mitigate emission intensity under certain economic conditions. In addition, Yu et al. (2023) demonstrated that aging-related consumption trends may improve CO_2 emission efficiency by adjusting the industrial structure and reducing carbon-intensive consumption. These findings indicate that demographic aging can generate structural economic changes that contribute to environmental improvement.

Besides that, this finding may reflect the effectiveness of government regulations and policy interventions in mitigating emissions and improving environmental quality. For instance, Xie et al. (2023) highlighted that targeted environmental policies significantly reduce CO_2 emissions and improve overall environmental conditions. Similarly, Rashid and Muhmad (2024) identified a negative association between green policy and CO2 emissions in Malaysia, suggesting a potential relationship between environmental regulations and CO2 emissions policy. Malaysia has increasingly incorporated environmental sustainability into its national development agenda through various green growth and climate-related policies. One of the most significant initiatives is the Eleventh Malaysia Plan (11MP) 2016–2020, which introduced green growth as a central strategic thrust for national development. (Ministry of Economy, 2016). The plan emphasized sustainable economic expansion, efficient resource utilization, low-carbon development, and environmental resilience as key priorities for long-term socio-economic sustainability. Under the 11MP framework, the government promoted green technology adoption, renewable energy development, sustainable urbanization, and environmentally friendly production and consumption practices. Importantly, the policy also recognized the need to improve quality of life for both present and future generations, which is closely linked to demographic transition and population well-being.

In addition, Malaysia has strengthened its climate governance framework through the introduction of the National Climate Change Policy (NCCP) 2.0, which aims to accelerate the country's transition toward a low-carbon economy while enhancing climate resilience. The updated policy integrates climate considerations into national development planning, governance, and economic transformation strategies. NCCP 2.0 supports Malaysia's commitment to achieving net-zero greenhouse gas emissions by 2050 and emphasizes sustainable development practices across multiple sectors (Ministry of Natural Resources and Environmental Sustainability, 2024). The policy is particularly relevant in addressing the environmental implications of demographic transition, as rising life expectancy and urban population concentration increase long-term energy consumption, transportation demand, and residential emissions.

Malaysia has also implemented various waste management and recycling initiatives that contribute to environmental sustainability amid changing demographic conditions. Recycling campaigns and the adoption of the 3R approach (Reduce, Reuse, and Recycle) aim to minimize waste generation, reduce reliance on landfills, and encourage sustainable household consumption behavior (Malaysian Green Technology and Climate Change Corporation, 2024). The government's circular economy agenda under the Twelfth Malaysia Plan further emphasizes resource efficiency, recycling, and sustainable consumption patterns to support long-term environmental sustainability (Ministry of Economy, 2021). Such policies may indirectly reduce carbon emissions by lowering waste accumulation, improving energy efficiency in waste management systems, and promoting environmentally conscious lifestyles among households.

The effectiveness of the policy is aligned with the policy implemented in Japan; key strategies include compact city planning to improve infrastructure efficiency, promoting resource-sharing in single-person households, and shifting to a circular economy to decouple CO_2 emissions from demographic changes (Onwe et al., 2024; Huang et al., 2024; and Tamakoshi & Hamori, 2020). Additionally, this outcome is further supported by the argument that greater environmental awareness, the adoption of cleaner technologies, and the implementation of sector-specific mitigation policies play a crucial role in reducing CO_2 emissions in developing economies (Zhou et al., 2020).

In addition, life expectancy is identified to positively affect CO_2 emissions, consistent with previous empirical evidence indicating that greater longevity tends to increase environmental pressure. Nevertheless, the results were found to be statistically insignificant. The results show that a 1% increase in life expectancy is associated with a 2.56% increase in CO_2 emissions. This relationship may be explained by the fact that higher life expectancy is often associated with improved economic conditions, which, in turn, can intensify environmental degradation (Yusuf et al., 2020). Similarly, A. Rjoub et al. (2020) reported a positive association between life expectancy and carbon emissions, suggesting that longer lifespans are associated with higher CO_2 emissions. Furthermore, Saidi and Omri (2020) argued that increases in life expectancy are often accompanied by higher energy consumption, which in turn leads to greater CO_2 emissions.

Furthermore, real GDP is positively associated with total CO_2 emissions. It is statistically significant, indicating that a 1% increase in real GDP is associated with a 1.78% increase in CO_2 emissions. These outcomes are consistent with much of the existing literature, which generally reports a direct and positive relationship between economic growth and environmental degradation. For instance, Hondroyiannis and Tsalaporta (2023) identified that real GDP is positively associated with CO_2 emissions generated from energy consumption. Similarly, Shahbaz et al. (2022) argued that higher income levels increase energy demand and contribute to rising emissions, largely driven by consumption-oriented lifestyles.

In contrast, the findings indicate that TEC does not reduce CO_2 emissions; instead, technological development is associated with slight increases in emissions. Specifically, a 1% increase in technology is associated with a 0.11% increase in CO_2 emissions. Although the results were not statistically significant, the existing literature provides mixed evidence regarding the environmental role of technological progress. For example, Xiaoyang et al. (2022) reported that technological innovation and research and development activities are positively associated with CO_2 emissions, suggesting that increased production and consumption effects may offset technological gains. Similarly, Zhang (2021) determined that patent activity alone does not necessarily lead to reductions in carbon emissions.

Short-run Model

This section focuses on the short-run dynamics derived from the error correction form of the ARDL model. The short-run results reflect the immediate influence of demographic and economic changes on CO_2 emissions, as well as the rate at which the system returns to long-run equilibrium after a shock.

Table 4: Short-Run Estimates of Population and Life Expectancy

Variables	Model: CO_2
ΔLPOP	
ΔLLE	
ΔLGDP	
ΔLTEC	
ECT_{t-1}	-0.46***
	(0.000)

Notes: The lag length is chosen based on the Akaike Information Criterion (AIC). *** indicate significance at the 1% level. Figures in the parentheses represent the p-value of the test.

To assess the combined short-run effects of the explanatory variables, Wald tests were applied to examine the joint significance of the lagged difference terms. According to Table 4, the error correction term is negative and statistically significant at the 1% level, supporting the earlier cointegration findings and confirming the presence of a long-run relationship among the variables. The findings show that the error-correction coefficient suggests that approximately

46% of any short-run disequilibrium in total carbon emissions (CO_2) is corrected within 1 year. This suggests that the speed of adjustment is faster, so any disturbance in the short run will be corrected more quickly.

Diagnostic Test

Several diagnostic and stability tests were conducted to evaluate the robustness and reliability of the estimated model. The ARCH test was applied to examine heteroskedasticity, while the Breusch–Godfrey LM test was used to detect serial correlation. In addition, the Jarque–Bera test assessed the normality of the residuals, and the Ramsey Regression Equation Specification Error Test (RESET) test examined potential misspecification of the functional form. Finally, the model's stability was verified using the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) tests to assess parameter stability and model consistency over time.

Table 5: Diagnostic Test Results

Indicator	Test statistics	p-value	Results
ARCH test	1.207	0.236	Do not reject H_0 No ARCH effect
Breusch-Godfrey Serial Correlation LM	0.134	0.894	Accept H0 No autocorrelation
Normality test	1.708	0.426	Do not reject H0 Normal distribution
Ramsey RESET test	0.709	0.502	Accept H0. Correct Model specification

Based on the results reported in Table 5, the diagnostic tests collectively confirm the robustness and reliability of the estimated models. First, the heteroskedasticity test indicates that the null of constant variance cannot be rejected across all specifications, suggesting that the models exhibit constant variance and are therefore homoscedastic. Second, the Breusch–Godfrey LM test results show no evidence of autocorrelation, as the null hypothesis of no serial correlation is retained for all models, confirming that the error terms are independent and the classical regression assumptions are satisfied.

In addition, the Jarque–Bera normality test for CO_2 emissions indicates that the residuals are normally distributed, as the null hypothesis of normality is not rejected. Finally, the Ramsey RESET test supports the model's correct functional form, providing no evidence of misspecification. Overall, these diagnostic results confirm that the estimated models are statistically reliable and satisfy the key econometric assumptions required for valid inference.

Stability Test

The final diagnostic check in this study involves the CUSUM and CUSUMQ tests, which assess parameter stability within the model. The results, presented graphically in Figures 4.1-4.12, indicate that all estimated models remain stable over the sample period. Both the CUSUM and CUSUMQ plots fall within the 5% critical boundaries, confirming that the model parameters are stable over time at the 5% significance level. The graphical results from the CUSUM and CUSUMQ tests show that the residuals remain within the critical boundaries across all models, indicating no evidence of structural instability. Consequently, the null hypothesis of parameter stability cannot be rejected at the 5% significance level.

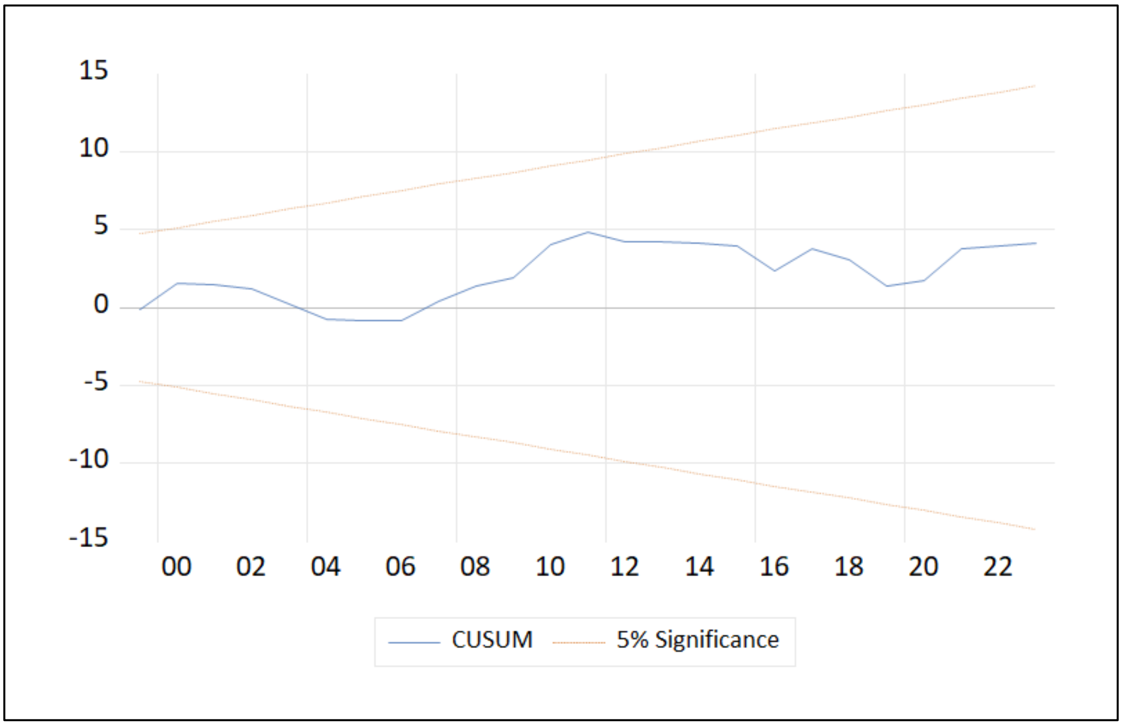

Figure 1: CUSUM Test

Source: The figure is based on the author's own work

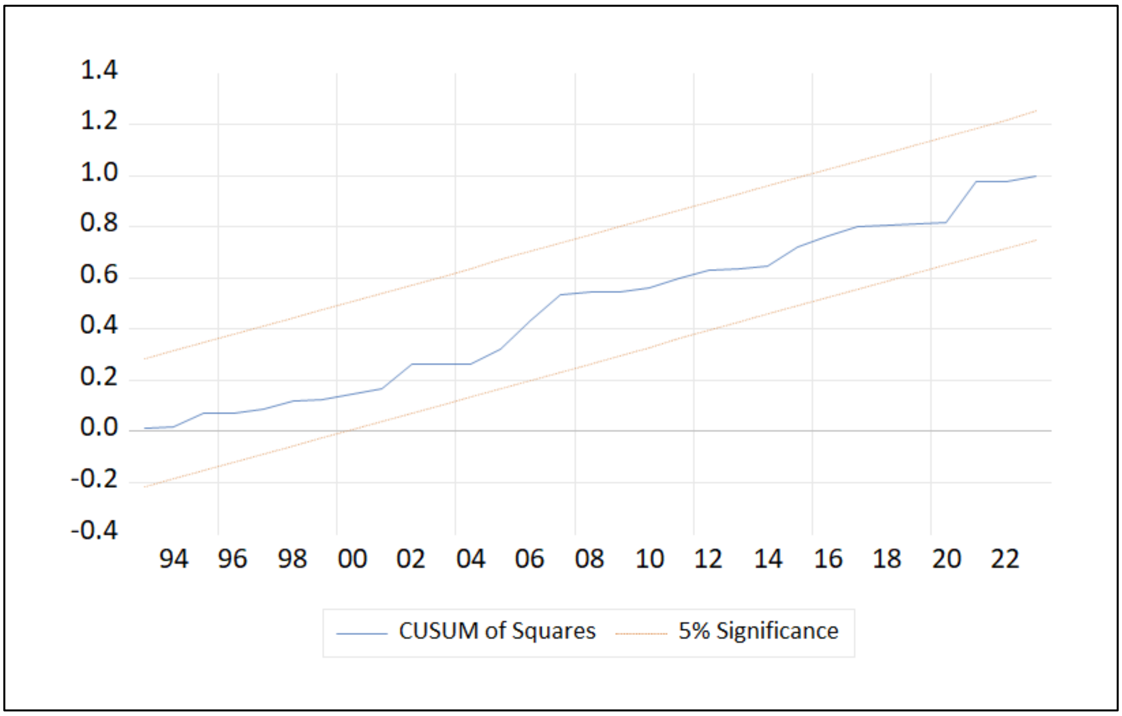

Figure 2: CUSUMQ Test

Source: The figure is based on the author's own work

Conclusions

This study examined the impact of demographic factors, particularly population growth and life expectancy, on carbon emissions in Malaysia within the STIRPAT framework using the ARDL approach. The empirical findings confirm the existence of a long-run relationship between demographic variables, GDP, technology, and CO_2 emissions in Malaysia. By integrating demographic transition variables into a standard STIRPAT specification, this study contributes to the growing literature that moves beyond conventional macroeconomic drivers of environmental degradation and highlights the importance of demographic structure in shaping sustainability outcomes. The results show that population growth is negatively associated with CO_2 emissions, suggesting that larger populations are linked to lower emissions in the Malaysian context. This counterintuitive outcome may reflect Malaysia's ongoing demographic transition toward an aging society, where slower population growth, structural changes in consumption behaviour, and policy-driven environmental improvements collectively reduce environmental pressure. In addition, strengthened environmental governance, rising environmental awareness, and the adoption of cleaner technologies may have further supported emissions reduction despite population expansion.

In contrast, life expectancy is found to have a positive, statistically significant effect on CO_2 emissions, indicating that longer lifespans contribute to greater environmental degradation. This result underscores an important but often overlooked dimension of sustainability: demographic aging as an environmental determinant. Increasing life expectancy reflects improvements in healthcare, income, and living standards, which are typically associated with higher energy demand, greater mobility, expanded residential consumption, and increased waste generation. Over time, these cumulative consumption effects intensify CO_2 emissions, highlighting the environmental trade-offs of demographic progress. This finding is particularly relevant for emerging economies undergoing rapid demographic and economic transitions, where improvements in human development may inadvertently generate additional environmental pressures if not accompanied by strong sustainability policies.

The findings reinforce the argument that demographic transition should be considered a core element in environmental and climate policy design, particularly in emerging economies like Malaysia. Policy strategies should therefore integrate aging-related dynamics into long-term sustainability planning, with greater emphasis on renewable energy adoption, low-carbon infrastructure, energy-efficient housing, and sustainable consumption behaviour across all age groups. Strengthening environmental regulations and promoting the diffusion of green technology will also be essential to offset the emissions associated with increased longevity.

Finally, this study extends the sustainability literature by demonstrating that demographic factors play a significant and evolving role in shaping environmental outcomes. By highlighting the contrasting effects of population growth and life expectancy on CO_2 emissions, the study provides new empirical evidence on the demographic–environment nexus within an emerging economy context. These insights underline that sustainable development strategies must account for demographic realities, particularly population aging, to ensure effective long-term climate mitigation. Future research should further explore multidimensional demographic indicators and comparative cross-country analyses to deepen understanding of how demographic transitions reshape environmental trajectories globally.

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