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Effects of marginal CO_2 emissions on life Expectancy: A linear and nonlinear panel analysis of Asean

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Abstract

This study investigates the asymmetric effects of marginal carbon dioxide (CO_2) emissions, defined as CO_2 emissions per unit of energy use, on life expectancy in ASEAN countries from 1990 to 2023. Unlike most existing studies that focus on total CO_2 emissions, this paper introduces a novel and policy-relevant indicator that more accurately reflects energy efficiency: marginal CO_2 emissions. Using both linear and nonlinear panel Autoregressive Distributed Lag (ARDL and NARDL) models, the findings reveal that rising marginal CO_2 emissions have a significant negative impact on life expectancy. In contrast, reductions in marginal emissions are associated with improvements in public health, confirming the presence of asymmetric effects. Interestingly, health expenditure and economic expansion exhibit unexpected negative long-term associations with life expectancy, whereas inflation shows contrasting short- and long-term effects. The nonlinear model demonstrates superior explanatory power compared to the linear approach, particularly in capturing these asymmetric dynamics. ASEAN countries are selected due to their rapid economic growth, high environmental vulnerability, and wide heterogeneity in energy efficiency and health systems, making them a critical and timely context for this analysis. Therefore, policymakers should prioritise enhancing energy efficiency and reducing emissions intensity to improve population health outcomes across the region.

Keywords Marginal CO_2 Emissions · Life Expectancy · Energy Efficiency · ASEAN

Introduction

The twin crises of climate change and public health are no longer separate issues—they are now closely linked and moving at a faster pace. A key factor connecting them is the rise in carbon dioxide (CO_2) emissions from the use of fossil fuels for energy. These emissions not only contribute to global warming but also pose significant risks to human health. While the environmental effects of CO_2—such as rising temperatures, extreme weather, sea-level rise, and loss of biodiversity—are well understood, the direct impacts on health and life expectancy remain unclear in research (Yang et al. 2021; Ogunkunle & Ahmed 2021).

This lack of focus on health is concerning, especially as more studies now demonstrate that air pollution—strongly linked to CO_2 emissions—is a significant contributor to non-communicable diseases. The World Health Organization ranks air pollution as one of the top environmental threats to human health, responsible for millions of deaths each year due to asthma, heart disease, strokes, cancer, and early death (Goshua et al. 2022; Shahriyari et al. 2022). Much of this pollution originates from outdated and inefficient energy systems, particularly in rapidly developing countries that still heavily rely on fossil fuels. While this approach helps identify long-term trends, it overlooks a critical dimension of environmental efficiency: the extent to

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which each incremental increase in energy use causes additional environmental harm. This is particularly relevant for rapidly industrializing countries where marginal increases in energy consumption may lead to disproportionately higher emissions and health risks. To address this gap, our study introduces marginal CO_2 emissions, defined as the change in emissions per unit change in energy consumption, as a more precise and policy-relevant indicator. By examining the asymmetric effects of marginal CO_2 emissions on life expectancy through both linear and nonlinear panel models, this study aims to uncover the complex and context-specific ways in which environmental pressures influence human health across ASEAN countries.

Although awareness of these problems is growing, many studies still rely on total CO_2 emissions as the primary measure of environmental harm (Wei et al. 2022; Gasimli et al. 2023; Li et al. 2023). While this measure helps track long-term trends and compare countries, it does not indicate how efficiently energy is used or the potential harm associated with each additional unit of energy. This is especially important in fast-growing economies, where small increases in energy use can lead to significantly larger increases in emissions and health problems.

In these settings, a slight rise in energy demand may lead to a sharp jump in pollution levels. This often occurs due to inadequate infrastructure, lax regulations, and a significant reliance on coal and oil. The result is more local air pollution, greater health risks, and added pressure on healthcare systems that may already be under strain. Moreover, CO_2-related health effects are not limited by borders, meaning that emissions in one country can also affect neighboring regions, highlighting the need to rethink how we measure environmental risks.

To address this gap, our study introduces marginal CO_2 emissions, defined as the change in emissions per unit change in energy consumption, as a more precise and policy-relevant indicator. Unlike total emissions, marginal emissions reflect the environmental intensity and efficiency of energy use, offering a sharper tool to assess how energy systems translate into health outcomes (Boateng et al. 2024; Holland et al. 2022; Shaari et al. 2023; 2024a). For instance, a country dependent on coal will have higher marginal emissions and, consequently, greater health costs compared to one that utilizes cleaner energy sources. This refined metric facilitates a deeper understanding of how energy consumption patterns affect public health, particularly in the context of development and energy transitions.

The ASEAN region provides a compelling case for this investigation due to its acute and multifaceted environmental challenges. Several member states, including Indonesia, Malaysia, and Thailand, experience recurring episodes of transboundary haze resulting from forest clearing and peatland fires, which significantly degrade regional air quality and increase the incidence of respiratory illnesses. Urban centres such as Jakarta, Manila, Bangkok, and Hanoi consistently exceed safe thresholds for PM2.5 concentrations, mainly due to vehicular emissions, industrial output, and open burning. Countries like Indonesia and Vietnam remain heavily reliant on coal-powered energy, contributing to high emissions intensity and poor energy efficiency. Furthermore, many parts of Southeast Asia are increasingly vulnerable to climate-related stressors, including sea-level rise, floods, heatwaves, and droughts, all of which have direct and indirect impacts on public health. These persistent environmental risks are exacerbated by institutional limitations in environmental enforcement and disparities in health system preparedness, highlighting the urgency of a regionally focused assessment of emission–health dynamics.

This study is motivated by the growing need to understand how marginal CO_2 emissions, rather than total emissions alone, influence public health outcomes, particularly life expectancy, in ASEAN countries. As these nations continue to experience rapid industrial development and increasing energy consumption, it is essential to evaluate whether additional emissions are contributing to disproportionate health risks.

This study makes three key contributions to addressing these gaps

First, it introduces a critical conceptual and empirical innovation by shifting the focus from total CO_2 emissions to marginal CO_2 emissions—defined as the additional emissions generated per unit increase in energy consumption. This metric more effectively captures the environmental intensity and inefficiency of energy systems, providing a more nuanced tool for assessing the impact of energy consumption on human health outcomes. For instance, a country that adds one unit of energy from solar or wind sources will have a negligible marginal emission rate. In contrast, a coal-dependent nation may experience a significant spike in emissions and associated health burdens. This distinction is essential for understanding the public health trade-offs of energy policy and for designing more effective mitigation strategies.

Second, methodologically, this study contributes by employing both Panel ARDL and Nonlinear ARDL (NARDL) models to assess the dynamic and potentially asymmetric effects of marginal CO_2 emissions on life expectancy. Traditional linear models often assume symmetric responses, overlooking the possibility that increases and decreases in emissions may have fundamentally different implications for health. For example, a rise in emissions could have an immediate and significant health impact, while a reduction might produce benefits only after a time lag or to a lesser extent. The use of NARDL modeling allows us to capture these real-world complexities and produce more policy-relevant findings. Third, the regional focus on ASEAN countries adds further value and novelty to this study**.** ASEAN represents a group of rapidly industrializing economies characterized by increasing energy consumption, high urban population density, and significant exposure to environmental risks. However, there is a paucity of empirical research that simultaneously considers energy intensity, emissions, and health outcomes in this context.

The empirical focus on ASEAN countries is justified on several grounds. The region comprises some of the fastest-growing economies globally, including Indonesia, Malaysia, Vietnam, and the Philippines, where energy consumption has increased rapidly in tandem with industrialization and urban development. However, this trajectory of growth has frequently been accompanied by environmental degradation, as evidenced by high or volatile levels of marginal CO_2 emissions in several member states. ASEAN nations also exhibit considerable diversity in terms of economic development, health infrastructure, and the maturity of their energy systems. This includes advanced economies such as Singapore and Brunei, as well as lower-middle-income countries like Cambodia and Laos. Such heterogeneity provides a valuable context for exploring the asymmetric effects of emissions on health outcomes, as it allows for comparative insights across different development levels. Additionally, the region's institutional cooperation, facilitated through mechanisms such as the ASEAN Plan of Action for Energy Cooperation (APAEC), provides a coherent policy framework for regional alignment. Therefore, selecting ASEAN as the empirical focus enhances both the analytical richness and the policy relevance of the study, particularly in the effort to balance energy development with public health objectives.

By applying this framework to ASEAN countries, a region characterized by rapid economic expansion, rising energy demand, and environmental vulnerability, our study provides timely and actionable insights. It not only enhances the empirical literature but also equips policymakers with a more effective lens to design targeted interventions that balance energy development with health protection. Ultimately, this research makes a novel and practical contribution to environmental economics, health policy, and sustainable development studies.

Overviews of life expectancy and marginal CO_2 emissions in Asean countries

Table 1 displays the life expectancy trends of ASEAN countries from 2013 to 2023. Singapore consistently recorded the highest life expectancy throughout the period, beginning at approximately 82.2 years in 2013 and increasing slightly to about 82.9 years by 2023. This stable upward trend reflects Singapore's highly developed healthcare infrastructure, efficient public health management, and strong socio-economic conditions. Thailand and Malaysia also recorded relatively high life expectancy rates. Thailand experienced a steady increase from 75.9 years in 2013 to 77.6 years in 2021, followed by a slight decline in 2022, and then a recovery to 76.4 years in 2023. Malaysia, which began the period at 75.5 years, reached 76.7 years in 2023, showing a consistent and robust upward trend with a temporary dip in 2021 due to the pandemic. Brunei exhibited a relatively stable pattern, with life expectancy moving from 74.9 years in 2013 to 75.3 years in 2023, including a minor decline in 2021, followed by a strong recovery over the next two years.

The middle-tier countries, including Vietnam, Indonesia, and the Philippines, demonstrated moderate growth over the decade. Vietnam showed consistent improvements in life expectancy, rising from 73.8 years in 2013 to 74.6 years in 2023. Despite a minor decline in 2021, Vietnam quickly recovered and maintained its upward trajectory. Indonesia experienced more fluctuations. Life expectancy increased gradually from 69.1 years in 2013 to 70.3 years in 2019, followed by a sharp decline to 67.5 years in 2021 due to the pandemic. However, it rebounded to 71.1 years in 2023,

Table 1 Life Expectancy in ASEAN (2013–2023)

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Brunei	74.9	74.9	74.9	74.9	74.9	75.0	75.0	75.1	74.9	72.9	75.3
Indonesia	69.1	69.3	69.5	69.7	70.0	70.1	70.3	68.8	67.5	70.9	71.1
Cambodia	68.8	69.1	69.4	69.6	69.8	70.0	70.1	70.1	69.3	70.5	70.7
Lao PDR	65.7	66.4	66.7	67.0	67.3	67.6	67.9	68.3	67.8	68.7	69.0
Myanmar	64.6	65.0	65.3	65.6	65.9	66.2	66.5	66.6	65.6	66.5	66.9
Malaysia	75.5	75.3	75.3	75.4	75.5	75.7	75.9	76.1	73.9	75.4	76.7
Philippines	69.3	69.3	69.5	69.5	70.0	69.8	69.7	70.1	66.7	69.5	69.8
Singapore	82.2	82.5	82.7	82.8	83.1	83.3	83.6	83.5	83.1	82.9	82.9
Thailand	76.0	76.3	76.6	76.8	77.0	77.2	77.2	77.3	77.6	75.3	76.4
Vietnam	73.8	73.9	74.0	74.0	74.0	74.1	74.2	75.4	74.1	74.5	74.6

Source: World Bank

surpassing pre-pandemic levels. The Philippines had a similar trajectory. It started at 69.3 years in 2013, peaked at 69.9 years in 2017, and then experienced a decline during the pandemic, reaching its lowest point at 66.7 years in 2021. The recovery was modest, with life expectancy increasing to 69.8 years in 2023. These trends reflect the varying degrees of healthcare resilience and pandemic response across these countries.

The lower-tier group, which includes Cambodia, Lao PDR, and Myanmar, showed notable progress despite having the lowest life expectancy rates in the region. Cambodia experienced a steady and gradual increase from 68.8 years in 2013 to 70.7 years in 2023, indicating long-term improvements in healthcare access and public health initiatives. Lao PDR began with one of the lowest life expectancy rates at 65.7 years in 2013 but showed significant growth, reaching nearly 69.0 years in 2023. The increase was consistent, even during the pandemic years, demonstrating some resilience in public health systems. Myanmar also showed gradual improvement from 64.6 years in 2013 to 66.9 years in 2023. However, the gains were slower and more modest compared to its regional peers. These countries still face challenges such as limited healthcare infrastructure and access, but their upward trends are promising and reflect the potential for continued progress. Overall, despite temporary setbacks during the COVID-19 pandemic, all ASEAN countries demonstrated positive long-term trajectories in life expectancy, highlighting the importance of sustained investment in health systems, education, and socio-economic development.

Figure 1 shows the trend in marginal CO_2 emissions across ASEAN nations. It is calculated as the change in CO_2 emissions per unit change in energy use, revealing important insights into energy efficiency and environmental sustainability trends across ASEAN countries. Indonesia stands out with consistently high positive marginal CO_2 emissions in most years, particularly in 2001 (3.84), 2011 (4.55), and 2021 (1.71). This indicates that increases in energy use are often accompanied by disproportionately high CO_2 emissions, suggesting poor energy efficiency and a heavy reliance on carbon-intensive sources. Conversely, countries like Malaysia and Singapore show more moderate and fluctuating marginal emissions. Malaysia experienced high values in some years (e.g., 2002 and 2014) but also recorded negative figures in others (e.g., 2012 and 2016), indicating possible shifts in energy sources or improvements in emissions control. Singapore, while mostly stable, also had years of decline, such as 2002 and 2010, which may be attributed to technological upgrades or cleaner energy policies.

Less developed countries, such as Cambodia, Laos, and Myanmar, exhibit greater variability in their economic development. Cambodia generally displays small but positive marginal emissions, with spikes in recent years, including a dramatic rise in 2022 (1.85), which may reflect a late but rapid industrial expansion. Laos also exhibits a positive trend, although values fluctuate, suggesting inconsistent energy and emissions management. Myanmar's marginal emissions display a mixed pattern, with certain years—such as 2006 and 2022—registering negative values. This may indicate improvements in energy efficiency or inconsistencies in emissions reporting. Notably, the Philippines and Vietnam emerge as particularly compelling cases for further analysis. The Philippines exhibits large positive spikes (e.g., 2007 and 2021), including a notable negative outlier in 2019 (−2.50), which reflects unstable energy-emission dynamics. Vietnam exhibits a more positive overall trajectory, peaking sharply in 2020 (3.27), but then turning negative in

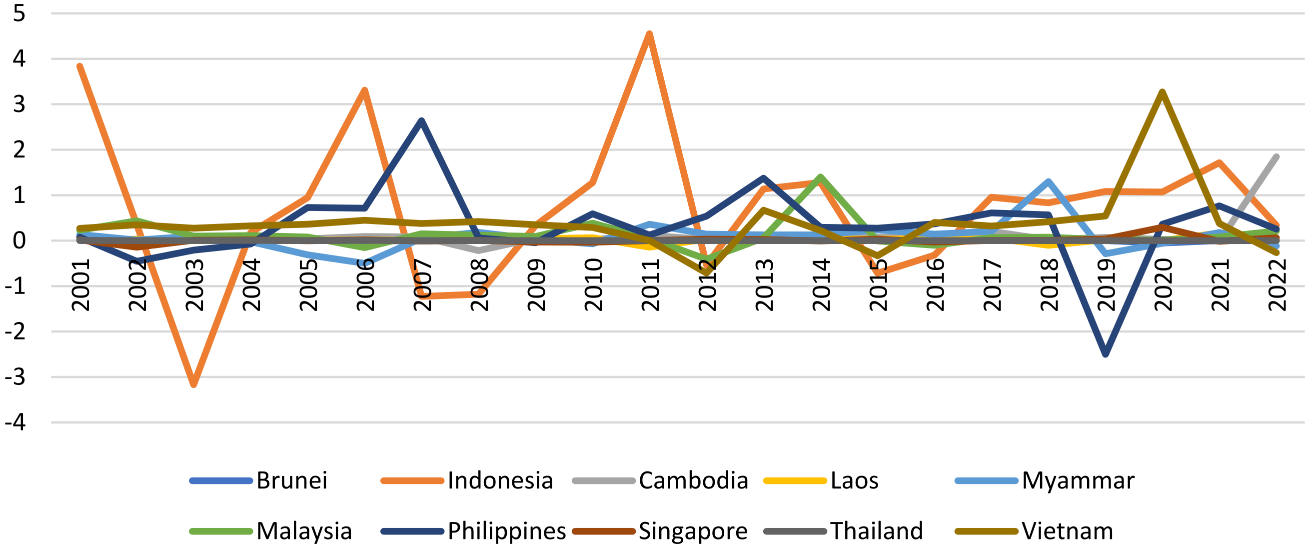

Fig. 1 Marginal CO_2 Emissions in ASEAN Countries.Source: World Bank

2022, suggesting recent gains in energy efficiency or policy impacts.

Thailand and Brunei had smaller magnitudes of marginal emissions, with relatively stable figures around zero. Thailand's values reflect consistent but minimal changes, which could indicate a mature energy infrastructure with limited new emissions per energy unit. Brunei, due to its small size and volatile energy profile, shows occasional spikes and negative values (e.g., 2020), reflecting its sensitivity to year-to-year changes in output and consumption.

Overall, the figure highlights a broad spectrum of energy efficiency performance in the region. Countries with persistently high marginal CO_2 emissions may need to prioritize the adoption of clean energy, the implementation of emission control technologies, and efficiency measures to mitigate their impact. Meanwhile, those with improving or stable figures may serve as models for regional cooperation and policy alignment toward sustainable energy use. These marginal measures provide more nuanced insights than total emissions and are crucial for tailoring interventions that align economic expansion with environmental sustainability.

Referring to the trends in life expectancy and marginal CO_2 emissions in ASEAN countries, studying the linkage between marginal CO_2 emissions and life expectancy in ASEAN countries is vital as the region's favorable economic expansion, industrialization, and rising energy demand often come at the expense of environmental quality. While life expectancy has generally improved across ASEAN, many countries simultaneously exhibit rising or volatile marginal CO_2 emissions, indicating a decline in energy efficiency and an increase in environmental stress. This divergence raises questions about the long-term sustainability of recent health achievements, especially in countries with limited infrastructure to manage pollution-related health risks. Given ASEAN's diverse economic structures and shared vulnerability to environmental degradation, this study can provide valuable insights for formulating region-specific policies that strike a balance between economic development, environmental protection, and public health.

Theoretical backgrounds

The foundation of this study rests on two influential theoretical frameworks: the Preston Curve and Grossman's Theory of the Demand for Health. The Preston Curve, first introduced by Preston (1975), depicts a non-linear relationship between a country's income level and the life expectancy of its population. It posits that in low-income countries, even modest increases in income can lead to significant gains in life expectancy due to improved access to essential services, such as healthcare, nutrition, clean water, and sanitation. However, as income levels rise, these gains tend to plateau, illustrating diminishing marginal returns of income on health outcomes (Preston 1975; Arvidsson & Nordelöf, 2025). In recent years, this framework has been refined to incorporate a broader set of explanatory variables. As De la Escosura (2023) emphasizes, contemporary interpretations of the Preston Curve now include factors such as public health expenditure, environmental quality, governance, and macroeconomic stability to better capture the complex dynamics shaping population health across countries.

Complementing this macro-level view, Grossman's Theory of the Demand for Health (Grossman 1972) offers a microeconomic perspective by conceptualizing health functions as a type of capital asset, with personal investments yielding returns in both productivity and well-being. In this model, health is considered both a consumption good that enhances present quality of life and an investment good that promotes future productivity, longer working lives, and improved economic productivity. Individuals allocate resources, such as time, income, and lifestyle choices, to maintain and improve their health capital. Notably, the model also accounts for factors that deteriorate health, including ageing, poor environmental conditions, and exposure to pollution. In this context, CO_2 emissions and environmental degradation serve as adverse health shocks, accelerating the depreciation of health capital and increasing the cost of maintaining good health.

Integrating these two frameworks provides a robust theoretical foundation for examining the relationship between marginal CO_2 emissions and life expectancy, particularly in rapidly developing regions such as ASEAN. While the Preston Curve explains how rising income levels influence population health at a macro level, Grossman's model highlights how environmental conditions, including emissions intensity, affect individuals' ability to invest in and maintain their health. By focusing on marginal CO_2 emissions and the incremental pollution associated with additional energy use, this study fills a critical gap in the literature. Previous research has primarily focused on total emissions, overlooking the efficiency and health implications of energy use at the margin. Therefore, this study contributes a novel and policy-relevant perspective by assessing the interaction between energy quality and environmental efficiency, and by capturing both the economic and environmental dimensions of health investment in the ASEAN context.

Literature review

Increasing empirical evidence suggests that carbon dioxide (CO_2) emissions have a detrimental impact on life expectancy, particularly in developing and emerging economies. Numerous studies consistently report that higher CO_2 emissions are significantly associated with lower life expectancy (Altaee et al. 2025; Shaari et al. 2024a; Javanshirova 2024; Saidmamatov et al. 2024).

Mahalik et al. (2022) examined the relationship between CO_2 emissions and life expectancy in 68 low- and middle-income countries from 1990 to 2017, employing Panel-Corrected Standard Errors (PCSE) and Feasible Generalized Least Squares (FGLS) estimators to ensure a robust analysis. Their results reveal a detrimental link between CO_2 emissions and life expectancy in both the overall sample and among emerging countries, regardless of whether emissions are based on consumption or production. The result is strongly parallel to the study in panel analysis sampled by SAARC countries, which was conducted by Guo et al. (2024). The presumption that drives the study also relies on the fact that modern urbanization generates pollution through CO2, which in turn impacts the issue of life expectancy. However, the outcome is deviated. Interestingly, in some developing countries, emissions appeared to be positively associated with life expectancy, possibly due to economic benefits derived from industrial expansion. Building upon this theme, Osabohien et al. (2021) provided evidence from Nigeria using the ARDL model for the period from 1980 to 2017. Their findings reinforce the conclusions of Mahalik et al. (2022) by demonstrating that increased environmental problems can harm life expectancy.

A similar conclusion is drawn by Redzwan and Ramli (2024), who examined the Malaysian context between 1997 and 2021. Using the ARDL bounds testing approach, they examined the long- and short-run relationships between carbon emissions, economic growth, healthcare expenditure, and life expectancy. The study found that CO_2 emissions and health expenditure significantly influenced life expectancy in the short term, while cointegration suggested a stable long-run equilibrium among the variables. This evidence adds a Southeast Asian perspective to the broader narrative, supporting the generalizability of harmful emissions–health links. Adding a more nuanced perspective, Das and Debnath (2023) evaluated the net effect of environmental deterioration on life expectancy in India from 1991 to 2018 using the ARDL cointegration method. Their study identified a quadratic long-run relationship, suggesting that India has already surpassed its optimal threshold of CO_2 emissions for health.

Expanding the geographical lens, Osei-Kusi et al. (2024) examined three decades of panel data from 82 countries across Sub-Saharan Africa (SSA), the Middle East and North Africa (MENA), and Europe and Central Asia (ECA), using FGLS and PCSE estimators. Their analysis revealed region-specific variations in the impact of CO_2 emissions and energy use on life expectancy, with some regions showing improvements in health outcomes while others experienced increases in mortality. This study underscores the asymmetric nature of the emissions–health relationship and introduces the Environmental Kuznets Curve (EKC) hypothesis, suggesting the possibility of nonlinear and even N-shaped environmental-health dynamics. In contrast, Altaee et al. (2025) focused on six Gulf Cooperation Council (GCC) countries from 1990 to 2020 and applied FMOLS, PCSE, and FGLS methods. Their findings consistently demonstrated that environmental degradation hurts life expectancy. However, economic growth, urbanization, and energy consumption were positively linked to improved longevity, suggesting a complex interplay in which energy use may simultaneously drive development and increase health risks. Notably, their study identified energy consumption as a mediating variable that can amplify the adverse effects of CO_2 emissions on public health. These studies collectively support the need for a more nuanced approach, such as examining marginal and asymmetric effects, which the present research contributes by focusing on ASEAN countries and employing both linear and nonlinear modeling techniques to assess how marginal emissions differentially affect life expectancy.

In a closely related regional context, Shaari et al. (2024b) analyzed the determinants of life expectancy in ASEAN-5 countries from 1995 to 2020 using FMOLS, DOLS, and CS-ARDL estimators. Their results highlight that health investment has a positive influence on life expectancy in countries such as Thailand and the Philippines. At the same time, economic growth contributes to improved longevity in several ASEAN member states. However, a consistent negative association was found between CO_2 emissions and life expectancy across the region. This study provides valuable regional insights, demonstrating that while development indicators such as investment and growth can improve public health outcomes, environmental degradation remains a significant risk. These findings support broader international arguments for cleaner energy transitions and reinforce the theoretical expectation that health and environmental policies should be considered jointly. Unlike the current study, however, their analysis is based on total emissions and assumes symmetrical effects. In contrast, the present research extends this by introducing marginal CO_2 emissions and testing for asymmetric relationships, thereby offering a more detailed understanding of how incremental environmental changes shape health outcomes in the ASEAN context.

Offering valuable insights from one of the world's most ecologically fragile regions, Saidmamatov et al. (2024) investigated the Aral Sea basin from 2002 to 2020 using FMOLS, DOLS, and Driscoll–Kraay estimation techniques. Their analysis revealed a significant negative relationship between CO_2 emissions and life expectancy, while increased investment in health and human capital was associated with improvements in longevity. This study underscores the heightened vulnerability of populations in environmentally degraded ecosystems and demonstrates how environmental stressors amplify existing health risks. Extending this environmental-health narrative, Javanshirova (2024) examined long-term data from Azerbaijan (1974–2022) using A-ARDL, CCR, and FMOLS models. The findings confirmed that rising CO_2 emissions lead to lower life expectancy, and the application of the Fourier Toda–Yamamoto causality test established a unidirectional causal relationship from emissions to life expectancy. Together, these studies provide both correlational and causal evidence that environmental degradation is not merely associated with declining health outcomes but can act as a direct driver. While these analyses enhance the understanding of the emissions–health linkage in specific ecological contexts, they primarily rely on total emissions and linear assumptions. The present study builds on these insights by focusing on marginal emissions and introducing nonlinear modeling to explore asymmetric effects, offering a more refined perspective on how incremental environmental stress influences life expectancy in the ASEAN region.

Finally, Li et al. (2023) examined the five largest carbon-emitting nations—China, the U.S., Russia, India, and Japan from 1975 to 2015, using Johansen cointegration and Gregory–Hansen structural break tests. Their findings indicate that long-run relationships exist between CO_2 emissions, mortality, energy consumption, GDP, and life expectancy. Structural shifts in health outcomes corresponded to significant policy changes, emphasizing the dynamic nature of the emissions–health nexus. This macro-level analysis highlights the critical role of national policies in shaping both environmental and public health trajectories.

While the existing literature offers robust evidence on the health effects of total CO_2 emissions, it largely overlooks the importance of marginal emissions as a more dynamic and policy-relevant indicator of energy efficiency. Moreover, the use of predominantly linear models may fail to capture the asymmetric nature of emission–health relationships. To address these gaps, this study introduces marginal CO_2 emissions as a central variable and applies both linear and nonlinear panel methodologies. By focusing on ASEAN countries, which are undergoing rapid energy transitions and experiencing uneven public health outcomes, this study offers new empirical insights into how changes in emissions intensity affect life expectancy in a region of growing strategic and environmental importance.

Research methodology

Conceptual Framework: Marginal Product and Marginal CO_2 Emissions

Marginal Product (MP) is a fundamental concept in economics that refers to the additional output generated when one extra unit of input is added. In contrast, all other inputs are held constant. It is used to measure the productivity of inputs such as labor or capital. The marginal product is calculated using the formula:

$$\mathrm{MP} = \frac{\triangle \mathrm{Q}}{\triangle \mathrm{L}}$$

where ΔQ represents the change in total output, and ΔL represents the change in input, typically labor. This concept is essential for firms to determine whether it is efficient and profitable to increase input usage.

Extending this concept, the present study introduces the idea of Marginal CO_2 Emissions (MCO_2) to analyze environmental outcomes associated with energy use. Marginal CO_2 emissions represent the change in carbon dioxide emissions resulting from the consumption of one additional unit of energy. This is expressed as:

$$\triangle \mathrm{CO}_2 = \frac{\triangle \mathrm{CO}_2}{\triangle \mathrm{EU}}$$

where ΔCO_2 is the change in total carbon emissions, and ΔEU is the change in energy consumption. This ratio serves as an indicator of energy efficiency. If Δ CO_2 increases, implying that additional energy consumption results in greater environmental harm, which suggests low energy efficiency. On the other hand, a decrease in ΔCO_2 suggests that more energy is being used with less environmental damage, which reflects improved energy efficiency. Understanding marginal CO_2 emissions is important for policymakers seeking to promote sustainable energy consumption. It helps evaluate whether increased energy use contributes proportionately to environmental degradation or whether cleaner, more efficient energy systems are in place.

To reveal the study's output and achieve its objectives, the Panel autoregressive distributed lag (ARDL) and nonlinear autoregressive distributed lag (NARDL) methodologies are employed and examined. The set of variables tested consists of Life Expectancy (LE) as the dependent variable. Meanwhile, the independent variables consist of Health Expenditure (LNHE), Economic expansion (LNGDP), Marginal CO_2 emissions (LNDCO2/DEU), and inflation (LNCPI). The linear Autoregressive Distributed Lag (ARDL) framework is used to evaluate the symmetric effect. However, the nonlinear Autoregressive Distributed Lag (NARDL) model is employed to assess the asymmetric impact of marginal CO_2 emissions on Life Expectancy in both the short and long run. Table 2 presents an examination of the variables' information.

Hence, the model specification can be written as follows:

$$\begin{aligned}&LNLE_{it} = \alpha_0 + \alpha_1 LNHE_{it} + \\ &\alpha_2 LNGDP_{it} + \alpha_3 LNCPI_{it} + \\ &\alpha_4 LNDCO2/DEU_{it} + \varepsilon_{it},\end{aligned} \tag{1}$$

In this model, LNLE represents the natural logarithm of Life Expectancy for entity *i* at time *t*. The explanatory variables include LNHE, which is the natural logarithm of Health Expenditure per capita; LNGDP, representing the natural logarithm of Economic expansion measured by GDP per capita; LNCPI, the natural logarithm of Inflation as measured by the Consumer Price Index; and LNDCO2/DEU, the natural logarithm of Marginal CO₂ Emissions per unit of energy use. α_0 is the intercept of the model, while α_1, α_2, α_3 and α_4 are the coefficients that capture the elasticity, indicating the percentage change in Life Expectancy resulting from a 1% change in each respective explanatory variable. Lastly, ε_{it} represents the error term, which accounts for other unobserved factors that may influence Life Expectancy but are not included in the model.

Table 2 Variable information

Variable	Proxy	Symbol	Source	Previous Studies
Life Expectancy	Life expectancy at birth, total (years)	LNLE	World Bank	(člának 2014; Alsalem, et al., 2020; You, et al. 2025)
Health Expenditure	Current health expenditure per capita (current US$)	LNHE	World Bank	(Fosu, et al. 2025; Ramadan, et al., 2025; Abouelela & Abdelhamid 2025)
Economic expansion	GDP per capita (constant US$)	LNGDP	World Bank	(Bodenstein & Scaramucci 2025; Hope 2025)
Inflation	Consumer price index	LNCPI	World Bank	(Septevenus, et al. 2025; Sichel & Mackie 2025)
Marginal CO_2 emission	CO₂ emission divided by energy used	LNDCO2/DEU	World Bank and authors' contributions	Authors' Calculation

The analysis employs two distinct approaches: the conventional ARDL method and its non-linear counterpart. The non-linear ARDL approach uncovers critical thresholds, turning points, and complex patterns that significantly shape the effect of Marginal CO₂ Emissions on Life Expectancy. This advanced approach addresses the limitations of traditional linear ARDL techniques, allowing for a deeper understanding of the complex relationship between these variables (Shaari et al. 2025). Through detailed examination, it uncovers the underlying intricacies of the subject. Non-linear models also provide a better fit to the data and explain a greater portion of the observed variation. The application of the non-linear ARDL method improves the model's accuracy and strengthens the estimation of the relationship between Marginal CO₂ Emissions and Life Expectancy. As noted by Mukhtar et al. (2018) and Shin et al. (2014), the NARDL method delivers more robust and dependable outcomes, offering superior insight into complex dynamic behaviors.

Panel ARDL

The model specification can subsequently be categorized into linear and asymmetric forms, both in the long and short run. In the case of the linear specification without accounting for asymmetry, the model can be expressed as shown in Eq. (2) and Eq. (3).

$$\begin{aligned}&\Delta LNLE_{it} = \beta_0 + \beta_1 LNLE_{it-1} + \\ &\beta_2 LNHE_{it-1} + \beta_3 LNGDP_{it-1} + \\ &\beta_4 LNCPI_{it-1} + \beta_5 LNDCO2/DEU_{it-1} + \\ &\sum_{I=1}^{n1} \delta_i \Delta LNLE_{it-I} + \sum_{j=1}^{n2} \gamma_j \Delta LNHE_{it-j} + \\ &\sum_{k=1}^{n3} \lambda_k \Delta LNGDP_{it-k} + \sum_{m=1}^{n4} \theta_m \Delta LNCPI_{it-m} + \\ &\sum_{p=1}^{n5} \phi_p \Delta LNDCO2/DEU_{it-p} + \varepsilon_{it},\end{aligned} \tag{2}$$

$$\begin{aligned}&\Delta LNLE_{it} = \omega ECT_{it-1} + \sum_{I=1}^{n1} \delta_I \Delta LNLE_{it-I} + \\ &\sum_{j=1}^{n2} \gamma_j \Delta LNHE_{it-j} + \sum_{k=1}^{n3} \lambda_k \Delta LNGDP_{it-k} + \\ &\sum_{m=1}^{n4} \theta_m \Delta LNCPI_{it-m} + \sum_{p=1}^{n5} \phi_p \Delta LNDCO2/DEU_{it-p} + \varepsilon_{it},\end{aligned} \tag{3}$$

The summary of Eqs. (2) and (3) can be described as follows:

- $\Delta LNLE_{it}$: Change in life expectancy for entity *i* at time *t*
- ωECT_{it-1}: Error correction term lagged one period (long-run equilibrium adjustment)

- o $\sum_{I=1}^{n1}\delta_I\Delta LNLE_{it-I}$: Lags of changes in life expectancy (short-run dynamics)
- o $\sum_{j=1}^{n2}\gamma_j\Delta LNHE_{it-j}$: Lags of changes in health expenditure
- o $\sum_{k=1}^{n3}\lambda_k\Delta LNGDP_{it-k}$: Lags of changes in GDP
- o $\sum_{m=1}^{n4}\theta_m\Delta LNCPI_{it-m}$: Lags of changes in inflation
- o $\sum_{p=1}^{n5}\phi_p\Delta LNDCO2/DEU_{it-p}$: Lags of changes in CO₂ emissions per energy use
- o ε_{it}: Error term

Nonlinear panel ARDL

The formulation in Eq. (1) can now be extended to account for asymmetry as follows:

$$LNLE_{it}=\rho_0+\rho_1 LNDCO2/DEU^+_{it}+ \rho_2 LNDCO2/DEU^-_{it}+\rho_3 LNHE_{it}+ \rho_4 LNGDP_{it}+\rho_5 LNCPI_{it}+\mu_{it}, \tag{4}$$

The underlying premise is that rising and falling marginal CO₂ emissions exert asymmetric effects on life expectancy (LNLE). Therefore, the asymmetric relationships in both the short and long term are formulated as shown in Eq. (5) below:

$$\begin{gathered}LNDCO2/DEU^+_{it}=\sum_{j=1}^{t}\Delta LNDCO2/DEU^+_{ij}= \\ \sum_{j=1}^{t}\max(\Delta LNDCO2/DEU^+_{ij},0) \\ LNDCO2/DEU^-_{it}=\sum_{j=1}^{t}\Delta LNDCO2/DUE^-_{ij}= \\ sum_{j=1}^{t}\min(\Delta LNDCO2/DEU^-_{ij,}0)\end{gathered} \tag{5}$$

Then the extension of the asymmetric model is constructed as follows:

$$\begin{aligned}&oneapN, capC, capP, \Delta LNLE_{it}= \\ &\eta_i+\gamma_{1i}LNLE_{it-1}+ \\ &\gamma^+_{2i}LNDCO2/DEU^+_{it-1}+ \\ &\gamma^-_{2i}LNDCO2/DEU^-_{it-1}+\gamma_{3i}LNHE_{it-1}+ \\ &\gamma_{4i}LNGDP_{it-1}+\gamma_{5i}LNCPI_{it-1}+ \\ &\sum_{j1}^{p1}\delta_{1ij}\Delta LNLE_{it-j}+ \\ &\sum_{j=1}^{p2}\left(\delta^+_{2ij}\Delta LNDCO2/DEU^+_{it-1}+ \right. \\ &\left.\delta^-_{2ij}\Delta LNDCO2/DEU^-_{it-1}\right)+ \\ &\sum_{j=1}^{p3}\delta_{3ij}\Delta LNHE_{it-1}+ \\ &\sum_{j=1}^{p4}\delta_{4ij}\Delta LNGDP_{it-1}+ \\ &\sum_{j=1}^{p5}\delta_{5ij}\Delta LNCPI_{it-1}+\varepsilon_{it}\end{aligned} \tag{6}$$

Meanwhile, the long-term asymmetric response of LNLE to positive and negative shocks in marginal CO₂ emissions is estimated from γ^+_{2i} and γ^-_{2i} The short-term asymmetric response is captured via δ^+_{2ij} and δ^-_{2ij}.

Table 3 Descriptive Statistics

	LNLE	LNHE	LNGDP	LNDCO2/DEU	LNCPI
Mean	4.2633	4.8547	8.3710	0.1178	4.5972
Median	4.2718	4.7020	8.0281	0.0284	4.6131
Maximum	4.4260	8.3711	11.1265	1.7142	5.2050
Minimum	4.0318	1.5319	5.7960	−1.4278	2.8989
Std. Dev	0.0810	1.4147	1.3238	0.3627	0.3211
Skewness	−0.2448	0.2921	0.6062	0.9084	−1.3730
Kurtosis	2.7077	2.6671	2.3771	9.2042	6.9910
Jarque–Bera	2.9545	4.1062	16.8771	379.6224	213.1713
Probability	0.2283	0.1283	0.0002	0.0000	0.0000
Observations	218	218	218	218	218

Table 4 Cross-Section Dependence Results

Test	Statistic	d.f	Prob
Breusch-Pagan LM	31.0903	45	0.9429
Pesaran scaled LM	−1.4662		0.1426
Pesaran CD	0.2060		0.8368

Findings

Table 3 presents the descriptive statistics for five variables over 218 observations. LNLE and LNHE exhibit relatively symmetric distributions with low skewness and are approximately normally distributed, as indicated by the Jarque–Bera test. In contrast, LNGDP, LNDCO2\DEU, and LNCPI deviate from normality, with significant skewness and leptokurtic characteristics, particularly LNDCO2\DEU (kurtosis = 9.20) and LNCPI (kurtosis = 6.99). Among all variables, LNHE and LNGDP show the highest variability, as indicated by their standard deviations. Overall, while some variables align closely with the normal distribution, others display non-normal traits, suggesting the need for careful consideration in subsequent econometric modeling.

Table 4 reports the results of cross-section dependence tests. All three tests, namely the Breusch-Pagan LM, Pesaran scaled LM, and Pesaran CD, yield high p-values (0.9429, 0.1426, and 0.8368, respectively), indicating that the null hypothesis of cross-sectional independence cannot be rejected. This suggests that there is no significant cross-sectional dependence among the variables in the panel, supporting the validity of models that assume independent cross-sectional units.

Table 5 presents the panel unit root test results using Levin-Lin-Chu (LLC), ADF, and PP tests. The results show that all variables are non-stationary at a level for at least one of the tests, particularly LNHE and LNGDP, which fail to

Table 5 Unit Root Results

		LLC		ADF		PP	
Variable	Form	Stat	Prob	Stat	Prob	Stat	Prob
LNCPI	Level	−5.1852	0.0000	30.7926	0.0580	69.1070	0.0000
	1 st Difference	−6.3252	0.0000	66.8484	0.0000	66.6608	0.0000
LNDCO2/DEU	Level	−11.7840	0.0000	127.9600	0.0000	152.7530	0.0000
	1 st Difference	−16.0778	0.0000	209.6770	0.0000	1025.9900	0.0000
LNLE	Level	−3.1135	0.0009	42.9386	0.0021	73.6213	0.0000
	1 st Difference	−2.1887	0.0143	78.0530	0.0000	927.8680	0.0000
LNHE	Level	−2.3022	0.0107	14.1580	0.8224	18.7485	0.5382
	1 st Difference	−11.4837	0.0000	131.1380	0.0000	135.0840	0.0000
LNGDP	Level	−3.6073	0.0002	15.1401	0.7683	29.4104	0.0800
	1 st Difference	−5.5991	0.0000	81.0121	0.0000	99.5907	0.0000

Table 6 Long-run Coefficient Symmetry

Variable	Statistic	Value	Probability
LNDCO2/DEU	F-statistic	132.7300	0.0000
	Chi-square	132.7300	0.0000

Table 7 Pedroni Residual Cointegration Results

Alternative hypothesis: common AR coefs. (within-dimension)		
	Statistic	Prob
Panel PP-Statistic	−7.02242	0.0000
Panel ADF-Statistic	−1.92431	0.0272
Alternative hypothesis: individual AR coefs. (between-dimension)		
	Statistic	Prob
Group PP-Statistic	−5.19275	0.0000
Group ADF-Statistic	−0.06523	0.4740

Table 8 NARDL and ARDL Estimations

		NARDL		
		Long run		
Variable	Coefficient	Std. Error	t-Statistic	Prob
LNHE	−0.0339	0.0066	−5.1485	0.0000
LNGDP	−0.0147	0.0085	−1.7271	0.0858
LNCPI	0.2297	0.0216	10.6462	0.0000
LNDCO2/DEU +	−0.0085	0.0027	−3.1960	0.0016
LNDCO2/DEU-	0.0089	0.0023	3.8780	0.0001
		Short run		
Variable	Coefficient	Std. Error	t-Statistic	Prob
ECT	−0.3245	0.1749	−1.8551	0.0651
D(LNHE)	0.0064	0.0113	0.5730	0.5679
D(LNGDP)	0.1380	0.0938	1.4712	0.1429
D(LNCPI)	−0.1163	0.0353	−3.2946	0.0012
D(LNDCO2/DEU +)	−0.2009	0.2200	−0.9134	0.3622
D(LNDCO2/DEU-)	−0.0002	0.0289	−0.0069	0.9945
C	1.1211	0.6177	1.8150	0.0711
		ARDL		
		Long run		
Variable	Coefficient	Std. Error	t-Statistic	Prob
LNHE	−0.0048	0.0031	−1.5774	0.1163
LNGDP	−0.0166	0.0031	−5.3649	0.0000
LNCPI	0.0703	0.0096	7.3028	0.0000
LNDCO2/DEU	−0.0008	0.0031	−0.2696	0.7877
		Short run		
Variable	Coefficient	Std. Error	t-Statistic	Prob
ECT	−0.1775	0.2586	−0.6863	0.4933
D(LNHE)	−0.0033	0.0090	−0.3689	0.7128
D(LNGDP)	−0.0075	0.0364	−0.2059	0.8371
D(LNCPI)	−0.0446	0.0329	−1.3546	0.1771
D(LNDCO2/DEU)	−0.0434	0.0403	−1.0762	0.2831
C	0.7003	1.0724	0.6530	0.5145

reject the null hypothesis of a unit root in the ADF and PP tests, despite being significant in the LLC test. However, after first differencing, all variables become stationary at the 1% level across all three tests (LLC, ADF, and PP), indicating they are integrated of order one, I(1). Since none of the variables are I(2) and most are I(1), the necessary precondition for applying the panel ARDL and NARDL models is satisfied. Therefore, it is appropriate to proceed with panel ARDL and NARDL estimations.

Table 6 presents the results of the coefficient symmetry test for LNDCO2/DEU, evaluating whether positive and negative changes exert symmetric effects on the dependent variable in the long run. In the long run, both the F-statistic and Chi-square values are 132.7300 with a p-value of 0.0000, indicating strong statistical evidence to reject the null hypothesis of symmetry. This suggests that increases and decreases in LNDCO2/DEU have significantly different long-run effects.

Table 7 reports the Pedroni residual cointegration test results. Under the within-dimension approach, both the Panel PP-statistic and Panel ADF-statistic are statistically significant at the 1% and 5% levels, respectively, indicating the presence of cointegration among the variables. Under the between-dimension approach, the Group PP-statistic also confirms cointegration with a p-value of 0.0000, while the Group ADF-statistic is not significant. Overall, the majority of the test statistics support the existence of a long-run cointegration relationship, thus justifying the use of long-run estimation techniques such as ARDL or NARDL models.

Table 8 presents a comparison of the long-run and short-run estimates from the NARDL and ARDL models. In the long run, the NARDL results suggest that several variables have a significant influence on life expectancy. Health expenditure shows a statistically significant adverse effect at the 1% level. Specifically, a 1% increase in health expenditure is associated with a 0.0339% decrease in life expectancy, suggesting potential inefficiencies or misallocations in healthcare spending. This finding is not unusual, as several previous studies—such as those by Shaari et al. (2025), Ahmed et al. (2011), and Kim and Lane (2013)—have also found a negative relationship between health expenditure and life expectancy. Inflation has a strong and positive impact on life expectancy, also significant at the 1% level. A 1% increase in inflation is associated with a 0.2297% increase in life expectancy. This finding differs from Movsisyan et al. (2024), who reported that inflation primarily harms health, particularly among certain socioeconomic groups that are more vulnerable. Bao et al. (2022) also found that inflation can hurt health. This counterintuitive finding may reflect underlying structural factors in the economy, such as higher inflation coinciding with economic growth or increased government spending on social services. Economic expansion exhibits a negative relationship with life expectancy, which is weakly significant at the 10% level. The results suggest that a 1% increase in economic activity may reduce life expectancy by 0.0147% in the long term, possibly due to environmental degradation or the widening of income inequality associated with rapid growth. This result is consistent with the findings of Hendrawaty et al. (2022), who reported a negative relationship between economic growth and life expectancy in the ASEAN region. Furthermore, the results demonstrate apparent asymmetric effects of marginal CO_2 emissions: a 1% increase in marginal emissions significantly reduces life expectancy. In comparison, a 1% decrease leads to a 0.0089% increase—statistically significant at the 1% level. These findings are broadly in line with Mahalik et al. (2022), who examined the impact of CO_2 emissions on life expectancy using different sources of emissions rather than marginal emissions. While their approach provides valuable insights, it lacks a focus on the efficiency dimension. The current findings emphasize that when energy use becomes less efficient, resulting in higher emissions per unit of energy consumed, it hurts health outcomes. Conversely, improving energy efficiency contributes to better health by reducing harmful emissions.

In the short term, the NARDL results indicate that only inflation has a statistically significant impact on life expectancy. Specifically, a 1% increase in inflation results in a 0.1163% decline in life expectancy, significant at the 1% level. This suggests that rising prices can rapidly erode access to essential services, such as healthcare, nutrition, and other necessities, thereby negatively impacting health outcomes. This finding is consistent with the results of Movsisyan et al. (2024) and Bao et al. (2022), who also identified the adverse effects of inflation on public health. In contrast, short-run variations in marginal CO_2 emissions, health expenditure, and economic growth do not exhibit statistically significant impacts, implying that their effects on life expectancy are either delayed or mediated through more complex, long-term mechanisms. Notably, improving energy efficiency (i.e., reducing marginal emissions) may contribute to better health outcomes over time. The error correction term (ECT) is negative and marginally significant, indicating a moderate pace of adjustment toward long-run equilibrium.

In contrast, the ARDL model shows that in the long run, only economic expansion and inflation have statistically significant effects on life expectancy. Economic expansion is significant at the 1% level, with a 1% increase in GDP associated with a 0.0166% decrease in life expectancy at birth. This negative relationship may reflect the environmental or social costs of rapid economic growth. Inflation is also significant at the 1% level, where a 1% rise in inflation corresponds to a 0.0703% increase in life expectancy, possibly indicating improved government spending or income redistribution during inflationary periods. However, marginal CO_2 emissions and health expenditure are not statistically significant, suggesting that a 1% increase in either variable does not lead to a measurable change in life expectancy in the long run. In the short run, the ARDL results reveal that none of the variables, including the error correction term (ECT), are statistically significant. This indicates weak short-term dynamics and limited responsiveness of life expectancy to sudden shocks or policy changes. Overall, the ARDL model suggests that while some long-run relationships exist, particularly between inflation, health expenditure, and economic expansion, the short-run effects on life expectancy are negligible.

Discussion

The findings of this study reveal that increasing health expenditure is associated with a reduction in life expectancy in ASEAN countries. Although this result may seem counterintuitive, it aligns with the findings of Shaari et al. (2025), highlighting that the effectiveness of health spending matters more than the amount spent. In other words, higher expenditure does not automatically translate into better health outcomes unless the resources are allocated efficiently and strategically. Supporting this view, Grigoli and Kapsoli (2013) emphasized that in developing economies, such as Malaysia and Indonesia, simply increasing public health expenditure may yield limited improvements in health indicators if the efficiency of spending remains low. Their analysis, using a stochastic frontier model, demonstrated that significant inefficiencies exist in the utilization of health resources, which limits the potential impact of such spending on health outcomes. Furthermore, this study reveals that economic expansion may lead to a decline in life expectancy.

Although higher GDP is generally linked to improved living standards, in the ASEAN context, rapid economic expansion is often driven by industrialization, urban expansion, and the exploitation of natural resources, which frequently result in environmental degradation and health-related challenges. Adverse effects such as increased air and water pollution, sedentary lifestyles, and heightened stress levels may offset the health gains typically associated with economic development, especially when such growth is uneven or unsustainable. Furthermore, higher economic expansion is commonly associated with increased CO_2 emissions (González-Álvarez & Montañés, 2023), and elevated emissions have been found to impact life expectancy negatively. Supporting this, Mahalik et al. (2022) reported a significant negative relationship between CO_2 emissions and life expectancy.

Inflation is negatively associated with life expectancy, primarily because it reduces individuals' purchasing power and increases the cost of healthcare. Bao et al. (2022) found that inflation contributes to higher mortality rates, thereby lowering life expectancy. Similarly, Lee et al. (2016) observed that rising inflation weakens consumers' ability to purchase essential goods and alters consumption patterns in ways that can lead to malnutrition and poor health. As prices increase, individuals, particularly those in low- and middle-income groups, struggle to afford necessities such as nutritious food, clean water, and healthcare services. This economic strain often forces households to cut back on vital health-related expenses, resulting in poorer health outcomes. Furthermore, inflation drives up the cost of medical goods and services, making healthcare less accessible. Consequently, many people may delay or avoid necessary treatments, allowing preventable conditions to progress. Together, these effects contribute to a decline in overall life expectancy.

While many studies, such as Shaari et al. (2024b) and Rahman et al. (2022), focus on the relationship between total CO_2 emissions and life expectancy, they often overlook the role of marginal CO_2 emissions. Marginal CO_2 emissions provide a more precise measure of energy efficiency by indicating the additional carbon emissions generated from a one-unit increase in energy use ($\Delta CO_2/\Delta EU$). This study confirms that rising marginal CO_2 emissions significantly reduce life expectancy, highlighting the adverse impact of inefficient energy use on public health. In contrast, a decrease in marginal emissions is associated with an improvement in life expectancy. This finding highlights the crucial link between environmental quality and public health. High marginal emissions imply that increased energy consumption is heavily reliant on fossil fuels, such as coal and oil, which emit large amounts of pollutants alongside CO_2, including particulate matter (PM2.5), sulfur dioxide (SO_2), and nitrogen oxides (NOx).

These pollutants are known to contribute to respiratory and cardiovascular diseases, cancer, and premature mortality. In densely populated urban areas, where industrial activity and vehicle usage are concentrated, the health burden of such emissions is even more severe. On the other hand, a decline in marginal CO_2 emissions suggests improved energy efficiency or a transition toward cleaner energy sources, such as hydro, solar, wind, or natural gas. When countries consume more energy without a proportional increase in emissions, it indicates progress toward decarbonization and sustainable development. This transition not only supports climate goals but also yields immediate health benefits by reducing exposure to air pollution. The improvement in air quality can lead to lower hospital admissions, reduced prevalence of chronic illnesses, and ultimately extended life expectancy.

Conclusion

This study examined the symmetric and asymmetric effects of marginal CO_2 emissions on life expectancy in ASEAN countries from 2000 to 2022, using both the Panel ARDL and Nonlinear ARDL (NARDL) approaches. The findings confirm that marginal CO_2 emissions have a significant and asymmetric influence on public health. Specifically, increases in marginal emissions lead to a reduction in life expectancy, while decreases contribute to its improvement. This result highlights the role of energy efficiency in shaping health outcomes and supports the superiority of the NARDL model in capturing these nonlinear dynamics.

In the long run, life expectancy was also found to be influenced by health expenditure, economic expansion, and inflation. However, the results reveal that increased health spending and economic growth were unexpectedly associated with declines in life expectancy, suggesting inefficiencies in health systems or environmental trade-offs linked to economic activity. Inflation, by contrast, had a positive long-term effect but was negatively associated with life expectancy in the short term. These findings reinforce the complex relationship between macroeconomic factors, environmental quality, and population health.

The implications of this study are particularly relevant for ASEAN stakeholders, including national governments, regional agencies, energy ministries, and public health authorities. Reducing marginal CO_2 emissions through investments in cleaner technologies, renewable energy, and more efficient energy use can lead to tangible improvements in health outcomes. At the same time, health sector reforms should focus on the effective allocation and monitoring of expenditures to ensure they translate into actual gains in life expectancy. Given the asymmetric effects observed, policy frameworks should account for both the direction and magnitude of changes in emissions when designing environmental and health strategies. A coordinated, multisectoral approach that integrates environmental sustainability, economic development, and health system strengthening is essential for safeguarding long-term population well-being across the ASEAN region.

Limitations and suggestions for future research

This study offers valuable insights into the asymmetric effects of marginal CO_2 emissions on life expectancy in ASEAN countries; however, several limitations should be noted. While the Panel ARDL and NARDL models effectively capture both short- and long-run dynamics, the analysis may be sensitive to model specification and the exclusion of important variables. Factors such as particulate matter exposure, renewable energy penetration, regulatory quality, and healthcare infrastructure were not included and may influence the outcomes. Additionally, the use of national-level data may obscure important regional differences within countries, particularly those with vast geographic and socioeconomic disparities. The study also does not fully account for external shocks, such as the COVID-19 pandemic or sudden energy transitions, which could temporarily disrupt the relationship between emissions and health. Moreover, potential endogeneity between variables such as GDP, health expenditure, and life expectancy could affect causal interpretation, despite the robustness of the methods used.

Future research should consider disaggregated health indicators, cross-regional comparisons, and more granular subnational data to gain a deeper understanding of the health landscape. The use of advanced econometric methods, such as dynamic panel models or structural modeling, may also help address endogeneity and nonlinearities while enriching the understanding of environmental and health linkages in rapidly developing regions.

Author contributions MSS contributed significantly to the analytical narrative, drafting the abstract, literature review, results, and discussion sections. MSS also played a central role in interpreting the empirical findings in relation to the existing literature. AHHM conceptualized the study framework and led the development of the introduction, theoretical background, limitations, and suggestions for future research sections. AHHM also managed the coordination of the manuscript's final submission and ensured coherence across sections. AS designed the research methodology and was responsible for articulating the methods and conclusion sections. All authors collaboratively reviewed, edited, and approved the final version of the manuscript.

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Declarations

Ethics approval and consent to participate This study did not involve human participants, human data, or human tissue. Hence, ethics approval and consent to participate were not required.

Consent for publication All authors have reviewed and approved the final manuscript and consent to its publication.

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