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Coal consumption as a moderator in the link between industrial output and life expectancy in ASEAN nations

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Abstract

This study examines the relationship between industrial output and life expectancy in ASEAN countries from 2000 to 2021, emphasizing coal consumption as a moderating factor. Using the Panel ARDL method, the findings reveal that industrial output positively impacts life expectancy, highlighting the economic benefits of industrialization, such as improved healthcare access and job creation. Model 1's industrial output coefficient is 0.1542, while Model 2's is 0.2352, both models giving a *p*-value of 0.0000. However, this positive effect is significantly offset by coal consumption, which detracts from life expectancy due to environmental degradation and health hazards such as respiratory and cardiovascular diseases. This coefficient is 0.0722 (*p*-value: 0.0000) in Model 2 and 0.8457 (*p*-value: 0.0000) in Model 1. The study further shows that the interaction between industrial output and coal consumption exacerbates these adverse effects, underlining the critical need for sustainable industrial practices. Practical implications include the necessity for targeted green policies, such as phasing out coal subsidies, adopting renewable energy technologies, and implementing carbon taxation, to mitigate the detrimental health impacts of coal consumption while maintaining industrial growth. Identifying critical thresholds, such as coal consumption exceeding 50% of the energy mix or industrial output growth surpassing 5–10% annually without corresponding energy efficiency improvements, provides actionable insights for policymakers. These findings highlight the importance of balancing industrial development with sustainable health and environmental outcomes through informed policy interventions.

Highlights

- Panel ARDL results reveal a significant positive effect of industrial output on life expectancy.
- Coal consumption mitigates the positive effect of industrial output, significantly reducing life expectancy due to environmental pollution and health risks.
- The study emphasizes the need for green policies such as subsidies, incentives, adopted renewable energy and encouraged public-private partnerships to reduce the harmful effects of coal consumption on life expectancy.

Keywords Coal consumption, Industrial output, Life expectancy, ASEAN, Environmental degradation

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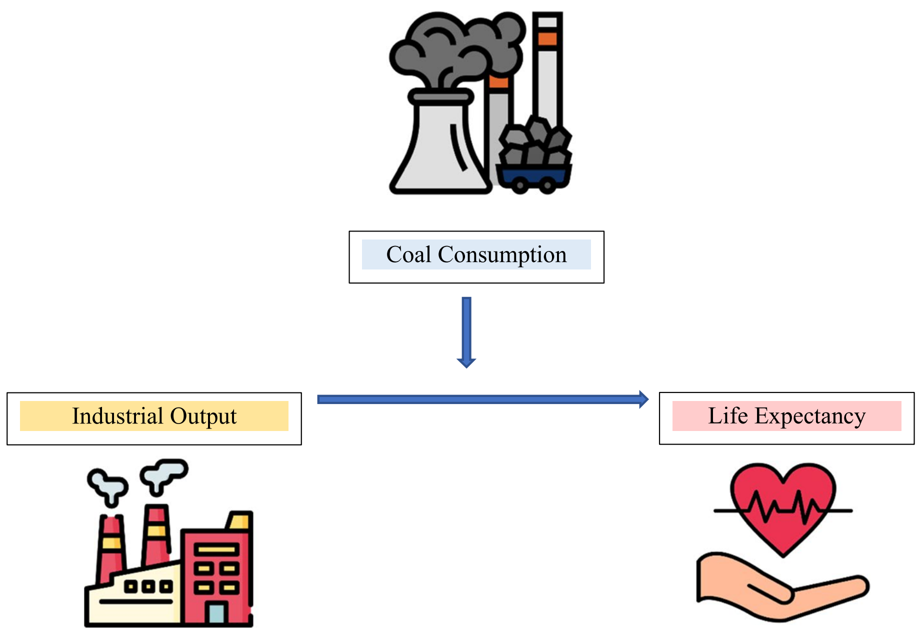
Graphical Abstract



1 Introduction

The linkage between economic activities and public health has garnered significant attention recently, particularly in developing regions (He and Li 2020; Luo and Xie 2020; Chuang 2021). However, this study exclusively focuses on Association of South East Asian Nation (ASEAN) countries due to their unique developmental trajectories, energy dependencies, and environmental challenges. As these nations pursue industrialization to boost economic expansion and improve living standards, industrial output has become a cornerstone of their development strategies. Industrial activities drive employment, infrastructure development, and innovation, making them essential for economic progress. Employment in the manufacturing sector contributed 16.8%, 14.2%, and 23.3% of the total in Malaysia, Indonesia, and Vietnam, respectively (Statista Research Department 2024). However, this rapid industrial growth often brings substantial environmental and health challenges, particularly due to the increased energy consumption that fuels these activities. One of the primary concerns associated with industrial expansion is the environmental degradation it causes, particularly air (Puntoon et al. 2022).

ASEAN nations face specific challenges in balancing industrialization with sustainability, given their reliance on coal, which is one of the most polluting energy sources. Figure 1 provides a breakdown of the energy supply mix (in percentage) across nine ASEAN countries: Malaysia, Indonesia, Singapore, the Philippines, Brunei, Vietnam, Cambodia, Thailand, and Myanmar. It shows a different energy source, showing the share of that source in the total energy supply for each country. Coal is a significant energy source for countries like Vietnam (45.14%) and Indonesia (36.39%), while its contribution is minimal in Myanmar (1.59%) and Singapore (1.11%). In comparison, natural gas dominates the energy mix in Brunei (57.74%) and Malaysia (47.03%) but plays a smaller role than coal in Vietnam (7.50%) and Myanmar (15.87%). Oil surpasses coal in importance in Singapore (71.43%) and Thailand (42.35%), whereas coal remains more dominant in Vietnam and Indonesia. Biofuels and waste are a key energy source in Myanmar (51.21%) and Cambodia (35.10%), though they are far less significant than coal in Vietnam and Indonesia. Hydropower has moderate importance in Vietnam (8.10%) but generally contributes less than coal across most countries. Similarly, renewable energy sources such as geothermal, solar, and wind are most prominent in the Philippines (14.67%) but remain a minor part of the energy mix compared to coal in other nations. Overall, coal remains a crucial energy source in Vietnam and Indonesia, while other countries like Singapore, Brunei, and Myanmar rely more on oil, gas, or biofuels.

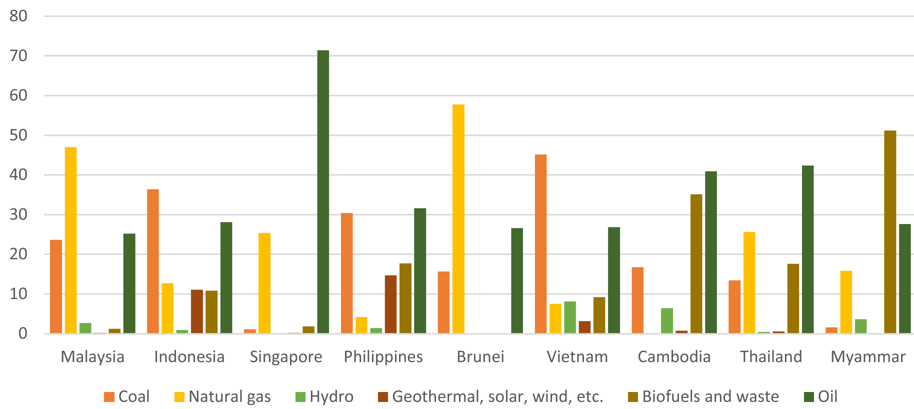


Fig. 1 Energy supply mix in ASEAN countries. Source: International Energy Agency (2024)

Industrial processes frequently rely on fossil fuels, including coal, which emit harmful pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), and particulate matter into the atmosphere. Due to industrial demands and economic expansion, coal remains an essential energy source for ASEAN. Coal-fired power plants dominate the energy mix in Indonesia, Vietnam, and the Philippines. Indonesia, the largest user and exporter, accounted for 36% of the region's primary energy supply and 40% of its power output in 2024 (Ambya and Hamzah 2022; International Energy Agency 2024; ASEAN Energy Database System 2024). To ensure energy security and affordability, ASEAN has increased its reliance on coal despite growing global decarbonization efforts. Vietnam and the Philippines primarily rely on coal for power, while Thailand, Vietnam, and Indonesia are major consumers. To reduce dependence on coal, ASEAN nations are increasingly focusing on renewable energy sources and stricter emissions regulations.

These pollutants have been linked to a range of health issues, including respiratory diseases, cardiovascular problems, and even premature mortality, thus negatively impacting public health. The concentration of industrial activities in urban areas exacerbates these health challenges, as densely populated regions experience more significant exposure to pollution. Moreover, the rise in energy consumption linked to industrial growth (Shaari et al. 2023) exacerbates environmental pressures, especially in countries that rely heavily on coal and other non-renewable energy sources. ASEAN's developmental context makes it a critical case study. Many of its member states are developing nations navigating the trade-offs between economic expansion and sustainable energy practices**.** The reliance on coal for industrial energy needs is particularly concerning, as it is one of the most polluting energy sources (Jakob et al. 2020). ASEAN's dependence on coal persists primarily because it is more cost-effective compared to renewable energy sources (Chen and Mauzerall 2021). This cost disparity makes transitioning to renewable energy sources, such as hydro and biofuel, more challenging. According to Albay (2024), coal consumption in ASEAN significantly impacts air quality and public health, as the burning of coal releases fine particulate matter (PM2.5), which is linked to respiratory and cardiovascular illnesses. In 2021, PM2.5 pollution led to tens of thousands of premature deaths in the region, including 221,600 in Indonesia, 101,600 in Myanmar, 99,700 in Vietnam, and 98,200 in the Philippines.

Previous research has investigated life expectancy factors, focusing on energy consumption and economic development. Salehnia et al. (2022) revealed that while hydroelectricity, a renewable energy source, hurt life expectancy, oil consumption had a positive effect. This highlights the complex and sometimes counterintuitive ways different energy sources and social factors can influence health outcomes. In contrast, Hendrawaty et al. (2022) explored the reliance of ASEAN countries on non-renewable energy to drive economic expansion. They identified a critical trade-off: although non-renewable energy contributes to short-term economic expansion, it often reduces life expectancy due to the adverse health effects associated with its consumption. This underscores the tension between pursuing economic expansion and maintaining health outcomes, particularly in regions heavily dependent on fossil fuels. Conversely, Somoye et al. (2023) demonstrated that fossil fuel and renewable energy consumption were associated with increased life expectancy. This suggests that energy consumption, when managed effectively, can positively impact health outcomes, regardless of the energy source. Alavijeh et al. (2024) concentrated on the role of renewable energy in enhancing life expectancy and reducing health expenditures. Their research, conducted in G-7 countries, underscores renewable energy's broader health and economic benefits, contrasting the more variable and often negative outcomes associated with non-renewable energy sources.

Despite significant research on the relationship between economic activity and public health, the specific impact of industrialization on public health has received limited attention. Additionally, the role of coal consumption as a moderating factor on life expectancy in developing ASEAN nations remains largely unexplored. The moderating role of coal consumption, a significant regional energy source, has been overlooked. This presents a key gap in understanding how industrial activities and coal usage impact public health outcomes in these countries. Our study fills this gap by investigating the linkage between industrial output and life expectancy in ASEAN countries, specifically focusing on coal consumption as a moderating factor. Since many ASEAN nations rely heavily on coal for their industrial activities, understanding its impact on life expectancy is crucial. Coal remains a significant energy source in the region due to its affordability and availability. Still, it is also one of the largest contributors to environmental pollution, including greenhouse gas emissions. These emissions directly and indirectly affect public health, potentially lowering life expectancy by exacerbating respiratory diseases, cardiovascular conditions, and other health issues associated with poor air quality. While the global energy landscape is shifting toward electrification and renewable energy, ASEAN nations lag in this transition, making the study of coal's role even more pressing. This research sheds light on how coal consumption undermines the health benefits of industrialization, even amidst technological progress in electrification**.**

By addressing this underexplored area, our study aims to provide a nuanced understanding of how industrial output affects life expectancy, especially considering the varying levels of coal dependency across ASEAN countries. The findings emphasize the need for region-specific strategies that align with global electrification trends, such as phasing out coal subsidies, implementing carbon taxation, and adopting renewable energy technologies. Furthermore, the study highlights the importance of leveraging real-time satellite-based monitoring to track emissions and health impacts effectively, ensuring informed policy decisions**.** The role of coal as a moderator allows us to assess whether the linkage between industrial growth and life expectancy is influenced or intensified by coal consumption. This approach is particularly relevant as the ASEAN region continues to industrialize while facing mounting environmental challenges. Our findings offer valuable insights for policymakers and ASEAN regional stakeholders tasked with balancing industrial growth and environmental sustainability. Understanding the trade-offs between economic progress and public health will help guide future energy policies, promote cleaner energy alternatives, and create strategies to mitigate the adverse effects of coal consumption on life expectancy. This research also contributes to global discussions on sustainable development, particularly in developing regions where industrial output and coal use remain critical components of economic expansion.

2 Literature review

Numerous research has examined the correlation between energy usage and longevity, and their results have revealed both commonalities and variations. The distinct insights provided by Weitensfelder et al. (2024), Salehnia et al. (2022), Kanat et al. (2024), and Zhang et al. (2021) are a result of the varied methodology, areas, and timeframes employed by each of these studies. By looking at data from 1972 to 2014, Weitensfelder et al. (2024) provide a worldwide view. In general, they find that energy use increases life expectancy. However, after a certain point, the benefits of energy use plateau, and further energy use has no further effect on life expectancy. The beneficial effects of energy use have limits, as this discovery shows.

Panel quantile regression is similarly employed by Salehnia et al. (2022) to evaluate data from one hundred nations spanning the years 2000–2018. Their research shows that energy consumption generally increases life expectancy, with variables like GDP and CO_2 emissions moderating this effect. Government services and economic inequality are examples of context-specific variables that their examination shows how energy's impact might vary. Applying the auto-regressive distributed lag (ARDL) model, Kanat et al. (2024) focused on Kazakhstan from 1990 to 2022. In the long run, they found that energy consumption and air pollution reduce life expectancy, while population growth and economic development increase it. The negative consequences of energy consumption in conjunction with high pollution levels are highlighted in their study. From 1991 to 2019, Zhang et al. (2021) used the Fully Modified Ordinary Least Squares (FMOLS) approach to analyze the effects of energy use on health outcomes across Asia. In areas with high pollution levels, they find that increasing energy use is linked to lower life expectancy and higher newborn mortality rates.

Research on renewable energy sources and healthcare expenditures complements existing findings and adds depth to the conversation. Wang et al. (2023) examined 121 nations to determine the correlation between renewable energy, GDP growth, and life expectancy. They discovered that in high-income countries in particular, people live longer when they use more renewable energy. But they may have ignored the problems in low-income countries, where energy consequences may be different owing to different economic and infrastructure situations, as they concentrated on high-income ones. A study conducted by Alavijeh et al. (2024) examined the linkage between urbanization, renewable energy, carbon emissions, health spending, and the G-7 countries using the Method of Moments Quantile Regression (MMQR). They proved that urbanization, health spending, and renewable energy all have a positive impact on life expectancy, whereas carbon emissions have a negative one. Findings may not be applicable to underdeveloped nations due to potential major differences in energy and health dynamics, but their comprehensive methodology does provide interesting insights. Using a Vector Error Correction Model (VECM), Liu and Zhong (2022) examined the impact of renewable energy and health spending on life expectancy in China over the long run. According to their research, both variables have a favorable effect on longevity in the long run. Due to China's one-of-a-kind economic and policy environment, the findings may not reflect larger regional or worldwide variances, even though this national focus provides distinctive insights for China.

Several studies, each with its own set of conclusions, shed light on how CO_2 emissions affect life expectancy. The immediate consequences of carbon dioxide emissions on human health are the subject of research by Das and Debnath (2023) and Emodi et al. (2022). The impact of transport networks on carbon dioxide emissions and health in nations of the Global South during 2006–2016 was investigated by Emodi et al. (2022). Their research shows that transport infrastructure upgrades have not increased life expectancy but have made mortality rates worse, highlighting the need for plans that combine infrastructure upgrades with efficient CO_2 reduction strategies. In a similar vein, Das and Debnath (2023) used the ARDL cointegration method to determine the association between CO_2 emissions and life expectancy in India from 1991 to 2018. They found a quadratic linkage over time, draw the conclusion that India's CO_2 levels are too high, and offer solutions to lower emissions and enhance health.

To provide some background, Kumar and Radulescu (2024) looked at 45 nations in Sub-Saharan Africa from 1991 to 2020 and see how CO_2 emissions, life expectancy, and inflation are related. Their research shows that CO_2 emissions rise in tandem with GDP, industrial activity, and inflation, and that urbanization and life expectancy also have a positive correlation with emissions. Economic expansion exacerbates environmental degradation at first, but it may eventually contribute to improvements, according to their results, which corroborate the Environmental Kuznets Curve hypothesis. Also utilizing quantile regression and the cross-sectional autoregressive distributive lag (CS-ARDL) model, Nica et al. (2023) examined the variables impacting Eastern European life expectancy from 1990 to 2021. Their research shows that while CO_2 emissions and fossil fuel usage have negative impacts on life expectancy, renewable energy use, higher health expenditures, and better institutional quality all have favorable effects. Their research shows that there is a small positive correlation between financial development and life expectancy.

While energy use generally has favorable impacts, these advantages can be impacted by factors like pollution, economic conditions, and geographical variances. Previous study highlights the nuanced link between energy consumption and life expectancy. To completely understand these processes, sophisticated, context-specific studies are necessary, given the diversity of approaches and areas of focus. But there is still a big hole: nobody has looked at coal use as a moderator in the correlation between industrial production and longevity.

The existing literature offers valuable insights into the relationship between life expectancy and energy consumption. For instance, Alavijeh et al. (2024) focused on the impact of renewable energy, while Das and Debnath (2023) examined the role of fossil fuels and environmental factors. These studies highlight a variety of methodologies, regional contexts, and moderating variables, showcasing the multifaceted nature of this relationship. However, a significant gap remains in understanding the connection between industrialization and life expectancy and the role of coal consumption as a moderating factor in this relationship. Industrialization plays a pivotal role in shaping energy consumption patterns, environmental degradation, and health outcomes, particularly in developing regions. However, its direct impact on longevity remains underexplored. Additionally, coal consumption has not been examined as a moderating factor in this relationship. Coal is a significant energy source for industrialization in many developing nations, particularly in ASEAN countries, where it contributes to both economic growth and environmental challenges. The absence of research on coal consumption as a moderator leaves a critical gap in understanding how reliance on this fossil fuel influences the interplay between industrial activity and life expectancy.

3 Data and methodology

3.1 Theoretical background

Selby Smith and Dunt's (1992) health model, which looks at how medical and non-medical inputs interact to affect health outcomes (LEXP), serves as the foundation for this investigation. This model helps to understand the broader determinants influencing public health.

According to this model, the determinants of health are multifaceted, involving not only medical resources but also a broad spectrum of socioeconomic factors. The health production function thus encompasses physical components, financial support, economic expansion, and various lifestyle-related factors (Segbefia et al. 2023).

Mathematically, this model is expressed as:

$$HO = f(M.E) \quad (1)$$

where HO represents health outcomes, M stands for medical resources, and E denotes non-medical inputs. The latter includes critical social and economic factors, such as education, income levels, and environmental conditions, which collectively influence population health. The health model posits that higher economic expansion can lead to improved well-being by enabling greater investments in medical infrastructure and health services, ultimately extending life expectancy. Building on this foundation, Or (2000) expanded the health production model by integrating three additional key dimensions: environmental, social, and physical factors. Or's expanded model offers a more holistic view of the determinants of health, recognizing that environmental quality (such as pollution levels), social structures (like inequality and education), and physical factors (including infrastructure) all play crucial roles in shaping health outcomes.

The extended model is represented as:

$$HO_{it} = \beta_0 + \beta_1 M_{it} + \beta_2 N_{it} + \varepsilon_{it} \quad (2)$$

In this equation, HO refers to health outcomes, where i denotes the country and t denotes the time period. The term M represents medical inputs (measured by health expenditure relative to economic expansion), while N is a vector of non-medical factors, encompassing human capital, technological innovation, carbon emissions, and renewable energy. The coefficients β_1 and β_2 capture the impact of medical and non-medical variables on health outcomes, while ε_{it} accounts for unobserved factors that may influence the model's results.

Or's (2000) model is crucial in contemporary studies as it emphasizes the interplay between environmental factors like carbon emissions and renewable energy with socioeconomic elements, impacting public health outcomes. Segbefia et al. (2023) used a similar model to examine environmental health determinants, reflecting the growing academic focus on understanding the health impacts of climate change and sustainability. Previous studies, like Kumar and Radulescu (2024), looked at the link between industrial activity and emissions, focusing on environmental impacts. Building on this, our study explores how industrial output affects life expectancy. This is important because it considers both the benefits of industrial growth, like better healthcare and living conditions, and the health risks from environmental damage. By examining this relationship, our study fills a gap in understanding how industrialization impacts public health. It provides insights that combine economic growth and environmental effects, helping to guide more balanced and sustainable policies. In the context of this study, two models are proposed to reflect different interactions within the health production framework. Model 3, which does not include a moderator, captures the direct effects of medical and non-medical inputs on life expectancy.

In Model 4, coal consumption is added as a moderator to better understand how it affects the relationship between industrial output and life expectancy, thereby addressing another gap in the previous research. Industrial output might improve life expectancy by boosting economic growth, which leads to better healthcare and living conditions. However, coal consumption can reduce these benefits because it causes air pollution and health problems like respiratory and heart diseases. Adding coal consumption as a moderator helps to show how environmental damage changes the positive impact of industrialization. This makes the analysis more detailed and provides useful insights for balancing economic growth with public health and sustainability. The models are derived as follows:

$$LNLE = f(LNHE, LNI, LNGDP, LNC) \quad (3)$$

$$LNLE = f(LNI * C, LNHE, LNI, LNGDP) \quad (4)$$

where LNLE refers to life expectancy, LNHE refers to government health expenditure, LNI refers to industrial output, LNGDP refers to Gross Domestic Product per capita, LNC refers to coal consumption, and LNI*C refers to the role of coal consumption as a moderating factor in the linkage between industrial output and life expectancy.

3.2 Data sources and management

The selection of ASEAN countries for this study was guided by the availability of reliable data over the period under investigation. The analysis focuses on a 21-year time frame, from 2000 to 2021, using panel data obtained from the World Bank database. This extended timeframe allows for a comprehensive examination of long-term trends and linkages among the variables of interest, ensuring robust statistical insights. Table 1 provides an overview of the key variables included in the analysis, along with their definitions and summary statistics. These variables represent a range of factors that are critical to understanding the dynamics of life expectancy and its determinants in the selected ASEAN countries. The inclusion of both medical and non-medical variables

Table 1 Description of variables

Variable/acronym	Symbols	Description	Sources
Life expectancy	LNLE	The number of years a newborn infant is expected to live (total)	WorldBank (2024)
Government Health expenditure	LNHE	The total government expenditure (US Dollars)	WorldBank (2024)
Industrial output	LNI	Value added of GDP (US Dollars)	WorldBank (2024)
Gross domestic product per capita	LNGDP	Total GDP per capita (constant US Dollars 2015)	WorldBank (2024)
Coal consumption	LNC	The total of coal consumption (terajoules, TJ)	International Energy Agency (2024)

Sources: Worldbank 2024; Segbefia et al. 2023; Oluoch et al. 2021

reflects the health production model framework, which acknowledges the nature of health outcomes.

The exclusion of other relevant variables, such as air quality indices or healthcare infrastructure, could limit the comprehensiveness of the analysis and introduce potential confounding effects. For example, air quality directly affects public health and could influence healthcare expenditure, yet it is not accounted for in the model. Similarly, healthcare infrastructure—such as the availability of medical services—could be an important factor influencing health outcomes and should be considered. Without controlling for these factors, the model may suffer from omitted variable bias, which can distort the relationships between the included variables and the outcome.

To address this, a sensitivity analysis could be performed by incorporating additional variables like air quality indices or healthcare infrastructure. This would help assess the robustness of the results and provide a more accurate understanding of how each factor contributes to the health outcomes under study. Such an approach is common in econometrics, as highlighted in studies by Selvakkumaran and Ahlgren (2017) and Doucouliagos and Ulubasoglu (2006), which emphasize the importance of accounting for a broader range of determinants when examining complex socio-economic relationships.

3.3 Econometrics procedure and estimation

The study begins by conducting a residual cross-sectional dependence test to determine whether the residuals across different entities exhibit any dependence or correlation (Segbefia et al. 2023). Cross-sectional dependence arises when the error terms from various cross-sectional units are correlated, which may result from factors such as shared external shocks, spillover effects, or unobserved common variables that simultaneously impact multiple units. Detecting and accounting for this dependence is crucial, as failing to do so can lead to biased and inefficient parameter estimates, erroneous standard errors, and flawed statistical inferences. In the context of panel data models, addressing cross-sectional dependence is essential because overlooking it can distort the accuracy of the results, potentially leading to incorrect conclusions. The presence of cross-sectional dependence suggests that the units under analysis are not entirely independent, meaning that changes or shocks affecting one unit may have a spillover effect on others. Such phenomena are particularly relevant in economic studies, where global or regional factors can simultaneously influence multiple countries or regions. Two primary tests are used in this study to detect cross-sectional dependence: the Breusch-Pagan LM test and Pesaran's CD test. The Breusch-Pagan LM test is well-suited for situations where the number of cross-sectional units (N) is relatively large, but the periods (T) are limited. This test is effective for identifying correlations in panels with more cross-sectional units than periods. On the other hand, Pesaran's CD test is preferable when both the number of cross-sectional units (N) and periods (T) are large, making it versatile for use in balanced or unbalanced panel datasets. The application of these two tests ensures a comprehensive evaluation of cross-sectional dependence in the study. While the Breusch-Pagan LM test provides insights into panels with large N and small T, Pesaran's CD test extends the analysis to panels with substantial data points in both dimensions. This dual approach enables the study to accurately capture any dependence among the countries being analyzed, enhancing the robustness of the results. The equations for these tests are presented in Eqs. (5) and (6), which detail the procedures for calculating cross-sectional dependence under both methodologies.

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{p}_{ij}^{2} \quad (5)$$

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \widehat{q}_{ij} \quad (6)$$

In this context, $\widehat{p}_{ij}$ represents the sample correlation of the residuals between cross-sectional units i and j while $\widehat{q}_{ij}$ is the sample pairwise correlation coefficient between the residuals of these units. Following the examination of cross-sectional dependence, a unit root test will be conducted to determine whether the panel data series is non-stationary and contains a unit root. A time series with a unit root is considered non-stationary, indicating that its statistical properties, such as the mean, variance, and autocorrelation, vary over time. When a unit root is present, the series must be different to achieve stationarity before moving forward with further econometric analysis. This study will utilize three widely used unit root tests: the Im-Pesaran-Shin (IPS) test, the Augmented Dickey-Fuller (ADF) test, and the Phillips-Perron (PP) test. These tests help assess whether the data series are stationary or require differencing to address non-stationarity issues. Equation (7) provides the formulation for the ADF test, which is a fundamental method for detecting unit roots in time series data.

$$\Delta y_t = \alpha + \beta_t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \quad (7)$$

whereas $\Delta y_t = y_t - y_{t-1}$ is the first difference of the series, α is the constant, β is the coefficient on the time trend, and ϒ is the coefficient on the lagged level of y_{t-1}. In the null hypothesis (H_0)—there is a unit root test, while in the alternative hypothesis (H_a)—the series is stationary. Like the ADF test, the null hypothesis for PP is that the series has a unit root. However, for IPS, a panel unit root test is used to assess whether a unit root is present in a panel data set. Thus, the null hypothesis is that all panels contain a unit root, while the alternative is that no panel contains a unit root.

Following that, the Pedroni cointegration test is used to determine whether a set of non-stationary panel data series are cointegrated, meaning they share a long-run equilibrium linkage despite being individually non-stationary. Pedroni's test allows for heterogeneity across the panel in both the cointegration vectors and the dynamics of the linkage. Equation (8) refers to the Pedroni test. Consider the following model for panel data with i = 1, 2, … , N (cross-sectional units) and t = 1, 2, … , T (periods). In this context, $\Delta y_t = y_t - y_{t-1}$ represents the first difference of the time series, α is the constant, β is the coefficient of the time trend, and ϒ is the coefficient of the lagged level of y_{t-1}. Under the null hypothesis (H_0), the series has a unit root, indicating non-stationarity, while the alternative hypothesis (H_a) asserts that the series is stationary. Like the ADF test, the Phillips-Perron (PP) test also tests the null hypothesis that the series contains a unit root. For the Im-Pesaran-Shin (IPS) test, which is a panel unit root test, the null hypothesis is that all panels have a unit root, whereas the alternative hypothesis is that no panel has a unit root. The IPS test is designed to evaluate whether unit roots are present in a panel dataset.

After unit root tests, the Pedroni cointegration test checks whether non-stationary panel data series are cointegrated, indicating a long-term equilibrium relationship despite their individual non-stationarity. Pedroni's test accounts for heterogeneity across the panel in both the cointegration vectors and the dynamics of the linkage. Equation (8) presents the Pedroni test, considering a panel data model with i = 1, 2, … , N representing cross-sectional units and t = 1, 2, … , T representing periods.

$$y_{it} = \alpha_i + \delta_i t + \beta_1 x_{1,it} + \beta_2 x_{2,it} + \cdots + \beta_m x_{m,it} + \varepsilon_{it} \quad (8)$$

In this model, y_{it} represents the dependent variable for unit i at time t, while $x_{m,it}$ denotes m^{th} independent variable for unit i at time t. The α_{it} refers to the individual-specific intercept, accounting for heterogeneity in the intercept across units, and δ_{it} represents the individual-specific time trend. The error term, ε_{it}, is tested for cointegration to assess whether a long-run equilibrium linkage exists between the variables. Pedroni's cointegration test involves several test statistics aimed at evaluating the null hypothesis of no cointegration, and these are divided into two categories: within-dimension (panel) and between-dimension (group) statistics. The within-dimension, or panel statistics, pool the residuals across the cross-sections and include the following tests: (i) panel v-statistic, (ii) panel rho-statistic, (iii) panel PP (Phillips-Perron) statistic, and (iv) panel ADF (Augmented Dickey-Fuller) statistic. These tests assume homogeneity in the cointegrating linkages across units. In contrast, the between-dimension, or group statistics, allow for heterogeneity in the cointegrating linkages across different cross-sectional units. These include: (i) group statistics, (ii) group PP statistics, and (iii) group ADF statistics. The inclusion of both within-dimension and between-dimension tests ensures a comprehensive assessment of the panel data for cointegration, considering potential heterogeneities across the units being studied.

Following the cointegration analysis, the data is examined using the ARDL (Autoregressive Distributed Lag) panel method and OLS (Ordinary Least Squares) panel estimation. The ARDL panel method, introduced by Pesaran, Shin, and Smith in 1999, is a versatile econometric framework used to analyse both short-term and long-term linkages between variables in panel data settings. The strength of the ARDL model lies in its ability to accommodate variables that may be non-stationary but are cointegrated. The ARDL model combines autoregressive elements—lagging the dependent variable—with distributed lags of the independent variables, allowing for a nuanced understanding of the dynamics at play. It is especially useful in cases where the time series may exhibit non-stationarity, but a stable, long-term equilibrium linkage exists between the variables. The ARDL approach allows the study to capture both short-term variations and long-term trends in the relationship between dependent and independent variables, providing a comprehensive analysis of the panel data. The general ARDL panel model can be expressed as follows, incorporating both the lagged values of the dependent variable and the distributed lags of the independent variables to capture these dynamic linkages. On the other hand, because Fixed Effects (FE) and Random Effects (RE) models do not include lagged variables, they are not suitable for examining short-term dynamics or long-term equilibrium changes. They are unable to adequately capture temporal dependencies and instead focus mainly on cross-sectional variations. By employing the ARDL method, the study is equipped to handle complex interactions in the panel data, ensuring a thorough analysis of both immediate and persistent effects across the ASEAN countries under investigation.

$$\Delta y_{it} = \alpha_i + \sum\nolimits_{j=1}^{p-1} \beta_j \Delta y_{i,t-j} + \sum\nolimits_{k=0}^{q} \gamma_k \Delta x_{i,t-k} + \lambda(y_{i,t-1} - \varnothing x_{i,t-1}) + \varepsilon_{it} \tag{9}$$

In this context, y_{it} represents the dependent variable for unit i at time t, while x_{it} is the independent variable for unit i at time t. The term α_i is the unit-specific intercept that captures individual heterogeneity, and β_j is the coefficient for the lagged dependent variable, where p represents the number of lags for y_{it}. Similarly, Υ_k is the coefficient for the lagged independent variable x_{it}, with q being the number of lags for x_{it}. The error term ε_{it} is generally assumed to be independent and identically distributed. This model effectively captures both short-run and long-run dynamics by incorporating lags for both the dependent and independent variables, making it suitable for analyzing complex linkages in panel data (Garidzirai and Muzindutsi 2020; Oluoch et al. 2021). In addition to using the ARDL approach, Models 1 and 2 were also tested using the panel Ordinary Least Squares (OLS) method for robustness. The OLS method estimates linear linkages in panel data, which combine cross-sectional and time-series dimensions. By applying OLS, the study assesses the linkages between variables across multiple entities over time, ensuring that the results are not sensitive to the estimation technique used. Equations (10) and (11) outline the panel OLS equations employed:

$$LNLE_{it} = \beta_0 + \beta_1 LNHE_{it} + \beta_2 LNI_{it} + \beta_3 LNGDP_{it} + \beta_4 LNC_{it} + \varepsilon_{it} \tag{10}$$

$$LNLE_{it} = \beta_5 + \beta_6 LNI^{*}C_{it} + \beta_7 LNHE_{it} + \beta_8 LNI_{it} + \beta_9 LNGDP_{it} + \varepsilon_{it} \tag{11}$$

In this context, β_0-β_9 represent the coefficient estimates, ε denotes the error term, i indicates the country, and t represents the year. This equation follows the pooled OLS framework, which does not account for country-specific or time-specific effects. As explained by Abdullah et al. (2022), the pooled OLS method is a simple linear regression approach that does not incorporate random or fixed effects. In this model, both the intercept and slope are assumed to remain constant across different periods and cross-sectional units.

4 Findings and discussion

The descriptive statistics results reported in Table 2 for the panel data, based on 152 observations, show key variations across the variables. LNLE has a relatively narrow range, with values between 4.0343 and 4.4260, indicating consistent life expectancy across the sample. LNHE shows considerable variation, ranging from −1.4271 to 1.6236, reflecting low spending in some countries. LNI has a wide disparity, with values between 2.2713 and 3.8822, while LNGDP ranges significantly from 5.6936 to 11.1954, indicating differences in economic prosperity. LNC shows extreme variability, with a minimum of −3.3901 and a maximum of 13.8430, highlighting significant differences in emissions across ASEAN countries. According to the Worldometer (2024) report, Indonesia, as a major coal consumer with an annual consumption of 102,623 million MMcf, has the potential to dominate the trends observed in countries with lower coal reliance. This could result in findings representing the energy profile of the largest consumer rather than the entire region,

Table 2 Descriptive statistics

	LNLE	LNHE	LNI	LNGDP	LNC
Mean	4.2803	−0.2234	3.5222	8.1691	8.6287
Median	4.2925	−0.6239	3.5954	8.0936	10.8229
Maximum	4.4260	1.6236	3.8822	11.1954	13.8430
Minimum	4.0343	−1.4271	2.2713	5.6936	−3.3901
Std. Dev	0.0782	0.9628	0.2719	1.3252	4.6522
Skewness	−0.3983	0.8849	−1.9371	0.5429	−1.0967
Kurtosis	3.1294	2.2883	8.2219	2.8337	3.0467
Observations	152	152	152	152	152

thereby limiting the generalizability of the conclusions. The descriptive statistics also reveal key insights into the variables used in the study. LNLE shows low variability and is relatively symmetrically distributed, while LNHE and LNC display higher variation and skewed distributions. LNI has a strong leftward skew and a leptokurtic distribution, indicating extremely low values. LNGDP shows moderate variation with a slight rightward skew. Overall, the data highlight significant differences in LNI, LNHE, and LNC across the ASEAN countries, which may have important implications for their impact on LNLE.

The results from Table 3 present the residual cross-section dependence tests, which assess whether there is cross-sectional dependence in the panel data. Cross-sectional dependence occurs when the residuals across different cross-sections are correlated. This is a critical assumption for the application of the panel ARDL model, as the presence of cross-sectional dependence can affect the validity of the results. All three tests indicate no evidence of cross-sectional dependence, with p-values well above the conventional significance levels. Given these results, it is reasonable to conclude that cross-sectional dependence is not a concern in this dataset. Therefore, it is appropriate to proceed with panel ARDL analysis, as the model's assumptions regarding cross-sectional independence hold based on these test outcomes.

Table 3 Residual cross-section dependence test

Test	Statistic	d.f	Prob
Breusch-Pagan LM	22.2323	21	0.3862
Pesaran scaled LM	0.1901		0.8492
Pesaran CD	0.1001		0.9203

The results of the unit root tests presented in Table 4 reveal that all the variables, including LNLE, LNHE, LNI, LNGDP, and LNC, are non-stationary at their levels. This insignificance is consistent across various statistical tests, such as IPS, ADF, and PP, indicating that the variables contain unit roots and thus do not exhibit stationarity in their level forms. However, when the variables are transformed into their first differences, they become statistically significant and stationary across all the tests. This confirms that the data follow an integrated process of order one, or I(1). Given the stationarity at first difference, it is appropriate to proceed with the Panel ARDL estimation, which is designed to handle variables that are a mix of I(0) and I(1) or purely I(1), allowing for long-run dynamics to be modeled effectively.

To determine if the variables are in a long-term equilibrium linkage under two models, we ran Pedroni co-integration tests, and the results are in Table 5. In addition to within-dimension (typical AR coefficients) and

Table 5 Pedroni Co-integration tests

Alternative hypothesis: common AR coefs. (Within-dimension)				
	Model 2		Model 1	
	Statistic	Prob	Statistic	Prob
Panel v-Statistic	0.7992	0.2121	0.7992	0.2121
Panel rho-Statistic	−1.5184	0.0645	−1.5184	0.0645
Panel PP-Statistic	−5.4851	0.0000	−5.4851	0.0000
Panel ADF-Statistic	−5.5490	0.0000	−5.5490	0.0000
Alternative hypothesis: individual AR coefs. (Between-dimension)				
	Model 2		Model 1	
	Statistic	Prob	Statistic	Prob
Group rho-Statistic	−0.0009	0.4996	−0.0009	0.4996
Group PP-Statistic	−3.7031	0.0001	−3.7031	0.0001
Group ADF-Statistic	−4.8611	0.0000	−4.8611	0.0000

Table 4 Unit root tests

	Level			First Difference		
	IPS	ADF	PP	IPS	ADF	PP
LNC	−1.0746	20.1436	18.0033	−9.6225	96.5138	97.2315
	(0.1413)	(0.1257)	(0.2066)	(0.0000)	(0.0000)	(0.0000)
LNGDP	−0.0464	10.4567	14.7949	−3.8028	48.4991	54.6706
	(0.4815)	(0.7281)	(0.3923)	(0.0001)	(0.0000)	(0.0000)
LNHE	−0.7129	21.4777	22.9074	−10.6088	106.925	110.821
	(0.2380)	(0.0900)	(0.0618)	(0.0000)	(0.0000)	(0.0000)
LNI	−0.3866	18.5515	21.9218	−9.7937	98.7037	188.306
	(0.3495)	(0.1828)	(0.0802)	(0.0000)	(0.0000)	(0.0000)
LNLE	−1.3434	21.1727	24.5073	−7.0363	80.7976	315.573
	(0.0896)	(0.0973)	(0.0398)	(0.0000)	(0.0000)	(0.0000)

between-dimension (individual AR coefficients) possibilities, the test also gives statistics for the latter. For each statistic, the co-integration tests produce varying conclusions. In contrast to the poor or nonexistent co-integration signals given by the v- and rho-statistics, the PP- and ADF-statistics provide significant evidence of a long-run co-integrating link between the variables in both models. The results show that there is strong evidence of co-integration across the panel, which means that the model variables have a long-term equilibrium linkage, even though some tests did not reject the null hypothesis. To investigate the ever-changing correlations between the variables, it is appropriate to use long-run panel analysis methods like Panel ARDL.

Table 6 presents the long-run results from the Panel ARDL model, with life expectancy as the dependent variable. The analysis explores the effects of industrial output, health expenditure, GDP per capita, coal consumption, and the interaction between industrial output and coal consumption on life expectancy. The results from both Model 1 and Model 2 are discussed together to compare their similarities and differences. In both models, industrial output shows a positive and highly significant impact on life expectancy. The coefficient for industrial output in Model 2 is 0.2352, and in Model 1, it is 0.1542, with both models reporting *p*-values of 0.0000. This suggests that higher industrial activity improves life expectancy in ASEAN countries. The benefits of industrialization—such as job creation, economic expansion, and improved access to resources—appear to outweigh negative factors like environmental pollution, especially when coal consumption is not directly considered. Elfaki et al. (2021) similarly concluded that industrial development promotes economic expansion, while Puntoon et al. (2022) found a weaker link between industrial output and life expectancy. In Model 1, coal consumption alone has a negative and significant effect on life expectancy, with a coefficient of −0.0811 (*p*-value: 0.0000). This suggests that greater dependence on coal as an energy source harms life expectancy, likely due to environmental and health issues such as air pollution and respiratory diseases. In Model 2, the interaction between industrial output and coal consumption is negative and highly significant, with a coefficient of −0.0811 (*p*-value: 0.0000). This indicates that when industrial activity is paired with high coal consumption, the harmful environmental effects of coal offset the economic benefits of industrialization, leading to a decline in life expectancy. Thus, while industrial output alone has a positive impact, its combination with coal use introduces substantial health risks. In both models, GDP per capita has a positive and highly significant influence on life expectancy, with an identical coefficient of 0.1116 (*p*-value: 0.0000). This result aligns with Wang et al. (2020), who found similar outcomes in Pakistan using a time series ARDL approach. The findings highlight the role of economic prosperity in improving life expectancy. Wealthier ASEAN countries can invest more in healthcare, infrastructure, and social services, resulting in better health outcomes and longer lifespans. Interestingly, health expenditure is statistically insignificant in both models, with a coefficient of −0.0011 and a *p*-value of 0.9368. This suggests that, in the long run, health expenditure does not significantly affect life expectancy in ASEAN countries when other factors like industrial output and GDP are accounted for. This might be due to inefficiencies in healthcare spending, meaning that funds are not being directed toward the most impactful areas, such as preventive care, rural healthcare access, or critical medical infrastructure. Ahmed et al. (2019) found that the majority of Asian countries demonstrated inefficiency in utilizing healthcare system resources. Misallocation of funds might prioritize urban areas or high-cost treatments over addressing basic healthcare needs in underserved communities. This contrasts with Onofrei et al. (2021), who found that improved access to healthcare facilities is crucial for reducing infant mortality. The insignificance of health expenditure could imply inefficiencies in spending or that other factors, such as environmental conditions, play a more prominent role in shaping life expectancy outcomes.

Table 6 Panel ARDL long-run estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
		Model 2		
LNI*C	−0.0811	0.0149	−5.4360	0.0000
LNHE	−0.0011	0.0137	−0.0796	0.9368
LNI	0.2352	0.0402	5.8550	0.0000
LNGDP	0.1116	0.0137	8.1573	0.0000
		Model 1		
LNHE	−0.0011	0.0137	−0.0796	0.9368
LNI	0.1542	0.0268	5.7572	0.0000
LNGDP	0.1116	0.0137	8.1573	0.0000
LNC	−0.0811	0.0149	−5.4360	0.0000

LNI*C represents industrial output multiplied by consumption, where coal consumption interatcs with industrial output

Table 7 presents the results of the Panel OLS estimation, which evaluates the robustness of the findings. The results from both Model 1 and Model 2 are discussed to provide a comprehensive overview of the linkages among the variables. In both models, industrial output has a positive and highly significant effect on life expectancy. In Model 2, the coefficient is 0.0722 (*p*-value: 0.0000), while in Model 1, it is 0.8457 (*p*-value: 0.0000). This consistent positive linkage indicates that higher industrial output is associated with improved life expectancy, likely due to the economic benefits of industrialization, such as enhanced infrastructure, better healthcare access, and

Table 7 Panel OLS estimation

Variable	Coefficient	Std. Error	t-Statistic	Prob
		Model 2		
LNI*C	−0.0045	0.0011	−4.0477	0.0001
LNHE	−0.0006	0.0058	−0.1035	0.9177
LNI	0.0722	0.0117	6.1552	0.0000
LNGDP	0.0526	0.0026	20.1942	0.0000
C	3.6510	0.0445	82.0613	0.0000
		Model 1		
LNHE	0.1118	0.0383	2.9145	0.0041
LNI	0.8457	0.0429	19.6945	0.0000
LNGDP	0.1583	0.0154	10.2518	0.0000
LNC	0.0020	0.0076	0.2600	0.7952

LNI*C represents industrial output multiplied by consumption, where coal consumption interatcs with industrial output

improved living standards. GDP per capita also shows a positive and highly significant effect on life expectancy in both models. In Model 2, the coefficient is 0.0526 (p-value: 0.0000), and in Model 1, it is 0.1583 (p-value: 0.0000). This finding aligns with the results from the ARDL approach. Miladinov (2020) similarly finds that higher economic prosperity is strongly correlated with longer life expectancy, as wealthier nations can invest more in health, education, and social welfare, leading to better health outcomes and increased longevity.

In Model 1, coal consumption has an insignificant impact on life expectancy, with a coefficient of 0.0020 and a p-value of 0.7952. This suggests that when accounting for other variables such as GDP and industrial output, coal consumption alone does not directly affect life expectancy in this model. This finding contrasts with results from the ARDL approach and may imply that the environmental and health impacts of coal are more complex or interact with other factors like industrial output. In Model 2, however, the interaction term between industrial output and coal consumption is negative and highly significant, with a coefficient of −0.0045 and a p-value of 0.0001. This indicates that when industrial output is combined with coal consumption, it negatively impacts life expectancy. The magnitude of the negative coefficient indicates a strong and statistically significant correlation between the two variables, supporting the idea that life expectancy decreases because of the combined effects of coal use and industrial output. Public health may suffer considerably due to the negative environmental effects of coal, such as air pollution, greenhouse gas emissions, and related health risks, which could outweigh the economic benefits of industrial growth. This finding underscores that, while industrial production may drive economic growth, reliance on coal as a primary energy source introduces serious health risks that hinder potential improvements in life expectancy. The detrimental health effects of coal use, such as heart and lung conditions, are severe enough to outweigh the benefits of industrial development. Furthermore, the impact of healthcare spending differs between the models, suggesting that while healthcare expenditure may not be sufficient to fully offset the health risks associated with coal use, it does help mitigate these adverse consequences.

In Model 1, health expenditure has a positive and significant effect on life expectancy, with a coefficient of 0.1118 and a p-value of 0.0041, suggesting that higher health expenditure is linked to better life expectancy. This suggests that improving public health requires increased spending on healthcare services, such as better access to care, illness prevention initiatives, and enhanced healthcare infrastructure overall. The positive correlation indicates that spending on healthcare not only improves life quality but also increases life expectancy by reducing mortality rates and preventing the spread of disease. The stability of this relationship is further supported by the statistically significant p-value, which provides confidence that higher healthcare spending is a crucial factor in raising life expectancy for all. This finding aligns with Jaba et al. (2014), despite inconsistency in the ARDL approach results. Conversely, in Model 2, health expenditure is insignificant, with a coefficient of −0.0006 and a p-value of 0.9177. This implies that, in the presence of the interaction between industrial output and coal consumption, health expenditure may not directly influence life expectancy. The extremely high p-value suggests that unlike in Model 1, the effect of health expenditure on life expectancy is not statistically significant when coal consumption and industrial output are considered together. This discrepancy could reflect the complex interaction between economic factors and environmental health risks, indicating that health expenditure alone might not be sufficient to counteract the negative effects of coal consumption on life expectancy. In environments where industrial pollution and coal usage are high, even substantial investments in healthcare may struggle to address the severe public health issues caused by air pollution and other environmental factors. This finding highlights the importance of a more integrated approach, where both environmental policies and healthcare spending are crucial in improving life expectancy.

5 Conclusion and policy recommendations

The effects of coal use on the linkage between industrial output and life expectancy in ASEAN countries are examined in this important study. The results show that industrial production significantly increases life expectancy, which means that the economic advantages of industrialization, including more employment and easier access to resources, also have a favorable impact on people's health. However, the prevalence of coal usage reduces the impact of this favorable aspect. Because of the pollution it causes, and the health hazards it poses, the study found that burning coal shortens people's lives. These detrimental impacts are amplified because of the feedback loop between industrial production and coal usage. The negative health effects of coal consumption exceed the positive health effects of industrialization when both are prevalent, resulting in a decrease in life expectancy. The relevance of economic prosperity in improving health outcomes is highlighted by the fact that GDP per capita has a strong positive influence on life expectancy. Healthier and longer life expectancies are a result of increased investment in healthcare, infrastructure, and social services in ASEAN nations with higher per capita incomes. However, this analysis found no substantial long-run influence of health expenditure on life expectancy. This study implies that health spending is not enough to improve health outcomes in ASEAN countries. It could be due to inefficient resource allocation or the impact of environmental factors taking precedence.

This study's findings highlight numerous important policy implications for ASEAN nations to improve life expectancy. There is an immediate need to encourage cleaner energy alternatives due to the detrimental effect of coal usage on life expectancy. Thus, governments must accelerate the industry's renewable energy transition. To help industries switch to solar, wind, and hydroelectricity, governments may offer subsidies, tax incentives, and financing (Pata and Ertugrul 2023). Renewable energy subsidies can help drive innovation, lower costs, and expand energy options (The London School of Economics and Political Science 2018). A phased reduction of coal subsidies, coupled with the reallocation of funds to renewable energy projects, is essential. This aligns with the ASEAN Plan of Action for Energy Cooperation (APAEC) targets, such as achieving 23% renewable energy in total primary energy supply by 2025 and reducing energy intensity by 32% relative to 2005 levels. The APAEC emphasizes energy sustainability through cooperation among ASEAN nations, focusing on enhancing energy connectivity, market integration, and accelerating energy transition to mitigate climate change and promote clean energy solutions (World Economic Forum 2024). Furthermore, India's transition to renewable energy offers a compelling example for ASEAN countries like Indonesia and Vietnam. Through government initiatives such as subsidies for solar power, India has rapidly expanded its renewable energy capacity, particularly in solar power.

Eliminating coal's negative effects on the environment and human health is possible with the switch to renewable energy sources. Reduced air pollution is associated with fewer cases of respiratory and cardiovascular ailments, and cleaner energy sources also reduce emissions of greenhouse gases. Implementing carbon pricing mechanisms, such as carbon taxes and emissions trading systems, can further discourage coal use while generating revenue for clean energy initiatives. Singapore's adoption of a carbon tax provides a valuable model for other ASEAN nations to emulate. Reducing energy consumption and pollution levels can also be achieved by making industrial processes more energy efficient. For example, in ASEAN, Singapore has implemented energy efficiency measures in its manufacturing sector through its Energy Efficiency National Partnership program, which encourages firms to adopt energy-saving technologies and practices (National Environment Agency 2013). Standardizing energy-efficient appliances and promoting smart energy management systems across industrial and residential sectors are actionable strategies to reduce emissions and optimize energy use**.** In industrial settings, the integration of energy-efficient equipment and practices can yield substantial savings. A global review of energy efficiency programs found that standards and labeling have driven significant reductions in energy consumption and emissions, delivering financial benefits along with broader societal advantages such as improved air quality and reduced health costs (International Energy Agency 2024). Thus, governments can promote sustainable industrial expansion while protecting public health by implementing these policies.

Industrial production increases life expectancy, but excessive coal consumption has negative consequences. All of this points to the need to manage industrial expansion in a way that reduces environmental damage, even though it can boost the economy and raise living standards. Achieving a balance between industrial growth and environmental protection can be achieved by the implementation of strict legislation to restrict emissions and investment in pollution control technologies. Promoting clean energy technologies, such as high-efficiency, low-emission systems, and expanding initiatives like the ASEAN Power Grid, ensures a more sustainable energy mix and reduces reliance on coal**.** Industrialization need not compromise public health if policies promote greener manufacturing processes and alternate energy sources. By striking a fair balance, nations can enjoy the monetary gains from industrialization while reducing its detrimental effects on the environment.

Despite the lack of a substantial long-term linkage between health expenditure and life expectancy in this study, the significance of healthcare investment remains unabated. The industry may use its revenues to upgrade hospitals, clinics, and water and air purification systems to keep healthcare investment relevant. There must be smart and efficient spending on healthcare infrastructure if it is to continue receiving funding. Improving the quality of healthcare services, increasing access to vital health services, and reducing inefficiencies in the healthcare system are all important goals to strive towards. High-quality health systems are essential to deliver care that improves health, earns trust, and adapts to population needs. Quality must be integral to all health systems, not a privilege or future goal. Without it, the right to health holds little meaning, as health systems cannot effectively enhance well-being (Kruk et al. 2018). Thus, priorities for healthcare funding should include initiatives to enhance health outcomes through preventative measures, early disease detection, and the management of chronic conditions. The general health of a nation's inhabitants can be improved if its healthcare budget is well-planned and allocated.

The fact that life expectancy is positively correlated with GDP per capita highlights the importance of economic prosperity in enhancing health outcomes. Life expectancy can be improved through the implementation of policies that promote economic expansion, which can raise GDP per capita. Governments can introduce sustainable economic growth policies to promote green and sustainable economic practices. In addition, governments can also promote economic growth through inclusive policies by implementing a range of strategies that have a positive impact on life expectancy. This involves doing things like investing in education and skill development, fostering an entrepreneurial spirit, and making conditions that are favorable to enterprises. Living standards, healthcare access, and investment in social services can all be enhanced with higher economic expansion, which in turn leads to longer and healthier life expectancies. Governments should also strengthen public–private partnerships to mobilize green financing for renewable energy projects, enabling large-scale adoption of sustainable practices. Agrawal et al. (2024) explain that green financing allocates financial resources to support research and development (R&D) in clean energy and eco-friendly products and processes, serving as a key complement to green innovation for environmental protection. Thus, governments can do more to boost health and prosperity by backing initiatives that increase the economy and decrease poverty.

6 Limitations and suggestions for future research

This study is not without its limitations. The analysis relies on data from 2000 to 2021, which may not fully capture recent developments or future trends. Additionally, the accuracy and completeness of data on health expenditure and environmental factors could impact the findings. The study also focuses on a limited set of variables, potentially overlooking other influential factors such as healthcare quality, lifestyle choices, and regional differences within ASEAN countries. Furthermore, while the study identifies associations between variables, it does not establish causation, highlighting the need for more detailed causal analysis. To address these limitations and strengthen future research, the incorporation of advanced econometric techniques such as Dynamic Panel Data models (e.g., System GMM) is recommended**.** These models can effectively account for potential endogeneity issues, providing more robust insights into the causal relationships between industrial output, coal consumption, and life expectancy. This study's exclusion of real-time air quality monitoring data and healthcare infrastructure details may constrain the accuracy and comprehensiveness of its findings. Future research could address these gaps by integrating advanced tools, such as satellite data, to track pollution levels and their temporal variations. Additionally, exploring the role of regional policy differences, including varying levels of environmental regulations and healthcare access, could provide a deeper understanding of the factors influencing health outcomes. These approaches could enhance the robustness of the analysis and its relevance to policy development. Additionally, future studies should utilize real-time data on coal emissions and their health impacts, leveraging advancements in satellite-based monitoring systems to enhance data accuracy and timeliness. Further exploration of emerging trends in carbon research is also crucial. Investigating the health impacts of transitioning from coal to cleaner energy sources using real-time monitoring could provide actionable insights. Future research could also focus on the role of healthcare quality and access in moderating the negative effects of coal consumption. Longitudinal studies that extend beyond 2021 and analyze evolving energy policies and technologies would offer valuable perspectives on how ASEAN nations can balance industrial growth with sustainable health outcomes**.** Finally, examining regional variations within ASEAN countries might uncover localized dynamics that influence life expectancy, enabling tailored policy recommendations. These methodological improvements and future directions will provide a more comprehensive understanding of the nexus between industrialization, energy use, and public health in ASEAN, contributing to more effective policymaking and sustainable development strategies.

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Authors' contributions
Mohd Shahidan Shaari has performed empirical analysis. Nor Ermawati Hussain and Rossazana Ab Rahim wrote the literature review. Abdul Rahim Ridzuan worked on the introduction and conclusion. Faiz Masnan worked on results and discussions. ARR reviewed the manuscript and provided fruitful comments.

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Declarations

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The author(s) adhered to the accepted ethical standards of a genuine research study.

Consent for publication
On behalf of all authors, I provide our consent for the publication of identifiable details to be published in this Journal. This consent is provided after discussion with co-authors including Mohd Shahidan Shaari, Nor Ermawati Hussain, Rossazana Ab Rahim, and Faiz Masnan.

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