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Examining the interplay between green technology, co$_2$ emissions, and life expectancy in the asean-5 countries: insights from the panel FMOLS and DOLS approaches

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Abstract
Conference of Parties (COP28) emphasized the critical need to support vulnerable nations, particularly in Southeast Asia, by addressing climate change and enhancing climate finance mechanisms, which are vital for the overall well-being of their citizens. In response, we used the Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Cross Sectional Autoregressive Distributed Lag (CS-ARDL) techniques to examine the effects of carbon dioxide (CO_2) emissions, green technology, and health expenditures on life expectancy in five Southeast Asian countries (ASEAN-5) from 1995 to 2020. Although there is a considerable body of work on the factors that affect life expectancy, this study closes a major gap in the literature by concentrating on the ASEAN-5 nations, which have not received enough attention in studies on life expectancy. Specifically, incorporating factors such as green technology, CO2 emissions, and health expenditure, which were not considered in those earlier analyses. The CS-ARDL results reveal that green technology could significantly enhance life expectancy, while CO_2 emissions could have a significantly negative impact on life expectancy. The heterogeneous results of the FMOLS and DOLS also show that heightened health expenditure significantly enhances life expectancy in Thailand and the Philippines, advocating for increased investments in healthcare infrastructure. Economic expansion emerges as a significant contributor to enhanced life expectancy in Thailand, the Philippines, and Singapore, emphasizing the importance of policies fostering sustainable economic development. Notably, adopting green technology correlates positively with increased life expectancy in Singapore and the Philippines, emphasizing the dual benefits of environmentally sustainable practices. Conversely, CO_2 emissions exhibit a consistent negative correlation with life expectancy across all ASEAN-5 countries, underscoring the imperative for robust environmental policies to safeguard public health. Based on the results, we recommend that policymakers in the ASEAN-5 prioritize healthcare investments and adopt sustainable economic strategies, such as promoting clean energy and circular economies. In addition, targeted incentives for green technology, including tax breaks for renewable energy investments and subsidies for carbon capture research, should also be implemented to mitigate CO_2 emissions while enhancing economic resilience, public health, and life expectancy across the region.

Keywords Economic growth · Health expenditure · Renewable energy · COP28 · SDGs · CS-ARDL

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1 Introduction

Amid growing environmental concerns, researchers, particularly in the field of economics, have devoted more attention to health-related issues, as seen in the exploration of Gavurova et al. [1] and Dong et al. [2]. This rise in studies examining the determinants of life expectancy, with particular attention to elements like energy usage and CO_2 emissions, reflects a collective commitment to inventing rules intended to prevent environmental deterioration [3]. At the recent COP28, the emphasis was on supporting nations at risk by addressing climate change's effects and improving climate finance mechanisms [4]. In alignment with these priorities, as well as the United Nation's Sustainable Development Goals (SDG), particularly SDG 7 (Affordable and Clean Energy)—many nations are actively seeking solutions to mitigate the harmful impacts of fossil fuels, such as petroleum and coal, on environmental and human health [5–8].

Energy consumption plays a pivotal role in shaping life expectancy through a complex interplay of environmental and health-related factors. One of the most immediate impacts is observed in air quality and health. Elevated energy consumption, particularly in regions heavily dependent on fossil fuels, leads to heightened air pollution, contributing to respiratory diseases and cardiovascular issues [9]. This presents a serious risk to the overall health of populations and, consequently, has the potential to reduce life expectancy. Addressing this issue aligns with SDG 3 (Good Health and Well-Being), highlighting the critical need to mitigate energy-related pollution to improve overall health outcomes. In light of these challenges, Wang et al. [10] and [11] advocate for a shift toward renewable energy consumption as a viable alternative to non-renewable sources. Their proposition underscores the potential to safeguard human health, thereby contributing to an increase in life expectancy.

A focus on affordable and renewable energy (SDG 7) not only promotes good health and well-being (SDG 3) but also significantly contributes to achieving SDG 13 (Climate Action). There is a proliferation of studies delving into the intricate linkages between CO_2 emissions and life expectancy. A noteworthy example is the research conducted by Das and Debanth [12], which establishes that CO_2 emissions substantially influence life expectancy through a myriad of interconnected pathways. The combustion of fossil fuels, recognized as a significant contributor to CO_2 emissions, releases pollutants that significantly contribute to air pollution [13, 14]. This, in turn, has the potential to instigate respiratory diseases and may ultimately curtail life expectancy, particularly in regions grappling with elevated pollution levels.

Furthermore, CO_2 is pivotal as a primary greenhouse gas, playing a central part in the larger picture of climate change. The resulting global warming manifests in increased severity and frequency of extreme weather events, inflicting direct harm upon individuals and causing disruptions to healthcare systems. Life expectancy is then directly impacted by these repercussions. Notably, alterations in climate patterns, driven by CO_2 emissions, can have cascading effects on the prevalence and distribution of disease vectors, thereby influencing the incidence of vector-borne diseases such as malaria and dengue fever. This underscores the intricate and multifaceted nature of the association between CO_2 emissions and life expectancy.

This study concentrates on the ASEAN-5 countries, including Thailand, the Philippines, Singapore, Malaysia, and Indonesia, which are currently at a pivotal crossroads in balancing rapid development with sustainability, particularly concerning the health of their populations. Southeast Asia's energy consumption has increased at an average yearly rate of 3% over the previous 20 years, a trend projected to continue throughout this decade. This surge in energy demand has caused the rise of carbon emission, which, at approximately 3% annually, significantly surpasses the global average of 1% reported in 2022 [15]. Given the well-documented negative consequences of carbon emissions on health and well-being, it is essential to examine the factors that affect life expectancy in this region, particularly as the ASEAN countries are recognized as one of the vulnerable regions highlighted at COP28 [4]. Understanding how factors such as renewable energy, CO_2 emissions, and health expenditures impact life expectancy is not only critical for informed policy-making but also fills in a major void in the body of current literature, making this research vital for advancing knowledge in this area.

This study makes significant contributions. Firstly, it explores the impacts of green technology and CO_2 emissions on life expectancy within the ASEAN-5 countries, filling a notable gap in the existing literature that has tended to overlook this specific region. This geographical focus is crucial as it recognizes the distinctive characteristics of the ASEAN-5 nations, offering insights into the nuanced associations between environmental factors, technological advancements, and population health in Southeast Asia. Previous studies, such as Chan [16] and Chan & Kamala [17], investigated the factors influencing life expectancy in three chosen ASEAN nations. However, these studies are now nearly a decade old, making their relevance to the current socio-economic and environmental context limited. Our study not only updates this research by focusing on five ASEAN nations—Thailand, Singapore, the Philippines, Malaysia, and Indonesia—but also incorporates contemporary factors such as green technology, CO_2 emissions, and health expenditure, which were not considered in those earlier analyses. Furthermore, recent literature has shifted focus to other regions, such as the SAARC countries [18], D-8 countries [19] or used time-series approaches, as in [20] and [21] in Nigeria and Turkey respectively, while others focused on selected Asian countries [22] which does not include any of the ASEAN countries. This reveals the lack of recent and comprehensive panel studies on the ASEAN region, making our study timely and necessary for advancing the understanding of life expectancy determinants in this fast-developing region.

Secondly, this study adopts a panel framework using the FMOLS, DOLS and the CS-ARDL method, diverging from the prevailing trend in previous research, which commonly employed the fixed effects methodologies and Ordinary least squares [10, 20]. The selection of these methods is grounded in the need for robustness and precision in estimating the associations under investigation. The FMOLS and DOLS techniques offer advantages in handling endogeneity and serial correlation issues, offering a more dependable examination of the enduring relationships between the variables. This departure from conventional methodologies enhances the methodological diversity in the literature, contributing to a deeper comprehension of the complexities involved in studying the determinants of life expectancy. The CS-ARDL models presume that the explanatory variables are not influenced by other factors and that there exists a long-term relationship between the response variable and the predictor variables [19, 20, 23].

Additionally, the study aligns its findings with the broader global policy discussions raised at COP28, particularly concerning climate finance and support for vulnerable regions. This connection to current policy debates allows the present study to offer not only academic contributions but also real-world implications for sustainable development in Southeast Asia.

Following this introduction is an overview of life expectancy in the ASEAN-5 countries. The subsequent sections include the theoretical background, literature review, methodology, findings, conclusion, and finally, the limitations and suggestions for future research.

1.1 An overview of life expectancy in the ASEAN-5 countries

Figure 1 provides a comprehensive longitudinal view of life expectancy at birth for the ASEAN-5 countries ranging from 1995 to 2020 obtained from World Bank database. Recognizing the significance of understanding these trends, there arises a compelling case for persistent and nuanced research within the context of the ASEAN-5 countries. The data reveals distinct trajectories in life expectancy across these nations. Singapore consistently exhibits the highest life expectancy among the ASEAN-5, while Indonesia records the lowest. Thailand, meanwhile, falls between these two extremes. These variations highlight the diverse patterns in life expectancy across the region. The observed diversity underscores the necessity for in-depth investigations into the specific determinants and policies influencing life expectancy within each country. Temporal fluctuations, particularly evident in Indonesia, hint at the influence of dynamic factors on life expectancy. These fluctuations may be attributed to various elements, including economic developments, healthcare infrastructure, and responses to emerging health challenges.

Analyzing these fluctuations not only provides insights into the resilience and adaptability of each nation's healthcare and social systems but also sets the stage for informed policy interventions. Anomalies, such as the dip in Singapore's life expectancy in 2020, merit further exploration. These outliers could signal unique events, potentially tied to pandemics or other crises impacting public health. It is crucial to have a thorough grasp of these irregularities for crafting responsive and adaptive public health policies that can effectively navigate unforeseen challenges. Life expectancy trends emerge

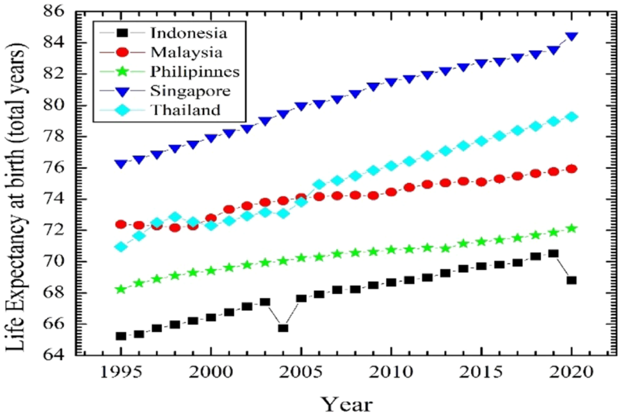

Fig. 1 Life Expectancy at birth (total years) in the ASEAN-5 Countries

as a critical barometer for evaluating the effectiveness of public health policies and interventions. Nations experiencing positive and sustained increases in life expectancy offer valuable lessons for others to glean from. Conversely, those encountering challenges necessitate a critical evaluation of existing policies, facilitating the identification of areas for improvement and optimization. Comparative studies across the ASEAN-5 countries offer an opportunity for benchmarking and the identification of best practices. Unraveling why certain nations consistently outperform others in life expectancy can inform evidence-based policy-making, fostering improved health outcomes and a more robust public health landscape.

In conclusion, the trends depicted in the table underscore the pressing need for continuous and nuanced studies on life expectancy within the ASEAN-5 countries. The dynamic nature of these trends, coupled with the ever-evolving global landscape, accentuates the imperative for ongoing research. Such endeavors not only inform adaptive policies but also contribute to sustainable improvements in public health across the ASEAN-5 nations.

2 Theoretical background

Life expectancy is closely linked to health outcomes, as demonstrated by various studies [24–26]. This correlation is unsurprising, considering that a variety of health issues, including cancer, asthma, heart disease, and premature mortality, have been identified as contributors to elevated global death rates, consequently reducing overall life expectancy [27, 28]. Grossman introduced a conceptual structure for health modeling in 1972. The health production function is a model that elucidates the association between various factors influencing health and the production of health. The framework is founded on the views that people value good health and that behavioral choices affect health status [22]. The model posits that health status is a function of healthcare inputs such as medical care, nutrition, and exercise, as well as individual behaviors like smoking, alcohol consumption, and exercise. Uddin et al. [22] assert that the theoretical framework presented is designed for a micro-level examination of health production. To extend its application to macro-level data, Fayissa and Gutema [29] rearranged the determining inputs into sub-sectoral vectors encompassing socio-economic and environmental elements. However, this reorganization was executed while preserving the underlying theoretical context. Aligned with this approach, this study examines the influence of clean technology, health expenditure, CO_2 emission on life expectancy, incorporating both economic and environmental factors into the analysis.

Subsequently, Smith and Dunt [30] offered a health production function framework outlining the intricate association between various medical (M) and non-medical (N) inputs contributing to overall health outcomes. According to this theory, health outcomes can be measured with variables such as life expectancy. Medical inputs (M) include factors like health expenditure, while non-medical variables (N) encompass elements such as economic factors (like GDP and Health expenditure) and environmental issues (such as CO_2 emissions and the use of clean energy). The model emphasizes that the well-being of individuals can be improved through increases in medical conditions as well as other socio-economic factors like improved economic expansion. Recent studies have adopted the Smith and Dunt [30] health production function [24–26]. In this study, we have also embraced this theory and included environmental activities such as the adoption of clean technology and CO_2 emissions as other non-medical factors that can determine people's health outcomes.

3 Literature review

Achieving sustainability remains a critical global objective, especially as nations strive to meet the Sustainable Development Goals (SDGs). A well-established consensus in the literature posits that energy consumption is essential for driving economic expansion. However, it is equally recognized that economic expansion, particularly in its conventional form, often exacerbates environmental degradation, leading to detrimental effects on ecological systems and human well-being [31–34]. In this context, the nexus between green technology adoption and life expectancy has garnered increasing attention from scholars.

Several studies have explored the connection between clean technology and life expectancy. Researchers have been particularly concerned with the adoption of green technology as a potential enhancer of life expectancy. This concern stems from consistent findings in past research, which have established the detrimental effects of CO_2 emissions not only on the environment but also on human health. Murthy et al. [19], for example, revealed that CO_2 emissions significantly reduce life expectancy in Developing-8 countries. Analogously, Uddin et al. [22] observed that carbon emissions and the ecological footprint were key contributors to the decline in life expectancy in certain Asian nations.

In a similar vein, Azam et al. [23] observed a consistent negative effect of CO2 emissions on life expectancy in Pakistan. Rodriguez-Alvarez [35] pointed out the harmful influence of air pollution on life expectancy and recommended greater investment in renewable energy sources. In their research on the countries involved in the North American Free Trade Agreement (NAFTA), Segbefia et al. [25] underscored the positive contributions of human capital, renewable energy, and technological advancements to life expectancy, while also highlighting the adverse effects of carbon emissions.

However, Amuka et al. [20] conducted a study spanning from 1995 to 2013, examining the association between CO_2 emissions and life expectancy in Nigeria. The findings indicated a significant positive association between CO_2 emissions and longevity. Similarly, Rjoube et al. [21] found a positive influence of CO_2 on life expectancy in Turkey. Consequently, it is challenging to draw a conclusive statement regarding the impact of CO_2 emissions on life expectancy, as findings remain inconsistent depending on the specificities of the country or region investigated. Meanwhile, Salehnia et al. [36] examined the impact of energy use, democracy, and public service provision on life expectancy, finding a decrease associated with CO_2 emissions and the democratic process. Despite these varied findings, previous studies consistently underscore the association between pollution from fossil fuel usage and various health issues, including cancer, asthma, heart disease, and premature mortality, contributing to increased death rates globally [27, 28].

In response, research has demonstrated that renewable energy adoption plays a pivotal role in improving environmental conditions by reducing pollution and mitigating carbon emissions [32, 37–41]. Simultaneously, sustained economic expansion—when pursued in conjunction with environmental policies—can lead to improved environmental quality over time [42–44]. Faced with the twofold task of promoting economic growth while addressing environmental concerns, governmental intervention becomes crucial. To combat climate change and foster sustainable energy adoption, it is crucial to implement robust strategies that cut down on greenhouse gas emissions and encourage the shift towards cleaner power sources [45–47]. In light of these considerations, many researchers have studied the influence of renewable energy on lifespan. Green technologies, encompassing renewable energy and environmentally friendly technologies, have the potential to contribute to improved public health by diminishing pollution and greenhouse gas emissions. This, in turn, can result in a healthier population, reducing exposure to air and water pollution, known contributors to various health issues [48, 49]. Increased access to green areas and tree canopy has been linked to longer lifespans, according to research [50]. A cleaner environment and enhanced public health can lead to heightened productivity, as individuals are healthier and more capable contributors to economic expansion [48].

Adom et al. [51] specifically explored the interplay between energy poverty, the transition to renewable energy, and development outcomes, emphasizing the compensatory role of the shift to green energy. Similarly, Ibrahim et al. [52] delved into the negative fallout of fossil-based energy on human development, highlighting the mitigating role of technology. These findings reflect the results of Wang et al. [10] and Karimi et al. [53], examining the association between green energy use, economic expansion, and life expectancy. Their studies emphasized a positive association, particularly in high-income countries and G-7 nations, respectively, demonstrating positive influences of clean energy use, health expenditure, and urbanization on lifespan. Rahman and Alam [54] also revealed a positive impact of renewable energy on life expectancy. Additionally, Majeed et al. [55] expanded their research to 155 economies, revealing a consistent positive correlation between renewable energy use and improved health outcomes. The consistent direction of these findings suggests that the adoption of clean energy positively contributes to increased life expectancy.

Jiang et al. [56] scrutinized the effects of digitalization and clean technologies on BRICS countries, concluding that green technology positively influences long-term life expectancy in Russia and China, though its short-term effect on health outcomes is minimal. The research results indicated that for every 1% increase in the use of clean technology, life expectancy rose by 0.125% in Russia and China, while in South Africa, it increased by 0.008%. Additionally, Mariani et al. [57] utilized an Overlapping Generations (OLG) model, which jointly considered the dynamics of life expectancy and environmental quality. The model demonstrated a positive association between longevity and the quality of the environment in the long term and during the transition phase. Furthermore, the adoption of sustainable energy sources has been linked to a reduction in the heat-related population impact caused by traditional energy production methods, demonstrating a positive impact on health outcomes, including lifespan and fatality rates [55].

The beneficial connection between green technology and lifespan serves as a catalyst for incentivizing innovation in the development of new technologies and processes that prioritize sustainability and enhance public health [10]. Additionally, adopting green technology can contribute to reduced healthcare costs. A lower life expectancy resulting from environmental degradation can lead to higher healthcare expenses, as more individuals require medical care for preventable illnesses. Green technology plays a crucial role in mitigating environmental degradation and fostering healthier lifestyles, thus helping to lower these healthcare costs [54]. A summary of these previous literature on the impacts of CO_2 emissions and green technology on life expectancy is presented in Table 1 below.

The review of existing literature reveals that the ASEAN-5 region has been largely overlooked, with much of the focus on broader geographical clusters or higher-income countries. Moreover, although some articles have explored the ties between green technology and lifespan, this paper is among the first to do so in the ASEAN-5 context while emphasizing green technology's role in improving life expectancy. It extends the dialogue beyond energy consumption alone and ties it to broader environmental sustainability efforts. This paper fills these gaps, offering insights into how Southeast Asian countries can tackle both environmental and health challenges.

3.1 Literature gaps

This study addresses a critical gap in the literature by examining the impacts of green technology and CO_2 emissions on life expectancy in the ASEAN-5 countries. Previous research, such as that of Chan [16] and Chan & Kamala [17], primarily focused on selected ASEAN nations, but these studies are now nearly a decade old and do not reflect the current socio-economic and environmental contexts. Additionally, while recent studies have expanded the scope to other regions, such as the SAARC [18] and D-8 countries [19], no comprehensive panel study has been conducted on the ASEAN-5. This leaves a significant gap in understanding the dynamic associations between environmental factors, technological advancements, and population health in Southeast Asia, which this study aims to fill.

Additionally, this study enhances methodological rigor by employing the FMOLS, DOLS and the CS-ARDL techniques, diverging from the widely used fixed effects and OLS approaches. This method is still relatively new in the literature as regards the investigation of the determinants of life expectancy. Moreover, few studies, such as Uddin et al. [22], which adopted similar econometric methods, did not include green technology and health expenditure as key variables, nor did they focus on the ASEAN region. Their analysis was limited to selected Asian nations, excluding the ASEAN countries central to this research. This methodological innovation not only advances econometric approaches in the field but also offers a more reliable framework for analyzing complex factors of lifespan in the fast-developing ASEAN region, filling a crucial gap in both empirical evidence and policy relevance.

The integration of these critical factors enables this probe not merely update the existing literature but also grant a more thorough insight of the determinants of life expectancy in the ASEAN-5 countries, effectively addressing gaps that previous research has overlooked.

4 Methodology

This study seeks to explore the intricate association among green technology, CO_2 emissions, and life expectancy within the ASEAN-5 countries. To accomplish this, four key independent variables are selected to fulfill our objective: economic growth (GDP), renewable energy consumption (RE), health expenditure (HE), and CO_2 emissions (CO2). Primarily, the sole dependent variable under scrutiny is life expectancy. Data spanning from 1995 to 2020 are gathered from the World Bank database for analysis. The model's specification is outlined below:

$$\mathrm{LnLE} = \alpha + \beta_{1i}\mathrm{lnGDP_i} + \beta_{2i}\mathrm{lnRE_i} + \beta_{3i}\mathrm{lnCO2_i} + \beta_{4i}\mathrm{lnHE} + \varepsilon_i \tag{1}$$

Within this framework, the symbol "i"embodies a specific country or region, while α symbolizes the intercept or constant term. This intercept signifies the expected value of the dependent variable when all independent variables are set to zero. The β coefficients, on the other hand, serve as the slope coefficients. Specifically, LE denotes life expectancy, GDP represents Gross Domestic Product, RE corresponds to renewable energy, HE stands for Health Expenditure, and CO2 represents CO_2 emissions. For detailed insights into these variables, refer to Table 2.

4.1 Estimation procedures

4.1.1 Panel unit root test

In this study, a panel unit root test is used instead of performing separate unit root tests for each country. This decision is based on the panel unit root test's ability to handle cross-sectional dependence and heterogeneity among the countries in the sample. By pooling data across countries, more efficient estimates of the unit root process are obtained, which helps in accounting for common factors that affect all countries in the panel. Additionally, the panel unit root test

Table 1 Research examining the relationship between CO2 emissions and human longevity

Author(s)	Methodology	Key findings	Region/country
Murthy et al. [19]	Panel ARDL	CO_2 emissions significantly reduce life expectancy	D-8 Countries
Uddin et al. [22]	CS-ARDL, FMOLS, and DOLS	Carbon emissions and ecological footprint negatively affect life expectancy	Selected Asian Nations
Lelieveld et al. [28]	data-informed atmospheric model	CO2 emissions contribute to higher premature mortality and lower life expectancy	Multiple Developing Nations
Azam et al. [23]	ARDL Bounds test	CO2 emissions levels significantly lowers life expectancy	Pakistan
Amuka et al. [20]	linear regression method and OLS techniques	Renewable energy decreases CO_2 emissions, improving life expectancy	Nigeria
Literature on Green Technology/Renewable Energy and Life Expectancy			
Wang et al. [10]	linear fixed-effect model and non-linear panel threshold model	Positive correlation between renewable energy and life expectancy, highest in high-income countries	121 countries of different income levels
Rodriguez-Alvarez [35]	Panel data, fixed effects model	Clean energy improves life expectancy by reducing pollution	Europe
Karimi Alavijeh et al. [53]	method of moments quantile regression	Renewable energy use boosts life expectancy	G-7 countries
Rahman and Alam [54]	Driscoll and Kraay's standard error technique and feasible generalized least square (FGLS) model	Renewable energy consumption leads to improvements in life expectancy	ANZUS-BENELUX countries
Majeed et al. [55]	pooled ordinary least squares	Clean energy increases life expectancy and reduces the mortality rate	155 economies
Jiang et al. [56]	ARDL model	Green technology enhances life expectancy	BRICS economies

Table 2 Variables description

Variables	Proxy	Unit of measurement
Gross domestic product (GDP)	Gross domestic product in US dollars	US dollars
Renewable Energy (RE)	Utilization of renewable energy consumption as a proxy for a percentage of total final energy consumption	percentage
Health Expenditure (HE)	Current health expenditure per capita (current US$)	US dollars
Carbon Dioxide Emission (CO_2)	CO_2 emissions (metric tons per capita)	tons per capita
Life Expectancy (LE)	Life expectancy at birth, total (years)	years

distinguishes between a unit root at the individual country level and a shared stochastic trend across the entire group. As a result, it provides more robust and reliable outcomes compared to testing each country individually. To assess the stationarity of the time-series data, the study applies three widely used unit root tests: Levin-Lin-Chu (LLC), Im, Pesaran, and Shin (IPS), and the Augmented Dickey-Fuller (ADF) test.

4.1.2 Levin-Lin-Chu (LLC)

Within the framework of the Levin-Lin-Chu (LLC) test, the fundamental hypothesis concerning the panel unit root can be expressed as follows:

$$\Delta y_{it} = \Phi_i y_{i,t-1} + \sum_{L=1}^{P1} \rho_{i,1} \Delta_{i,t-L} + \varepsilon_{i,t} \quad m = 1, 2 \ldots \tag{2}$$

where,

The variable yit represents lnGDP, lnRE, lnCO2, and lnLE. Δ indicates the first difference operator. The hypothesis test is structured as follows:

$H0\ :\ \phi 1 = 0$ to test for the presence of a unit root.

$H1\ :\ \phi 1\ <\ 0$ across all i to establish the absence of a unit root.

4.1.3 Im, Pesaran, and Shin (IPS)

The IPS method begins by constructing separate Augmented Dickey-Fuller (ADF) regressions for each cross-section. These regressions account for individual effects while excluding any time trend.

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + \sum_{j1}^{P1} \beta_{ij} \Delta y_{i,t-j} + \varepsilon_{it} \tag{3}$$

The null hypothesis is expressed as $H0\ :\ \rho i\ =\ 0$ for all $i = 1, \ldots N$ while the alternative hypothesis is stated as:

$$H_1\ :\ \begin{cases} \rho_i = 0 & for\ i = 1, 2, \ldots \ldots N1 \\ \rho_i < 0 & for\ i = N+1, N+2, N, with \quad 0 < N_1 \le N \end{cases} \tag{4}$$

4.1.4 Augmented Dickey-Fuller (ADF)

The core of the Augmented Dickey-Fuller (ADF) test lies in estimating the test regression:

$$\Delta y_t = \beta_0 + \delta y_{t-1} + \gamma_1 \Delta y_{t-1} + \gamma_2 \Delta y_{t-2} + \ldots \gamma_p \Delta y_{t-P} + u_t \tag{5}$$

The null hypothesis is stated as $\mathrm{H0}\ :\ \delta = 0$, while the alternative hypothesis is represented as $H1\ :\ \delta < 0$.

4.1.5 Pedroni co-integration

The objective behind panel cointegration analysis is to uncover enduring associations among variables, revealing whether these variables move collectively over the long term. Various tests for panel cointegration, stemming from distinct methodologies, are available in the literature. These tests can be divided into three categories: maximum likelihood-based testing, like the Larsson et al. [58] test, residual-based tests, like the Pedroni [59] and Kao [60] panel cointegration tests, and error correction-based tests, like the ones proposed by Westerlund [61]. The Pedroni [59] test was used in this investigation, and the null hypothesis stated that there was no cointegration among the variables in the cross-section. This test is known for its high explanatory power and superior performance, especially in smaller sample sizes [62].

A set of seven tests was presented by Pedroni [59] with the purpose of testing the alternative hypothesis of non-cointegration among the variables against the null hypothesis of cointegration. Two categories of panel cointegration statistics apply to these tests. Four statistics make up the first group, which Pedroni refers to as within-dimension or Panel t-statistics. These include a variance ratio statistic, a Dickey-Fuller type t-statistic, a nonparametric ρ-statistic, and a nonparametric Phillips and Perron type t-statistic. Three panel cointegration statistics, also known as group t-statistics or between-dimension statistics, make up the second group. These include an Augmented Dickey-Fuller type t-statistic, a nonparametric Phillips and Perron type t-statistic, and a Phillips and Perron type ρ-statistic.

Pedroni suggests rescaling the seven test statistics so that they have a distribution similar to the conventional normal. The standardization process for cointegration statistics can be outlined as follows:

$$\frac{K_{NT} = \mu\sqrt{N}}{\sqrt{\upsilon}} \Rightarrow N(0,1) \tag{6}$$

where K_{NT} denotes the standardized form of the test statistic concerning N and T, the values of the mean (μ) and variance (ν) are tabulated.

4.1.6 FMOLS and DOLS cointegrating estimator

Applying traditional Ordinary Least Squares (OLS) techniques to non-stationary economic data introduces challenges like autocorrelation, heteroscedasticity, and endogeneity, which often lead to biased and inefficient estimators, resulting in spurious regressions. To address these problems and improve performance with non-stationary data, the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) methods were developed. These approaches are designed to estimate long-run equilibrium parameters for cointegrated variables, taking into account endogeneity and serial correlation, thereby providing consistent and efficient estimator [62].

FMOLS and DOLS exist in various forms due to ongoing methodological advancements. Among them, the group-mean estimator introduced by Pedroni [63] has demonstrated superior performance in both heterogeneous and homogeneous panel data specifications. Consequently, this study adopts the FMOLS and DOLS estimators to explore the association between green technology, CO_2 emissions, and life expectancy in ASEAN-5 countries. The estimators for FMOLS and DOLS, as outlined by Pedroni [63], are presented below:

$$\beta^{\curlywedge}_{N,T} - \beta = \left(\sum_{i=1}^{N} w_{22,i}^{-2} \sum_{i=1}^{T} \left(x_{i,t} - \bar{x}_{i,t}\right)^2\right) \sum_{i=1}^{N} w_{11i}^{-1} w_{22,i}^{-1} \left(\sum_{i=1}^{T} \left(x_{i,t} - \bar{x}_i\right)\right) \varepsilon^{\wedge}_{i,t} - T^{*}_{\curlyvee i} \tag{7}$$

where,

$$\beta^{\curlywedge}_{i,t} = \varepsilon_{i,t} - \frac{\hat{w}_{21,i}}{\hat{w}_{22,i}} \Delta x_{i,t}, \overset{\wedge}{_{\curlyvee i}} = \hat{\gamma}_{21,i} \hat{\Omega}^{0}_{21,i} - \frac{\hat{w}_{21,i}}{\hat{w}_{22,i}} \left(\hat{\gamma}_{21,i} + \hat{\Omega}^{0}_{22,i}\right) \tag{8}$$

The $\widehat{w}_i$ represents the minimum triangulation of $\widehat{\Omega}_i$. Both DOLS and FMOLS exhibit an asymptotic distribution that is identical, showcasing efficient and consistent performance in estimating parameters.

4.1.7 The CS-ARDL method

This research employs the CS-ARDL approach as introduced by Pesaran et al. [64]. This error correction technique is adept at capturing both short- and long-term associations [65]. The CS-ARDL estimator operates under the assumption that the explanatory variables are exogenous and that a long-run association exists between the dependent and independent variables [66]. In contrast to the mean group (MG) estimator, which averages coefficients across countries and assumes equal slope coefficients and error variances for all countries, the CS-ARDL approach assumes that the long-term coefficients are uniform across countries, while allowing for variation in short-term coefficients and error variances [66, 67]. Moreover, da Silva et al. [68] argue that the panel-ARDL method is superior to other panel data techniques, such as fixed effects, instrumental variables, and GMM estimators, which may yield biased results unless coefficients are consistent across countries. The panel-ARDL approach, by including the lag structure of variables, ensures both consistent and efficient estimations while addressing the issue of endogeneity [67].

The ARDL (p, q, q, …, q) panel model, as outlined by Pesaran et al. [64], is introduced with Life Expectancy (LE) as the dependent variable for group i, influenced by multiple factors, detailed as follows:

$$LE_{it} = \sum_{j=1}^{P} \alpha_{ij} LE_{i,t-j} \sum_{j=0}^{q} \delta_{ij}{\prime} X_{i,t-j} \mu_i + \varepsilon_{it} \tag{9}$$

In this model, X represents the vector of explanatory variables for group i, including lnGDP, lnRE,lnCO2 and lnHE, with t denoting the time period. The coefficient vectors are symbolized by $\delta_{ij}{\prime}$, while μ_i represents the fixed effects. The reparametrized model is presented as Eq. (10) below.

$$\Delta LE_{it} = \phi_i \left(LE_{i,t-j} - \beta_i{\prime} X_{it} \right) \sum_{j=1}^{p-1} \alpha_j^{*} \Delta LE_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij}^{*\prime} \Delta X_{i,t-j} \mu_i + \varepsilon_{it} \tag{10}$$

Here, $\beta_i{\prime}$ represents the long-term effect of the explanatory variables on renewable energy consumption, while ϕ_i captures the influence of the error correction mechanism. The disturbances ε_{it} are assumed to be independently distributed over time and across units, with a mean of zero and a constant variance for each unit.

5 Findings

The descriptive statistics results reported in Table 3 reveal noteworthy patterns in the variables. lnCO2 exhibits a positively skewed distribution with a mean of 1.1503, indicating a rightward concentration. lnGDP displays substantial variability with a standard deviation of 1.1994, suggesting economic disparities among the observed entities. lnHE demonstrates a negatively skewed distribution, signifying concentration towards lower values. lnLE and lnRE portray relatively stable patterns, with lnLE characterized by a narrow distribution. The Kurtosis values for lnGDP, lnHE, lnLE, and lnRE suggest moderately heavy tails. These findings provide a preliminary understanding of the data distribution, offering insights for further investigation into the interplay of economic, environmental, and health factors.

Table 3 Descriptive statistics results

	lnCO2	lnGDP	lnHE	lnLE	lnRE
Mean	1.1503	8.4272	−3.6867	4.2909	2.2093
Median	1.1442	8.1925	−4.0687	4.2836	3.0933
Maximum	2.4749	11.0213	−1.3502	4.4200	3.9255
Minimum	−0.1863	6.1295	−5.1850	4.1780	−1.1087
Std. Dev	0.8716	1.1994	1.1460	0.0603	1.6397
Skewness	0.0127	0.6046	0.9725	0.3127	−0.8243
Kurtosis	1.5784	2.5718	2.5528	2.3825	2.1104
Jarque–Bera	10.192	8.2966	20.080	3.8939	17.6915
Observations	121	121	121	121	121

The results of the residual cross-section dependence tests, as presented in Table 4, offer evidence to reject the null hypothesis, which suggests no cross-section dependence or correlation. This conclusion is based on the non-significant outcomes from the Breusch-Pagan LM, Pesaran scaled LM, and Pesaran CD tests, all of which point to the lack of heteroscedasticity.

The panel unit root results displayed in Table 5 indicate stationarity for all variables in their first differences, as evident by significant p-values ($p < 0.05$). This suggests that the variables are integrated of order one, supporting the use of FMOLS and DOLS models, which assume stationarity in the data. The substantial reduction in unit root significance in first differences allows us to proceed with cointegration analysis, enhancing the reliability of our long-run estimations.

The results of the CADF Panel Unit Root Test in Table 6 indicate that all variables are stationary, either at the level or after first differencing. The test statistics for lnHE(−2.606), lnGDP(−2.743), lnLE(−2.991), ΔlnRE(−2.610), and ΔlnCO2(−3.783) are statistically significant, with p-values below 0.05. This signifies the rejection of the null hypothesis of a unit root, confirming that these variables are suitable for further econometric analysis.

The co-integration results in Table 7 reveal significance in 5 of the 7 statistics examined. This leads to the inference of a co-integration association among health expenditure, CO_2 emissions, green technology, economic growth, and life expectancy. The notable results across various metrics emphasize the interconnectedness of these variables, demonstrating a significant long-term association in the analyzed data. Table 7 further confirms this by showing a significant long-run association between the variables, as indicated by the Westerlund cointegration test. With a test statistic of 1.7723 and a p-value of 0.0382, the null hypothesis of no cointegration is rejected at the 5% significance level. This suggests that, over the long term, the variables tend to move in tandem, maintaining a stable equilibrium

Table 4 Residual cross-section dependence results

Test	Statistic	d.f	Prob
Breusch-Pagan LM	18.05334	10	0.0541
Pesaran scaled LM	1.800783		0.0717
Pesaran CD	0.909997		0.3628

Table 5 Panel unit root results

	LLC		IPS		ADF	
Variables	Level	1st Diff	Level	1st Diff	Level	1st Diff
lnHE	2.11428	−3.8287**	2.1882	−4.6174**	2.90129	42.1851**
	(0.9828)	(0.0001)	(0.9857)	(0.0000)	(0.9837)	(0.0000)
lnGDP	0.5995	−4.68539**	2.5719	−4.4475**	1.25063	38.2311**
	(0.7256)	(0.0000)	(0.9949)	(0.0000)	(0.9995)	(0.0000)
lnRE	1.4206	−2.8902**	1.6913	−4.4573**	4.92621	38.3031**
	(0.9223)	(0.0019)	(0.9546)	(0.0000)	(0.8961)	(0.0000)
lnCO2	−1.5434	−4.3883**	0.3595	−5.4695**	7.38885	48.2927**
	(0.0614)	(0.0000)	(0.6404)	(0.0000)	(0.6883)	(0.0000)
lnLE	-0.7594	−2.1831**	1.6567	−5.1657**	3.10963	45.9277**
	(0.2238)	(0.0145)	(0.9512)	(0.0000)	(0.9787)	(0.0000)

Significance levels are denoted as follows: ** at the 5% level ($P < 0.05$). Standard errors are reported in parentheses

Table 6 CADF panel unit root test

Test Variables	T-bar	Z[T-bar]	P-values
lnHE	−2.606**	−2.758	0.003
lnGDP	−2.743*	−2.266	0.012
lnLE	−2991**	−4.012	0.000
ΔlnRE	−2.610**	−2.628	0.004
ΔlnCO2	−3.783**	−4.663	0.000

Significance levels are denoted as follows: ** at the 5% level ($P < 0.05$) and * at the 10% level ($P < 0.10$)

Table 7 Panel Co-integration Results

	Within Dimension	
	Statistic	Prob
Panel v-statistic	6.1767**	0.0000
Panel rho-statistic	0.1761	0.5699
Panel PP-statistic	−2.3846**	0.0085
Panel ADF-statistic	−3.5976**	0.0002
	Between dimension	
	Statistic	Prob
Group rho-statistic	1.5134	0.9349
Group PP-Statistic	−1.889*	0.0294
Group ADF-Statistic	−3.9263**	0.0000
Westerlund test	1.7723*	0.0382

Significance levels are denoted as follows: ** at the 5% level ($P < 0.05$) and * at the 10% level ($P < 0.10$)

association. Essentially, the findings indicate that despite short-term variations, the variables remain linked over time, confirming the existence of a long-run connection in the panel data.

The regression estimation results in Table 8, employing both FMOLS and DOLS models, shed light on the impact of key variables—green technology, health expenditure, economic growth, and CO_2 emissions—on life expectancy. Significantly, both FMOLS and DOLS models consistently reveal positive and statistically significant associations between increased green technology, health expenditure, economic growth, and life expectancy. These findings align with established empirical research demonstrating positive correlations between advancements in green technology and life expectancy [10], increased health expenditure and life expectancy [69], and economic growth with enhanced life expectancy [70]. However, noteworthy distinctions exist between our study and theirs. For instance, Wang et al. [10] focused on 141 countries with diverse income groups, utilizing fixed effects. In contrast, Wang et al. [70] concentrated on Pakistan, employing the ARDL approach. While Radmehr and Adebayo [70] applied the FMOLS and DOLS models, they omitted green technology as a potential determinant and centered their study on Mediterranean countries—distinct from our focus on the ASEAN-5 nations. These differences underscore the unique contributions of our research, filling a crucial gap and providing a nuanced understanding of the impacts of green technology and CO_2 emissions on life expectancy in the ASEAN-5 countries. Contrarily, both models find an adverse association between $\ln CO_2$ and life expectancy. This aligns with the discovery by [19], although their study concentrated solely on Malaysia utilizing the ARDL approach. Consequently, there remains a gap in comprehensively understanding the ramifications of CO_2 emissions on life expectancy across the ASEAN-5 countries. Their exclusive focus on Malaysia neglects insights into other vital members of the ASEAN community, including Indonesia, the Philippines, Thailand, and Singapore.

Table 9 presents the findings from the CS-ARDL model, which explores the short- and long-term impacts of various factors on the dependent variable. In the short term, CO_2 emissions have a significant negative effect, with a coefficient of −0.0067 and a p-value of 0.000, indicating that increased emissions lower life expectancy. Other factors, such as health expenditure and renewable energy consumption, exhibit positive but statistically insignificant effects,

Table 8 Regression estimation results of FMOLS and DOLS

Variable	FMOLS	DOLS
lnRE	0.0107	0.0564*
	(0.3410)	(0.0285)
lnHE	0.0147**	0.0779**
	(0.0025)	(0.0000)
lnGDP	0.0162**	0.0668**
	(0.0001)	(0.0000)
lnCO2	−0.0470**	−0.0318
	(0.0002)	(0.2916)

Significance levels are denoted as follows: ** indicates at the 5% level ($P < 0.05$) and * at the 10% level ($P < 0.10$). Standard errors are reported in parentheses

Table 9 Results of CS–ARDL

Variable	Coefficient	Std. Error	Prob.*
Short run			
lnHE	0.0011	0.0071	0.871
lnRE	0.0133	0.0112	0.244
$\ln CO_2$	−0.0067*	0.0013	0.000
lnGDP	−0.0216	0.0107	0.051
Mean Group	−1.5075	0.2094	0.000
Long run			
lnHE	0.1106	0.0647	0.096
lnRE	0.1212**	0.0381	0.003
lnCO2	−0.2554*	0.1258	0.049
lnGDP	−0.1285	0.0815	0.124

suggesting minimal short-term influence. The mean group coefficient of -1.5075 reflects a significant negative short-term adjustment, with significance at the 1% level.

In the long term, renewable energy consumption shows a strong positive effect, with a coefficient of 0.1212 and a p-value of 0.003, indicating that greater use of renewable energy improves life expectancy over time. CO_2 emissions continue to have a significant negative long-term effect, with a coefficient of −0.2554 and a p-value of 0.049. Health expenditure has a positive, though marginally insignificant, long-term effect, while GDP demonstrates an insignificant negative association in both the short and long term. Overall, these results emphasize the harmful impact of CO_2 emissions and the beneficial role of renewable energy in the long-run outcomes.

The Diagnostic test results reported in Table 10 show that the model satisfies the assumptions of normality and homoskedasticity. The Jarque–Bera Normality test indicates that the residuals are normally distributed. The Heteroskedasticity test results suggest no evidence of heteroskedasticity. Both tests confirm the model's suitability for reliable inference.

The regression estimation results in Table 11 provide valuable insights into the nuanced associations between health expenditure, economic growth, CO_2 emissions, green technology, and life expectancy across five distinct countries—Thailand, Singapore, Philippines, Malaysia, and Indonesia. In Thailand, both FMOLS and DOLS models reveal a positive impact of increased health expenditure on life expectancy, underscoring the crucial role of healthcare investment. However, the FMOLS results also suggest that higher emissions may have a detrimental effect on life expectancy. The DOLS findings highlight the importance of elevated economic growth and health expenditure to enhance life expectancy. In Singapore, significant influences of economic growth on life expectancy are evident in both models, emphasizing the need to stimulate economic development. The FMOLS model indicates that greater green technology positively correlates with increased life expectancy, while higher CO_2 emissions are associated with reduced life expectancy. The Philippines showcases the pivotal role of green technology and economic growth in both FMOLS and DOLS models, contributing positively to life expectancy. However, higher CO_2 emissions are linked to a decrease in life expectancy. DOLS results emphasize the importance of increased health expenditure in boosting life expectancy. In Malaysia, both FMOLS and DOLS models suggest that CO_2 emissions can harm life expectancy. Indonesia's FMOLS results emphasize the adverse effect of CO_2 emissions on life expectancy, signaling the necessity of considering environmental factors in public health policies.

Table 10 Diagnostic Tests

Diagnostic tests	statistic	Prob
Normality Test [Jarque–Bera]	3.004	0.222
Heteroskedasticity Test	0.5708	0.639

Table 11 Regression estimation results for each country

Variable	Thailand	Singapore	Philippines	Malaysia	Indonesia
			FMOLS		
lnRE	0.1112	0.0350**	0.1222**	0.0098	0.0196
	(0.0671)	(0.0064)	(0.0000)	(0.0685)	(0.3840)
lnHE	0.0424*	−0.0060	0.0332**	0.0011	0.0051
	(0.0271)	(0.5108)	(0.0010)	(0.9329)	(0.6130)
lnGDP	−0.0172	0.0502**	0.0308**	0.0087	0.0087
	(0.3972)	(0.0000)	(0.0000)	(0.2676)	(0.1401)
$lnCO_2$	−0.1898**	−0.0668*	−0.0671**	−0.0680**	−0.1110**
	(0.0014)	(0.0245)	(0.0000)	(0.0002)	(0.0053)
			DOLS		
lnRE	0.0874	0.0326	0.1603**	0.0089	−0.0758
	(0.4209)	(0.0619)	(0.0000)	(0.4670)	(0.3699)
lnHE	0.1895*	−0.0353	0.0198	0.1537	0.0086
	(0.0210)	(0.0861)	(0.1208)	(0.0517)	(0.7468)
lnGDP	0.1386*	0.0734**	0.0364**	0.0526	0.0330
	(0.0420)	(0.0043)	(0.0000)	(0.1483)	(0.0603)
$lnCO_2$	−0.0288	−0.0399	−0.0663**	−0.0900*	−0.1140
	(0.6811)	(0.1938)	(0.0000)	(0.0425)	(0.4121)

Significance levels are denoted as follows: ** indicates at the 5% level ($P < 0.05$) and * at the 10% level ($P < 0.10$). Standard errors are reported in parentheses

6 Discussion

Our regression results show that green technologies, health expenditure and economic growth positively influences life expectancy. Green technologies such as renewable energy sources and electric vehicles, contribute to lower levels of air pollution. Reduced exposure to particulate matter and nitrogen dioxide decreases the risk of respiratory diseases and cardiovascular problems, ultimately improving life expectancy. Higher health expenditure enables the development and maintenance of robust healthcare infrastructure, including hospitals, clinics, and medical facilities. This increased infrastructure enhances accessibility to healthcare services, ensuring individuals have timely access to medical treatments, preventive care, and health interventions. Thus, higher life expectancy ensues. Economic growth often leads to increased income levels and improved living standards. Higher incomes enable individuals to access better housing, nutrition, and sanitation, improving overall health and increasing life expectancy. These robust findings provide compelling evidence supporting the crucial role of environmental sustainability, healthcare investment, and economic development in fostering longer life expectancy. Robust empirical evidence strengthens the credibility of the observed associations. The positive coefficients for green technology and health expenditure underscore the potential benefits of advancements in environmentally friendly technologies and increased investments in healthcare systems.

Contrarily, the adverse coefficient for $lnCO_2$ implies a potential link between increased CO_2 emissions and diminished life expectancy. CO_2 is a major greenhouse gas contributing to climate change. Changes in climate patterns can lead to extreme weather events, heat waves, and altered disease patterns, all of which pose health risks. Increased frequency and intensity of heatwaves can result in heat-related illnesses and fatalities, particularly affecting vulnerable populations, such as the elderly and those with pre-existing health conditions. While the significance varies between the two models, this observation highlights a concerning trend that necessitates attention. This implies the imperative for comprehensive policies prioritizing sustainable practices, healthcare advancements, and economic prosperity to address the multifaceted factors influencing life expectancy collectively. These results call for a holistic and integrated approach to public policies to enhance overall well-being and longevity in populations.

7 Conclusions

In conclusion, this study has meticulously examined the associations between economic growth, health expenditure, CO_2 emissions, green technology, and life expectancy in the ASEAN-5 countries using the FMOLS, DOLS, and CS-ARDL approaches from 1995 to 2020. The comprehensive results shed light on the crucial role of health expenditure, economic growth, and green technology in positively influencing life expectancy while highlighting the adverse impact of CO_2 emissions on this pivotal societal indicator.

Firstly, increased health expenditure emerges as a significant driver of enhanced life expectancy in Thailand and the Philippines. This underscores the importance of health system investments as a policy priority in these nations. Policymakers should consider strategies to augment healthcare infrastructure, improve accessibility, and ensure efficient resource allocation to bolster public health outcomes. Secondly, the positive correlation between economic growth and life expectancy in Thailand, the Philippines, and Singapore underscores the role of sustained economic development in fostering healthier populations. Policymakers must focus on creating an environment conducive to economic growth through targeted investments, regulatory frameworks, and initiatives promoting inclusive development, positively impacting life expectancy. Thirdly, the study highlights the positive association between green technology adoption and increased life expectancy in Singapore and the Philippines. This underscores the importance of environmentally sustainable policies that mitigate climate change and contribute to improved public health. Governments should incentivize research and development in green technologies, offer subsidies for their adoption, and implement regulations to encourage businesses to embrace environmentally friendly practices. Conversely, the study underscores the detrimental impact of CO_2 emissions on life expectancy across all ASEAN-5 countries. Policymakers must prioritize environmental conservation efforts, such as transitioning to cleaner energy sources, implementing emissions reduction strategies, and promoting sustainable practices across industries. Mitigating CO_2 emissions not only protects the environment but also safeguards public health.

The findings of this study resonate with the discussions at COP28, particularly regarding the urgent need for climate finance and support for vulnerable regions like the ASEAN-5. By addressing the interconnected challenges of health, economic growth, and environmental sustainability, policymakers can align their strategies with global efforts to promote resilience and well-being in regions facing the dual threats of climate change and public health crises. In doing so, the ASEAN-5 nations can better position themselves to leverage international support and resources, ultimately contributing to sustainable development goals and enhancing the quality of life for their populations.

8 Limitations and suggestions for future research

The first limitation pertains to data constraints. The study heavily relies on available data for the ASEAN-5 countries from 1995 to 2020. Any limitations or inaccuracies in the data may introduce uncertainties and potentially influence the robustness of the findings. Ensuring the accuracy and reliability of the data sources would be essential for future research endeavors. Another limitation involves causality issues. While the research employs econometric techniques to identify associations, establishing causality remains challenging. Unobserved factors or bidirectional associations among variables may impact the accuracy of causal inferences. Future studies could explore more sophisticated methodologies or incorporate additional control variables to address these complexities. One notable limitation is the omission of other ASEAN member states beyond the ASEAN-5 (Thailand, the Philippines, Singapore, Malaysia, and Indonesia). Neglecting the experiences of countries such as Vietnam, Cambodia, Laos, and Myanmar, among others, may overlook unique regional characteristics and hinder the generalizability of the findings. These nations might exhibit distinct socioeconomic, political, and cultural features contributing to the associations between economic, health, environmental factors, and life expectancy variations.

Future studies could extend the analysis over a longer time period to mitigate these limitations. A longer timeframe would enable a deeper exploration of the changing trends and dynamics related to economic growth, healthcare spending, CO_2 emissions, green technology, and life expectancy. Additionally, incorporating other socioeconomic factors like education, income inequality, and healthcare accessibility could enrich future research, offering a more comprehensive understanding of the determinants of life expectancy in ASEAN-5 countries. Expanding the research scope to include more ASEAN member states—such as Vietnam, Cambodia, Laos, and Myanmar—would also provide a broader perspective on regional dynamics, acknowledging the diversity among nations. This approach would allow for a more detailed assessment of the factors affecting life expectancy across the ASEAN region.

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Declarations

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