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The twist of longevity: exploring the convergence of the health production function and life-cycle hypothesis in Malaysia's life expectancy through savings

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Received: 8 January 2025 / Accepted: 23 May 2025
Published online: 02 June 2025

Abstract

In an era of dynamic global challenges, understanding the socioeconomic determinants of public health is crucial. Life expectancy, a key indicator of societal well-being, is shaped by healthcare advancements and broader economic, environmental, and demographic factors. While financial determinants are widely recognized, the impact of savings on life expectancy remains largely unexplored. Past studies show that CO2 emissions reduce life expectancy, while recent findings suggest that savings help lower CO2 emissions and may improve life expectancy. However, no study has explicitly analyzed the direct relationship between savings and life expectancy. This study bridges this gap by investigating, for the first time, the role of savings in life expectancy, incorporating CO2 emissions, renewable energy, and urbanization as additional determinants. Using annual data from Malaysia (1980–2020) and employing the ARDL technique, this study provides novel insights into the interplay between financial and environmental factors in shaping public health outcomes. Surprisingly, the findings indicate that savings would have an adverse effect, leading to a decrease in life expectancy. Conversely, urbanization was found to influence life expectancy positively. Additionally, CO_2 emissions are identified as detrimental to life expectancy, while the consumption of renewable energy emerges as an enhancing factor within the Malaysian context. These results imply that the potential harm from savings on longevity can be offset by simultaneous improvements in the standard of living, mainly through factors like urbanization. Furthermore, the negative impact of CO_2 emissions on life expectancy can be mitigated by incorporating renewable energy consumption, thereby enhancing overall life expectancy. Accordingly, we recommend that policymakers prioritize the adoption of clean energy to improve the well-being of citizens and, thereby, increase life expectancy. Additionally, efforts should be directed toward urbanization initiatives, providing citizens with enhanced amenities and further contributing to improved life expectancy. However, caution is advised in promoting savings among citizens unless accompanied by a parallel increase in the standard of living, measured through various parameters, including urbanization.

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Keywords *Savings* · CO_2 *emissions* · *Urbanization* · *Renewable energy* · *Life expectancy* · *ARDL*

1 Introduction

In an era defined by dynamic global challenges, grasping the intricate relationships between socioeconomic factors and public health is imperative. A paramount indicator of societal well-being, life expectancy, is shaped by advancements in healthcare and intricately linked to broader economic, environmental, and demographic determinants [1]. Despite the acknowledged influence of financial factors on life expectancy, the role of savings as a determinant has been largely overlooked.

The impact of savings on life expectancy extends beyond individual financial security. Economic stability, shaped by savings patterns at both the personal and societal levels, significantly affects healthcare accessibility, lifestyle choices, and overall well-being. Higher savings rates are associated with improved healthcare infrastructure, increased investments in public health, and a population's resilience during economic downturns [2], potentially contributing to longer life expectancies. Furthermore, financial decisions influence health outcomes, as debt exposure often leads to unhealthy coping behaviors such as alcohol, drug, and cigarette consumption [3]. These factors reveals the intricate link between financial decisions and both mental and physical health, strengthening the argument for considering savings as a key determinant of life expectancy.

The relationship between income, savings, and health investment further highlights disparities in healthcare access. Ricketts et al. [4] found that individuals with lower incomes allocate more of their resources to savings for future consumption rather than immediate health investments. Conversely, as income rises, individuals tend to increase their healthcare spending, suggesting that those in lower-income brackets may struggle to invest adequately in their health. This reality highlights the potential role of savings as a buffer against adverse health conditions, particularly for low-income populations.

According to the World Economic Forum [5] the global life expectancy gap is narrowing, with Asia progressively closing the gap with Europe and North America. By 2050, the global average life expectancy is projected to reach 77.3 years. Malaysia serves as a representative case within the Asian context, making it a suitable focus for this study.

Malaysia is a nation committed to economic development and environmental sustainability. It has transitioned from an agrarian economy to a rapidly industrializing and urbanizing nation. Malaysia's life expectancy at birth has improved significantly, rising from 72.8 years in 2000 to 76.65 years in 2023 [6]. This surpasses the global average and outperforms several developing nations in the region, although it remains lower than that of advanced economies [7]. Factors contributing to this trend include poverty reduction, lower unemployment, and higher incomes, all of which have been identified as drivers of longevity [7]. Urbanization has further improved healthcare access, leading to better health outcomes [8].

However, sustainability challenges complicate this progress, particularly due to the health risks posed by CO2 emissions [9]. While savings are generally linked to reduced CO2 emissions in other D-8 countries, [10] found that, in the short run, increased savings might contribute to environmental degradation in Malaysia. This paradox raises important concerns about the role of savings in Malaysia's sustainability and public health. The tension between economic resilience (e.g., savings-driven growth) and ecological health highlights the need to examine its impact on life expectancy. A key question remains: Does savings influence life expectancy in Malaysia?

To address this gap, this study goes beyond general trends in life expectancy improvement and examines Malaysia's distinct economic and environmental landscape. By investigating the relationships between savings, environmental degradation, renewable energy, and urbanization, this research provides novel insights into life expectancy determinants amidst evolving global challenges.

Against this backdrop, this study makes the following contributions: (1) it provides empirical evidence on the relationship between savings and life expectancy, incorporating CO2 emissions, renewable energy, and urbanization as key determinants; (2) it extends the literature on financial development and public health by positioning savings as a crucial variable rather than a supporting factor; and (3) it focuses on Malaysia, offering policy insights relevant to similar developing economies navigating industrialization and environmental challenges.

The remaining sections of this study encompass the theoretical framework, literature review, methodology, results, and conclusions.

2 Theoretical framework

In 1972, Grossman introduced the health production function (HPF), a theoretical framework that sheds light on the intricate association between various factors influencing health and the production of health [11]. This model is built on the principles that individuals inherently value good health, and behavioral choices play a pivotal role in determining health status [12]. Health issues like cancer, asthma, heart disease, and premature mortality contribute to elevated global death rates, affecting overall longevity [13, 14]. Therefore, because the HPF focuses on the Quality Adjusted Life Year, the function is considered a good proxy for life expectancy. Hence, it is often tied to health [15, 16].

The Health Production Function (HPF) suggests that an individual's health outcome, measured in Quality Adjusted Life Years (QALY), is influenced not only by healthcare inputs but also by personal behaviors such as smoking, alcohol consumption, and exercise [17]. QALY is a typical indicator of how well medical therapies are working, determined by weighing the extra years of life that a therapy adds to life and accounting for annual variations in health. The quality rankings allow for negative values for exceptionally unpleasant states of existence, ranging from one for perfect health to zero for death [18]. This measure is widely used in cost-effectiveness analyses to compare the added health benefits of different treatments [19]. The HPF framework emphasizes the importance of considering healthcare inputs and personal behaviors in determining an individual's health outcome. When delving into behavioral choices, particularly from an economic standpoint, it is imperative to acknowledge the LCH (Life Cycle Hypothesis).

The Life Cycle Hypothesis, pioneered by Franco Modigliani in the 1950s, is an economic theory describing spending and saving habits over a lifetime [20, 21]. It suggests that people seek to smooth consumption, considering future income. According to the LCH, people take on debt when they are young, thinking that their salary in the future will allow them to repay it. After that, in middle age, people start saving so that when they retire, their level of consumption won't change. The hypothesis expresses that wealth accumulation follows a "hump-shaped" pattern, low at the beginning of adulthood and in old age and rising in the middle. The LCH predicts wealth accumulation follows a "hump-shaped" pattern, mirroring health investments through the Health Production Function [22].

The intersection of the Life Cycle Hypothesis (LCH) and the Health Production Function (HPF) unveils a comprehensive understanding of the intricate relationship between socioeconomic activities and health outcomes, as shown in Fig. 1a and b. The LCH, which underscores the significance of financial decisions throughout a lifetime, introduces a crucial dimension to the HPF. As individuals navigate through various life stages, their financial choices, including savings (the shaded part of Fig. 1b), become integral determinants of their economic well-being and health production.

In the socio-economic activities depicted on the health production curve, including savings as a key factor adds a layer of complexity. Savings, viewed through the lens of the LCH, can act as a buffer against unforeseen health expenses, facilitate access to healthcare resources, and contribute to a sustained, consistent standard of living (as shown in Fig. 1a). The HPF, in turn, captures how these financial decisions influence lifestyle choices, preventive measures, and overall health outcomes.

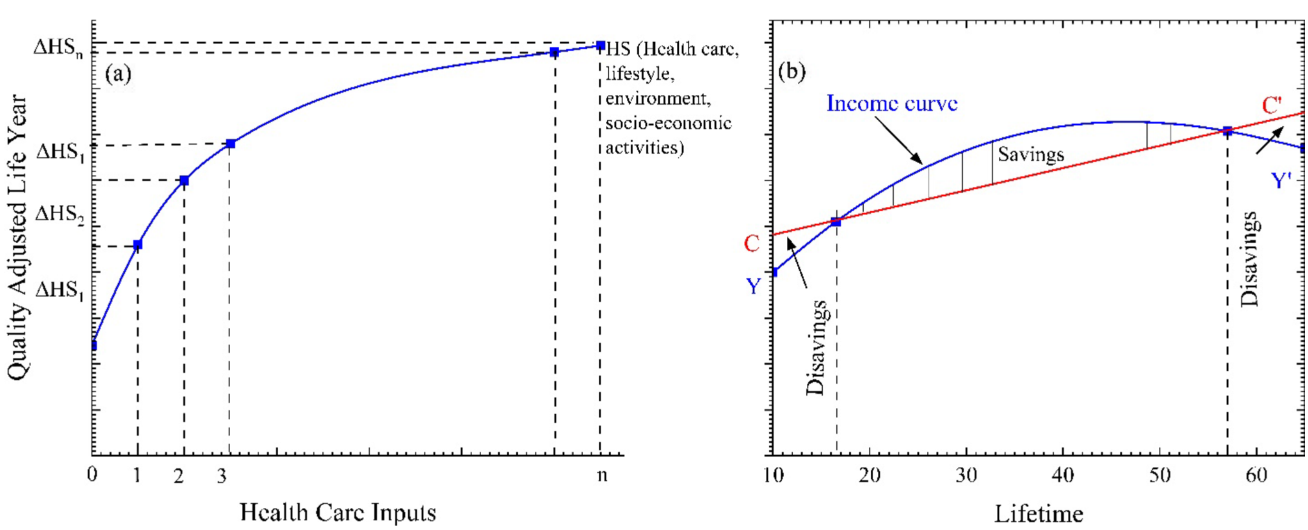

Fig. 1 (**a**) the Health Production Function and (**b**) the Life Cycle Hypothesis curve

This integrated perspective recognizes that economic decisions, particularly savings, play a pivotal role in shaping the trajectory of health production over the life cycle. It highlights the reciprocal relationship between financial choices and health, emphasizing the need for a holistic approach that considers economic and health dimensions to understand individual well-being. Both frameworks (HPF and LCH) recognize the intertwining of economic decisions with maintaining a consistent standard of living. The LCH emphasizes financial choices for a lifetime, while the HPF underscores how lifestyle choices impact health. Savings are a significant behavioral choice, increasingly recognized as an influential determinant of health outcomes and longevity. Therefore, we have put forth two hypothesized effects of savings on longevity.

2.1 Hypothesized positive impact of savings on longevity

Both the HPF and LCH frameworks demonstrate that savings can positively impact life expectancy by promoting financial stability and enhancing the capacity to invest in health over time. Within the HPF framework, prudent financial planning that allows for savings plays a crucial role in shaping individuals' health outcomes and overall quality of life. This interplay between financial decisions and health is intricate, with profound implications for individuals. Individuals engaging in prudent financial planning are more likely to have better access to healthcare resources [3]. Financial stability enables the acquisition of health insurance, regular medical check-ups, and the ability to afford necessary treatments without causing significant financial strain. This, in turn, promotes a proactive and preventive approach to healthcare, contributing to overall well-being.

Similarly, the LCH posits that effective financial management enables individuals to smooth consumption over their lifetime, and financial stability resulting from prudent planning empowers individuals to make healthier lifestyle choices. Affordability becomes less of a barrier to adopting a balanced and nutritious diet, exercising regularly, and participating in health-promoting activities. Investing in these aspects of a healthy lifestyle further enhances an individual's overall physical and mental well-being.

The convergence of the Health Production Function (HPF) and Life-Cycle Hypothesis (LCH) reveals the critical role of savings in meeting basic needs and facilitating sustained health investment throughout the life course. Moreover, financial stability allows individuals to pursue educational opportunities, engage in leisure activities, and actively participate in social and community events. This strategic financial behavior cultivates a framework in which long-term health and longevity are achievable, as it ensures continuous access to resources essential for maintaining well-being across different stages of life.

2.2 Hypothesized negative impact of savings on longevity

Households often deviate from LCH patterns and sometimes cannot consistently generate enough income to allocate towards savings. Consequently, they usually oscillate between saving and incurring short-term debt to maintain their current consumption levels [3]. Saving at a time when income is insufficient for basic needs can exacerbate financial strain, which in turn may lead to adverse health outcomes. The stress of prioritizing savings over immediate necessities can manifest in health challenges such as malnutrition, increased susceptibility to illness, and stress-related conditions [23]. Under the HPF model, the behavioural outcome of forced savings during periods of inadequacy is often malnutrition, as individuals struggle to afford a balanced and nutritious diet. Additionally, the stress of financial insecurity further compounds the health challenges, contributing to stress-related issues that can manifest physically and mentally. In extreme cases, the body's prolonged deprivation of essential nutrients and exposure to chronic stress may lead to the development of severe conditions like ulcers, highlighting the direct impact of inadequate financial resources on physical well-being. This persistent strain not only undermines health in the short term but can also accelerate the deterioration of overall health, ultimately shortening life expectancy.

This persistent strain extends beyond immediate health concerns to the overall quality of life and life expectancy. Chronic health challenges arising from the lack of sufficient income and resource allocation can progressively erode an individual's well-being, negatively influencing their longevity. The long-term consequences of neglecting immediate health needs in favour of savings create a concerning cycle wherein compromised health becomes a barrier to achieving a fulfilling and extended life. It emphasizes the critical importance of addressing immediate financial needs to safeguard both short-term well-being and long-term life expectancy [24]. It stresses the interconnected nature of financial decisions and health outcomes in shaping an individual's overall quality of life.

2.3 Deduction on the hypothesized impacts of savings on longevity

The hypothesis highlights the link between prudent financial planning, savings practices, and health outcomes. In line with the Life-Cycle Hypothesis (LCH), balancing immediate needs with future financial stability is crucial for longevity.

Incorporating savings as a behavioral choice in the Health Production Function (HPF) emphasizes the interaction between economic decisions and health, offering a holistic view of well-being. Prudent financial choices promote stability and healthier lifestyles, reinforcing a positive feedback loop that enhances life expectancy.

3 Literature review

Life expectancy is a key indicator of public health, quality of life, welfare, and economic development. As a result, numerous studies have examined its determinants across different countries and regions. Azam et al. [25] classified these determinants into three main categories: economic, social, and environmental factors. To maintain clarity, this literature review follows Azam et al.'s framework [25], organizing the discussion into three distinct subsections, each addressing one of these key factors influencing life expectancy.

3.1 Economic determining factors of life expectancy

According to Azam et al. [25], key economic factors influencing life expectancy include income, food production, and inflation. Roffia et al. [26] used fixed-effects multiple regression analysis to conduct a longitudinal study on OECD countries from 1999 to 2018. Their findings showed that higher GDP levels and increased per capita healthcare expenditure positively impact life expectancy at birth. Expanding on this, [27] examined EU accession candidate countries and highlighted that rising economic growth and declining infant mortality contribute to longer life expectancy, underscoring the importance of socioeconomic conditions.

Similarly, Wang et al. [28] analyzed global life expectancy trends from 1960 to 2016, identifying regional variations and correlations between economic growth, air pollution, and life expectancy. Azam et al. [25] supported this pattern in Pakistan, where higher per capita income and greater health expenditure were linked to longer life expectancy. Likewise, a positive relationship was found between GDP and life expectancy [29], while similar trends were observed in OECD Asia/Pacific countries [30].

Further exploring this relationship, Wang et al. [31] studied financial development, economic growth, energy use, and life expectancy in Pakistan. Their findings indicated that while economic growth increases life expectancy, financial development has a negative impact, and high energy consumption reduces life expectancy due to environmental degradation. In China, Luo and Xie [32] examined economic inequality and found that a widening income gap negatively affects life expectancy. These studies collectively highlight that improved economic conditions generally enhance life expectancy.

3.2 Social determining factors of life expectancy

Life expectancy determinants categorized under social factors include population growth, birth rate, and death rate [25]. Moga et al. [33] examined how changes in educational attainment and economic freedom influence life expectancy in new EU member states from 2000 to 2019. Their co-integration and causality tests highlighted the significance of both factors, with educational attainment proving to be more effective.

Similarly, birth rate, urbanization, and population growth was identified as contributors to increased life expectancy in Pakistan [25]. In a study of 43 African nations, it was found that health spending positively impacts life expectancy, with government effectiveness playing a moderating role [34]. Their findings also emphasized the importance of economic activity and school enrollment in promoting longevity.

Uddin et al. [12] employed the CS-ARDL method to analyze the socioeconomic drivers of life expectancy in selected Asian countries. Their results indicated that institutional quality, health expenditure, and financial development contribute to longer life expectancy, whereas birth rate, population growth, and death rate have the opposite effect.

Consistent with these findings, Rahman and Alam [9] concluded that good governance plays a crucial role in improving life expectancy.

3.3 Environmental determining factors of life expectancy

Azam et al. [25] highlighted the negative impact of CO_2 emissions on life expectancy in Pakistan, a finding consistent with Uddin et al. [12], who observed similar effects of carbon emissions and ecological footprint in selected Asian countries. Likewise, Rodriguez-Alvarez [35] underscored the detrimental consequences of air pollution on life expectancy, advocating for increased investments in renewable energy as a mitigation strategy. This is particularly relevant since renewable energy can enhance environmental sustainability [36, 37, 69].

While environmental pollution adversely affects longevity in ANZUS-BENELUX countries, Rahman and Alam [29] found that renewable energy positively contributes to life expectancy. Similarly, Wang et al. [28] examined the relationship between renewable energy consumption, economic growth, and life expectancy, demonstrating their positive correlation, particularly in high-income countries. Karimi et al. [38] further emphasized the beneficial effects of renewable energy consumption, health expenditure, and urbanization on life expectancy in G-7 countries. Expanding this analysis to 155 economies, Majeed et al. [39] confirmed the positive association between renewable energy and improved health outcomes, reinforcing the idea that clean energy enhances life expectancy.

Conversely, Ibrahim et al. [40] explored the adverse effects of non-renewable energy on human development, stressing the mitigating role of technology in reducing its negative impact. Adom et al. [41] examined the interplay between energy poverty, the renewable energy transition, and development outcomes, highlighting the compensatory role of transitioning to green energy. Segbefia et al. [42] focused on NAFTA countries, demonstrating the positive contributions of human capital, clean energy, and technological innovation to life expectancy while acknowledging the harmful effects of carbon emissions. Meanwhile, Salehnia et al. [43] investigated the influence of energy consumption, democracy, and government service delivery on life expectancy, revealing that reductions in CO_2 emissions and a robust democratic process contribute to improved longevity.

3.4 Insights into savings-life expectancy nexus

The existing literature unveils the importance of strengthening financial sectors, increasing healthcare budget allocations, and adopting clean and green technologies to enhance life expectancy and achieve sustainable development goals. However, limited attention has been given to improving the financial sector while simultaneously reducing reliance on unclean energy sources that contribute to environmental degradation and pose health risks.

In our recent work [10], we address this gap by investigating the role of savings as a potential determinant of CO_2 emissions. Our findings introduce a novel perspective, revealing that savings can serve as a mitigating factor for environmental pollution. This suggests that financial decisions and economic strategies play a crucial role in shaping ecological outcomes. This buttress the findings of Ximei et al. [44] that green financial development can improve environmental sustainability in Asia–Pacific Economic Cooperation (APEC) economies.

Notably, existing studies [25, 45, 67] have consistently highlighted the negative impact of CO_2 emissions on life expectancy. However, our research [10] provides a fresh perspective by demonstrating that savings, as a financial variable, can contribute to environmental sustainability and potentially influence life expectancy.

Recognizing savings as a determinant of life expectancy is critical for several reasons. First, it aligns with the broader understanding that economic factors significantly shape health outcomes. By establishing a link between savings and CO_2 emissions, we emphasize the role of financial decisions in shaping environmental conditions and public health. Second, incorporating savings into life expectancy research opens avenues for policy interventions that promote both economic prudence and environmental stewardship. This perspective reinforces the interconnectedness of economic, environmental, and public health considerations, fostering a more comprehensive approach to improving well-being and longevity.

3.5 Literature gap

Despite extensive research on the determinants of life expectancy, significant gaps remain, particularly regarding the role of financial factors such as savings. While previous studies have primarily examined economic, social, and environmental determinants, the impact of financial decision-making—especially savings—on life expectancy has been largely overlooked. Most existing research [25, 45] emphasizes the role of GDP, healthcare expenditure, and institutional quality in shaping life expectancy. However, savings play a crucial role in ensuring financial security, access to healthcare, and the ability to afford a healthier lifestyle, all of which can contribute to increased life expectancy. By incorporating savings into the discussion, this study introduces a novel dimension to understanding the financial determinants of longevity.

Methodologically, existing studies often rely on panel data techniques such as fixed-effects models, CS-ARDL, and causality tests to examine the relationship between economic growth, environmental factors, and life expectancy [12, 26]. However, these approaches may not fully capture the long- and short-term effects of the determinants of life expectancy. To address this limitation, this study employs the ARDL model, which allows for a more nuanced analysis of both immediate and long-run dynamics. By using this approach, this research provides deeper insights into how financial stability through savings can influence life expectancy over time.

4 Methodology

Table 1 shows the variables employed for this research, along with their respective data sources—the meticulous selection of these variables suits the scope of this study. Data has been gathered from 1980 to 2020, specifically for Malaysia. The limitation of utilizing data only up to 2020 is imposed due to the lack of availability for most variables beyond that year. Though acknowledged, possible biases like measurement discrepancies and omitted variables (like healthcare expenditure or access to medical services) do not detract from the dependability of the results, which is enhanced by the use of credible data sources, the long coverage period, and the application of strong econometric methods.

Variables	Symbols	Unit of Measurement	Data Sources
Life Expectancy	LE	Total years of Life expectancy at birth	World Bank Database (https://data.worldbank.org/indicator/SP.DYN.LE00.IN
Savings	S	Gross savings (% of GDP)	World Bank Database https://data.worldbank.org/indicator/NY.GNS.ICTR.ZS
Carbon dioxide (CO_2) emissions	CO_2	CO_2 emissions (Tons per capita)	Countryeconomy.com https://countryeconomy.com/energy-and-environment/
Renewable energy	RE	A compilation of Hydropower, Biodiesel, solar, Biomass, and Biogas (ktoe)	Malaysia Energy Information Hub https://meih.st.gov.my/statistics;jsessionid=99BAB7737321CDFAB08030CFBD441085
Urbanization	UR	Urban population (% of total population)	World Bank Database https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

Table 1 Descriptive Statistics

	lnLE	lnS	ln CO_2	lnRE	lnUR
Mean	4.2873	3.4458	1.5872	5.1660	4.0854
Median	4.2873	3.4549	1.7440	5.2002	4.1268
Maximum	4.3299	3.6851	2.1199	5.2751	4.3459
Minimum	4.2231	3.1724	0.7130	4.9645	3.7387
Std.Dev	0.0292	0.1464	0.4918	0.0982	0.1947
Skewness	– 0.3904	– 0.2125	– 0.5520	– 0.7566	– 0.3049
Kurtosis	2.1253	2.0355	1.7742	2.2509	1.6978
Observations	41	41	41	41	41

Note that lnLE, lnS, ln CO_2, lnRE, and lnUR stand for the logarithm values of Life expectancy, savings, CO2 emissions, Renewable energy, and Urbanization, respectively

4.1 Specifying the econometric model

In this study, the time series model is used for our analysis. Life expectancy (LE) is the dependent variable, while savings (S), renewable energy (RE), Urbanization (UR), and CO_2 emissions (CO_2) are the explanatory variables. In order to examine the relationships between savings and life expectancy in Malaysia, we specify the model below:

$$LE = f\left(S_t, CO_{2t}, RE_t, UR_t\right) \tag{1}$$

For standardization, the natural logarithm of the variables for analysis is taken; thus, Eq. (1) is expressed as

$$\ln LE_t = f\left(\ln S, \ln CO_2, \ln RE, \ln UR_t\right) \tag{2}$$

The inclusion of *In* before all the parameters shows that they are now in their natural logarithm form.

The empirical analysis includes several estimation tests, allowing the formulation of Eq. (2) as follows:

$$\ln LE_t = \beta_0 + \beta_1 \ln S_t + \beta_2 \ln CO_{2t} + \beta_3 \ln RE_t + \beta_4 \ln UR + \varepsilon_t \tag{3}$$

where β_0 is the intercept, and β_1, β_2, β_3 and β_4 are the coefficients of the independent variables? ε stands for the error term and t denotes time series, which is 40 years spanning from 1980 to 2020.

4.2 Estimation approach

To investigate the impact of savings on life expectancy, this study first examines the stationarity of the time series data using the Augmented Dickey-Fuller (ADF) test, following recent studies such as [46; 47]. Ensuring stationarity is critical, as the reliability of multivariate time series analysis depends on this property. The ADF test serves as a rigorous tool for detecting the presence of unit roots, determining whether a series is non-stationary and requires differencing or if it is trend-stationary [46]. This distinction is essential for selecting the appropriate methodology to achieve stationarity.

Once stationarity is established, a cointegration test is conducted to validate the long-term relationship between life expectancy (LE) and savings. Additionally, a likelihood ratio test is performed to assess the redundancy of variables, ensuring a more refined model. By addressing potential non-stationarity at the outset, the ADF test helps prevent spurious regression results, thereby enhancing the robustness and validity of the study's findings, particularly within the ARDL framework.

4.3 ARDL (autoregressive distributed lag)

This study employs the Autoregressive Distributed Lag (ARDL) methodology to evaluate the long- and short-term impacts of savings, renewable energy consumption, CO2 emissions, and urbanization on life expectancy in Malaysia. The ARDL approach, originally developed by Pesaran and Pesaran [48], is selected for its unique advantages over other cointegration techniques.

This model is particularly suitable for time series analysis when the variables involved are integrated at different orders, specifically I(0) or I(1), but not I(2) [25]. This flexibility is crucial for the current study, allowing us to accurately capture the dynamic relationships among variables without the restrictive requirement for uniform integration levels imposed by other cointegration methods, such as those of Engle-Granger or Johansen and Juselius. Another effectiveness of ARDL model is in its estimation of short-term and long-run elasticities, especially when working with small sample sizes [49]. Moreover, the ARDL approach is known for providing robust and reliable results, even under the constraints of smaller samples, due to its reliance on ordinary least squares (OLS) assumptions to determine cointegration [25].

Despite these advantages, the ARDL model has its limitations, particularly in addressing potential endogeneity concerns. Recent studies have highlighted that failing to address endogeneity can lead to biased and inconsistent estimates, potentially distorting policy implications. Alternative econometric techniques, such as Instrumental Variable (IV) estimation and Structural Equation Modeling (SEM), explicitly address endogeneity issues. IV approaches mitigate endogeneity by using external instruments that are correlated with the endogenous regressors but uncorrelated with the error term [50]. However, identifying valid instruments remains a challenge in macroeconomic time series analysis, as weak instruments can exacerbate estimation biases [51].

Similarly, SEM allows for simultaneous equation modeling to capture bidirectional causality [52], but it requires large datasets to ensure statistical power and reliable parameter estimates—an issue when working with annual time series data.

Despite these considerations, the ARDL approach remains appropriate given the study's objectives and data constraints. The ARDL bounds testing procedure is effective in establishing long-run relationships, even in small sample sizes, making it preferable to traditional cointegration techniques [53]. Recent studies have employed the ARDL approach in energy and macroeconomic analyses, demonstrating its robustness in capturing short- and long-run dynamics. To mitigate endogeneity concerns, this study incorporates robustness checks, including the bounds test for cointegration and diagnostic tests for autocorrelation, heteroscedasticity, and functional form [54].

Additionally, the use of natural logarithms ensures that the estimated coefficients can be interpreted as elasticities, providing meaningful insights into the proportional relationships among variables [47].

In light of these, the ARDL model is applied in this study to rigorously examine the relationships between the selected variables. This approach enables us to assess both short-term and long-term effects, providing a comprehensive understanding of how these factors influence life expectancy in Malaysia. The results derived from this methodology are expected to offer valuable insights into the interplay between economic and environmental variables and public health outcomes, thereby contributing to the broader discourse on sustainable development.

4.4 Lag length selection for ARDL model

The selection of the optimal lag length is essential in the ARDL bounds-test approach, as it ensures that the model appropriately captures both the short-run and long-run dynamics of the variables involved. In this study, the Akaike Information Criterion (AIC) was used to determine the optimal lag length due to its reliability in small sample sizes and its balance between model fit and complexity. Given the annual data, a maximum lag length of 2 was considered, and the optimal lag structure for the ARDL model, determined using the Akaike Information Criterion (AIC), was (1, 0, 0, 1, 0). This indicates a lag of 1 for life expectancy, 0 for savings and renewable energy, 1 for CO2 emissions, and 0 for urbanization. The chosen structure ensures the model captures both short- and long-run dynamics while maintaining plausibility.

Following the model of past literature [10, 47], the ARDL bounds-test model is articulated as follows:

$$\begin{aligned}\Delta \ln LE_t = \beta_0 + \sum_{i=1}^{\rho} \beta_{1i}\Delta \ln LE_{t-1} + \sum_{i=1}^{\rho} \beta_{2i}\Delta \ln S_{t-1} + \sum_{i=1}^{\rho} \beta_{3i}\Delta \ln\ CO_{2t-1} + \sum_{i=1}^{\rho} \beta_{4i}\Delta \ln\ RE_{t-1} + \sum_{i=1}^{\rho} \beta_{5i}\Delta \ln\ UR_{t-1} \\ +\lambda_1 \ln\ LE_{t-1} + \lambda_2 \ln\ S_{t-1} + \lambda_3 \ln\ CO_{2t-1} + \lambda_4 \ln\ RE_{t-1}\lambda_4 + \lambda_5 \ln\ UR_{t-1} + \varepsilon_t\end{aligned} \tag{4}$$

In Eq. (4), *In* represents the natural logarithm function, β_0 is the intercept, and ε is the error term. *LE* denotes life expectancy, *S* represents savings, CO_2 stands for CO_2 emissions, *RE* represents renewable energy, and *UR* indicates urbanization. The variable *t* represents time, covering a 40-year period from 1980 to 2020.

The summation signs in the equation indicate the short-term estimates, while **λ** represents the long-run relationships. The Wald test (F-statistic) is used in the ARDL cointegration technique to confirm the presence of cointegration among the variables. Pesaran et al. [55] introduced two critical bounds for the F-test. If the computed F-test value falls below the lower bound, it indicates no meaningful long-run relationship among the variables. Conversely, if the F-test value exceeds the upper bound, it confirms the presence of cointegration. However, if the value falls between the two bounds, the results are considered inconclusive.

To assess the short-run relationships among the variables, the following Error Correction Model (ECM) is developed within the ARDL framework.

$$\begin{aligned}\Delta \ln LE_t = \beta_0\ + \sum_{i=1}^{\rho} \beta_{1i}\Delta \ln\ LE_{t-1} + \sum_{i=1}^{\rho} \beta_{2i}\Delta \ln\ S_{t-1} + \sum_{i=1}^{\rho} \beta_{3i}\Delta \ln\ CO_{2t-1} + \sum_{i=1}^{\rho} \beta_{4i}\Delta \ln\ RE_{t-1} \\ + \sum_{i=1}^{\rho} \beta_{5i}\Delta \ln\ UR_{t-1} + \partial_1 ECT_{t-1} + \varepsilon_t\end{aligned} \tag{5}$$

This research examines the stability of the ARDL model by conducting a heteroskedasticity test and a serial correlation test. Additionally, the strength of the regression model is assessed through CUSUM and CUSUM square tests. Finally, the robustness of the result is ascertained through the DOLS and FMOLS tests.

4.5 The DOLS and FMOLS tests

For robustness, this study employs Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) as additional estimation techniques, following recent studies such as [9, 56]. While McCoskey and Kao (1998) proposed the DOLS estimator—a residual-based test that yields effective results for cointegrated variables—Phillips and Hansen [57] introduced the FMOLS estimator.

FMOLS is particularly reliable for small sample sizes, addressing issues of endogeneity and serial correlation among variables, as highlighted by Hamit-Haggar [58] and Merlin et al. [59]. The application of FMOLS requires prior knowledge of the cointegration properties of explanatory variables and their order of integration, as determined by unit root tests [10]. Notably, Rahman et al. [9] emphasize that DOLS exhibits less distortion compared to FMOLS estimation.

Due to their superior ability to address serial correlation and endogeneity issues, FMOLS and DOLS serve as essential robustness checks in ARDL-based studies. While ARDL effectively models dynamic relationships and accommodates variables integrated at I(0) or I(1), FMOLS enhances robustness by non-parametrically correcting for autocorrelation and heteroskedasticity, while DOLS mitigates endogeneity through a parametric approach that reduces correlations between explanatory variables and error terms. This dual approach strengthens the reliability and precision of long-run parameter estimates, reinforcing the validity of the ARDL model's findings.

Furthermore, DOLS outperforms FMOLS in terms of bias elimination, particularly in small sample sizes [10, 60]. The two equations are expressed as follows:

$$\tilde{\zeta}\, FMOLS = \left[\mathrm{N}^{-1} \sum_{t-1}^{t} \left(\sum_{t-1}^{t} U_t - \underset{t}{\tilde{U}} \right) \right]^{-1} \times \left[\left(\sum_{t-1}^{T} U_t - \underset{t}{\bar{U}} \right) \underset{t}{\hat{S}} - T\Delta_{eu} \right]$$

$$\tilde{\zeta}\, DOLS = \left[\mathrm{N}^{-1} \sum_{i=1}^{N} \left(\sum_{i=1}^{t} C_t C\prime_t \right)^{-1} \left(\sum_{i=1}^{t} C_t C\prime_t \right) \right]$$

5 Findings and discussion

The statistical summary presented in Table 1 provides valuable insights into the distribution and characteristics of five variables: *lnLE, lnS, lnCO2, lnRE, and lnUR*.

Starting with measures of central tendency, the mean and median indicate the typical or central values for each variable. The mean helps in understanding the average behavior of the natural logarithm-transformed variables, while the median provides insights into the middle values, which are less influenced by extreme observations.

The range of the data is explored through the maximum and minimum values. For instance, the maximum and minimum values of $lnCO_2$ reflect the highest and lowest levels of CO_2 concentration in the dataset, respectively. Understanding the range is crucial for identifying potential outliers and assessing overall data variability.

The standard deviation measures the dispersion or spread around the mean. A higher standard deviation indicates greater variability in the data. In this context, the relatively higher standard deviations for *lnS* and $lnCO_2$ suggest more significant fluctuations in the natural logarithm of savings and CO2 emissions compared to the other variables.

Skewness provides insights into the symmetry of the distribution. Negative skewness values, observed in *lnLE, lnS, lnCO2, lnRE,* and *lnUR,* indicate a left-skewed distribution, suggesting a longer tail on the left side.

Kurtosis measures the sharpness and tail behavior of the distribution. A normal distribution has a kurtosis value of 3, indicating a mesokurtic distribution. However, all examined variables exhibit negative kurtosis (platykurtic), with values below 3, suggesting a relatively flatter distribution.

The application of the ARDL approach requires that the variables under consideration exhibit stationarity at order 0 or 1 but not at order 2. Consequently, we have employed the widely accepted Augmented Dickey-Fuller (ADF) unit root

Table 2 ADF Unit Root Tests

		lnLE	lnS	lnCO$_2$	lnRE	lnUR
At level	Intercept	− 1.9948 (0.2878)	− 0.9770 (0.7523)	− 2.1679 (0.2207)	− 2.3656 (0.1579)	− 3.1681** (0.0318)
	Intercept with trend	− 2.8181 (0.1997)	− 0.7461 (0.9622)	0.1037 (0.9963)	0.0090 (0.9949)	− 0.0577 (0.9934)
At First Difference	Intercept	− 3.9343*** (0.0043)	− 5.6086*** (0.0000)	− 4.7286*** (0.0005)	− 6.9180*** (0.0000)	0.1187 (0.9619)
	Intercept with trend	− 4.1291*** (0.0127)	− 6.1293*** (0.0000)	− 5.3354*** (0.0005)	− 7.8277*** (0.0000)	− 3.3877* (0.0721)

*Note that lnLE, lnS, ln CO$_2$, lnRE, and lnUR stand for the logarithm values of Life expectancy, savings, CO2 emissions, Renewable energy, and Urbanization, respectively. ***, ** and * represents significant levels of 1%, 5% and 10% respectively*

Table 3 Bounds Test

Test statistics		Signifi	critical values	
Optimal lag length	(1,0, 0, 1,0)		I(0)	I(1)
F-Statistic	8.919596	1%	3.81	4.92
K	4	5%	3.05	3.97
		10%	2.68	3.53

test to ensure that none of the variables are second-differenced stationary, as the ARDL technique is not designed to handle variables with an order of integration greater than one.

Table 2 presents the findings of the stationarity test conducted using the ADF test. According to these results, all variables, except for urbanization, exhibit non-stationarity at the level. However, urbanization is found to be stationary at this level. Notably, after first differencing, the results shown in the fourth and fifth rows of Table 2 indicate that the unit root problem is resolved for all variables. Therefore, it can be concluded that the selected variables achieve stationarity at the first difference. The inclusion of variables with a mixed order of integration further justifies the use of the ARDL approach.

Following the determination of the integration order, we conducted the bounds test to examine the existence of a long-run cointegrating relationship. Table 3 presents the results of this analysis, specifically focusing on the F-test outcomes for the bounds test. The findings indicate a strong cointegrating relationship among the variables. Moreover, the null hypothesis is consistently rejected in all cases. This conclusion is supported by the computed F-test values, which exceed the upper bound critical values. Therefore, based on the results in Table 3, we confirm the presence of a long-run cointegrating relationship among the selected variables.

After confirming the long-run cointegration relationship, Table 4 presents both short-term and long-term results. The error correction term (ECT) is negative and statistically significant, confirming the stability of long-run estimates. The ECT coefficient also indicates the speed at which short-term imbalances adjust to long-run equilibrium, reinforcing the relationship between the explanatory variables and life expectancy.

The ARDL results show that, in the long run, a 1% increase in savings leads to a 0.09% decline in life expectancy, significant at the 5% level. In the short run, the negative impact remains but is weaker, with a coefficient of 0.02%. This suggests that savings may lower life expectancy if they do not translate into higher disposable income. In economies with limited social protection and healthcare infrastructure, elevated savings rates may reflect precautionary motives, thereby reducing present consumption on health and welfare needs. As Majekodunmi et al. [10] noted, savings can reduce CO_2 emissions, but without sufficient spending power, they may not benefit overall well-being. Savings are most effective when they support both investment and consumption.

The effect of environmental degradation on life expectancy is not statistically significant in the long run. However, in the short run, pollution has a negative impact at the 10% significance level. This suggests that pollution affects health more immediately than over time. Similar findings were reported by Murthy et al. [45] for D-8 countries and Azam et al. [25] for Pakistan.

Table 4 ARDL Results

	DV lnLE		Optimal lag length		(1,0, 0, 1,0)	
		lnS	lnCO_2	lnRE	lnUR	C
Long run	Coefficient	− 0.0932**	− 0.0470	0.2698**	0.3804**	− 0.0009**
	t-Statistics	− 2.1791	− 1.5809	2.2726	2.0931	− 2.2556
	Probability	0.0368	0.1237	0.0299	0.0444	0.0311
Short run	Coefficient	− 0.0198***	− 0.0010**	0.0364***	0.0809***	
	t-Statistics	− 3.8238	− 1.9375	2.781	3.0883	
	Probability	0.0006	0.0616	0.0090	0.0041	
ECT						− 0.2127***
R^2						0.99
Adjusted-R^2						0.99

*Note that lnLE, lnS, lnCO_2, lnRE, and lnUR stand for the logarithm values of Life expectancy, savings, CO2 emissions, Renewable energy, and Urbanization, respectively. ***,** and * represents significant levels of 1%, 5% and 10% respectively*

Table 5 Robustness check

	DV lnLE					
		lnS	$lnCO_2$	lnRE	lnUR	C
FMOLS	Coefficient	− 0.0200**	− 0.0143	0.0703**	0.1554***	− 0.0009***
	t-Statistics	− 2.4449	− 1.2986	2.2284	5.8384	21.7176
	Probability	0.0197	0.2026	0.0324	0.0000	0.0000
R^2						0.98
Adjusted R^2						0.98
DOLS	Coefficient	− 0.0289**	− 0.0244	0.1677**	0.1291**	3.0346***
	t-Statistics	− 2.1831	− 1.2899	2.0956	2.4764	9.1306
	Probability	0.0405	0.2111	0.0484	0.0219	0.0000
R^2						0.99
Adjusted R^2						0.98

*Note that lnLE, lnS, $lnCO_2$, lnRE, and lnUR stand for the logarithm values of Life expectancy, savings, CO2 emissions, Renewable energy, and Urbanization, respectively. ***,** and * represents significant levels of 1%, 5% and 10% respectively*

Renewable energy has a strong positive effect on life expectancy. A 1% increase in renewable energy use raises life expectancy by 0.27% in the long run. In the short run, this effect remains positive but weaker, showing that renewable energy improves health both immediately and over time. These findings are consistent with [29, 31, 38].

Urbanization also has a significant positive impact. A 1% increase in urbanization raises life expectancy by 0.38% in the long run. In the short run, urbanization continues to have a positive effect, highlighting its role in improving health outcomes. This aligns with Karimi et al. [38] for G-7 economies and Azam et al. [25] for Pakistan. Urban areas often provide better healthcare, infrastructure, and living conditions, which contribute to higher life expectancy.

This study conducted the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) tests for a comprehensive robustness analysis to assess the stability and reliability of the results (see Table 5). These tests were essential to ensure the robustness of the findings. Notably, the outcomes of both FMOLS and DOLS are highly consistent in terms of statistical significance and the direction of effects, aligning with the ARDL long-run results. This consistency reinforces the reliability of the study's conclusions, despite minor differences in coefficient values. Such variations are expected due to differences in analytical methodologies.

Consistent with the ARDL results, both FMOLS and DOLS confirm that an increase in savings (lnS) is associated with a decline in life expectancy (lnLE), with statistical significance at the 5% level. Similarly, environmental degradation ($lnCO_2$) does not have a statistically significant impact on lnLE in either FMOLS or DOLS, mirroring the ARDL long-run results. The positive and significant relationship between renewable energy (lnRE) and life expectancy, observed in the ARDL model at the 5% level, is also supported by FMOLS and DOLS. Additionally, both robustness tests confirm that urbanization significantly increases life expectancy, consistent with the ARDL findings. The strong alignment of key results across all models validates the study's findings and underscores their reliability. The slight variations in coefficient values reflect methodological differences, demonstrating the study's commitment to rigor and transparency.

Furthermore, we conducted essential diagnostic tests to ensure that the estimated model is free from major econometric issues. These tests assessed serial correlation, heteroscedasticity, normality, and functional form, with results presented in Table 6. The findings indicate that the model does not suffer from serial correlation, as the null hypothesis of no serial correlation cannot be rejected at the 5% significance level. Additionally, the Ramsey test confirms the correct functional form of the model, while the Jarque–Bera test verifies the normality of the residuals. The Breusch-Pagan-Godfrey test indicates the absence of heteroscedasticity, as the null hypothesis cannot be rejected at conventional significance levels.

Table 6 Diagnostic test

Model	Serial correlation (LM)	Functional Form (RR)	Normality (JB)	Heteroscedasticity (BPG)
	2.903208 (0.0984) [No Serial correlation]	1.072611 (0.2917) [No functional form misspecification]	0.016220 (0.9919) [Normality assumption is not violated]	1.128741 0.3700 [No heteroscedasticity]

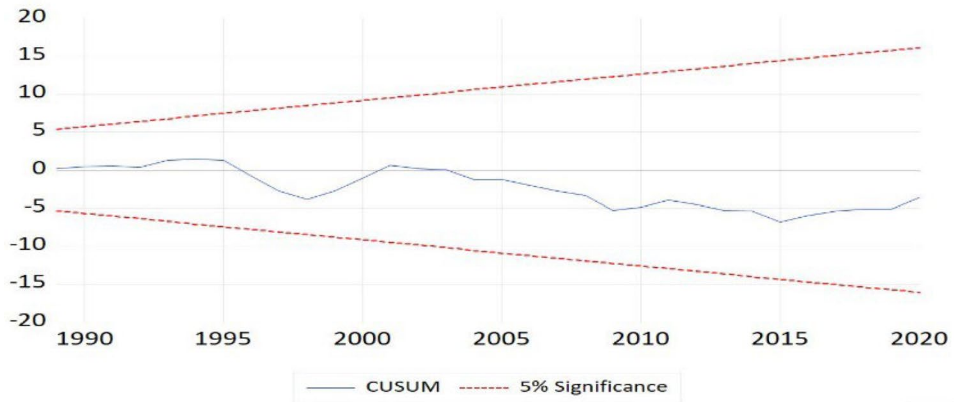

Fig. 2 Cumulative Sum of Recursive Residuals (CUSUM)

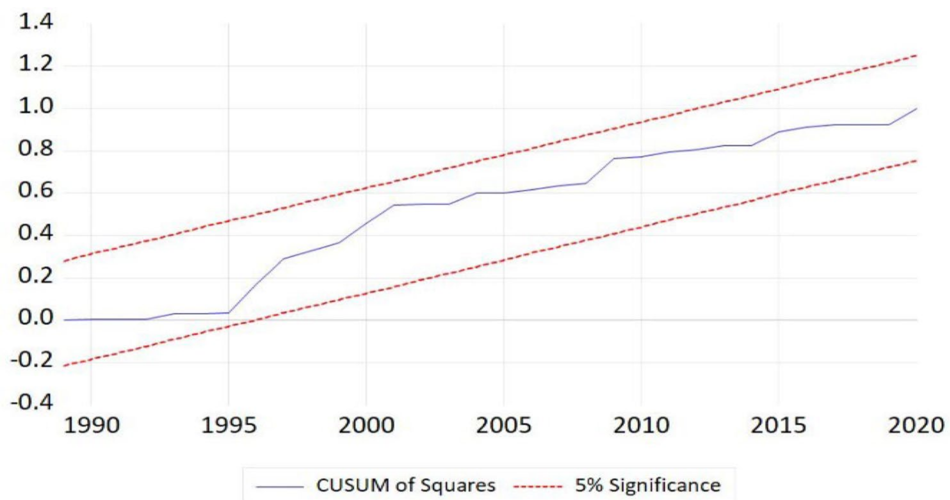

Fig. 3 Cumulative Sum of Squares of Recursive Residuals (CUSUMQ)

Moreover, to assess the model's stability, we conducted the CUSUM and CUSUMQ tests. Figures 2 and 3 display the CUSUM and CUSUMQ plots at the 5% significance level, respectively. The red dotted lines represent the confidence intervals, while the blue lines indicate the residual values. The results show that, at the 5% significance level, the residuals consistently remain within the confidence bounds, confirming the model's stability.

6 Observed negative relationship between savings and life expectancy in Malaysia

Empirically, CO2 emissions negatively influence life expectancy [45], while savings reduce CO2 emissions [10]. Given this, it seems reasonable to expect that savings, by reducing CO2 emissions, would improve life expectancy. Our findings in the Malaysian context challenge this expectation. Contrary to the anticipated positive impact of savings on life expectancy, we observe an unexpected negative relationship. Notably, this aligns with trends over the past twenty years, where these two variables have exhibited an inverse relationship.

As depicted in Fig. 4, life expectancy and savings exhibit opposing trends in Malaysia, particularly from 1999 to 2021. Between 1999 and 2009, savings (% of GDP) steadily increased, yet life expectancy declined. Specifically, savings rose from 47.43% in 1999 to 46.08% in 2000 and further to 43.28% in 2007. Simultaneously, life expectancy increased from 72.28 to 72.78 years, and then to 74.21 years, indicating a clear inverse relationship. This pattern becomes even more pronounced post-2009 when savings dropped significantly, and life expectancy rose in parallel. For example, between 2017 and 2020, savings fell from 32.42 to 26.03%, while life expectancy increased from 75.48 to 75.97 years.

A sharp turning point was observed in 2021, when a surge in savings to 29.34% coincided with a notable decline in life expectancy to 74.89 years. This distinct intersection in trends, particularly post-2009, suggests that in the

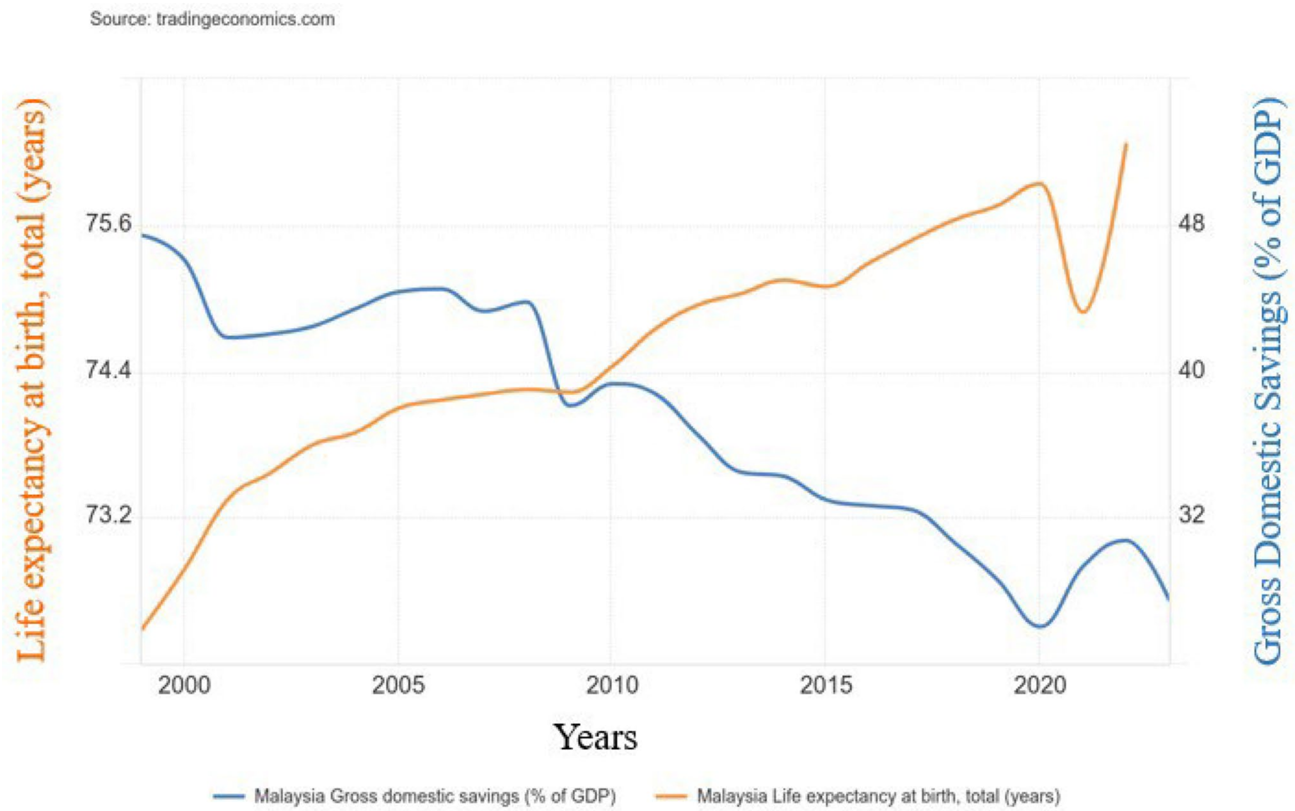

Fig. 4 Variation of life expectancy and savings in Malaysia (1999–2023). Source: Trading Economics [68]

Malaysian context, savings may not have the anticipated positive impact on life expectancy. Instead, the data reflects a more complex and perhaps context-specific dynamic where savings and life expectancy move in opposing directions.

Moreover, as explained in the theoretical framework, households often deviate from the Life-Cycle Hypothesis (LCH) by struggling to save consistently, especially when income is insufficient for basic needs [3]. This financial strain, when combined with the pressure to save, can lead to adverse health outcomes like malnutrition and stress-related conditions [23]. Under the Health Production Function (HPF) model, forced savings during financial hardship exacerbates these health risks, potentially accelerating physical deterioration and shortening life expectancy. This suggests that in a developing economy like Malaysia, where household savings are often driven by precautionary motives rather than discretionary wealth accumulation [61], the opportunity cost of savings in terms of immediate health expenditures cannot be overlooked. Unlike in high-income nations where savings contribute to financial security and better healthcare access, in Malaysia, forced savings may limit the ability of individuals to afford quality nutrition, preventive medical care, and overall well-being [62].

Additionally, the negative savings-life expectancy relationship can be partially attributed to the rising costs of healthcare in Malaysia. Despite economic growth, medical inflation has outpaced wage growth, leading to higher out-of-pocket health expenses [63]. When households prioritize saving over spending, they may delay seeking medical treatment, contributing to worsening health outcomes and reduced longevity. Hence, it is only when savings is backed up with adequate social safety nets that it can be linked to improved public health indicators [64]. This aligns with findings from other developing economies, like Botswana, where excessive savings behavior in the face of inadequate social safety nets has been linked to deteriorating public health indicators [65].

Furthermore, while savings theoretically contribute to long-term economic stability, its immediate effects on quality of life depend on the socioeconomic environment. In Malaysia, household debt levels have also risen in parallel with savings, indicating that individuals may be forced to save not for future security but to meet existing financial obligations, thereby exacerbating stress and reducing life expectancy. A similar trend has been observed in South Korea, where high savings rates have coincided with increased economic anxiety and deteriorating mental health outcomes [66].

This insight helps explain the observed negative relationship between savings and life expectancy in Malaysia, as financial insecurity directly impacts health, undermining potential benefits from savings. Thus, instead of assuming a universal positive link between savings and life expectancy, policymakers should consider targeted interventions that balance financial security with adequate healthcare access.

7 Policy implications

In light of these findings, we align with Uddin et al. [12] and recommend that the Malaysian government implement policies to reduce financial insecurity and mitigate the adverse health outcomes associated with forced savings. Expanding pension schemes, unemployment benefits, and healthcare subsidies can strengthen social safety nets, ensuring financial security and preventing economic constraints from hindering life expectancy improvements. Additionally, increasing public healthcare expenditure will improve access to quality medical services, enabling citizens to receive necessary healthcare regardless of financial limitations. Policymakers should also develop sustainable financial policies that encourage savings while ensuring households allocate sufficient resources to health, nutrition, and overall well-being. Furthermore, strengthening green energy policies and CO_2 reduction strategies will foster a healthier environment, mitigating the indirect negative impacts of savings-driven economic activities.

The private sector also has a crucial role to play in supporting these initiatives. Financial institutions should introduce savings and investment products that integrate healthcare benefits, such as savings plans with built-in medical insurance, to enhance financial security and access to healthcare. Businesses should prioritize employee well-being by offering health benefits, wellness programs, and sustainable work-life balance initiatives, which contribute to overall workforce health and productivity. Additionally, financial institutions should encourage green investments that align with Malaysia's sustainability goals, ensuring that economic growth does not come at the expense of environmental and public health.

Beyond government and private sector efforts, promoting financial education is essential. Implementing financial literacy programs will help individuals manage their savings effectively while maintaining adequate healthcare and nutrition expenditures. Encouraging citizens to balance long-term savings with necessary health and wellness expenses can prevent financial stress and its associated health risks. Additionally, greater participation in retirement schemes and healthcare insurance programs will secure financial stability without compromising overall well-being.

Furthermore, the Malaysian government should prioritize renewable energy adoption to enhance citizens' well-being while simultaneously increasing life expectancy. This dual approach not only improves public health but also reduces CO_2 emissions, which negatively impact life expectancy. In addition, policymakers should focus on urbanization efforts, as providing citizens with access to modern amenities further contributes to improved living standards and life expectancy.

8 Conclusion

This study adopts the ARDL approach to analyze the "twist of longevity," examining the determinants of life expectancy and introducing savings as a potential influencing factor in Malaysia from 1980 to 2020. To ensure robustness, we employ the FMOLS and DOLS estimation techniques. The macroeconomic variables considered include national savings, CO_2 emissions, renewable energy, and urbanization as determinants of life expectancy.

Our previous research on the economic influence of national savings on CO_2 emissions [10] and the connection between CO_2 emissions and life expectancy [45] prompted us to explore the relationship between savings and life expectancy alongside these other determinants. Based on these prior findings, it seemed logically plausible that savings, by mitigating CO_2 emissions, could contribute to an improvement in life expectancy. However, contrary to our expectations, this study finds that savings may actually decrease life expectancy in Malaysia.

Conversely, urbanization is found to enhance life expectancy, aligning with the results reported by Azam et al. [25]. According to Ritchie and Roser [67], urbanization serves as an indicator of a country's standard of living, as wealthier nations tend to exhibit higher levels of urbanization, with urban areas generally providing better living conditions than rural ones. This suggests that improvements in the standard of living can enhance overall well-being, thereby contributing to increased life expectancy.

Based on these findings, we conclude that while savings may have unintended negative consequences on longevity, improvements in living standards through factors like urbanization can counteract these effects. Additionally, consistent with past literature, our study confirms that CO_2 emissions negatively impact life expectancy [45]. However, renewable energy is found to improve life expectancy both directly and indirectly. Not only does renewable energy mitigate CO_2 emissions [53], but it also serves as a direct enhancer of longevity.

In light of these findings, we recommend policies that balance financial security and public health, ensuring savings do not come at the cost of well-being. Strengthening social safety nets, promoting sustainable savings, and increasing public healthcare investment are crucial. Additionally, prioritizing renewable energy and urbanization can further enhance life expectancy by improving environmental and living conditions.

9 Limitations of the study

This study acknowledges several limitations that may influence the interpretation of its findings. One potential limitation is the choice of savings as an aggregate measure, which may introduce biases in data selection. We adopted aggregate savings for simplicity and consistency, ensuring a broader representation of national economic behavior while avoiding complexities associated with disaggregated data. However, alternative measures, such as per capita savings or household savings, could yield different insights into the relationship between savings and life expectancy. Future research could explore these alternative savings indicators to provide a more nuanced understanding of this dynamic.

Additionally, this study does not incorporate healthcare expenditure or access to medical services, both of which are critical determinants of life expectancy due to our focus on macroeconomic determinants like savings, CO2 emissions, renewable energy, and urbanization. Including these variables in future research could provide a more comprehensive perspective on the factors influencing longevity.

Furthermore, this study focuses exclusively on Malaysia, which limits the generalizability of the findings to other countries with different economic structures, social welfare systems, and healthcare policies. Comparative studies across multiple countries or regions would offer broader insights into the relationship between savings and life expectancy under diverse economic and institutional contexts.

Despite these limitations, this study makes a novel contribution by employing time series data analysis, allowing for a detailed examination of long-term trends and relationships. This approach enhances the robustness of the findings and provides a foundation for further research. Ultimately, this study advances the understanding of life expectancy determinants, offering valuable insights into the interactions between national savings, CO2 emissions, renewable energy, and urbanization, while highlighting areas that warrant further exploration and policy attention.

10 Recommendations for future studies

To build on the findings of this research, future studies should explore the impact of different savings measures, such as household or per capita savings, on life expectancy. Additionally, incorporating healthcare expenditure and access to medical services as key determinants could provide a more comprehensive understanding of longevity. Expanding the analysis to multiple countries would help determine whether the observed relationship holds across different economic and social systems. Furthermore, integrating qualitative insights, such as policy case studies from other nations, could strengthen the policy recommendations derived from the findings. Future research should also consider cross-country comparisons and institutional factors, including healthcare policies, social protection mechanisms, and labor market conditions, to better understand the underlying economic, social, and environmental dynamics influencing this relationship.

Acknowledgements We would like to express our sincere appreciation to Universiti Malaysia Sarawak (UNIMAS) for awarding us Grant UNI/F01/CATALYST/86464/2024. This support has been pivotal in enabling our team to push forward with our research goals and pursue innovative solutions within our field. The proofreading services of this paper is financed by Strategic Research Partnership Grant -100-RMC/5/3/SRPINT (010/2022), provided by Universiti Teknologi MARA, Malaysia.

Author contributions Temitayo B. Majekodunmi: First Draft -METHODOLOGY.RESULTS AND DISCUSSION Mohd Shahidan Shaari- First Draft -METHODOLOGY.RESULTS AND DISCUSSION Abdul Rahim Ridzuan -METHODOLOGY.RESULTS AND DISCUSSION Jaheer Mukthar K.P-First Draft -METHODOLOGY-SECOND DRAFT -PROOFING Nora Yusma Mohamed Yusoff-METHODOLOGY-SECOND DRAFT Mohd Juraij Abd Rani-METHODOLOGY-SECOND DRAFT Vennila J -Third Draft-Revision -proofing -final draft Mujeeb Saif Mohsen Al Absy-First Draft -METHODOLOGY–Second Draft.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal. This study received financial support from the Accounting and Financial Science Department, College of Administrative and Financial Science, Gulf University. The funding institution had no involvement in the study's design, data collection, interpretation, or manuscript preparatio.

Data availability The data supporting this research were sourced from publicly available and reputable datasets, ensuring the transparency and reproducibility of our findings. Further details and supplementary data are available upon reasonable request from the corresponding author at jaheermukthar@gmail.com.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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