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The asymmetric relationship between pollution, economic growth, urbanization, renewable energy consumption, and life expectancy in Ghana: a novel Quantile-on-Quantile analysis

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Abstract
This study investigates the determinants of life expectancy in Ghana, focusing on the effects of economic growth, environmental pollution, urbanization, and renewable energy consumption. The research employs a novel Quantile-on-Quantile (QQ) regression approach to capture the non-linear relationships and varying impacts across life expectancy levels. This method allows for a more detailed analysis of how these factors affect life expectancy across different population segments. The results show that GDP growth positively impacts life expectancy, especially in higher quantiles with more pronounced economic benefits. In contrast, CO_2 emissions have a negative impact, particularly in lower quantiles, highlighting the vulnerability of certain population groups to environmental degradation. Urbanization presents mixed effects, with positive impacts in some cases and harmful in others, reflecting the complex challenges of rapid urban growth. Renewable energy consumption consistently improves life expectancy, underscoring the importance of sustainable energy policies. The study concludes that targeted policies promoting inclusive economic growth, stronger environmental regulations, improved urban infrastructure, and expanded renewable energy use are essential for enhancing life expectancy in Ghana. These findings provide crucial insights for policymakers aiming to bridge the gap between economic development and public health.

Keywords Quantile-on-quantile · Life expectancy · Carbon emissions · Economic growth · URB · Renewable energy

Abbreviations

GDP	Economic Growth
CO_2	Carbon Dioxide
EKC	Environmental Kuznets Curve
QQ	Quantile-on-Quantile
SDGs	Sustainable Development Goals
RE	Renewable Energy
WHO	World Health Organization
LEO	Life Expectancy
RNE	Renewable Energy Consumption
URB	Urbanization

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PM 2.5	Particulate Matter (particles with a diameter of 2.5 µm or less
PM 10	Particulate Matter (particles with a diameter of 10 µm or less)
ADF	Augmented Dickey-Fuller
PP	Phillips-Perron

Introduction

The 28th Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change, held in Dubai, marked a significant event in the global climate agenda, with several vital outcomes and areas of focus. COP28 brought together approximately 85,000 stakeholders to address critical issues such as energy transition, climate financing, and the intersection of health, climate, and food systems (Varyvoda 2024). A notable development was introducing a dedicated 'health' day, emphasizing the health impacts of climate change and the benefits of transitioning to lower-carbon economies (Lokmic-Tomkins and Bone 2024). This inclusion of health in the climate discourse is seen as a potential catalyst for transforming global health action. However, challenges remain in adapting these initiatives to diverse global contexts (Illingworth 2024). The conference highlighted the need for urgent action to mitigate climate change, which is increasingly recognized as a critical determinant of public health and life expectancy. Climate change, driven by greenhouse gas emissions, has been linked to various health risks, including increased mortality rates due to heat-related illnesses, particularly among older adults (Romanello et al. 2023).

Life expectancy (LEO) is a critical indication of a population's well-being and welfare. Given the current death rates, it indicates the average number of years a baby is projected to survive (World Health Organization 2021). Globally, LEO has improved dramatically over the last century, with innovations in healthcare, nutrition, and living circumstances contributing to this development. However, differences in LEO exist among nations and regions, with different variables such as economic growth (GDP), environmental pollution, and access to healthcare having a significant influence (Wang et al. 2020). According to the World Bank (2021), worldwide LEO at birth has climbed from 52.6 years in 1960 to 72.7 years in 2019. This significant growth may be linked to various causes, including advances in public health measures, medical treatments, and contact with hygienic water and sanitation (Dos Santos et al. 2017). However, the COVID-19 pandemic has had a detrimental effect on LEO, with projections estimating a loss of 1.2 years in 2020 (Aburto et al. 2021). Despite general gains, considerable inequalities in LEO persist between high-income and low-income nations. In 2019, the average LEO in high-income nations was 80.8 years, associated with 64.4 years in low-income countries (World Bank 2021). This disparity may be ascribed to several variables, including access to healthcare, education, and economic opportunity. GDP has been highlighted as a crucial driver of LEO. Studies have demonstrated that nations with more significant economic development tend to have longer life expectancies (Aburto et al. 2020; Kontis et al. 2017). This association may be explained by the higher healthcare, education, and infrastructure resources in more prosperous nations (Armeanu et al. 2017).

However, the link between economic growth and LEO is not necessarily linear. The "Preston curve" notion argues that GDP influence on LEO declines as nations get wealthy (Preston 1975). This indicates that other variables, such as the distribution of wealth and access to healthcare, have become more relevant in influencing LEO in high-income nations (Wirayuda & Chan 2021). Environmental pollution has been acknowledged as a danger to public health and LEO. Air pollution, in particular, has been associated with several health concerns, including respiratory disorders, cardiovascular diseases, and cancer (Cohen et al. 2017). The World Health Organization (W.H.O) (2021) approximates that air contamination causes 7 million premature deaths yearly. The association between environmental pollution (CO_2) and LEO has been examined extensively. A meta-analysis by Xie et al. (2024) indicated that exposure to air pollution, specifically particulate matter (PM2.5 and PM10), was related to a substantial decrease in LEO. The research also emphasized the disproportionate effect of air pollution on low- and middle-income nations, where exposure levels are generally greater. Urbanization (URB), or the expansion of urban inhabitants, has been a prominent worldwide trend in recent decades. In 2020, 56.2% of the world's population lived in urban areas, which is anticipated to climb to 68% by 2050 (United Nations, 2018). URB may have both beneficial and harmful influences on LEO. On the one hand, metropolitan regions frequently have greater access to healthcare, education, and other services that might enhance health outcomes (Probst et al. 2019). However, fast and unplanned URB may also lead to congestion, inadequate sanitation, and greater exposure to environmental pollutants, which can significantly influence LEO (Eckert and Kohler 2014). Renewable energy (RNE) sources have been suggested as a viable technique for enhancing public health and LEO. In ASEAN countries, energy consumption significantly and positively affects life expectancy, but the reliance on non-renewable energy poses long-term sustainability challenges. This underscores the need to shift towards RNE to sustain health improvements (Hendrawaty et al. 2022). In Asia and Africa, the relationship between energy consumption and life expectancy is influenced by economic progress and CO_2 emissions, with renewable energy offering a pathway to mitigate adverse environmental impacts and enhance life expectancy (Younus et al. 2022). The G-7 countries provide evidence that renewable energy consumption, health expenditure, and urbanization increase life expectancy while higher carbon emissions reduce it. This highlights the dual benefits of renewable energy in promoting health and reducing environmental harm (Alavijeh et al. 2023). RNE sources, such as wind, solar, and hydropower, emit less air pollution than fossil fuels (Rahman et al. 2022a, b). By lowering exposure to dangerous pollutants, switching to RNE might lead to considerable health advantages and enhanced LEO. Research by Buonocore et al. (2016) indicated that deploying RNE in the United States might avert 175,000 premature deaths by 2030, primarily via reductions in air pollution. Similarly, worldwide research by Lelieveld et al. (2019) estimated that switching to RNE might avert 3.6 million premature deaths yearly by 2050.

Like many rising countries, Ghana has achieved dramatic LEO advances over several decades. According to the World Bank (2021), LEO at birth in Ghana grew from 45.8 years in 1960 to 64.1 years in 2019. This success may be linked to numerous causes, including GDP, advances in healthcare, and expanded access to education (Agyei-Mensah and de-Graft Aikins 2010). However, Ghana still faces obstacles to further boosting LEO. Environmental contamination, especially air pollution, remains a severe problem. Research by Amegah and Agyei-Mensah (2017) indicated that exposure to PM2.5 in Accra, Ghana's capital city, was connected with an elevated risk of early death. The authors stressed the need for legislation to minimize air pollution and promote public health. URB is another element affecting LEO in Ghana. While urban regions in Ghana usually have greater access to healthcare and other services, growing URB has also led to overcrowding and inadequate sanitation (Cobbinah et al. 2015; Mose et al. 2024). Addressing these concerns would be vital for further boosting LEO in the nation. LEO is a complicated and diverse topic, impacted by several variables, including GDP, ecological degradation, URB, and access to healthcare. While worldwide LEO has improved dramatically over the last century, discrepancies continue between high-income and low-income nations and within countries. Emerging nations like Ghana have made tremendous progress in raising LEO but are still confronting issues connected to ecological pollution, URB, and access to healthcare. Understanding the complicated links between these variables and LEO is vital for designing effective policies and interventions to enhance public health and well-being.

Research motivation and contribution

The dynamic relationship between economic development, environmental sustainability, and public health remains a critical area of inquiry, particularly in developing nations like Ghana. Life expectancy, as a critical indicator of population health and well-being, serves as a lens through which we can examine the complex interplay of these factors. Ghana's trajectory of economic growth, coupled with rapid urbanization and environmental challenges, presents a unique case study for understanding how these dynamics influence population health outcomes. The primary objective of this study is to analyze the relationships between economic growth, CO_2 emissions, urbanization, and renewable energy consumption and their collective impact on life expectancy in Ghana. Consequently, this study is motivated by the pressing need to unravel the multifaceted determinants of life expectancy in Ghana, with the ultimate goal of informing evidence-based policies to enhance its citizens' quality of life. Our research makes several significant contributions to the existing literature:

I. We introduce the QQ approach to studying life expectancy determinants in Ghana, offering a more sophisticated analysis that captures non-linear relationships and heterogeneous effects across different quantiles of dependent and independent variables.
II. By simultaneously examining the impacts of environmental (CO_2 emissions), economic growth (GDP), demographic (urbanization), and energy (renewable consumption) factors on life expectancy, we provide a holistic view of the challenges and opportunities facing Ghana's public health landscape.
III. We test the applicability of both the Environmental Kuznets Curve hypothesis and the Preston Curve theory in the Ghanaian context, contributing to the broader discourse on the relationship between economic development and environmental and health outcomes in developing countries.
IV. Our findings yield tailored policy recommendations that address Ghana's developmental challenges, with potential implications for other developing nations facing similar issues.

The remainder of this paper is structured as follows: Sect. 2 presents a comprehensive review of related literature, situating our study within the broader academic discourse. Section 3 delineates our research methodology, including data sources, variable selection, and a detailed explanation of the QQ approach. Section 4 presents our empirical results and thoroughly discusses our findings. Finally, Sect. 5 concludes the study by synthesizing our key findings and proposing evidence-based policy recommendations to improve life expectancy and overall well-being in Ghana.

Review of related literature

Summary of studies between CO_2 emissions and life expectancy (LEO)

Numerous studies have studied the connection between CO_2 emissions and LEO. Nevertheless, these results depict conflicting conclusions from the empirical investigations. For instance, Azam and Adeleye (2023) did research that correlates with the United Nations Sustainable Development Goals 3 and 11, which concentrate on guaranteeing healthy lives and fostering welfare for everyone. The study aims to evaluate the influence of CO_2 emissions from liquid and solid fuels on LEO across various socioeconomic classes in Asia and the Pacific. Their results revealed that CO_2 emissions from liquid and solid fuel emissions considerably adversely impacted LEO, with liquid fuel emissions displaying the most excellent unfavorable effect. Similarly, Mahalik et al. (2022) analyzed pioneering research assessing the influence of CO_2 emissions on LEO in 68 low- and middle-income economies. The study findings demonstrated a negative connection between LEO and CO_2 emissions for the overall sample and the rising nations group, independent of the source of emissions. Moreover, the research by Osabohien et al. (2020) also indicates that CO_2 emissions considerably adversely impacted LEO, with a 0.35% drop on average. These results contrast the study of Matthew et al. (2020), who studied the influence of CO_2 emissions on agricultural production and LEO in West Africa using data from 2000 to 2018 and the two-stage least squares econometric approach. Their results revealed that a 1% rise in CO_2 emissions resulted in a 3.818% drop in agricultural productivity, demonstrating that carbon emissions severely affect agronomic output in the area. Surprisingly, a 1% rise in CO_2 emissions resulted in a 0.123% increase in LEO, showing that CO_2 emissions improve West Africa's LEO. Bhutto et al. (2022) studied the long-run impacts of global warming by (greenhouse gas emissions, carbon dioxide, methane, and nitrous oxide), GDP, and forest area on LEO in Pakistan using yearly time-series data from 1990 to 2016. The research utilized the enhanced Dickey-Fuller test, Johansen cointegration, Generalized Linear Model (GLM) for long-run effects, and Least Squares and Robust Least Squares Method for robustness. The Granger causality test was performed to define causation among the variables. The GLM calculations demonstrated a negative connection between total greenhouse gas emissions, CO_2 emissions, and forest area and a constructive connotation of methane and nitrous oxide emissions with LEO. Granger causality studies demonstrated bidirectional causation between CO_2 emissions and LEO. Similarly, Alavijeh et al. (2023) evaluated the impact of RNE, CO_2 emissions, health disbursements, and URB on LEO in G-7 nations from 2000 to 2019. The work applied a new Method of Moments Quantile Regression (MMQR) and robustness tests using completely modified ordinary least squares, dynamic ordinary least squares, and fixed effect ordinary least square estimators. The findings indicated that health spending and URB increased LEO across all quantiles, but rising CO_2 emissions lowered LEO. Setiawan et al. (2023) investigated the variables that impact GDP and LEO using the Two-Stage Least Square Equation Model and found that mortality and CO_2 emissions had a minor unfavorable effect on LEO. Li et al. (2023) revealed that CO_2 emission and LEO have a poor association in Japan and Russia, suggesting a minimal influence on health indices compared to energy consumption and GDP. Steinberger et al. (2020) also stress that CO_2 emissions and LEO are somewhat associated, with just a fourth of LEO gains linked to energy and carbon increases, primarily due to wealth growth, revealing a carbon-development contradiction. Polcyn et al. (2023) also observed that CO_2 emissions harmed LEO in Asian nations.

Summary of studies between GDP and LEO

Many research studies prove that economic growth (GDP) and LEO are closely related. Using panel cointegration analysis and panel causality testing, he and Li (2018) assessed the long- and short-term associations between LEO and GDP for 65 countries in three aging phases between 1980 and 2014. The findings demonstrated statistically favorable long-run connections between LEO and GDP in most nations, although the particular associations differed across age ranges. The favorable effect of LEO on GDP was more considerable in the group with a greater aging level. The panel causality tests demonstrated short-run unidirectional causation from LEO to economic development for the younger generation. A unidirectional causation flowed from monetary expansion to LEO only for the elderly group. Wang et al. (2020) performed research on the link between GDP and LEO utilizing both the classic and sophisticated unit root tests for the observation of the stationary features of the constructs. The research indicated that GDP is positively linked with LEO. Rahman et al. (2022a, b) studied the drivers of LEO in 31 of the world's most contaminated nations, using data from 2000 to 2017. The research utilized panel-corrected standard errors, feasible general least square estimations, and Granger causality tests. The findings verified the Preston Curve, suggesting a positive influence of GDP on LEO. Sharma (2018) employed an imbalanced panel of 17 advanced economies from 1870–2013 by utilizing a panel generalized technique of moments estimator. The research demonstrated a substantial long-term cointegration link between LEO and GDP. LEO positively affects GDP, as a 1% rise in LEO at birth corresponds to a 0.67% increase in GDP (Sharma 2018). Using annual data from 1970 to 2012, Shahbaz et al. (2019) investigated the nonlinear relationships between globalization, financial development, GDP, and LEO in 16 sub-Saharan African (SSA) countries. The research applied non-parametric cointegration and multivariate Granger causality tests to establish a non-linear empirical knowledge of the variables impacting LEO. The findings revealed that financial growth, globalization, and GDP improved LEO in most SSA nations, save for Gabon and Togo.

Summary of studies between URB and LEO

During significant urbanization and growth in North America and Europe between 1861 and 1910, the influence of populace movement from low-mortality rural regions to high-mortality urban areas on variations in lifetime wages in Scotland was investigated by Torres et al. (2019). The research used vital registration data and a novel decomposition technique to separate the effects of changes in mortality and inhabitant configuration from variations in LEO. The findings demonstrated a greater death rate in urban areas due to fast URB in Europe and North America in the nineteenth and twentieth centuries. Ren and colleagues (2023) further examined, using panel data from 134 nations between 1960 and 2018, the spatiotemporal patterns of gender gaps in LEO (GGLE) and the impact of URB and population-weighted PM2.5 on GGLE. GGLE showed a continuous increase and apparent global geographical heterogeneity, as shown by using a Bayesian spatiotemporal model in the research. With favorable impacts in America and the Eastern Mediterranean and negative ones in Africa and Europe, the data demonstrated a considerable influence on LEO. According to Michel (2020), URB may influence LEO via waterborne infections, air pollution, and severe weather events, impacting aging populations' health outcomes. Vezhnovets et al. (2023) also discovered a negligible impact on average LEO. However, in moderately developed areas, the death rate from cardiovascular disorders was most significant, while in less urbanized areas, it was lowest. The extent of and dynamics underwriting to rural–urban LEO modifications between grown-ups in Indonesia using data from the 2000, 2007, and 2014/2015 surfs of the Indonesian Family Life Survey were investigated by Sudharsanan & Ho (2020) using life tables and Poisson regression to estimate rural–urban differences in LEO among 18,867 adult respondents aged 30 ages and above. After that, the scientists used a brand-new g-formula-based decomposition to calculate how much the variations in body mass index (BMI), smoking, and blood pressure (BP) between rural and urban areas contributed to the variations in LEO. The findings showed that, compared to their urban counterparts, LEO at age 30 was 2.2 years greater for rural males and 1.2 years higher for rural women. If systolic blood pressure and BMI distribution were equalized between persons living in urban and rural areas, the urban mortality penalty would be lowered by 22% for men and 78% for women. The primary reason for this decrease would be the variations in BMI between rural and urban zones. The inner-city death consequence did not increase with smoking for either gender. Accordingly, adult LEO is lower in Indonesian cities than in rural settings, which may be partially attributed to variations in systolic and BMI. Using a time series unit root test, Kibria and Ullah (2020) examined the effects of GDP, URB, and carbon dioxide on labor earnings in Bangladesh on an annual frequency. The study established a bidirectional affiliation between URB, CO_2 emissions, and LEO.

Summary of Studies between RNE and LEO

It has been discovered that RNE significantly affects LEO in several nations. According to Alavijeh et al. (2023), research conducted on G-7 nations between 2000 and 2019 revealed that RNE positively affected LEO by raising it across all quantiles. Using the Toda-Yamamoto causality test, Yilmaz and Sensoy (2023) examined the association between RNE and LEO in Turkiye. The research did not discover the Granger causality association between RNE and LEO, which was analyzed from 1990 to 2019, suggesting that RNE had little effect on LEO in Turkiye. Nonetheless, the research discovered a Granger causation link between RNE and LEO, indicating that raising RNE in Turkiye may result in better LEO. Using time series data from 2000Q1 to 2020Q4, Liu and Zhong (2022) examined the effects of health spending and renewable energy on LEO in China. The data analysis method used in the research was the Vector Error Correction Model (VECM). The findings indicate a long-term relationship between LEO, renewable energy, and health costs. Research shows that more health expenditure enhances LEO, and RNE favors LEO in China. Using panel vector autorepression, Sodhi and Gök (2022) examined the effects of RNE on LEO across four channels for 23 developing market nations between 1994 and 2015: GDP per capita, URB, GDP emissions, and technology level. According to the research, using more renewable energy raises LEO by raising GDP per capita, URB, and technology while lowering CO_2 emissions. Because renewable energy sources emit less carbon dioxide, which lessens the negative externalities of pollution, they have a less negative effect on health quality than non-renewable energy sources.

Research gap

It is clear from the examined empirical research that the link between GDP, CO_2 emissions, URB, RNE, and LEO needs to be well-established. Prior studies by Azam and Adeleye. (2023), Mahalik et al. (2022), Osabohien et al. (2020), Alavijeh et al. (2023), and Polcyn et al. (2023) found a negative correlation between CO_2 emissions and LEO, while Matthew et al. (2020); Bhutto et al. (2022); Setiawan et al. (2023); Li et al. (2023) and Steinberger et al. (2020) found a positive or negligible correlation. The effect of URB on LEO varies across different countries and regions, with some studies suggesting a negative impact (Torres et al. 2019; Ren et al. 2023; Michel 2020; Sudharsanan & Ho 2020) and others finding an insignificant effect (Vezhnovets et al. 2023). Similarly, the impact of GDP on LEO is positive in several studies (Li et al. 2022; He & Li 2018; Wang et al. 2020; Sharma 2018; Shahbaz et al. 2019). Some research (Alavijeh et al. 2023; Liu & Zhong 2022; Sodhi & Gök, 2022) have established a favorable link between RNE and LEO, whereas other studies (Yilmaz and Sensoy 2023) have not discovered any significant relationship. Adebayo et al. (2023) studied the relationships between hydroelectricity, natural gas consumption, and sustainability, and the current study builds on this work by further exploring the impact of these energy sources on environmental sustainability and life expectancy, which are vital to public health. Furthermore, most research employed classic empirical methodologies with simple measurements, and only a few studies evaluated the diverse connection between these variables using sophisticated econometric techniques. Afshan and Yaqoob (2022) underlined the necessity of using cutting-edge econometric methods to solve this issue and highlighted the significance of methodology in generating objective study results. The unique and advanced quantile-on-quantile (QQ) approach was used in this work to evaluate the relationship between GDP, URB, RNE, LEO, and pollution in Ghana. Understanding the complex relationships between pollution, GDP, URB, RNE, and LEO needs to be improved in studies, especially in developing nations like Ghana. By using the quantile-on-quantile method to investigate the varied association between these factors in Ghana from 1990 to 2020, the current research seeks to close this gap.

Research methodology

Theoretical underpinning

The Preston Curve is a theoretical foundation for this study's relationship between GDP and LEO. Preston (1975) proposed this theory, which suggests a positive but diminishing marginal effect of income on LEO. According to the Preston Curve, a solid affirmative link exists between GDP and LEO at lower income levels. Still, as countries become wealthier, the marginal effect of additional income on LEO decreases. In this current study, we propose a positive association between GDP per capita and LEO across quantiles, which aligns with the Preston Curve's postulation. The hypothesis that GDP positively affects LEO in Ghana supports this theory, as higher income levels enable improved access to healthcare, better nutrition, and overall living standards, contributing to increased LEO. The Preston Curve's applicability in this study is further reinforced by the prediction that the progressive consequence of GDP on LEO is more distinct at higher quantiles, suggesting a potentially diminishing marginal effect at higher levels of economic development. A relevant theoretical framework for the study is the Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger 1991). The EKC posits an inverted U-shaped relationship between environmental degradation and GDP, suggesting that in the initial stages of economic development, ecological degradation increases due to automation and URB. However, the trend reverses after a certain income level, and environmental quality improves as economies shift towards more sustainable practices and cleaner technologies. The EKC hypothesis regarding the correlation between CO_2 emissions and LEO applies to this study. It is hypothesized in this study that there is a predominantly negative impact of carbon emissions on LEO, particularly at higher quantiles, suggesting that excessive emissions may harm health outcomes. This observation aligns with the EKC hypothesis, as high carbon emissions associated with GDP and industrialization initially lead to environmental degradation and adverse health effects (Wiredu et al. 2023). However, as economies transition towards cleaner technologies and sustainable practices, the negative impact of CO_2 emissions on LEO may diminish or reverse, reflecting the latter stages of the EKC. This study gains a more robust conceptual grounding by incorporating the Preston Curve and the Environmental Kuznets Curve hypothesis as theoretical frameworks. These theories provide valuable insights into the complex interplay between GDP, environmental degradation, and LEO, enhancing the interpretation and program suggestions of the empirical conclusions.

Data

The study used time series data from 1990 to 2020. The World Bank indicator database included the time series data for Life expectancy (LEO), GDP per capita (GDP), CO_2 emissions (CO_2), Urban population growth (URB), and Renewable energy consumption (RNE). The study settled on the abovementioned period due to data availability for the selected variables. Table 1 includes information on the unit of measurement and data source for the chosen variables.

Figure 1 showcases the trends in CO_2 emissions, GDP, life expectancy, renewable energy consumption, and urbanization from 1990 to 2020. Over these 30 years, both CO_2 emissions and GDP have increased. This indicates a correlation between GDP and higher emissions. LEO has also increased, which is a positive reflection of better health and living conditions. Renewable energy consumption has indeed shown growth, but it is essential to analyze the rate of increase in overall energy consumption during this period. Urbanization has increased, indicating a growing preference for city living. The graph provides a means to analyze the connections and potential tradeoffs between these essential development indicators, such as emissions, energy use, and demographics, from 1990 to 2020. This allows for deeper analysis to understand the strengths of the relationships and separate the impacts of each factor.

Table 1 Variable description

Variable	Symbol	Details of Variables	Source
Life expectancy	LEO	Life expectancy at birth, total (years)	WDI
Economic Growth	GDP	Per Capita (constant 2015 US$)	WDI
Urban population growth	URB	annual %	WDI
CO_2 emissions	CO_2	metric tons per capita	WDI
Renewable energy consumption	RNE	% of total final energy consumption	WDI

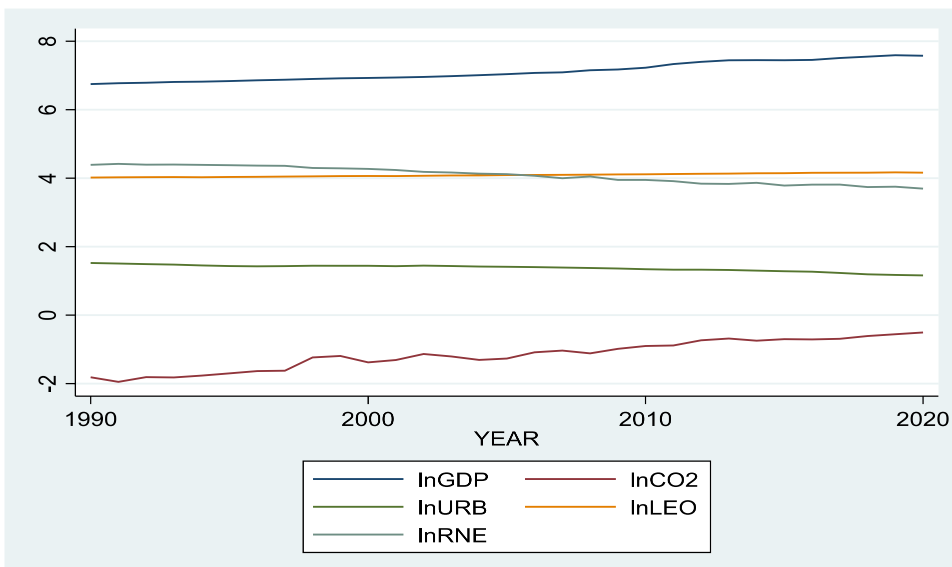

Fig. 1 Graph illustrating CO_2 emissions ($LNCO_2$), GDP (LNGDP), life expectancy (LNLEO), renewable energy consumption (LNRNE), and urbanization (LNURB)

Table 2 Descriptive statistics

	$LNCO_2$	LNGDP	LNLEO	LNRNE	LNURB
Mean	−1.164617	7.117633	4.090879	4.092244	1.376430
Median	−1.135373	7.038947	4.090337	4.117898	1.411823
Maximum	−0.506025	7.591667	4.170379	4.417997	1.523549
Minimum	−1.948632	6.748081	4.018543	3.695110	1.160661
Std. Dev	0.432819	0.278455	0.047969	0.242482	0.096935
Skewness	−0.252161	0.385268	0.130352	−0.101622	−0.743286
Kurtosis	1.875658	1.674280	1.717322	1.540307	2.682090
Jarque–Bera	1.961376	3.037042	2.212920	2.805515	2.984991
Probability	0.375053	0.219036	0.330728	0.245918	0.224811
Sum	−36.10311	220.6466	126.8173	126.8596	42.66932
Sum Sq. Dev	5.619971	2.326111	0.069032	1.763928	0.281890

Descriptive statistics

The descriptive statistics are provided in Table 2; the following findings can be summarised: The variables under consideration are natural logarithms of CO_2 emissions ($LNCO_2$), GDP (LNGDP), life expectancy (LNLEO), renewable energy consumption (LNRNE), and urbanization (LNURB).

The standard deviations indicate that $LNCO_2$ has the highest variability (0.432819), followed by LNRNE (0.242482), LNGDP (0.278455), LNURB (0.096935), and LNLEO (0.047969) has the lowest variability. The skewness values suggest that LNGDP (0.385268) and LNLEO (0.130352) are Slightly positively skewed, while $LNCO_2$ (−0.252161), LNRNE (−0.101622), and LNURB (−0.743286) are adversely skewed. The kurtosis values indicate that all constructs have a leptokurtic distribution (kurtosis > 3), with LNURB (2.682090) having the most peaked distribution. The Jarque–Bera test statistics and corresponding probabilities suggest that the null hypothesis of the normal distribution cannot be rejected for any of the variables at the 5% significance level. Negative skewness for $LNCO_2$, LNRNE, and LNURB indicates more observations on the higher side of the mean. Positive skewness for LNGDP and LNLEO means lower values. Kurtosis over 3 for all variables shows leptokurtic distributions with heavier tails than the normal distribution.

Brock-Dechert-Scheinkman (BDS) test

Table 3 presents the results of the BDS test. This was utilized to identify nonlinearities in time series data (Broock et al. 1996). The test is performed on the variables under consideration: CO_2, GDP, LEO, RNE, and URB. The test is run on embedding dimensions ranging from 2 to 6, and the findings show that all variables have substantial nonlinearity at the 1% level across all embedding dimensions.

These results strongly indicate nonlinear serial dependence in the time series data for all the variables under consideration. This suggests that the null hypothesis of independence and identical distribution (IID) can be rejected for all variables. The presence of nonlinearity in these variables justifies the importance of using the advanced econometric technique, the QQ approach, to understand better the relationships between LEO and its determinants in Ghana. The presence of nonlinear serial dependence in the data justifies using nonlinear econometric models, such as the QQ estimation method employed in the study, to capture the potential nonlinearities and asymmetries in the relationships between the variables. Nonlinear serial dependence implies that the relationships between the variables are likely to be nonlinear and potentially asymmetric. Traditional linear econometric models, such as ordinary least squares (OLS) regression (Cleveland & Grosse 1991; Cleveland 1979; Stone 1977), assume that the relationships between variables are linear and symmetric. However, when the data exhibits nonlinear dependencies, as indicated by the BDS test results, these linear models may fail to capture the true nature of the relationships, leading to biased and inefficient estimates. Consequently, nonlinear serial dependence in the data necessitates using nonlinear econometric techniques to account for potential nonlinearities and asymmetries in the relationship between variables. This is where the QQ estimation approach employed in this study becomes particularly relevant and justified by Sim and Zhou (2015). The QQ estimation approach is a powerful nonlinear econometric technique that examines dependencies across different quantiles of the variables under consideration. Unlike traditional linear models that focus on the conditional mean of the dependent variable, the QQ approach provides insights into how different quantiles (low, medium, and high values) of the independent variables influence different quantiles of the dependent variable. The ability of the QQ approach to capture nonlinearities and asymmetries, as justified by the BDS test results, makes it a suitable and powerful econometric technique for investigating the intricate dynamics of CO_2, URB, RNE, GDP, and LEO nexus in Ghana.

The correlogram provided in Fig. 2 shows the relationships between the dependent variable, LEO, and the independent variables of GDP, CO_2, URB, and RNE. A robust affirmative correlation exists between LEO and GDP. This suggests that as a country's GDP increases, its LEO also rises. A moderate negative correlation exists between LEO and CO_2. This implies that higher carbon emissions are associated with lower LEO. A weak positive correlation exists between LEO and URB. This suggests that increased URB has a small but positive impact on LEO. A weak positive correlation exists between LEO and RNE. This indicates that greater use of RNE sources is linked to slightly higher LEO. The correlogram shows that GDP has the most substantial positive impact on LEO, while CO_2 emissions have the most significant adverse effects. URB and RNE also have small positive associations with LEO but to a lesser degree than GDP and CO_2 emissions.

Table 3 Non-linearity BDS test

	$M=2$	$M=3$	$M=4$	$M=5$	$M=6$
CO_2	16.289***	15.447***	15.705***	17.368***	19.092***
GDP	17.226***	16.785***	16.856***	16.979***	17.670***
LEO	23.701***	23.853***	24.586***	25.644***	27.315***
RNE	20.749***	22.521***	23.731***	25.637***	28.216***
URB	15.176***	14.440***	13.744***	13.182***	12.552***

*** shows a 0.01 level of significance

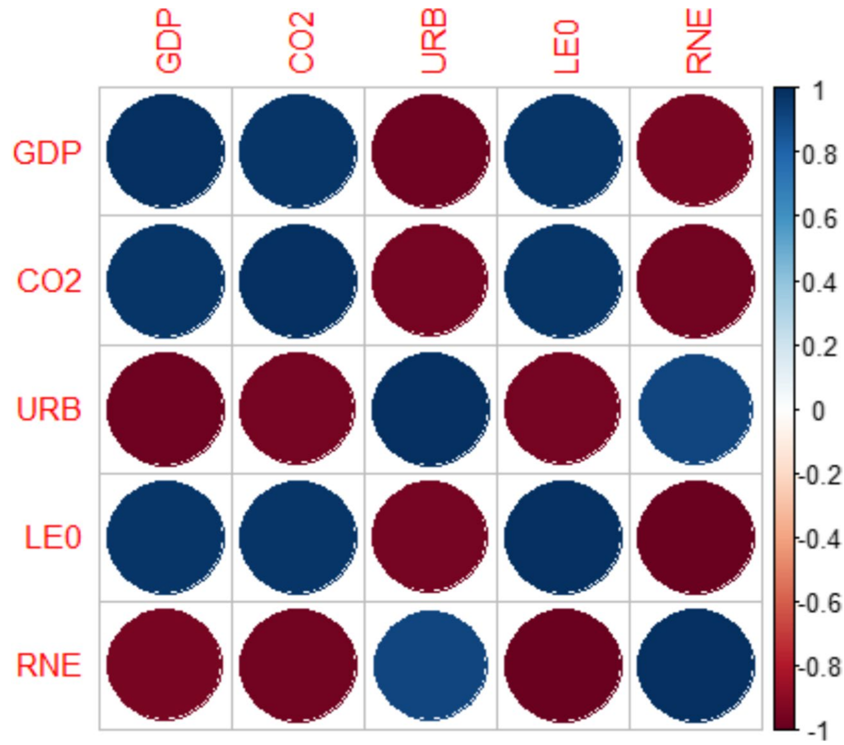

Fig. 2 Correlogram of all variables under consideration

Estimation approach

The link between LEO and the independent variables GDP, CO_2, RNE, URB, and CO_2 emissions is then thoroughly investigated using the QQ technique first presented by Sim and Zhou (2015). The conventional quantile regression model, which examines the relationship between the quantiles of one independent variable and the various quantiles of the dependent variable, is extended by this model. Quantile regression and nonparametric estimates form the main foundation of this approach. Conventional quantile regression is first used to find out how an explanatory variable influences various quantiles of the dependent variable. The usual quantile regression model enhances the ordinary least squares method. Unlike linear regression, quantile regression looks at a variable's impact on the many quantiles of the dependent variable in addition to its conditional mean. The quantile regression model is more thorough in this regard than the least squares method. In addition, the primary linear regression method developed by Cleveland (1979) and Stone (1977) is used to examine the relationship between the dependent variable and different quantiles of the independent variable. Researchers may explore the relationship between various quantiles of the explanatory variable and different quantiles of the dependent variable by combining standard quantile regression and classic linear regression methods. Therefore, rather than using conventional methods like OLS and straightforward quantile regression, combining these two processes might aid in our understanding of the underlying link. Additionally, we use Sim and Zhou's (2015) quantile-on-quantile estimate to the following nonparametric quantile regression model to assess the impact of distinct quantiles of X on the various quantiles of

$$Y_t = \beta^{\theta}\left(X_{t-1}\right) + \alpha^{\theta} Y_{t-1} + \mu_t^{\sigma} \tag{1}$$

Y_t represents the dependent variable (LEO) in period t, while X_t represents the independent variables (GDP, RNE, URB, and CO_2) in time t. σ represents the σth quantile of the X distribution. Additionally, μ_t^{σ} represents the quantile error term, where the projected σth quantile equals zero and β^{θ} is the unknown function. Finally, while undertaking nonparametric analysis, it is critical to understand bandwidth selection. The bandwidth selection is crucial because it smoothes out the target point and sets the size of the surrounding neighborhood, which influences the pace at which the output converges. A large bandwidth (h) would minimize variance while raising the estimate deviation, and vice versa. In this investigation, we choose a bandwidth value of h = 0.10. For several reasons, larger bandwidths 0.1, 0.2, 0.3 up to 0.9 are justified in quantile-on-quantile regression analysis. More consistent estimates are obtained by smaller bandwidths, especially in datasets with high noise levels or erratic patterns. This method is consistent with balancing bias and variance, as (Cornell & Silverman 1986) explained, whereby higher bandwidths lower variation at the expense of higher bias, improving the robustness of the findings. Härdle et al. (1993) also stress the need to choose bandwidths that are suitable for the particular features of the data and the goals of the study, thereby recommending the use of a variety of bandwidths for thorough exploration analysis. As Hsiao et al. (2007) proposed, we may better comprehend the sensitivity of the results and guarantee their resilience across various quantiles by using a spectrum of bandwidths from 0.1 to 0.9. Thus, the established nonparametric regression principles provide a solid foundation for this methodological decision. The QR parameters exclusively indexed by θ can be generated from the QQ parameters around τ. For example, the impact of X on Y is calculated using the measurement of the QR model slope, represented by γ1(θ). Building upon the framework established by Sim and Zhou (2015), the econometrics method of QQ regression can be outlined as follows:

$$\beta^{\theta} X_{t-1} \approx \beta^{\theta}\left(X^{t}\right) + \beta^{\theta}\left(X^{t}\right)\left(X_{t-1} - X^{\tau}\right) \equiv b_0(\theta,\tau) + b_1^{t}(\theta,\tau) \tag{2}$$

Next, we substitute Eq. (2) into Eq. (1)

$$Y_t = \beta^{\theta}(X^{\tau}) + \beta^{\theta}(X^{\tau})\left(X_{t-1} - X^{\tau}\right) + a^{\theta} C_{t-1} + \varepsilon_t^{\theta} \tag{3}$$

We then solve Eq. (3) by considering:

where $p_{\theta}(.)$ solved by the θ –conditional quantile of Y_t denotes the absolute function of the slope (Lin & Su 2020). The Gaussian Kernel function K (.) with h is the bandwidth. We select the bandwidth value h using a cross-validation (CV) method according to (El Heda & Louani 2018).

The robustness of the study is encapsulated in the QR estimates; the QR parameters exclusively indexed by θ can be generated from the QQ parameters around τ. For example, the impact of X on Y is calculated using the coefficient of the QR model slope, represented by $Y_1(\theta)$

$$\gamma_1 \equiv \beta_1(\theta) = \frac{1}{S}\sum\nolimits_{\tau} Y_1(\theta,\tau) \tag{5}$$

Empirical results

Pre-estimation tests

The variables' stationarity properties were validated using the standard Augmented Dickey-Fuller (ADF) (Dickey & Fuller 1979) and Phillips-Perron PP (Phillips & Perron 1988) unit root tests. The ADF and PP unit root test results are shown in Tables 4 and 5, respectively. Stationarity is a necessary assumption for many time series analysis

$$min_{b_0(\theta,\tau),b_1(\theta,\tau),a^{\theta}(\tau)} \sum\nolimits_{t=1}^{T} p\theta[C_t - b_0 - b_1\left(X_{t-1} - X^{T}\right) - a^{\theta} C_{t-1}] K\left(\frac{X\left(X_{t-1}\right) - \tau}{h}\right) \tag{4}$$

Table 4 Unit roots test (ADF)

		$LNCO_2$	LNGDP	LNLEO	LNRNE	LNURB
With Constant	t-Statistic	−0.1908	0.8643	−0.4041	0.8613	1.4947
	Prob	***0.9294***	***0.9935***	***0.8962***	***0.9935***	***0.9989***
		No	no	no	no	no
With Constant & Trend	t-Statistic	−3.5127	−1.7067	−2.6772	−3.9991	−0.1813
	Prob	***0.0561***	***0.7232***	***0.2522***	***0.0198***	***0.9905***
		*	no	no	**	no
Without Constant & Trend	t-Statistic	−4.6815	6.4424	7.0052	−4.7281	−3.6816
	Prob	***0.0000***	***1.0000***	***1.0000***	***0.0000***	***0.0006***
		***	no	no	***	***
		$d(LNCO_2)$	d(LNGDP)	d(LNLEO)	d(LNRNE)	d(LNURB)
With Constant	t-Statistic	−9.4838	−3.0542	−6.3992	−9.2403	−3.0297
	Prob	***0.0000***	***0.0416***	***0.0000***	***0.0000***	***0.0438***
		***	**	***	***	**
With Constant & Trend	t-Statistic	−15.1638	−2.7808	−6.2391	−9.3184	−3.2613
	Prob	***0.0000***	***0.2149***	***0.0001***	***0.0000***	***0.0928***
		***	no	***	***	*
Without Constant & Trend	t-Statistic	−5.1790	−1.9641	−3.3428	−5.7850	−1.8692
	Prob	***0.0000***	***0.0488***	***0.0016***	***0.0000***	***0.0596***
		***	**	***	***	*

(*)Significant at the 10%; (**)Significant at the 5%; (***) Significant at the 1%. and (no) Not Significant

Table 5 Unit roots test (PP)

		At Level				
		$LNCO_2$	LNGDP	LNLEO	LNRNE	LNURB
With Constant	t-Statistic	−1.4737	0.0491	0.1586	0.7127	2.0150
	Prob	***0.5286***	***0.9558***	***0.9648***	***0.9903***	***0.9998***
		no	no	no	no	no
With Constant & Trend	t-Statistic	−4.6533	−2.9028	−2.8180	−2.6141	0.3407
	Prob	***0.0057***	***0.1789***	***0.2022***	***0.2774***	***0.9980***
		***	no	no	no	no
Without Constant & Trend	t-Statistic	−3.6800	2.2305	4.8584	−4.6106	−2.0465
	Prob	***0.0007***	***0.9922***	***1.0000***	***0.0000***	***0.0409***
		***	n0	n0	***	**
		d($LNCO_2$)	d(LNGDP)	d(LNLEO)	d(LNRNE)	d(LNURB)
With Constant	t-Statistic	−6.7070	−3.0729	−6.3987	−5.8055	−3.0297
	Prob	***0.0000***	***0.0400***	***0.0000***	***0.0000***	***0.0438***
		***	**	***	***	**
With Constant & Trend	t-Statistic	−3.6385	−3.0073	−6.2401	−5.8921	−3.0922
	Prob	***0.0484***	***0.1474***	***0.0001***	***0.0002***	***0.1274***
		**	no	***	***	n0
Without Constant & Trend	t-Statistic	−2.1148	−2.0027	−1.0203	−0.2526	−0.7800
	Prob	***0.0353***	***0.0449***	***0.2688***	***0.5854***	***0.3685***
		**	**	no	no	no

(*)Significant at the 10%; (**)Significant at the 5%; (***) Significant at the 1%. and (no) Not Significant

*MacKinnon (1996) one-sided p-values

methods, and non-stationary variables must be differentiated to obtain stationarity before continuing with the analysis. Table 5 shows the findings of two frequently used unit root tests: the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP). These tests are performed under three distinct conditions: with a constant term, constant and trend, and without a constant or trend. The tests are performed on the variables' levels and, if non-stationary, their initial differences.

The findings from the PP test indicate that at the level, the variables $LNCO_2$, LNGDP, LNLEO, and LNURB are non-stationary under all three specifications, as the test statistics fail to reject the null hypothesis of a unit root at conventional significance levels. However, the variable LNRNE is stationary at the 5% level, including a constant and trend. When the first differences are considered, all variables become stationary under all three specifications, suggesting that they are integrated of order one, I(1). The ADF test results generally confirm the findings from the PP test. At this level, the variables $LNCO_2$, LNGDP, LNLEO, and LNURB are non-stationary under the constant and constant trend specifications. LNRNE is stationary without a constant or trend at the 1% level. After taking the first differences, all variables achieve stationarity under at least one specification, indicating that they are I(1) processes. Based on these unit root test results, we conclude that most variables are non-stationary at their levels but become stationary after taking the first difference. This implies that the variables are integrated into order one, I(1).

QQ approach results

The primary observed results of the QQ analysis of the effects of CO_2 emission, GDP, RNE, and URB on LEO are presented in this study section. The estimates of the slope coefficient, $\beta1(\theta, \tau)$, for Ghana are shown in Fig. 3a–f. They illustrate the impact of the τth quantile of X on the θth quantile of Y for different values of θ and τ for Ghana. Figure 2a-l illustrates the QQ approach's results.

Figure 3a shows the impact of CO_2 emissions on LEO. Carbon emissions have a mostly detrimental impact on LEO transversely all quantiles (0.1–0.9). To summarize, the effect of CO_2 emissions on LEO is negative for most carbon emission quantiles, suggesting that an increase in carbon emissions hurts LEO. Additionally, Fig. 3b depicts the impact of LEO on carbon emissions. LEO has a momentous favorable influence on carbon emissions in the two quantiles (0.1–0.9). This shows that a rise in LEO has a favorable effect on carbon emissions. The findings do not indicate a feedback relationship between carbon emissions and LEO. Figure 3c shows that the impact of GDP on LEO is largely favorable across all quantiles of GDP and LEO. This suggests that increasing GDP has a favorable influence on LEO. Figure 3d

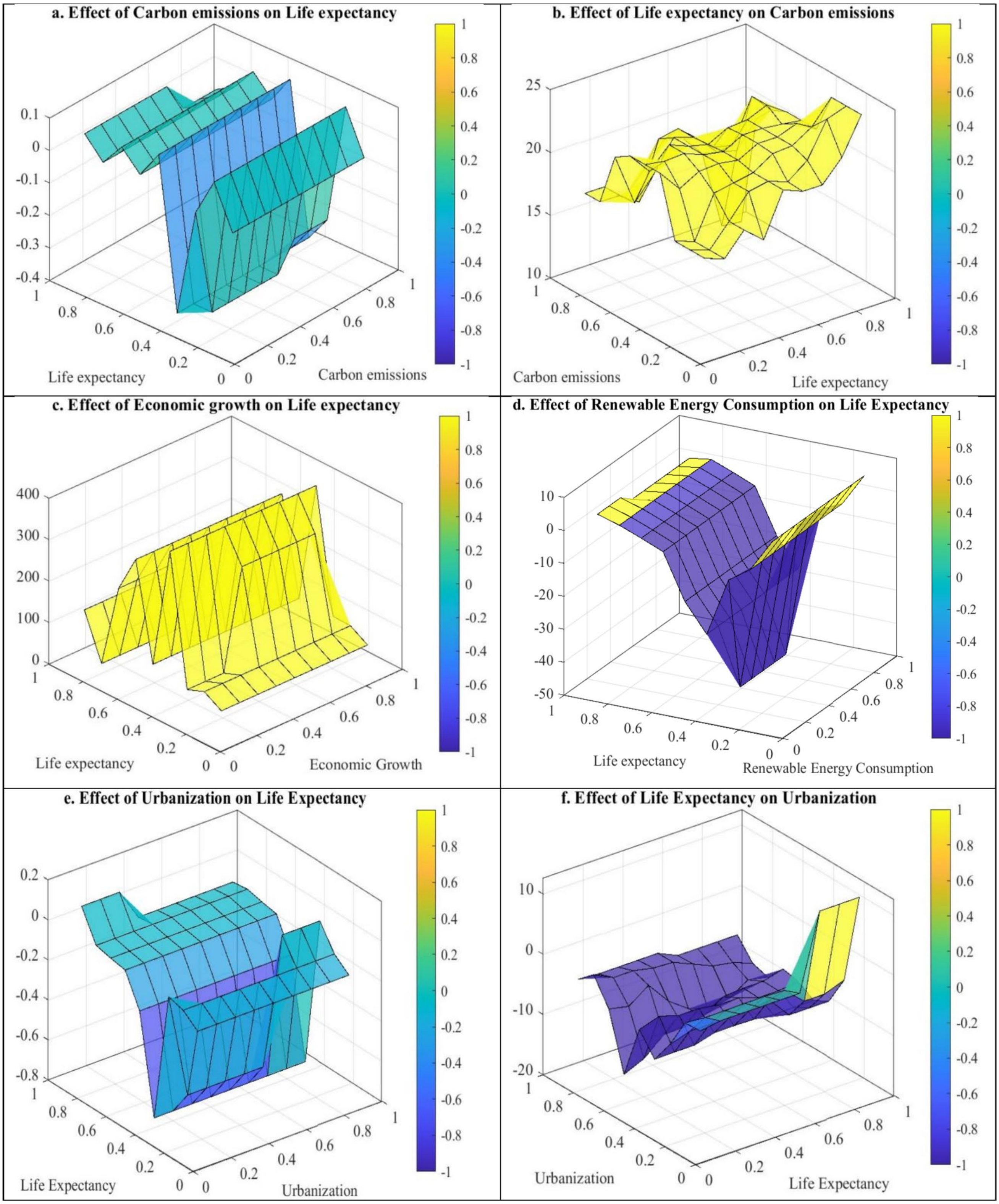

Fig. 3 Quantile-on-Quantile analysis

shows how RNE affects LEO. The results demonstrate a negative influence for the majority of RNE and LEO quantile combinations; however, at extremely high (0.8–0.9) and very low quantiles of LEO (0.1–0.2), as well as all RNE quantiles (0.1–0.9), the effect of RNE on LEO is positive. We consequently infer that RNE has a detrimental impact on LEO. Figure 3e shows the influence of URB on the LEO. We find a negative relationship between all URB and LEO quantiles. Therefore, we infer that an increase in URB has a detrimental influence on LEO. Furthermore, Fig. 3f shows the effect of LEO on URB. The results demonstrate a negative influence in most of the two quantile combinations. However, LEO has a beneficial influence on URB for high LEO quantiles (0.8–0.95) and low URB quantiles (0.1–0.25). The data indicate a feedback interaction between URB and LEO.

Robustness analysis

Subsequently, we advanced to contrast the QQ estimates' outcomes with the conventional quantile regression (QR). The results of traditional quantile regression align with the QQ estimations. The quantile regression parameters are only indexed by θ since the QR model employed in this research is only concerned with degenerating the θth quantile of Y on X. Nevertheless, as previously stated, the indicators will be specified by both θ and τ since the QQ exploration degenerates the θth quantile of Y on the quantile of X. Because the QQ approach views this link as intrinsically diverse through X quantiles, it offers more detailed information about the X–Y fitting together than the quantile regression model. The classic quantile regression estimates may be obtained from the QQ estimates due to the intrinsic decomposition aspect of the QQ technique.

The plots in Fig. 3a–f demonstrate how the averaged QQ estimates of the slope coefficient are remarkably similar to the QR estimates for Ghana, regardless of the quantile used. This graphical evidence shows that the more detailed information provided in the QQ estimates, including a convincing defense of the QQ approach, may be used to extract the main structures of the QR model.

The plots in Fig. 4a-f indicate that, regardless of the quantile used, the averaged QQ estimates of the slope coefficient are similar to the QR estimates for Ghana for just a subset of the connections. This graphical proof demonstrates that the significant feature of the QR model may be obtained by presenting the more detailed features included in the QQ estimates, providing a convincing rationale for the QQ technique. To explore the impact of using different quantile values (τ) when generating the QR parameters from the QQ estimates, we re-estimated the models using τ = [0.10, 0.20, and 0.90]. The results show that the discrepancies between the QQ and QR estimates for the carbon emissions and URB relationships persist, indicating that the choice of quantiles does not significantly impact the divergence between the two approaches for these variables. While the differences between the QQ and QR estimates may be minor, they can still have meaningful economic implications. For example, the QQ approach suggests a slightly more substantial negative impact of carbon emissions on LEO than the QR model, particularly at higher quantiles. This heterogeneity across quantiles, better captured by the QQ method, could have important policy implications for targeted interventions to mitigate pollution's adverse effects on health outcomes.

Discussion of findings

This research gives unique insights into the country's developmental difficulties and prospects. The predominantly negative impact of carbon emissions on LEO, particularly at higher quantiles, aligns with the initial stages of the EKC premise, where GDP and industrialization lead to increased environmental degradation and adverse health effects (Grossman & Krueger 1991). This observation suggests that Ghana's economic development and URB processes have been accompanied by rising CO_2 emissions, which may have contributed to poorer air quality and compromised public health outcomes. Secondly, our study reveals a positive association between GDP and life expectancy (LEO) across quantiles, with a more pronounced effect at higher income levels. This finding aligns with the Preston Curve's postulation of a positive but diminishing marginal effect of income on LEO (Preston 1975; He and Li 2018). It is also consistent with recent studies by Wang et al. (2020) and Rahman et al. (2022a, b), who found positive relationships between GDP and LEO in various developing countries. However, our results provide a more nuanced understanding by showing that the effect varies across different quantiles, which these previous studies did not capture. Ghana's robust economic growth over the past two decades, driven by agriculture, mining, and oil production sectors, has likely contributed to increased LEO through improvements in healthcare infrastructure, access to medical services, and overall living standards. This observation is in line with Sharma. (2018) findings demonstrated a substantial long-term cointegration link between LEO and GDP in advanced economies. However, our study extends this understanding to a developing country context, specifically Ghana. Additionally, contrary to existing literature, our study found a negative relationship between urbanization (URB) and LEO, highlighting Ghana's challenges in managing urban growth. This finding contrasts with Alavijeh et al. (2023), who found that URB increased LEO across all quantiles in G-7 nations. However, our results are more consistent with those of Torres et al. (2019) and Sudharsanan and Ho (2020), who observed the negative impacts of rapid URB on health outcomes in developing contexts. The discrepancy with Alavijeh et al. (2023)

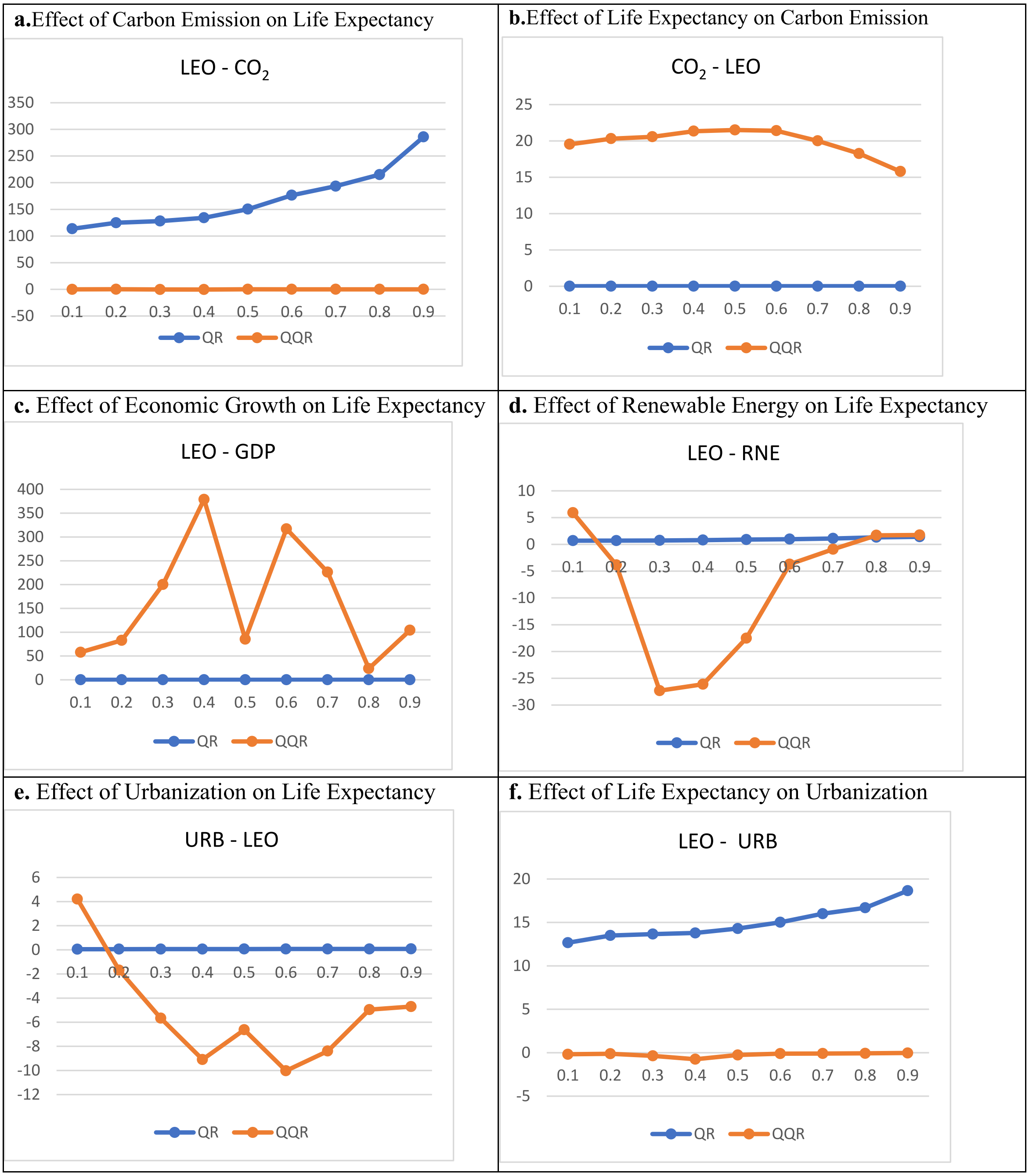

Fig. 4 Quantile regression (QR) estimates

likely stems from differences in the development and urban planning level between G-7 nations and Ghana. Also, our finding of a negative association between LEO and renewable energy (RNE) consumption differs from several existing studies. For instance, Alavijeh et al. (2023) found a positive effect of RNE on LEO in G-7 countries, and Liu and Zhong (2022) observed similar positive effects in China. Our contrasting result may reflect Ghana's substantial dependence on fossil fuels and attempts to meet expanding energy needs through more economical but less clean sources. This discrepancy underscores the importance of country-specific analyses and highlights developing nations' unique challenges in their energy transitions. The mixed effects observed across different quantile combinations in our study highlight the complex and heterogeneous relationships between LEO and its determinants. This finding is particularly significant as it reveals nuances that traditional regression techniques, used in many previous studies, may overlook. For example, while Shahbaz et al. (2019) found that financial development, globalization, and GDP improved LEO in most sub-Saharan African countries, they did not capture the potential variations across different quantiles of these variables. The QQ approach provides a more comprehensive understanding of these relationships, revealing non-linearities and heterogeneities crucial for informed policy-making. This methodological contribution extends beyond the findings of studies like Osabohien et al. (2020) and Matthew et al. (2020), which used more traditional econometric approaches. These discoveries collectively emphasize the need for multi-faceted policy approaches that balance economic growth, sustainable urbanization, and environmental sustainability to improve Ghana's LEO and overall well-being. While our results largely support existing literature on the positive impact of economic growth on LEO, they also highlight the unique challenges facing developing countries like Ghana in managing urbanization and transitioning to cleaner energy sources. Future research could further explore these country-specific dynamics and their implications for public health and development policies.

Conclusion and policy direction

Conclusion

This study, employing the quantile-on-quantile (QQ) approach, has shed valuable light on the complex and heterogeneous relationships between LEO and critical factors such as pollution, GDP, URB, and RNE in Ghana during the 1990–2020 period. The empirical results show vital insights that may lead to sustainable development initiatives to enhance the health and well-being of Ghana's population. The analysis indicated a largely negative effect of increased CO_2 emissions on LEO, particularly at higher quantiles, reflecting the earliest phase of the Environmental Kuznets Curve hypothesis. As Ghana continues industrializing, excessive environmental degradation from activities such as fossil fuel combustion, mining operations, and unsustainable agricultural practices undermines gains in improving public health. The adverse effects of carbon emissions were more pronounced at higher quantiles, suggesting that the adverse impacts on LEO intensify as emission levels increase. On the other hand, GDP exhibited a markedly strong positive association with LEO across quantiles, aligning with the Preston Curve theory, which links economic development to population health outcomes. Ghana's economic trajectory over recent decades, driven by robust agricultural, mining, and oil and gas sectors, has contributed substantially to improving access to healthcare services, raising nutritional levels, and elevating overall living standards nationwide. Notably, the positive effect of GDP on LEO was more substantial at higher income quantiles, indicating a potential diminishing marginal returns effect as predicted by the Preston Curve. Additionally, the study uncovered mixed effects of URB on LEO in Ghana, underscoring the country's unique challenges in this sphere. While urban centers tend to provide better access to health services and amenities, rapid unplanned urban growth has simultaneously led to a proliferation of slum settlements, inadequate housing conditions, poor sanitation infrastructure, and higher exposure to environmental hazards for many urban residents. The effects of URB varied across different quantile combinations, highlighting the complex interplay between urban development and health outcomes. Moreover, Ghana's continued heavy reliance on fossil fuels as its primary energy source is reflected in the study's finding of a relatively weak positive link between renewable energy use and LEO during the period analyzed. This suggests that the country's efforts to meet increasing energy demands through more affordable but less clean sources may have undermined potential gains in LEO associated with adopting renewable energy technologies. The QQ approach's ability to capture these heterogeneous effects and non-linearities across different quantile combinations provides a more nuanced understanding of the intricate relationships between LEO and its determinants in Ghana. These findings emphasize the need for comprehensive and battered program interpolations about the multidimensional tests of balancing GDP, URB, environmental sustainability, and public health objectives.

Policy direction

Based on these diverse observations, the research offers numerous crucial policy recommendations for established and emerging governments, particularly in the Ghanaian context. To begin with, Ghana's economic policies must promote inclusive growth, ensuring that the benefits of GDP growth reach all population segments. By targeting investments in healthcare, education, and social protection programs, the government can uplift low-income groups, enhancing life expectancy nationwide. In addition, diversifying the economy away from an over-reliance on primary commodities is essential. By fostering the development of value-added industries, Ghana can stabilize income levels and reduce poverty, thereby creating a more resilient economy. This economic stability is crucial because it directly impacts public health outcomes, as stable income and reduced poverty are linked to better access to healthcare and improved living conditions. Moreover, the study emphasizes the critical need for stronger environmental regulations to control CO_2 emissions and mitigate their adverse effects on health. Therefore, Ghana should adopt comprehensive environmental policies such as carbon taxes, emission trading systems, and incentives for adopting green technologies. These policies will help reduce environmental pollution, contributing to a healthier environment that supports longer life expectancy. Furthermore, it is imperative to invest significantly in green infrastructure. By prioritizing expanding renewable energy sources like solar and wind, the government can reduce the country's carbon footprint, create jobs in the green economy, and promote healthier living conditions. These measures will improve public health and contribute to the country's long-term sustainability goals. In addition to environmental sustainability, addressing the challenges of rapid urbanization is crucial. Urbanization, while contributing to economic growth, often leads to overcrowding, inadequate housing, poor sanitation, and limited access to essential services. Consequently, these conditions pose significant public health risks. To combat these challenges, Ghana must implement sustainable urban planning policies that improve living conditions in rapidly growing urban areas. This includes developing affordable housing, improving sanitation, and ensuring access to clean water and waste management services. Furthermore, expanding healthcare infrastructure in urban areas is vital. Ghana can significantly enhance public health outcomes and improve life expectancy by increasing the availability and quality of healthcare services and ensuring equitable access. Moreover, addressing demographic challenges is a critical factor in improving life expectancy. Ghana should prioritize health programs focusing on the most vulnerable demographic groups, such as children, women, and the elderly. For instance, initiatives to reduce infant and maternal mortality rates, improve nutrition, and increase access to preventive care are essential. Education and awareness campaigns should also be intensified to promote healthy lifestyles and prevent non-communicable diseases. National campaigns that focus on reducing tobacco use, improving diets, and encouraging physical activity can help reduce the burden of chronic diseases, which are becoming more prevalent as the population ages. In this way, these efforts can significantly extend life expectancy and improve overall quality of life. Finally, strong governance and institutional capacity are essential for the effective implementation of these policies. To ensure that health, environmental, and economic policies are well-coordinated, Ghana should establish inter-ministerial committees or task forces that oversee their integration. This coordination will prevent policy fragmentation and ensure all sectors work towards common goals. Additionally, building the capacity of local governments and public institutions is crucial. This includes training public officials, investing in data collection and analysis, and establishing robust accountability mechanisms. By strengthening these capacities, Ghana will enhance the effectiveness of policy implementation, which is critical for improving public health outcomes and extending life expectancy. In conclusion, these strengthened policy recommendations are designed to address the unique challenges identified in this study. By implementing these recommendations, Ghana can achieve sustainable development, improve public health, and enhance its citizens' overall quality of life.

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Data availability Data will be made available upon request.

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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