

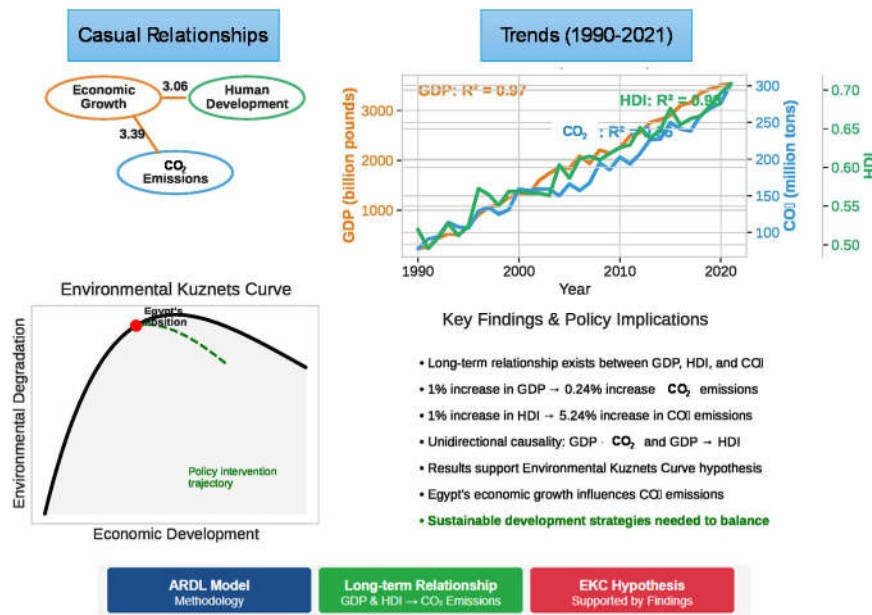
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The Paradox of Progress: How Economic and Human Development Drive CO₂ Emissions in Egypt

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Graphical Abstract:



Abstract: Climate change is one of today's most pressing and widely recognized global challenges. This study explores the intricate relationships between economic growth, human development, and environmental degradation in Egypt, focusing on CO₂ emissions. Utilizing the Autoregressive Distributed Lag (ARDL) model, we investigate how the Gross Domestic Product (GDP) and the Human Development Index (HDI) influence carbon emissions from 1990 to 2021. Our findings reveal a significant long-term relationship between these variables, indicating that economic growth and improvements in human development contribute to increased CO₂ emissions. The results support the Environmental Kuznets Curve hypothesis, suggesting that economic development can lead to better environmental outcomes if managed effectively. The study highlights the need for sustainable development strategies that balance economic growth with environmental protection, providing valuable insights for policymakers aiming to address climate change challenges in developing countries like Egypt.

Keywords: Economic Growth; Human Development; Climate Change; Carbon neutrality.

1. Introduction

In recent decades, rising energy demand has significantly increased CO₂ emissions, particularly in global economic and social development (Khan et al., 2021). In 2023, CO₂ concentrations averaged 420.0 ppm, a 151% increase from pre-industrial levels, primarily

driven by fossil fuels, which accounted for 73.7% of total greenhouse gas emissions(WMO, 2024). Since the 1990s, a growing body of literature has explored how rising economic activities contribute to environmental challenges, particularly in developed countries(Kurnia et al., 2019). Consequently, the intricate relationship between economic growth and ecological degradation has garnered significant attention from researchers and policymakers (Sasana et al., 2022).

Much of this literature has increasingly utilized climate change, economic growth metrics, and energy consumption as key variables to analyze this relationship and mitigate specification bias in their findings(Ahmed and Elfaki, 2024; Awosusi et al., 2022). The recognition of these connections is further emphasized by global initiatives such as Agenda 2030 and the Sustainable Development Goals (SDGs), which highlight the interdependencies among energy needs (SDG 7), economic development (SDG 8), and climate change mitigation efforts (SDG 13)(Soergel et al., 2021). Fulfilling these goals is especially critical for developing nations like Egypt, where sustainable energy production and consumption are vital for fostering economic growth while preserving the natural environment (Rabie, 2022).

However, the relationship between economic growth, human development, and environmental sustainability is crucial amid global challenges such as climate change and resource depletion (Aye and Edoja, 2017). This connection is especially evident in Egypt and many developing nations (Aboagye, 2019). The Human Development Index (HDI) serves as a composite measure of health, education, and living standards, reflecting the socioeconomic progress of a nation (Karedla et al., 2021). Simultaneously, the Gross Domestic Product (GDP) measures economic performance but often correlates with increased ecological footprints due to industrialization and urbanization (Bui Minh et al., 2023; Onofrei et al., 2022).

Despite significant economic growth in Egypt, prior studies indicate that energy consumption and CO₂ emissions have escalated even faster (Fathy Sharaf, 2016). A critical challenge remains in deciphering the authentic relationship between energy consumption, economic growth, and CO₂ emissions (Nkengfack and Fotio, 2019). While previous research has employed the Autoregressive Distributed Lag (ARDL) model to evaluate causal links among environmental degradation, energy consumption, economic expansion, and global trade growth (Rashdan and Ibrahim, 2024b), there has been a notable oversight regarding the ecological impact of HDI (Abd El-Aal et al., 2024).

Previous research has shown mixed results regarding the interaction of these variables. For instance, Rashdan and Ibrahim (2024a) found that energy consumption significantly impacts CO₂ emissions, while Abd El-Aal et al. (2024) highlighted that urbanization contributes positively to emissions. Other studies have indicated that economic growth can lead to negative and positive environmental outcomes depending on the context and methodology of Abd El-Aal et al.(2024) and Nkengfack and Fotio(2019). This study aims to fill this gap by employing the ARDL model to investigate the relationships between HDI, GDP, and environmental degradation in Egypt. By incorporating HDI into this framework, this study seeks to provide a more comprehensive understanding of how socioeconomic factors influence environmental outcomes in Egypt. The findings are expected to contribute valuable insights for policymakers aiming to create strategies that promote sustainable development while addressing the pressing challenges of climate change and ecological degradation.

2. Methodology and data estimate

2.1. Data Collection and Variable Construction

The interconnections between energy needs, economic development, and climate change mitigation are vital to the 2030 Agenda for Sustainable Development(UN, 2015). Consistent with the findings presented in Table 1, our research aims to assess the relationships among CO₂, GDP, and HDI in Egypt. We structure our research by period, region, results, and methodology to produce the most relevant findings. The data on CO₂ emissions, GDP, and HDI have been gathered from the Central Bank of Egypt (CBE, 2023) and World Development Indicators (WBDI, 2023). This analysis is focused on CO₂ emissions (in million tons) as the primary dependent variable, with GDP (in billion pounds) and HDI included as explanatory variables reflecting economic growth and social development.

Table 1. The variables descriptions and the data source.

| Variables | Description | Logarithmic forms | Measurement units | Source | Period |
|-----------------|--------------------------|-------------------|-------------------|--------------|-----------|
| CO ₂ | carbon dioxide emissions | LnCO ₂ | million tons | (WBDI, 2023) | 1990-2021 |
| GDP | Economic growth | LnGDP | billion pounds | (CBE, 2023) | 1990-2021 |
| HDI | Human Development Index | LnHDI | - | (WBDI, 2023) | 1990-2021 |

Note: (1) WBDI: World Development Indicators; CBE: the Central Bank of Egypt; (2) Ln: means the variable in natural logarithms.

We converted all variables into natural logarithms while analyzing the estimated parameters to enhance the accuracy and reliability of our findings. Table 1 summarizes the variables, descriptions, units, and resources. Figure 1 represents the variables' annual evolution. The following model will be created to investigate how economic growth and HDI affect CO₂ emissions:

$$Co_{2t} = \alpha_0 + \beta_1 GDP_t + \beta_2 HDI_t \tag{1}$$

where α_0 denotes the intercept, and t indicates the time series (1990–2021). Additionally, β_1 and β_2 reflect the coefficients. The model of economics can be expressed through the following form of Eq. (2):

$$Co_{2t} = \alpha_0 + \beta_1 GDP_t + \beta_2 HDI_t + \mu_1 \tag{2}$$

where μ_1 is the error term.

After applying the natural logarithm, the preceding model can be expressed as follows:

$$lnco_{2t} = \alpha_0 + \beta_1 lnGDP_t + \beta_2 lnHDI_t + \mu_1 \tag{3}$$

Figure 3 displays the flow chart of statistical techniques used to analyze the dynamic relationship between Egypt's GDP, HDI, and CO₂ emissions.

2.2. Methodology specification

Various time series econometric techniques are utilized in this study. They analyze the relationship between Egypt's economy and HDI, reflecting social aspects of sustainable

development. Data stationarity is also examined using various statistical tests. The ARDL method is commonly applied to time-series data. According to Yousaf Raza and Lin (2021), these models can evaluate numerous hypotheses if the output variable is analyzed at the first or second derivative level. Testing for cointegration is essential when applying the error correction technique in the ARDL model. Jordan and Philips (2018) noted that they developed the cointegration method (Pesaran et al., 2001). Given the limited sample size, having 80% or fewer cases is insufficient for typical sociological studies. Consequently, the ARDL cointegration method requires more data than the basic 'two-step' Engle and Granger model (1987) or the Johansen cointegration process (1988). However, this cointegration measure does not directly apply to standard statistical interpretations.

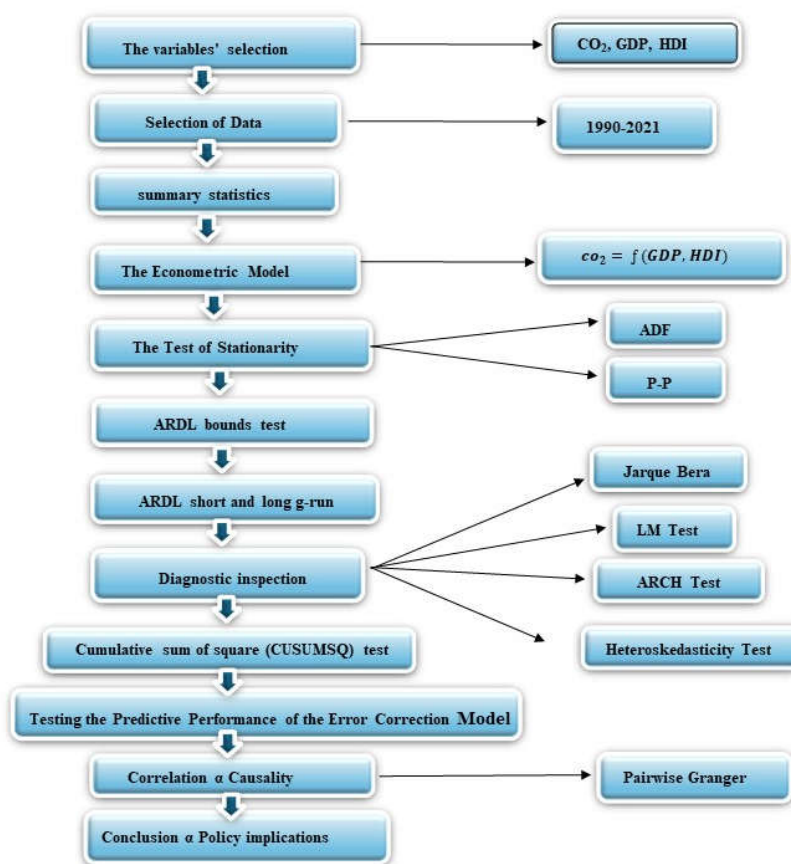


Fig. 3. Illustration representative methodology strategy

In addition to its error-correction procedure, the ARDL approach may have imposed complex requirements, such as multiple lags, novel variants, and lagging. This has complicated the analysis of how explanatory variable (s) changes affect outcomes, especially regarding short- and long-term shifts. To tackle this, Jordan and Philips (2018) developed a common command that allows users to explore ARDL techniques while simultaneously incorporating the ECM dynamically. Employing the ARDL simulation method, this study investigates the actual change of independent influences brought on by explanatory variables. This method aims to overcome the constraints of traditional ARDL models when analyzing econometric parameters in both short- and long-term contexts. Figure 2 presents a graphical view of the

model's specifications and data.

2.2.1. Unit root tests

Unit root techniques were used to classify variables as stationary or non-stationary. The dependent and independent variables were identified as I(0) and I(1) by the ARDL approach. Typically, unit root tests are conducted before the ARDL bounds test. For example, recent studies by Omay and Baleanu (2021), Lu et al. (2024), and Li et al. (2024) utilized these tests in their analyses. Our econometric analysis employs the Augmented Dickey-Fuller (ADF) unit root test to assess the stationarity of each variable (Dickey and Fuller, 1981; Phillips and Perron, 1988). The relationships between the variables were verified using the following expression in Eq. (4).

$$lncO_{2t} = \alpha_0 + \beta_1(\ln GDP_t) + \beta_2(\ln HDI_t) + \mu_1 \tag{4}$$

where t represents time, CO₂ is carbon dioxide emissions, GDP is gross domestic product, and HDI is the human development index. Equation (4) includes a constant (α_0), two descriptive factor coefficients (β_1 and β_2), and an error term (μ_1).

2.2.2. Cointegration approach

The ARDL bounds test for cointegration investigates whether the examined variables share a long-term relationship. The data series is classified as I(1) when the behaviour of the variables results from all prior stochastic shocks, including recent changes. This series highlights the connection between integration and cointegration. However, since not all relationships within the I(1) data series indicate the presence of cointegration, it is essential to revalidate the findings of the cointegration analysis. The limits test equation is presented in Eq. (5).

$$\Delta \ln CO_{2t} = \alpha_0 + \lambda_1 \ln CO_{2t-1} + \lambda_2 \ln GDP_{t-1} + \lambda_3 \ln HDI_{t-1} + \sum_{i=1}^r \beta_1 \Delta \ln CO_{2t-i} + \sum_{i=0}^r \beta_2 \Delta \ln GDP_{t-i} + \sum_{i=0}^r \beta_3 \Delta \ln HDI_{t-i} + \mu_{1-1} \tag{5}$$

where Δ refers to the first-order difference between CO₂ emissions, GDP, and HDI. The optimal lags preferred by the Akaike Information Criterion (AIC) are further indicated by $i - 1$. These include λ_1 , λ_3 , and β_1 , β_3 estimations of short- and long-term connections, respectively. This enables us to compare ARDL techniques over short and long periods (Jordan and Philips, 2018).

$$H_0 = \varphi_1 = \varphi_2 = \varphi_3 = 0$$

$$H_1 = \varphi_1 = \varphi_2 = \varphi_3 \neq 0$$

The decision to accept or reject the hypothesis is based on the results of the F statistic. According to Özdemir and Çevikalp (2021), if the F-statistic exceeds the upper bound value, it indicates a long-term relationship. Conversely, if the F-statistic is below the lower bound, it suggests that no long-term relationship exists. The outcome is ambiguous when the F-statistic falls between the upper and lower bounds.

2.2.3. Distributed lag selection

The ARDL method offers significant analytical advantages over other cointegration techniques. Unlike other methods, the ARDL approach allows for applying different lag lengths for independent and dependent variables. This flexibility means the ARDL cointegration method can accommodate varying lag lengths for independent and dependent variables, whereas other techniques typically require similar lag lengths (Shahani and Raghuvansi, 2020; Zhang et al., 2019). Additionally, this model can be applied to I(0) or I(1) series without any specific order constraints (Brown et al., 1975). The ARDL method is also effective with small sample sizes. We utilized the ARDL technique to identify long-term relationships between variables, as shown in Eq. (6).

$$\Delta \ln CO2_t = \alpha_0 + \sum_{i=0}^r \sigma_1 \Delta \ln CO2_{i-1} + \sum_{i=0}^r \sigma_2 \Delta \ln GDP_{i-1} + \sum_{i=0}^r \sigma_3 \Delta \ln HDI_{i-1} + \mu_1 \tag{6}$$

In the equation above, σ_1 to σ_3 represents the variables' long-term dispersion. For this research, the Akaike Information Criterion (AIC) was utilized to determine the optimum lag for the independent variables. After deciding the long-term relationship between the series, this study utilized Eq. (7) to compute the short-term parameters' coefficients.

$$\Delta \ln CO2_t = \alpha_0 + \sum_{i=0}^r \beta_1 \Delta \ln CO2_{i-1} + \sum_{i=0}^r \beta_2 \Delta \ln GDP_{i-1} + \sum_{i=0}^r \beta_3 \Delta \ln HDI_{i-1} + \varphi ECT_{i-1} + \mu_1 \tag{7}$$

In the previous equation, the parameter β represents the short-term dynamics. At the same time, the error correction term (ECT) quantifies the adjustment rate influenced by short-term variables, with its value ranging from 0 to 1 (Khan et al., 2020). A negative and statistically significant error correction coefficient indicates that each variable adjusts to maintain equilibrium in the subsequent period.

Hence, this study employed the pairwise linear Granger-causality test, established by Granger (1969), to explore the existence of a causal association among the factors. Whenever a time series Y can potentially predict the future behaviour of a different time series X, it can be indicated as "Granger-causing" X. In the present study, the F test can be utilized to determine Granger causality among variables X and Y. The variables X_t and Y_t maybe shown in a bivariate autoregressive model at time t:

$$X_t = \beta_1 + \sum_{i=1}^n \alpha_i Y_{t-1} + \sum_{i=1}^n \mu_i X_{t-1} + e_t \tag{8}$$

$$Y_t = \beta_2 + \sum_{i=1}^n \Omega_i Y_{t-1} + \sum_{i=1}^n \infty_i X_{t-1} + u_t \tag{9}$$

where n refers to lag numbers, stated explicitly in the data criteria $\beta_1, \beta_2, \alpha_i, \Omega_i, \mu_i,$ and ∞_i as variables for evaluation, as well as e_t and u_t as residual terms.

The results indicate that the coefficients of the ARDL model are stable if the data points in

the plot fall within critical limits at a 5% significance level. Additionally, we employed several tests to evaluate model performance, including the Durbin-Watson test, Serial Correlation LM test, ARCH test, Heteroskedasticity test, and Jarque-Bera reset test.

3. Results and discussion

3.1. Multicollinearity, descriptive statistics, and graphical representation of data

Economic growth is typically associated with increased resource consumption and pollution, posing significant environmental challenges (European Environment Agency, 2021; Everett et al., 2010). However, it is possible to decouple economic growth from environmental degradation through effective policies and technological innovations (Columbia University, 2020). For instance, the U.S. has successfully reduced pollution while maintaining economic growth by implementing regulations and investing in pollution control technologies (Columbia University, 2020).

The time series data for this study, transformed into natural logarithms, are shown in Figure 2. Table 2 comprehensively summarizes the primary statistics for all variables, including mean, median, standard deviation, minimum, maximum, skewness, kurtosis, and Jarque-Bera test.

Table 2. Descriptive statistics for the variables

| | ΔLnCO_2 | ΔLnGDP | ΔLnHDI |
|-------------|------------------------|-----------------------|-----------------------|
| Mean | 2.54e-16 | -8.88e-16 | -4.16e-17 |
| Median | -0.003011 | 0.006902 | 0.001109 |
| Maximum | 0.046923 | 0.214908 | 0.011195 |
| Minimum | -0.034358 | -0.176177 | -0.015938 |
| St. dev. | 0.021946 | 0.078403 | 0.007048 |
| Skewness | 0.439269 | 0.225013 | -0.508490 |
| Kurtosis | 2.192404 | 4.234972 | 2.548066 |
| Jarque-Bera | 1.661380 | 2.015624 | 1.444906 |
| Probability | 0.435748 | 0.365017 | 0.485560 |
| Obs. | 32 | 32 | 32 |

Note: $\Delta \text{Ln GDP}$; $\Delta \text{Ln CO}_2$; $\Delta \text{Ln HDI}$: are the natural logarithmic forms of Egypt's gross domestic product, carbon dioxide emissions, and Human Development Index, respectively. *Source:* Authors' estimation using E-Views 12.

The findings from this study support the notion that economic growth, as measured by GDP, is associated with increased carbon emissions (ΔLnCO_2) and improvements in human development (ΔLnHDI). This relationship is consistent with previous studies indicating that economic expansion often results in higher energy consumption and environmental impacts (Chaabouni and Saidi, 2017; Ziramba, 2010). The Environmental Kuznets Curve (EKC) hypothesis suggests that economic growth harms the environment at low-income levels, but as income rises, environmental quality improves (Jayachandran, 2022). Economic development can ultimately lead to better ecological outcomes if appropriately managed.

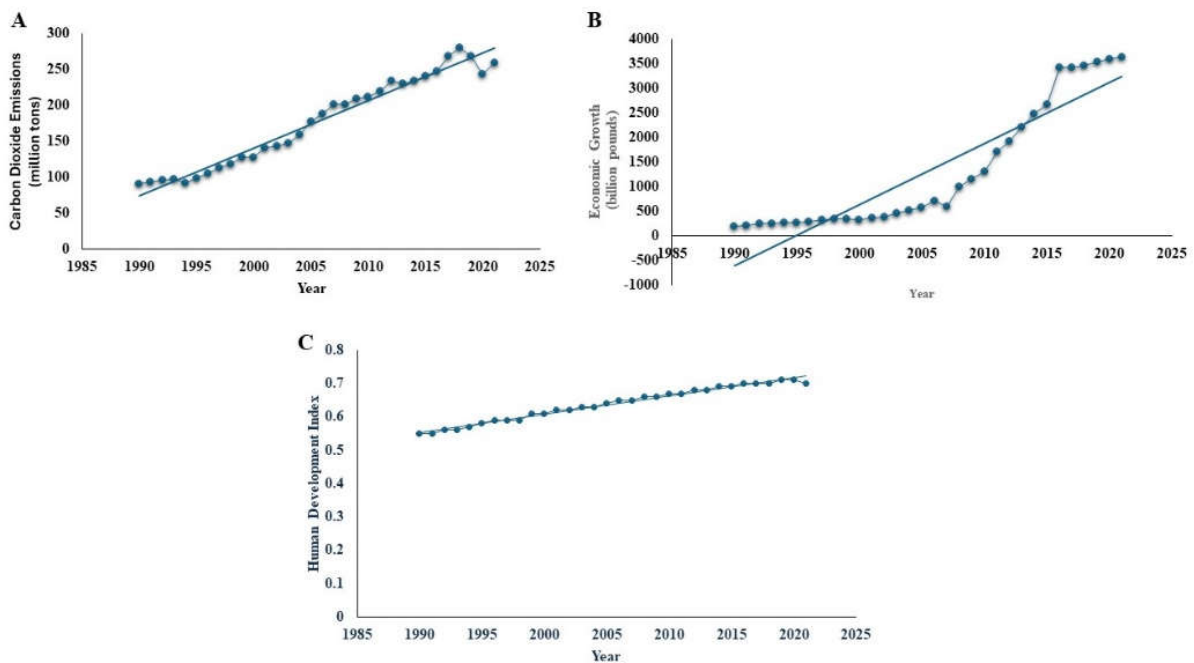


Fig. 1. Annual trend of the variables from 1990 to 2021. Carbon dioxide emissions (A); Economic growth (B); Human Development Index (C), (CBE, 2023 and (WBDI, 2023).

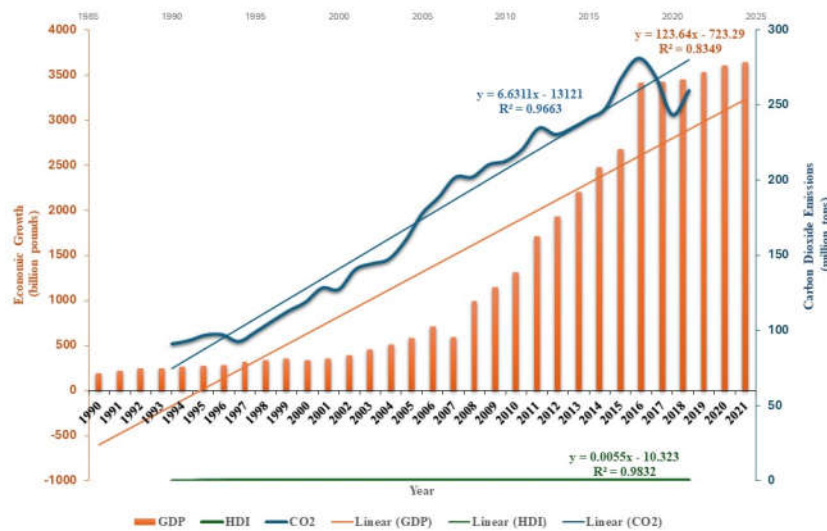


Fig. 2. The fitting curves of the total emission of CO₂ (million tons), Gross Domestic Product (GDP), and the Human Development Index (HDI) in Egypt from 1990 to 2021, (CBE, 2023 and WBDI, 2023).

3.2. Unit root test with Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP)

Unit root tests, such as the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests, are crucial in determining the stationarity of time series data. These tests are essential in determining the order of integration of each variable before proceeding with Autoregressive

Distributed Lag (ARDL) modeling.

Table 3 presents the results of this study's ADF and PP unit root tests. It reveals that all variables are stationary at the first difference, except for HDI, which achieves stationarity at I (0) according to both tests. Thus, the results indicate that the null hypothesis is rejected for all variables, confirming their stationarity and fulfilling the ARDL modeling requirement for the series to be I (0) or I (1). Following the stationarity assessment, an appropriate lag order was chosen for the ARDL model, considering the sensitivity of the F-test to the lag order. previous studies, such as those by Abbasi et al. (2021), suggest that the ADF should be analyzed under the unit root null hypothesis. The null hypothesis for the ADF unit root, applicable to nearly all variables, cannot be rejected at the I(0) level unless it is dismissed at the first or second I(1) difference, as shown in Table 3. Consequently, all data series are integrated of order one and at level, allowing ARDL bounds to cointegrate.

Table 3. Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) stationary tests

| ADF test | | | | | | |
|------------------------|--------------|----------------------------|---------------------|----------------------------|-------------|----------------------------|
| Variables | Intercept | | Intercept and trend | | None | |
| | Level | 1 st difference | Level | 1 st difference | Level | 1 st difference |
| ΔLnCO_2 | -1.184628 | -4.632531*** | - | - | 3.948902*** | -3.269496*** |
| ΔLnGDP | -0.109283 | -6.472589*** | - | - | 4.374165*** | -2.020551*** |
| ΔLnHDI | - | -7.204513*** | 0.085319 | - | - | -1.451800 |
| | 4.667047*** | | | 5.418984*** | 5.506468*** | |
| PP test | | | | | | |
| Variables | Intercept | | Intercept and trend | | None | |
| | Level | 1 st difference | Level | 1 st difference | Level | 1 st difference |
| ΔLnCO_2 | -1.218302 | -4.557969*** | - | - | 3.726898*** | -3.206446*** |
| ΔLnGDP | -0.123791 | -6.387727*** | - | - | 4.333042*** | -4.438665*** |
| ΔLnHDI | -3.387158*** | -7.378208*** | - | - | - | -4.657234*** |
| | | | 0.998247 | 14.29196*** | 8.244459*** | |

Note: (1) The unit root test was performed for individual intercepts, trends, and intercepts, and none were found for each variable. (2) The lag lengths were selected automatically using the Akaike information criterion (AIC). (3) $\Delta \text{Ln GDP}$; $\Delta \text{Ln CO}_2$; $\Delta \text{Ln HDI}$: are the natural logarithmic forms of Egypt's gross domestic product, carbon dioxide emissions, and Human Development Index, respectively. (4) *** designate the significance level of 1%. *Source:* Authors' estimation using E-Views 12.

3.3. ARDL bound test for cointegration and the diagnostic tests

Following the stationarity assessment, we conducted the ARDL bounds test to evaluate the presence of cointegration among the variables. The F-test was performed using an optimal lag length determined by the lowest Akaike Information Criterion (AIC) values, ensuring the most efficient model specification. The results of the ARDL bounds test, as presented in Table 4, indicate that cointegration exists when $\Delta \ln \text{CO}_2$ is treated as the dependent variable. Specifically, the F-statistic for the relationship $\Delta \ln \text{CO}_2 = f(\Delta \ln \text{GDP}, \Delta \ln \text{HDI})$ exceeds the critical values at 5% and 10% significance levels, surpassing the I(1) threshold. This suggests a long-run relationship exists among these variables when CO_2 emissions are the focus. Conversely, no cointegration is observed when $\Delta \ln \text{GDP}$ and $\Delta \ln \text{HDI}$ are considered dependent variables.

The ARDL bounds test involves comparing the calculated F-statistic against the critical values. If the F-statistic exceeds the lower and upper bounds, it indicates the presence of a long-run relationship among the variables. In this analysis, the estimated F-value (14.8) surpasses the critical upper values at 10% and 5% significance levels, rejecting the null hypothesis of no cointegration. This finding supports a long-run relationship among CO_2 emissions, GDP, and HDI. This finding is consistent with the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between environmental degradation and economic growth (Grossman and Krueger, 1991; Panaiotov, 1993). The EKC hypothesis suggests that environmental degradation initially increases with economic development but eventually decreases as income levels rise beyond a certain threshold due to increased environmental awareness and the adoption of cleaner technologies (Kijima et al., 2010; Pesaran et al., 2001).

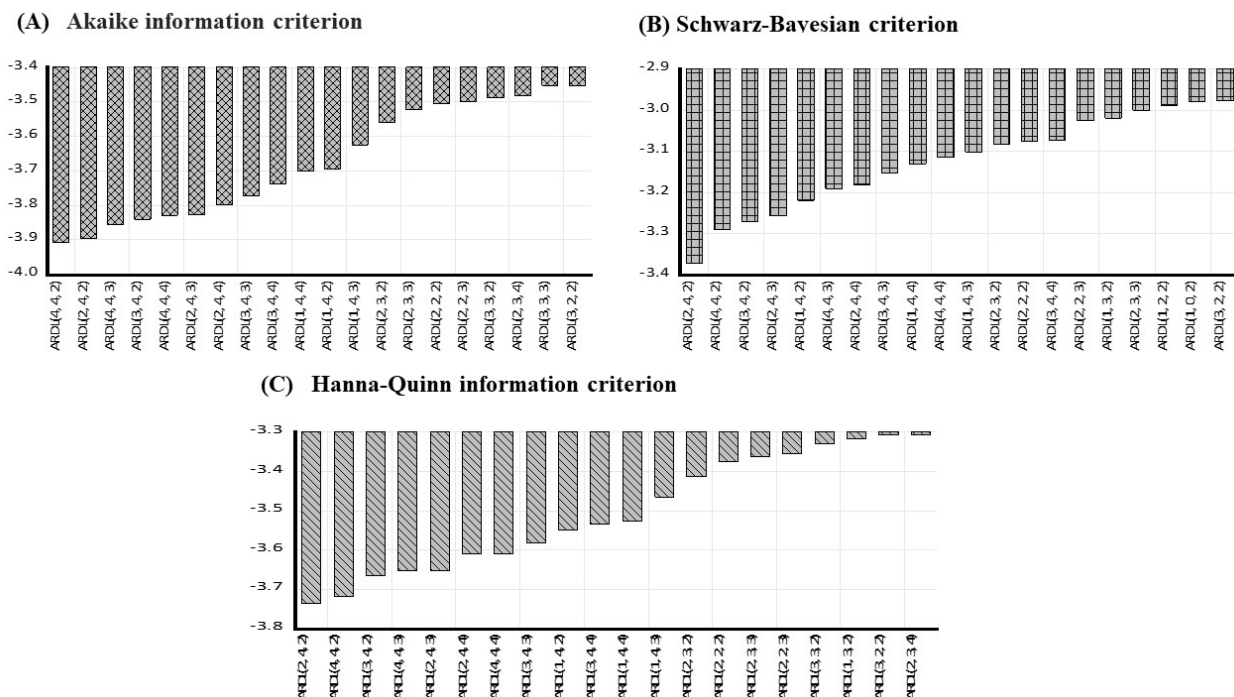


Fig. 4. Lag selection criteria for Autoregressive Distributive Lag (ARDL) model using Akaike information criterion (AIC), Schwarz Bayesian criterion (SBC), and Hanna-Quinn information criterion (HQC), (CBE, 2023 and WBDI, 2023).

Table 4. ARDL bound test for co-integration

| F-bounds test | | Null hypothesis: No degrees of relationship | | |
|----------------|------------|---|-------|-------|
| Test statistic | Estimate | Significance | I (0) | I (1) |
| F-statistic | 14.81972** | At 10% | 3.17 | 4.14 |
| K | 2 | At 5% | 3.79 | 4.85 |
| | | At 1% | 5.15 | 6.36 |

Note: (1) Lower critical bound (I (0)); upper critical bound (I (1)). (2) At the 1%, 5%, and 10% significance levels, the rejection of the null hypothesis of no-level relationship is indicated by **. *Source:* Authors' estimation using E-Views 12.

To ensure the validity of the ARDL model, various diagnostic tests were conducted, which are shown in Table 5. These included the Durbin-Watson (DW) statistic for serial correlation, the Lagrange Multiplier (LM) test for serial correlation, the ARCH test for autoregressive conditional heteroskedasticity, tests for heteroscedasticity, and the CUSUM and CUSUM-Squared tests for model stability. The results of these tests indicate no serial correlation or heteroscedasticity in the model, confirming that the model is correctly specified.

Table 5. Diagnostic test outcomes

| Diagnostic tests | F-statistic | T-statistic | P value | Obs* R-squared | P value | Decision |
|------------------------------|-------------|-------------|---------|----------------|---------|---|
| Ramsey Reset Test | 12.63 | 3.55 | 0.0032 | - | - | No linear relationship exists |
| Serial correlation LM | 0.37 | - | 0.69 | 1.53 | 0.46 | No serial correlation exists |
| ARCH Test | 0.76 | - | 0.39 | 0.79 | 0.37 | There is no evidence of heteroscedasticity. |
| Heteroskedasticity test | 0.37 | - | 0.95 | 6.46 | 0.89 | The model is properly specified |
| Jarque-Bera test | | | | | | Residuals are normally distributed |
| Theil Inequality Coefficient | | | 0.002 | | | A strong correlation |
| Bias Proportion | | | 0.000 | | | between the model's |
| Variance Proportion | | | 0.000 | | | anticipated and actual |
| Covariance Proportion | | | 0.99 | | | values. |
| CUSUM | | | | | | Model is stable |
| CUSUM-Square | | | | | | Model is stable |

Source: Authors' estimation using E-Views 12.

The absence of cointegration when $\Delta \ln \text{GDP}$ and $\Delta \ln \text{HDI}$ are considered as dependent variables suggests that these variables do not have a long-run equilibrium relationship with CO_2 emissions in this context. However, the presence of a long-run relationship when CO_2 emissions are the focus indicates that economic growth and human development can influence CO_2 emissions over time, aligning with the EKC hypothesis.

The stability of this relationship is further supported by the absence of serial correlation and heteroscedasticity in the model, as confirmed by various diagnostic tests. This stability implies that deviations from the long-run equilibrium are self-correcting, suggesting a robust

and sustainable relationship between these variables.

The findings of this study contribute to the broader literature on the EKC hypothesis, which has been extensively explored in various contexts (Ansari et al., 2021; Balsalobre-Lorente et al., 2021; Biyase et al., 2024; Bradford et al., 2005; Lorente et al., 2021). The use of ARDL bounds testing to establish cointegration is consistent with the approach outlined by Pesaran et al. (2001), which is suitable for analyzing relationships between variables with mixed orders of integration.

3.3.1. Short-run and long-run relationships

Two steps were taken to establish the long-term relationship in the analysis. First, the optimal lag order for the model was determined using the AIC, as highlighted by Pesaran et al. (2001). Second, the ARDL model assessed the current framework, demonstrating that GDP and HDI are significant long-term predictors of Egypt's CO₂ emissions. We then explored the long-term elasticity of demand and the ECM, utilizing results based on the ideal rank ($r = 1$). Table 6 presents the long- and short-run analyses based on standardized coefficients for CO₂ emissions.

The optimal lag length was (4, 4, 2) based on the AIC criteria, as shown in Figure 4. Table 5 provides the long-term coefficients measured by the ARDL, along with standard errors and significance levels. The long- and short-term t-ratios for GDP and HDI elasticities have also been updated. The findings indicate that in the long term, a 1% increase in GDP leads to a 0.24% rise in CO₂ emissions, while in the short term, the increases are 0.24%, 0.20%, and 0.23% at lags of 1, 2, and 3, respectively, all statistically significant at the 1% level. This suggests that fluctuations in CO₂ emissions are closely linked to GDP fluctuations, indicating that Egypt's GDP growth significantly influences CO₂ emissions faster than the average for similar countries (Chindo et al., 2014; Muhammad and Khan, 2019).

Egypt's CO₂ emissions have increased with GDP growth, largely due to heavy dependence on fossil fuels, as supported by Rashdan and Ibrahim (2024a). Over the last decade, coal consumption has risen significantly, greatly impacting the country's carbon footprint as projected by Timilsina and Sebsibie (2024). Although there are commitments to renewable energy, coal still constitutes 90% of energy production as approved by Morgado Simões and Stanicek (2022). In 2020, natural gas emerged as Egypt's primary energy source, accounting for 33.7% of the total energy supply (Statista, 2022).

Furthermore, our results show that HDI positively impacts carbon emissions in both the long term (5.24) and the short term (1.8). Specifically, a 1% increase in HDI is associated with a 5.24% rise in CO₂ emissions in the long term and a 1.8% increase in the short term, both statistically significant at the 1% level. This finding is consistent with some studies that argue higher levels of human development can initially lead to greater environmental degradation due to increased energy consumption and industrial activities (Sallam et al., 2022). However, it contrasts with other research suggesting no direct relationship between HDI and CO₂ emissions or proposing varying dynamics depending on economic conditions (Ritchie et al., 2022). Conversely, at lag 1, HDI shows a negative and statistically significant effect on CO₂ emissions. The analysis of the ECT_{t-1} variable indicated a negative value, statistically significant at the 1% level in the short term. This suggests that if any effects in the model could be adjusted through the adjustment process, the long-term equilibrium speed should adjust by 1.03.

Table 6. Estimated outcomes for both short- and long-run ARDL

| Selected Model: ARDL (4,4,2) | | | | |
|-------------------------------------|-------------|------------|----------------------|---------|
| Variable | Coefficient | Std. Error | T-statistic | P value |
| C | 7.86 | 1.46 | 5.37** | 0.00 |
| $\Delta \text{LnCO}_2_{(-1)}$ | 1.03 | 0.23 | (4.45)** | 0.00 |
| $\Delta \text{LnGDP}_{(-1)}$ | 0.24 | 0.04 | (0.98) | 0.34 |
| $\Delta \text{LnHDI}_{(-1)}$ | 5.24 | 0.96 | 5.48** | 0.00 |
| Short-run estimation | | | | |
| $\Delta(\text{LnCO}_2_{(-1)})$ | 0.52 | 0.13 | 3.97** | 0.00 |
| $\Delta(\text{LnCO}_2_{(-2)})$ | 0.02 | 0.17 | 0.13 | 0.90 |
| $\Delta(\text{LnCO}_2_{(-3)})$ | 0.36 | 0.17 | 2.08* | 0.05 |
| $\Delta(\text{LnGDP})$ | -0.06 | 0.05 | (1.17) | 0.25 |
| $\Delta(\text{LnGDP}_{(-1)})$ | 0.24 | 0.05 | 4.72** | 0.00 |
| $\Delta(\text{LnGDP}_{(-2)})$ | 0.20 | 0.06 | 3.29** | 0.00 |
| $\Delta(\text{LnGDP}_{(-3)})$ | 0.23 | 0.07 | 3.58** | 0.00 |
| $\Delta(\text{LnHDI})$ | 1.08 | 0.56 | 1.93 | 0.07 |
| $\Delta(\text{LnHDI}_{(-1)})$ | -4.03 | 0.76 | (5.30)** | 0.00 |
| CointEq(-1) | -1.03 | 0.15 | (7.10)** | 0.00 |
| <hr/> | | | | |
| F-statistic | 298.46** | | Sum Squared Residual | 0.01 |
| R ² | 0.99 | | Log Likelihood | 67.72 |
| R ⁻² | 0.99 | | DW | 1.61 |
| S.E. of Regression | 0.03 | | Schwarz Criterion | -3.29 |
| Akaike Criterion | -3.91 | | S.D. Dependent | 0.34 |
| Hannan-Q Criterion | -3.72 | | | |

Note: (1) The Lag selection criteria for the Autoregressive Distributive Lag (ARDL) model using the Akaike information criterion (AIC). (2) $\Delta \text{Ln GDP}$; $\Delta \text{Ln CO}_2$; $\Delta \text{Ln HDI}$: are the natural logarithmic forms of Egypt's gross domestic product, carbon dioxide emissions, and Human Development Index, respectively. (3) ** designate the significance level of 1%. **Source:** Authors' estimation using E-Views 12.

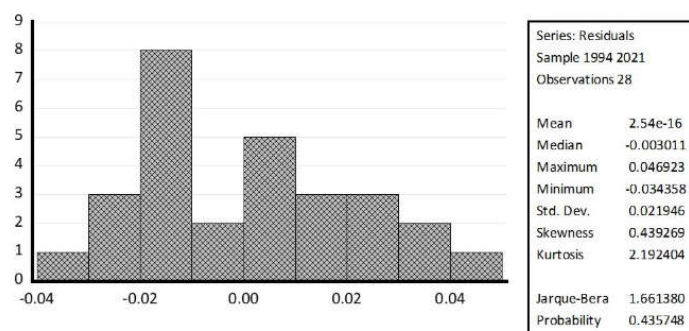


Fig. 5. Jarque -Bera: Normality Test, (CBE, 2023 and WBDI, 2023).

Table 6 displays the estimates for CO₂ emissions, GDP, and HDI derived from the ECM representation of the ARDL (4, 4, 2) model. At the 1% significance level, CO₂ emissions, GDP,

and HDI are statistically significant, indicating both long- and short-term causation in that direction. Tables 5 and 6 also include analytical estimations (F-value, R^2 , DW statistics, serial correlation LM, ARCH, heteroscedasticity, CUSUM, and CUSUM-Squared), confirming that the model is accurately specified according to tests for serial correlation, heteroscedasticity, and normality.

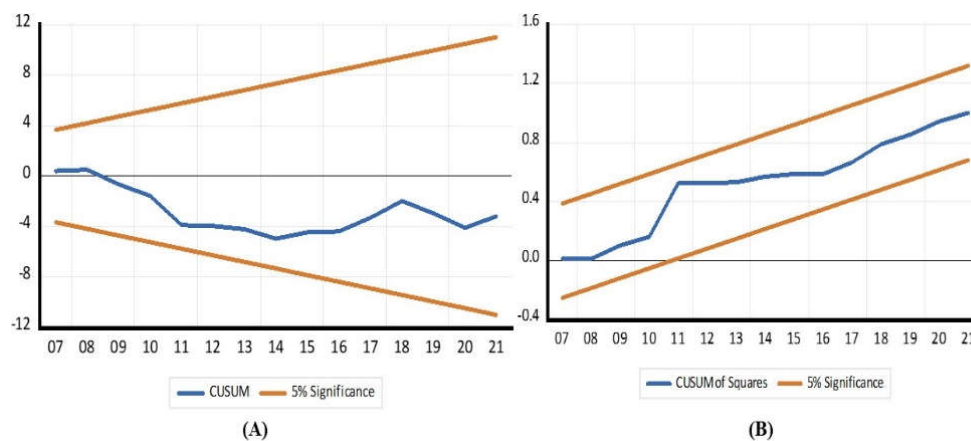


Fig. 6. Stability test: CUSUM and CUSUM of square test, (CBE, 2023 and WBDI, 2023).

The stability of the model is assessed through the CUSUM and CUSUM-Squared tests, presented in Fig. 6. This aligns with findings from various studies, including Abokyi et al. (2019). The purpose of Fig. 6 is to evaluate the structural stability of the model, which is confirmed by the curve remaining within the 95% critical bounds. This stability suggests that the current model is reliable and suitable for making further policy recommendations. In addition, the Jarque-Bera test shown in Figure 5 indicates a value of 1.66 with a p-value of 0.43, reinforcing the conclusion that the residuals are normally distributed. Furthermore, Figure 7 displays the Forecast Performance Test results, confirming the model's effectiveness and robustness.

3.4. Pairwise Granger causality analysis

The analysis of pairwise Granger causality is comprehensively illustrated in Table 7 and Figure 8, including the direction of causality among the variables. The F-statistic confirms the presence of Granger causality, indicating a unidirectional causal relationship that flows from left to right. Specifically, the pairwise Granger causality test shows unidirectional causality from GDP to CO₂ emissions and from GDP to HDI, with statistical significance leading to the rejection of the null hypothesis. This finding aligns with Al-Mulali et al. (2015) and Shahbaz et al. (2013). Both studies demonstrate that rising GDP increases CO₂ emissions due to industrialization and energy consumption. This brings out a causal link between economic growth and environmental degradation in developing countries like Egypt.

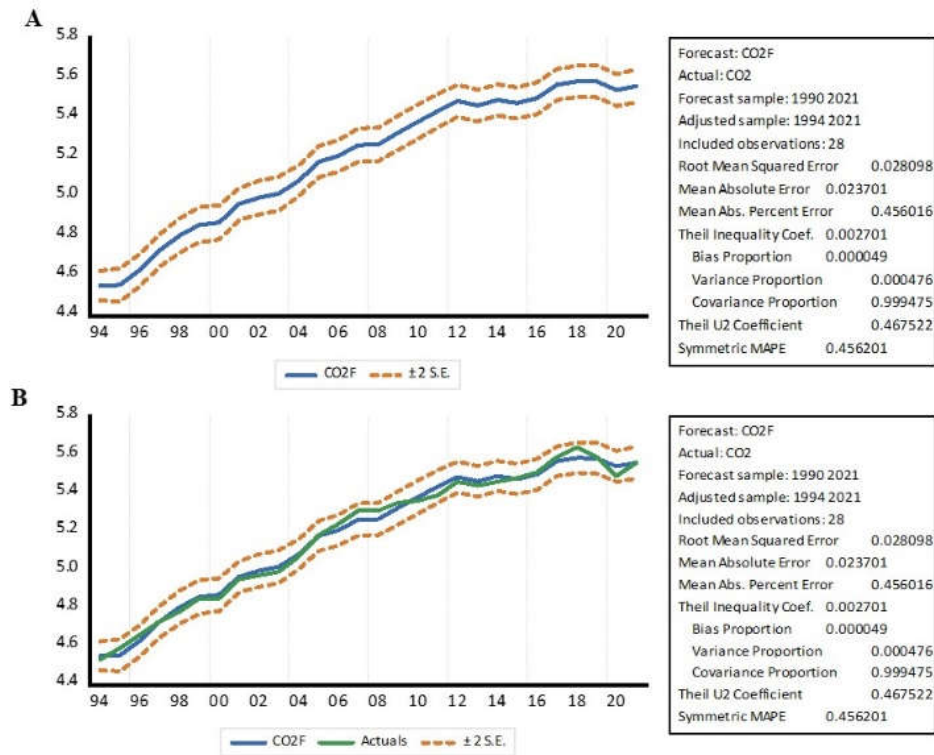


Fig. 7. Forecast performance test for prediction of CO₂ emissions in Egypt from 1990 to 2021, (CBE, 2023 and WBDI, 2023).

Table 7. The outcomes of the pairwise Granger causality test

| Dependent Variable | Direction of Causality | | |
|--------------------|-----------------------------|---------------------|--|
| | Short-Run Granger Causality | | Long-Run Granger Causality |
| | F-statistic | | t-statistic |
| | ΔCO_2 | ΔGDP | ΔHDI |
| | | | E_{t-1} |
| ΔCO_2 | | 3.29095** (0.03) | -0.042902** -2.451958** (0.0291) |
| ΔGDP | | | |
| ΔHDI | | 3.06104** (0.04) | |

Note: ** designate the significance level of 5%. Source: Authors' estimation using E-Views 12.

The unidirectional causality from GDP to HDI also suggests that economic growth boosts human development by increasing education, healthcare, and innovation resources. Apergis and Payne(2010) also reported similar findings, noting that GDP growth positively affects HDI in emerging economies.

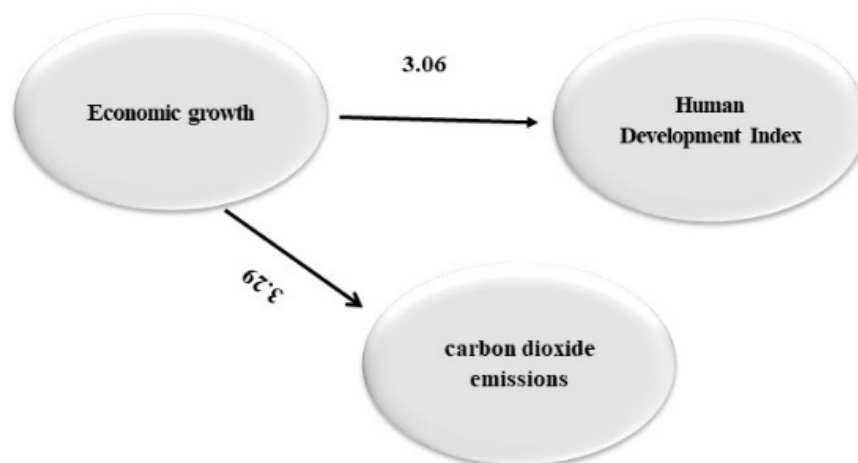


Fig. 8. Granger causality relationship between the factors.

Finally, Table 6 indicates that the signs of $\Delta \ln \text{GDP}$ and $\Delta \ln \text{HDI}$ align with theoretical expectations. The statistical evidence shows that CO_2 emissions are associated with increasing GDP levels over the years, while HDI is declining. The long- and short-run relationships between CO_2 emissions and the variables in this analysis are consistent with findings from previous studies (Ali et al., 2020; Rehman et al., 2021; Zmami et al., 2021).

Given Egypt's heavy reliance on fossil fuels, the methodology employed here adapts a traditional carbon emission model to suit Egypt's specific context. The results suggest that GDP is a more significant predictor of CO_2 emissions than HDI. Since 2000, Egypt has experienced a GDP growth rate of 5.5%, alongside a similar increase in HDI, despite a total fossil fuel consumption rise of 6.3% in 2020 (World Energy, 2020). Consequently, the findings indicate limited connections between oil and gas usage across sectors such as industry, agriculture, transportation, and government and national income levels. This is attributed to the essential role that oil and gas play in the manufacturing processes of various industries (EIA, 2024; IRENA, 2023). By implementing these policies, Egypt can mitigate the environmental impact of its economic growth and human development, transition to a low-carbon economy, and achieve its sustainable development goals. Continuous monitoring and evaluation of these policies are essential to ensure their effectiveness and make necessary adjustments over time.

4. Conclusion and policy implication

In recent decades, the world has witnessed a significant increase in CO_2 emissions, largely driven by rising energy demands associated with global economic and social development. This study investigates the complex interplay between economic growth, human development, and environmental degradation in Egypt, focusing on CO_2 emissions. By employing the Autoregressive Distributed Lag (ARDL) model, we analyze the impact of Gross Domestic Product (GDP) and the Human Development Index (HDI) on carbon emissions from 1990 to 2021. Our findings from the ARDL bounds test confirm long-term cointegration among CO_2 emissions, GDP, and HDI. Our results indicate that economic growth (GDP) and human development (HDI) improvements are linked to increased CO_2 emissions. This supports the Environmental Kuznets Curve hypothesis, suggesting that effective economic development

can lead to better environmental outcomes.

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