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Growth and the Environment in Sudan: Myth or Reality of the EKC Hypothesis?

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ABSTRACT

The link between economic development and environmental outcomes has become increasingly evident. The study examines how economic growth influences environmental degradation in Sudan, using annual time series data spanning 1980-2022. The analysis accounts for potential structural breaks in unit root and cointegration testing. An Autoregressive Distributed Lag model is employed to assess the long-run relationship. The Environmental Kuznets Curve hypothesis is evaluated using three different approaches. Findings indicate that the EKC does not hold in the case of Sudan. The results suggest that, as developing a country, Sudan's income level remains below the threshold at which economic growth would start to reduce environmental harm. The study also highlights the significant impact of energy consumption on the country's carbon emissions. To address these challenges, robust and well-enforced environmental policies are recommended to mitigate the adverse effects of future generations.

Keywords: Economic Growth, Environment Degradation, EKC, Carbon Footprint, ARDL
JEL Classifications: Q56, Q53, C32, O13

1. INTRODUCTION

Many countries around the world are witnessing an overall increase in the growth rates of their real gross domestic product (GDP). Mostly, the increment of economic activities in different countries comes at the cost of environmental degradation (Bashir et al., 2022). The accumulation of greenhouse gas emissions has resulted in unprecedented heat waves, temperature rise and ocean acidification, frequent and extreme rainfall, and the rise of average sea level (Petrović and Lobanov, 2020; Ren et al., 2023). In particular, the expansion of any economy starts initially with the transformation from the primary activities to some degree of industrialization, where various natural resources are used as inputs for production. The intensive use of raw materials in production or even consumption processes involve releasing by-products or what is known as residuals to nature, which most of them are harmful to human health and ecology (Callan and Thomas, 2013). Therefore, economic activities, particularly natural resources exploitation, are widely regarded as a major factor driving environmental pollution causing severe global warming and climate change (Devi and Gupta, 2019). Some reports estimated that approximately 95% of global warming is attributed to human behavior towards natural environment (Mongo et al., 2021), largely since 92% of global carbon dioxide emissions originate from burning fossil fuels (Perone, 2024). On the other hand, a notable group of theorists argue that human influence on climate change is minimal. They support the natural cycle theory, which asserts that climate change is a fundamental part of Earth's natural fluctuations, with changes in temperature resulting from factors such as shifts in the planet's orbit, sporadic volcanic activity across different regions, and solar cycles (Kocak and Alnour, 2022). However, this viewpoint is increasingly challenged by empirical evidence. For example, during the COVID-19 lockdowns, reduced energy use led to a significant drop in carbon emissions—levels not observed in nearly a century (EIA, 2021). Yet, with the partial economic rebound in 2021, global greenhouse gas emissions increased by around 4% compared to the previous year (IEA, 2022). Since then, global CO_2 emissions from energy use have continued to rise, reaching a record 37.4 billion tons (Gt) (IEA, 2023). Consequently, unless the heavy dependence on fossil fuels is curbed, carbon emissions will keep intensifying global warming challenges (He et al., 2022; Jiang et al., 2019).

Theoretically, Environmental Kuznets Curve (EKC) has been widely used as a theoretical underpinning for the nexus between economic activities and environmental deterioration. For decades, beginning with the pioneering work of Kuznets (1955) and later expanded by Grossman and Krueger (1995), the EKC hypothesis has served as a central framework in exploring the link between economic growth and environmental degradation, particularly in the search for sustainable development strategies (Awan et al., 2022). The EKC theory initially posits that in the early stages of economic development, environmental quality tends to decline due to increased pollution and waste, driven by the demand for more resources, a phenomenon known as the scale effect. However, as income levels rise and economies advance, a turning point is reached where environmental conditions begin to improve. This phase is attributed to structural changes in the economy and the adoption of cleaner technologies, referred to as the composition and technique effects (Ulucak and Bilgili, 2018), forming an inverted U-shaped relationship. Nevertheless, some scholars have argued that when the capacity for innovation diminishes, a "technological obsolescence effect" may emerge. This effect can overshadow the benefits of cleaner technologies, potentially leading to increased pollution once again and forming an N-shaped curve (Lorente and Alvarez-Herranz, 2016). This concern has prompted numerous researchers to investigate alternative shapes and dynamics beyond the traditional EKC model, as discussed by Gyamfi et al. (2021), Sterpu et al. (2018), and Zeraibi et al. (2022).

Recently, large number of studies have investigated the association between economic growth and environmental degradation under the EKC framework. Despite the valuable research outcomes, we report several literature shortcomings. First, voluminous research has been primarily confined to developed and industrial economies, while the natural resources-based economies such as Sudan have been widely ignored in the relevant literature. (Kassouri, 2021) claimed that, unlike industrial nations, developing and natural resources-based economies are still the first stage of development. Thus, testing the EKC farmwork for developing economies allows them to evaluate their environmental regulations and the outcomes of green growth projects. Second, prior studies have extensively relied on carbon dioxide (CO_2 hereafter) emissions as an indicator of environmental degradation, which contributes only a part of the total environmental damage (Uddin et al., 2017). Another comprehensive measure for environmental degradation is the carbon footprint (CFP hereafter). For instance, Liu and Lai, (2021) validated the EKC hypothesis by tracing the CFP of waste imports, making it an essential indicator of environmental degradation. Third, majority of the studies that examined the EKC hypothesis using the conventional approach suffer from methodological weaknesses. In particular, many studies have relied on GDP and its squared term to evaluate the EKC hypothesis, which often leads to econometric issues such as multicollinearity and model misspecification, as highlighted by Stern (2004). Additionally, using a quadratic or polynomial term in models involving integrated time series can be problematic if these terms are not properly integrated, as noted by Wagner (2015). To address these shortcomings, Narayan and Narayan (2010) proposed an alternative framework that distinguishes between long-run and short-run elasticities of GDP when testing the EKC. Brown and McDonough (2016), however, raised concerns about this methodology and advocated for a third approach that directly assesses whether the ECK relationship holds.

This study contributes to the empirical literature on the EKC by adopting a different perspective. It uses carbon footprint per capita as the indicator of environmental degradation in Sudan, covering annual data from 1980 to 2022. Furthermore, the analysis employs three distinct estimation techniques to enhance the robustness of the findings. The Autoregressive Distributed Lag (ARDL hereafter) model developed by Pesaran et al. (2001) is used to test for cointegration. Crucially, the study also accounts for potential structural breaks that may have occurred over the sample period by incorporating appropriate unit root and cointegration tests (Perron, 1997; Lee and Strazicich, 2003; Gregory and Hansen, 1996; Hatemi-j, 2008). As far as we are aware, this study is one of the few to explore the relationship between economic growth and environmental degradation in Sudan, and the first to employ three distinct methodological approaches.

The reminder of the paper is organized as follows. Section 2 shows the review of important literature. Section 3 explains the research methods and data. Section 4 presents the results and discussion. Section 5 provides the conclusion of the paper.

2. LITERATURE REVIEW

According to Grossman and Krueger's (1995) EKC hypothesis there exists an inverted U-shaped relationship between economic growth and environmental degradation. At the initial level of economic development, the increase in economic activities lead to worsening environmental degradation, but it improves environmental quality eventually (Uddin et al., 2017).

Over past decades, several empirical studies have been done to verify the validity of the growth–environment relationship as postulated by the EKC hypothesis (Lau et al., 2025). Numerous empirical investigations have assessed the EKC hypothesis across various countries by applying diverse econometric methods. Nonetheless, the findings from these studies remain inconsistent and do not offer definitive conclusions. For example, Özokcu and Özdemirb (2017) analyzed how per capita income related to CO_2 emissions under two distinct scenarios. The first scenario focused on 26 high-income OECD nations over the period 1980–2010, where panel data results indicated an inverted N-shaped relationship, contradicting the EKC. The second scenario examined 52 emerging economies over the same timeframe, with findings supporting an N-shaped patter, further suggesting that EKC does not hold. Although Sirag et al. (2018) revealed the existence of EKC hypothesis in developed economies, however, the hypothesis was not true in the sample of developing countries. Their findings indicate a strong link between countries' income level and environment degradation.

Previous research has explored various dimensions of the EKC hypothesis in diverse contexts. For instance, Bölük and Mert (2015) analyzed both the short-term and long-term dynamics linking CO_2 emissions, income levels, and renewable electricity generation in Turkey, covering the years 1961 to 2010. Similarly, Ahmad et al. (2017) assessed whether the EKC pattern holds in Croatia over the period 1992-2011. Dogan and Inglesi-Lotz (2020) focused on how the economic structure of European nations influences the validity of the EKC within those economies. Furthermore, Destek and Sarkodie (2019) investigated how inflows of foreign direct investment, economic progress, and patterns of energy use contribute to sectoral greenhouse gas emissions across developing countries. Moreover, Kearsley and Riddel (2010) tested the EKC in 27 OECD member countries. Kacprzyk and Kuchta (2020) analyzed data from a panel of 161 countries over the years 1992-2012 to determine whether fossil fuel-related CO_2 emissions follow an inverted U-shaped trajectory as income levels change. Furthermore, Moutinho et al. (2017) checked the validity of the EKC in Portugal and Spain. Sarkodie and Ozturk (2020) assessed whether the ECK framework holds in Kenya by incorporating measures of energy efficiency and consumption. Likewise, Hanif and Santos (2017) analyzed data from 86 developing nations between 1972 and 2011 to evaluate the hypothesis. Chen and Taylor (2020) explored the applicability of the EKC concept in the context of Singapore, while Ullah and Khan (2020) conducted a comparable investigation focused on Pakistan. Collectively, these studies found evidence supporting an inverted U-shaped linkage between per capita income and environmental degradation, as indicated by CO_2 emissions.

While CO_2 emissions are commonly employed as a proxy for environmental degradation, it does not incorporate all aspects of the environment since it does not take into consideration pollutants such as soil, forestry, fishing and oil stock (Solarin and Bello, 2018). An essential part of the Ecological Footprint Account is the carbon footprint of all forms of fossil fuel uses. Accordingly, this study adopts carbon footprint alongside real GDP per capita as key variables to analyze how economic growth interacts with environmental degradation in the context of Sudan. Recent studies (e.g., Al-Mulali et al., 2015; Ulucak and Lin, 2017; Yilanci and Ozgur, 2019; Dogan et al., 2020; Altıntaş and Kassouri, 2021) have argued that the ecological footprint provides a more comprehensive metric for assessing environmental degradation. The ecological footprint was introduced to measure the extent of resource use and waste production resulting from human economic activities, and relate these pressures to the Earth's ability to regenerate resources and assimilate the resulting waste (Charfeddine and Mrabet, 2017). In a related analysis, Mohamed et al. (2024) revisited the EKC hypothesis by including the role of renewable energy generation in influencing both CO_2 emissions and the ecological footprint in Malaysia, applying time series econometric techniques. Their findings confirmed the presence of an inverted U-shaped relationship and highlighted the important contribution of renewable energy in mitigating emissions.

In general, the empirical econometrics testing procedures of the EKC hypothesis can be divided into three approaches.[1] First, the conventional approach that involves the use of the GDP and its polynomial term(s). Second, Narayan and Narayan (2010) suggested using the long-term and short-term income elasticities. Third, Brown and McDonough (2016) recommended using the de-meaned values of the logarithm of the real GDP and its square term. Among all the previous studies some have given attention to the shortcomings of the estimation approaches (e.g., Stern, 2004; Narayan and Narayan, 2010; Mrabet et al., 2017; Sirag et al., 2018). For example, Sirag et al. (2018) attempted to address the methodological issue by using a non-linear estimation technique of the dynamic panel threshold. While, Mrabet et al. (2017) used the ecological footprint as a measure for the environment, and relied on the Narayan and Narayan (2010) suggested procedure to test for the EKC hypothesis. Nevertheless, Brown and McDonough (2016) argued that the long- and the short-run elasticities are not indicative of the shape of the EKC. To large extent, the outcomes of the EKC literature were contingent on the measurement used for the environmental outcomes, on the one hand, and the empirical approach adopted to test for the EKC hypothesis, on the other hand. Using the approach suggested by Brown and McDonough (2016) would help filling the gap in the literature. Most of the EKC studies have relied on only one approach in examining the EKC hypothesis and the combination of the three testing procedures may be a valuable contribution to the existing studies.

3. METHODOLOGY

3.1. Model Specification and EKC Testing Approaches

The conventional empirical methodology of the EKC hypothesis involves using the GDP and its polynomial or quadratic term. To test the EKC via the conventional approach, the empirical model may be specified as follows:

$$lnCFP_t = \beta_0+\beta_1 lnGDP_t+\beta_2 lnGDP_t^2+\beta_3 TO_t+\beta_4 lnEC_t+\varepsilon_t \tag{1}$$

where *CFP* is the carbon foot print, *GDP* is the real GDP, *TO* is trade as a percentage of GDP, and *EC* is primary energy consumption per capita, respectively, and β_1, β_2, β_3, β_4 are their long-run elasticities, while ε is the error terms of equation (1). All the variables are transferred to the natural logarithm, except *TO* which is measured in terms of GDP ratio. For the EKC to hold, both β_1 and β_2 are expected to be statistically significant, but the former is positive and the later is negative.

The alternative EKC approach proposed by Narayan and Narayan (2010) comprises the estimation and comparison of the long-run and short-run GDP elasticities of GDP. To test the EKC hypothesis based on the idea of Narayan and Narayan the following model is specified as:

$$lnCFP_t = \alpha_0+\alpha_1 lnGDP_t+\alpha_2 TO_t+\alpha_3 lnEC_t+e_t \tag{2}$$

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[1] Some studies used other techniques such panel threshold (for example, Sirag et al., 2018).

where variables are defined in equation (1), and α_1, α_2, α_3 are their long-run elasticities, while *e* is the error terms of equation (2). All the variables are transferred to the natural logarithm, except *TO* ratio of GDP. As we can see, the GDP squared term is excluded from the model and alternatively the coefficients of the long-run and short-run will be compared to make a decision regarding the existence of the EKC.

However, the ECK hypothesis can be empirically tested using another approach recommended by Brown and McDonough (2016). To address the issue of strong multicollinearity among the polynomial terms, the logarithmic real GDP series is adjusted by subtracting it from the mean. This adjusted variable is subsequently employed to derive the quadratic component. Applying the Brown and McDonough (2016) methodology, the EKC is evaluated through the following empirical specification:

$$lnCFP_t = \beta_5 + \beta_6(lnGDP_t - \overline{lnGDP}) + \beta_7(lnGDP_t - \overline{lnGDP})^2 + \beta_8 TO_t + \beta_9 lnEC_t + u_t \qquad (3)$$

where $(lnGDP_t - \overline{lnGDP})$ and $(lnGDP_t - \overline{lnGDP})^2$ represent the mean-adjusted values of GDP and its squared term, while β_6, β_7, β_8, β_9 denote the estimated long-run elasticities. The closer the term $(lnGDP_t - \overline{lnGDP})$ to zero in the absolute value, the weaker the linear association between $(lnGDP_t - \overline{lnGDP})$ and it square; conversely, as this term moves away from zero, the linearity strengthens. In order to judge whether the EKC hold or not, the inferences should be on based on the joint significance of $\hat{\beta}_6$ and $\hat{\beta}_7$, as both have to be significantly different and the former should be positively signed and the latter is negative. More importantly, the turning point of the real GDP is calculated as

$$\tau = e^{-\frac{\hat{\beta}_6}{2\hat{\beta}_7} + \overline{lnGDP}}$$

where τ is the income turning point, *e* refers to the exponential function, and $\overline{GDP}$ is the mean value of the real GDP. Note that the estimation of the turning point is meaningful when both polynomials' coefficients are significant.

3.2. Method of Estimation (ARDL)

To examine the existence of the EKC in Sudan, the study uses ARDL according to Pesaran et al. (2001). Investigating the existence of cointegration relationship among the variables in equations (1), (2), and (3) requires using the unrestricted error correction models as follow:

$$\Delta lnCFP_t = \delta_0 + \delta_1 lnCFP_{t-1} + \delta_2 lnGDP_{t-1} + \delta_3 lnGDP^2_{t-1} + \delta_4 TO_{t-1} + \delta_5 lnEC_{t-1} + \sum_{i=1}^{q}\delta_6 \Delta lnCFP_{t-i} + \sum_{i=0}^{p}\delta_7 \Delta lnGDP_{t-i} + \sum_{i=0}^{p}\delta_8 \Delta lnGDP^2_{t-i} + \sum_{i=0}^{p}\delta_9 \Delta TO_{t-i} + \sum_{i=0}^{p}\delta_{10} \Delta lnEC_{t-i} + \mu_t \qquad (4)$$

$$\Delta lnCFP_t = \gamma_0 + \gamma_1 lnCFP_{t-1} + \gamma_2 lnGDP_{t-1} + \gamma_3 TO_{t-1} + \gamma_4 lnEC_{t-1} + \sum_{i=1}^{q}\gamma_5 \Delta lnCFP_{t-i} + \sum_{i=0}^{p}\gamma_6 \Delta lnGDP_{t-i} + \sum_{i=0}^{p}\gamma_7 \Delta TO_{t-i} + \sum_{i=0}^{p}\gamma_8 \Delta lnEC_{t-i} + \nu_t \qquad (5)$$

$$\Delta lnCFP_t = \theta_0 + \theta_1 lnCFP_{t-1} + \theta_2 (lnGDP_t - \overline{lnGDP})_{t-1} + \theta_3 (lnGDP_t - \overline{lnGDP})^2_{t-1} + \theta_4 TO_{t-1} + \theta_5 lnEC_{t-1} + \sum_{i=1}^{q}\theta_6 \Delta lnCFP_{t-i} + \sum_{i=0}^{p}\theta_7 \Delta(lnGDP_t - \overline{lnGDP})_{t-i} + \sum_{i=0}^{p}\theta_8 \Delta(lnGDP_t - \overline{lnGDP})^2_{t-i} + \sum_{i=0}^{p}\theta_9 \Delta TO_{t-i} + \sum_{i=0}^{p}\theta_{10} \Delta lnEC_{t-i} + \nu_t \qquad (6)$$

where equations (4), (5), and (6) are ARDL (q,p,p,p,p), (q,p,p,p), and (q,p,p,p,p) models and the lag lengths are chosen according to the evaluation of the diagnostic tests for several models and also based on the Akaike Information Criterion (AIC). The bounds testing approach to cointegration evaluates the joint null hypothesis that no long-run relationship exists among the variables in question. In particular, $H_0{:}\delta_1{=}\delta_2{=}\delta_3{=}\delta_4{=}\delta_5{=}0$, $H_0{:}\gamma_1{=}\gamma_2{=}\gamma_3{=}\gamma_4{=}0$, and $H_0{:}\theta_1{=}\theta_2{=}\theta_3{=}\theta_4{=}\theta_5{=}0$ are tested against the alternatives $H_1{:}\delta_1{\neq}\delta_2{\neq}\delta_3{\neq}\delta_4{\neq}\delta_5{\neq}0$, $H_1{:}\gamma_1{\neq}\gamma_2{\neq}\gamma_3{\neq}\gamma_4{\neq}0$, and $H_1{:}\theta_1{\neq}\theta_2{\neq}\theta_3{\neq}\theta_4{\neq}\theta_5{\neq}0$ for models (4), (5), and (6), respectively. These are tested using the Wald F-statistic, which assesses whether the coefficients of the lagged level variables are jointly equal to zero. The resulting F-statistic for each model is then compared against critical value bounds: if the test statistic exceeds the upper bound, the null hypothesis of no cointegration is rejected, indicating the a long-run equilibrium relationship is present. Conversely, if the statistic falls below the lower bound, the null cannot be rejected, suggesting no evidence of cointegration. In cases where cointegration is confirmed, an error correction model (ECM) can subsequently be specified in line with the Engle and Granger (1987) framework. The ECM captures both the short-term adjustments and the rate at which the model corrects back toward its long-run equilibrium following a shock. Further, as far as the EKC hypothesis is concerned, the long-run income elasticity is compared with that of the short-run. The EKC holds only if the short-run elasticity of real GDP is greater than its long-run elasticity.

3.3. Unit Root Tests and Structural Breaks

This study applies the Perron (1997) unit root test, which accounts for the presence of a single endogenous structural break.[2] In this framework, the null hypothesis postulates the

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[2] Conventional unit root tests (ADF, PP, and KPSS) are conducted, but not reported to save space.

existence of a unit root with break, while the alternative suggests stationarity with structural change incorporated. Additionally, the Lagrange Multiplier (LM) unit root test developed by Lee and Strazicich (2003) (LS) is employed to assess stationarity more comprehensively by allowing for up to two endogenous structural breaks within the series. Their approach includes two specifications: one that considers two breaks in the level (crash model), and another that accounts for breaks in both level and trend. Under the LS methodology, the null hypothesis assumes the presence of a unit root with structural breaks, whereas the alternative hypothesis indicates stationarity despite structural shifts.

3.4. Cointegration with Structural Breaks

The ARDL bounds testing approach to cointegration offers several benefits, one of its drawbacks is its inability to account for structural or regime shifts within the cointegrating relationship (Gregory and Hansen, 1996; Hatemi-j, 2008). To address this limitation, Gregory and Hansen (1996) introduced a residual-based cointegration procedure that incorporates the possibility of a single structural change within the long-run equation. This test retains the null hypothesis of no cointegration, as in the Engle and Granger (1987) framework, but allows for one unknown break under the alternative hypothesis. Recognizing that more that one break may weaken the effectiveness of the Gregory and Hansen procedure, Hatemi-j (2008) extended this methodology to accommodate two endogenous breaks. In this study, both Gregory and Hansen (1996) and Hatemi-j (2008) tests are employed, with the corresponding ADF statistics used to assess the statistical significance of the cointegration results.

3.5. The Data

To investigate the EKC hypothesis in Sudan, the study uses the CFP as a right-hand-side variable, which is an aggregate indicator for measuring the environmental degradation. The CFP reflects the amount of CO_2 generated from burning fossil fuels. In ecological footprint analysis, this carbon is expressed as the land area required to absorb it through natural processes. Because carbon emissions consume part of the planet's biocapacity and contribute to ecological overshoot, they are incorporated into the overall ecological footprint.[3] The time series data for Sudan was collected from the Global Footprint Network.

The data of independent variables such the GDP in per capita term is measured as constant prices (2015 US$). Moreover, the *TO* is measured by the ratio of exports and imports to the GDP. While the *EC* is primary energy consumption per capita (kWh/person). The *GDP* and *TO* data were obtained from the World Bank.[4] Whereas, the for EC was obtained from Our World in Data.[5] Also, the CO_2 emissions data for robustness purposes was measured by metric tons and attained from the World Bank.

Income (economic growth) is the major factor that affects the EKC hypothesis. The principal explanatory factor of environmental degradation is the income level (Lindmark, 2002). As income of individuals initially rises, their consumption of goods and services increases, and that will lead to higher environmental degradation. Beyond a certain level of income, further economic growth will play a positive role and leads to a decrease in the environmental degradation. The association between income and environmental degradation is hypothesized as an inverted U-shaped relationship (Grossman and Krueger, 1995).

Another significant EKC explanatory factor is trade openness. Generally, the size of the economy increases as a result of exporting and importing various final and intermediate goods and thereby pollution rises. According to Hecksher-Ohlin theory, trade openness has a positive relationship with environmental degradation. The theory states that as trade openness increases the consumption, processing and manufacturing of goods rise, which stimulate environmental degradation. Regarding the last explanatory variable, several empirical studies have obtained clear evidence regarding the direct effect of energy consumption on carbon emissions (Sirag et al, 2018).

4. RESULTS AND DISCUSSION

Table 1 reports the results of Perron (1997) unit root test, which accounts for a single structural break. The findings clearly show that all variables are integrated of order one, I(1). Moreover, the outcomes from the Perron test are consistent with those obtained from the LS unit root test, which allows for two endogenous structural breaks, as presented in Table 2. Overall, the analysis of multiple unit root tests confirms that the variables are suitable for estimation using the ARDL model.

Table 3 illustrates the results of the bounds testing for cointegration for equations (4), (5), and (6). The F-statistics are shown to be larger than the upper critical bound statistics at 5% significance

Table 1: Perron unit root test with one structural break

Variable	Perron			
	C	Break date	CandT	Break date
$ln\ CFP_t$	−4.393	2001	−4.175	2003
$\Delta(lnGDP_t - ln\overline{GDP})$	−1.435	2016	−2.751	2010
$\Delta(lnGDP_t - ln\overline{GDP})$	−3.339	2004	−3.729	1986
$ln\ GDP_t$	−1.435	2016	−2.751	2010
$ln\ GDP^2{}_t$	−1.434	2016	−2.747	2010
TO_t	−2.652	1997	−2.803	2003
$ln\ EC_t$	−3.074	2001	−2.984	1999
FD_t	−3.791	2001	−2.677	2016
$\Delta ln\ CFP_t$	−9.580[a]	1993	−10.035[a]	2005
$\Delta(lnGDP_t - ln\overline{GDP})$	−6.878[a]	1987	−7.252[a]	1986
$\Delta(lnGDP_t - ln\overline{GDP})^2$	−7.937[a]	1987	−7.416[a]	1987
$\Delta ln\ GDP_t$	−6.878[a]	1987	−7.252[a]	1986
$\Delta ln\ GDP^2{}_t$	−6.770[a]	1987	−7.211[a]	1997
ΔTO_t	−7.389[a]	1986	−7.742[a]	1986
$\Delta ln\ EC_t$	−7.761[a]	1999	−7.948[a]	1999
ΔFD_t	−6.439[a]	2006	−6.841[a]	2006

[a]Denotes significant at 1%. C refers to intercept, CandT refers to intercept and trend.
Source: Authors' calculation

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3 Global Footprint Network (2025). https://www.footprintnetwork.org/our-work/climate-change/

4 World Bank. (2025). World Development Indicators. http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators.

5 Our World in Data (2025). https://ourworldindata.org/energy

level. This indicates that the variables in equations (4), (5), and (6) are cointegrated and thereby the log-run relationship is meaningful. The outcomes of ARDL bounds test presented in Table 3, may have low power especially if structural changes exist (Gregory and Hansen, 1996). Therefore, the study conducted cointegration with structural breaks tests to validate the bounds test results. Table 4 reveals the findings of Gregory-Hansen (1996) test with one endogenous break. Based on the ADF statistic, the Gregory-Hansen (1996) test reveals evidence of structural changes in the three estimated models. The test identified 2002 as a break date for the three models. When two breaks are allowed, however, the findings of Hatemi-j (2008) test fail to provide evidence of cointegration for the three specifications as shown in Table 5. Therefore, we will rely on the evidence of cointegration provided by the ARDL bounds test and Gregory-Hansen test to estimate the EKC testing models.

After establishing cointegration, the long- and short-run models are estimated. As a structural change is suggested by Gregory-Hansen cointegration test, a dummy variable is introduced to equations (4), (5), and (6). Table 6 presents the estimation of ARDL model for the three model specifications. The findings of model 1, which represent the conventional approach to test the validity of the EKC hypothesis, show that GDP and GDP squared are statistically insignificant in the long-run, but GDP is found to be negative and significant in the short-run. These findings lean towards indicating that the EKC hypothesis does not hold given the sample of study. Moreover, the TO is negative and insignificantly related to CFP in the long-run. However, EC is shown to have a positive sign and statistically meaningful in its relationship with CFP in the long-run. Specifically, if energy consumption per person rises by 1%, the CFP will increase by approximately 0.33%. The estimation of the short-run coefficients indicated the insignificance of GDP^2, TO, and EC in explaining the variation in the CFP. Interestingly, the structural change dummy coefficient appears to have positive sign and significantly different from zero. This may indicate the direct role of structural transformation that took place in the Sudanese economy, especially after the discovery of oil between 1999 and 2000, in boosting carbon emissions. Importantly, the ECT coefficient is revealed to be negative and significant at 1% and that provides further support to the results of the cointegration tests. The ECT coefficient (-0.732) indicates the disequilibrium is corrected by 73% annually. The results of the conventional EKC hypothesis empirical testing procedure present evidence contrary to the presence of the EKC hypothesis.

The diagnostic tests show no evidence of model misspecification. The LM test for serial correlation suggests no significant autocorrelation. The ARCH test reveals the absence of heteroskedasticity. Normality of the residuals is confirmed by the Jarque-Bera test with a P-value of 0.86. The RESET test for functional form misspecification produces a P-value of 0.68, implying the absence of misspecification errors. Finally, the stability tests (CUSUM and CUSUM of Squares), shown in Figure 1, indicate that the tests statistics remain withing the 5% significance bounds throughout the sample, indicating no evidence of structural breaks or parameter instability.

The findings of model 2, which referred to the EKC testing approach according to Narayan and Narayan (2010), demonstrate the significance of real GDP in explaining the CFP in the long-run. It reveals that 1% change in GDP per capita leads to a positive change in the CFP by 0.57%. While the variable TO is found insignificant in the long-run. However, higher consumption of primary energy has a positive impact on CFP in the long-run. The coefficient suggests that as EC rises by 1%, CFP increases by roughly 0.35%. On the other hand, the short-run coefficients show the insignificance of all the variables in explaining the variation in the CFP. Nonetheless, the dummy variable's coefficient is positively related to CFP and null hypothesis is rejected at 1% significance level. Notably, the significance and the negative sign of the error correction term endorses the previous outcomes of the bounds test. The error correction term coefficient indicates that the disequilibrium is corrected by 75% annually. As the short-run elasticity is not significant and less than that of the long-run, this particular finding presents evidence against the existence of the

Table 2: Lee and Strazicich unit root test with two structural breaks

Variable	*t*-stat	Break dates
$ln\ CFP_t$	−5.819	1993-2004
$(lnGDP_t - ln\overline{GDP})$	−5.308	1995-2008
$(lnGDP_t - ln\overline{GDP})^2$	−5.540	2003-2018
$ln\ GDP_t$	−5.308	1995-2008
$ln\ GDP^2_t$	−5.252	1995-2008
TO_t	−5.062	1996-2003
$ln\ EC_t$	−4.972	1995-2009
FD_t	−5.517	1995-2003
$\Delta ln\ CFP_t$	−6.556^b	1987-2001
$\Delta(lnGDP_t - ln\overline{GDP})$	−7.085^a	2000-2010
$\Delta(lnGDP_t - ln\overline{GDP})^2$	−8.973^a	20002006
$\Delta ln\ GDP_t$	−7.085^a	2000-2010
$\Delta ln\ GDP^2_t$	−7.000^b	2000-2010
ΔTO_t	−6.731^b	1990-1993
$\Delta ln\ EC_t$	−6.494^b	1997-2011
ΔFD_t	−7.528^a	1991-2001

^{a}, ^{b}Denote significant at 1% and 5%, respectively. Source: Authors' calculation

Table 3: Bound test for cointegration

The model	F-statistic	Critical values	
		I (0)	I (1)
$ln\ CFP_t\ f\ (ln\ GDP_t,\ ln\ GDP^2_t,\ ln\ TO_t,\ ln\ EC_t)$	5.352^b	2.893	4.000
$ln\ CFP_t\ f\ (ln\ GDP_t,\ ln\ TO_t,\ ln\ EC_t)$	7.057^b	3.100	4.088
$ln\ CFP_t\ f((lnGDP_t - ln\overline{GDP}),\ (lnGDP_t - ln\overline{GDP})^2,\ ln\ TO_t,\ ln\ EC_t)$	5.352^b	2.893	4.000

^{b}Denotes significant at 5%. Source: Authors' calculation

Table 4: Gregory-Hansen cointegration test

Specification	ADF t-stat	Break date
Model 1	-6.60^{b}	2002
Model 2	-6.59^{b}	2002
Model 3	-6.60^{b}	2002

Table 5: Hatemi-J cointegration test

Specification	ADF t-stat	Break dates
Model 1	−7.314	1990-1995
Model 2	−6.955	1990-1995
Model 3	−7.314	1990-1995

Model 1, Model 2, and Model 3, are the EKC testing approaches shown in equations (1), (2), and (3), respectively. The 5% critical value for model 1, model 2, and model 3 are−7.903, −7.352, and−7.903, respectively. Source: Authors' calculation

Table 6: ARDL results – CFP as dependent variable

Variable	Model 1	Model 2	Model 3
	Long-run coefficients		
Intercept	8.649 (28.546)	-8.707^{a} (1.227)	-4.590^{a} (1.005)
$ln\ GDP_t$	−4.469 (8.268)	0.566^{a} (0.177)	-
$ln\ GDP^2_t$	0.369 (0.606)	-	-
$(lnGDP_t - ln\overline{GDP})$	-	-	0.661^{b} (0.245)
$(lnGDP_t - ln\overline{GDP})^2$	-	-	0.368 (0.606)
TO_t	−0.001 (0.003)	0.0002 (0.002)	−0.001 (0.003)
$ln\ EC_t$	-0.328^{b} (0.141)	0.352^{a} (0.129)	0.328^{a} (0.141)
Joint-Significance	-	-	4.932^{b}
Bounds Tests	6.366^{a}	7.695^{a}	6.366^{a}
	Short-run coefficients		
$\Delta ln\ GDP_t$	-3.964^{a} (0.627)	−0.272 (0.250)	
$\Delta ln\ GDP^2_t$	-		
$\Delta(lnGDP_t - ln\overline{GDP})$	-	-	−0.209 (0.248)
$\Delta(lnGDP_t - ln\overline{GDP})^2$	-	-	-
$\Delta\ TO_t$	-	-	-
$\Delta ln\ EC_t$	-	-	-
Dummy	0.133^{a} (0.024)	0.136^{a} (0.025)	0.133^{a} (0.024)
ECT_{t-1}	-0.732^{a} (0.111)	-0.746^{a} (0.114)	-0.731^{a} (0.110)
	Diagnostic tests		
LM {1}	[0.55]	[0.60]	[0.55]
LM {2}	[0.83]	[0.87]	[0.83]
ARCH {1}	[0.26]	[0.23]	[0.26]
ARCH {2}	[0.33]	[0.32]	[0.33]
JB	[0.86]	[0.79]	[0.86]
RESET	[0.68]	[0.45]	[0.68]

Model 1, Model 2, and Model 3, are the EKC testing approaches shown in equations (1), (2), and (3), respectively. ^{a}and ^{b}denote significant at 1% and 5%, respectively. Between ( ) and [ ] are standard errors and P values, respectively. The lag length selected based on the diagnostic tests and AIC. Source: Authors' calculation.

EKC hypothesis meaning that further increase in GDP per capita will result in more damage to the environment.

The model appears to satisfy standard diagnostic checks. The LM test for serial correlation at different lags, shows that both P-values are well above the 5% significance level, indicating no autocorrelation in the errors. Similarly, the ARCH test for heteroskedasticity gives P-values that are >0.05, suggesting homoscedastic errors. The Jarque-Bera test for normality yields a high P-value of 0.79, supporting the assumption of normally distributed residuals. Moreover, the RESET test shows a P-value of 0.45, implying the functional form of the model is appropriate. Figure 2 shows the CUSUM and CUSUM Squares tests. The results of CUSUM and CUSUM of Squares tests confirm parameter stability, as both statistics stay within the 5% confidence bounds throughout the period analyzed. Thus, the diagnostic and stability tests collectively confirm that the model is well-specified and the assumptions underlying the estimation are not violated.

The outcomes of model 3, the third EKC testing approach suggested by Brown and McDonough (2016), reveal that GDP and its quadratic term have positive sign in the long-run, but GDP is significant at 5% and GDP-squared is insignificant. The finding of the GDP indicates that a change by 1% in the real GDP per capita will lead to change in CFP by approximately 0.66% in the long-run. Although the joint-significance test shows that the null hypothesis is rejected at 5% level, still the EKC hypothesis is not present due to the positive sign of both coefficients. The variables TO is insignificant in revealing the changes in the CFP over the long-run. In the short-run, GDP per capita is negatively signed but insignificant. Although the EKC hypothesis is a long-run phenomenon, the short-run coefficients of the GDP and its squared term are important to explain how the environment interacts with economic activities and how the relationship between them evolves overtime (Brown and McDonough, 2016). The other explanatory variables, including GDP-squared, seem meaningless to the short-run changes in CFP. Significantly, the dummy for structural break is positively related to CFP. The error correction term is negative and significant, which confirms the earlier results of cointegration tests. The ECT term specifies the instability in the model is corrected by approximately 73% annually. In the same vein, the findings of model 3 tend to show similar conclusion to the one provided the conventional and Narayan and Narayan (2010) approaches, and reveal no confirmation for the hypothesis EKC in Sudan. Also, Figure 3 illustrates the scatter graph for the CFP and GDP per capita. The graph provides support of the regression results and undoubtedly indicates that the relationship is still beyond the turning point.

To assess the adequacy of the estimated model, several diagnostic tests were performed. The Breusch-Godfrey LM test provided P-values of 0.55 and 0.83, indicating no evidence of serial correlation. The ARCH tests for heteroskedasticity yielded P-value higher than any significance level, suggesting that the variance of the residuals is constant. The Jarque-Bera test for normality resulted in a P-value of 0.86, which supports the normality assumption of the error. Similarly, the Ramsey RESET test for model misspecification produced a P-value of 0.68, implying that the model specification is appropriate. Overall, none of the tests reject the null hypotheses, confirming the reliability of the model. This is also confirmed by stability tests. Figure 4 illustrates the findings of CUSUM and CUSUM of Squares tests for stability. Both the CUSUM and CUSUM of Squares statistics remain within the critical limits at the 5% level, suggesting that the estimated parameters are stable and the model does not exhibit structural instability over the sample period.

Another analysis is conducted to examine the validity of the EKC hypothesis using the CO_2 emissions as a dependent variable.

Figure 1: CUSUM and CUSUM of Squares tests (Model 1). Source: Authors' calculation

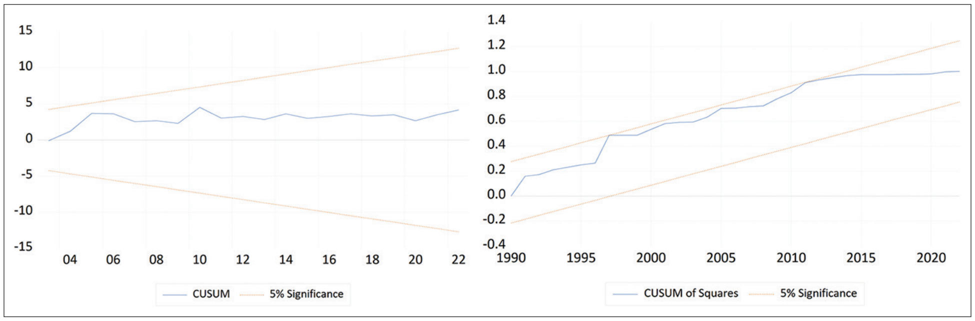


Figure 2: CUSUM and CUSUM of Squares tests (Model 2). Source: Authors' calculation

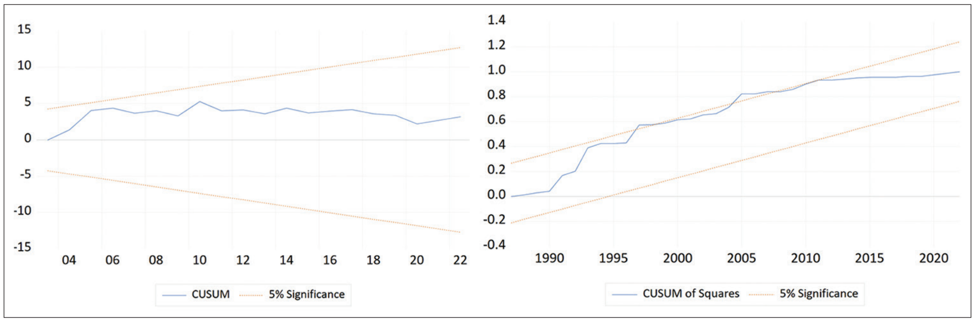
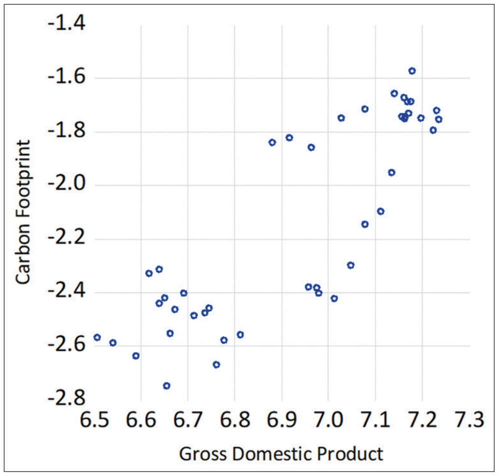


Figure 3: GDP and CFP. Source: Authors' calculation



Although the CO_2 is not a comprehensive indicator, it has been widely used as a measure for environmental degradation, therefore, it may provide further useful robustness analysis of the EKC hypothesis in Sudan. Table 7 displays the findings of the ARDL model when the CO_2 is used as a dependent variable. The outcomes of model 1 show that the coefficients of GDP and GDP-squared are not correctly signed and insignificant, as GDP is negative and its squared term is positive, providing no support for the EKC hypothesis. Obviously, the long-run coefficient of TO is statistically insignificant. However, the primary consumption of energy (EC) is positively correlated with higher CFP in the long-run. In the short-run, the GDP is found to have a negative and significant impact of the CO_2 emissions on CFP. This suggests that higher level of income may help to improve the environmental quality in the short-run. The diagnostic and stability tests, shown in Table 7 and Figure 5, show the appropriateness of the estimated model.

Unsurprisingly, the results of model 2 reveal that real GDP per capita has insignificant effect on the CO_2 emissions in the long-run. But the short-run effect of GDP on CO_2 is negative and significant. Particularly, the CO_2 will change by roughly −0.895% if the real GDP per capita changes by 1%. Although the short-run elasticity seems to be larger than the long-run, but the EKC still invalid due to the insignificance of the long-run coefficient. The variable EC shows positive and significant effect on CO_2 in the long-run but not in the short-run. The diagnostic and stability checking, shown in Table 7 and Figure 6, reveal the adequacy of the estimated model.

Finally, the findings of model 3 reveal that both coefficients of GDP and its quadratic term are positively signed but only GDP is significant in the long-run. Although both coefficients of GDP and GDP-squared are jointly significant, still there is no evidence EKC hypothesis due to the insignificance and positive sign of GDP-squared coefficient. Similar to the previous models' results, the TO is insignificant while EC is positive and significant in the long-run. The short-run results illustrate that GDP is found to be negative but insignificantly related to CO_2. The explanatory variables are insignificantly correlated with CFP in the short-run. All in all, when the CO_2 emission is used as an indicator for the environmental degradation the findings are in agreement with the previous outcomes of the main analysis. The diagnostic and stability tests, shown in the table and Figure 7, reveal the adequacy of the estimated model.

A key result of this study indicates that the EKC hypothesis does not hold in Sudan. This outcome suggest that the country's current

Figure 4: CUSUM and CUSUM of Squares tests (Model 3). Source: Authors' calculation

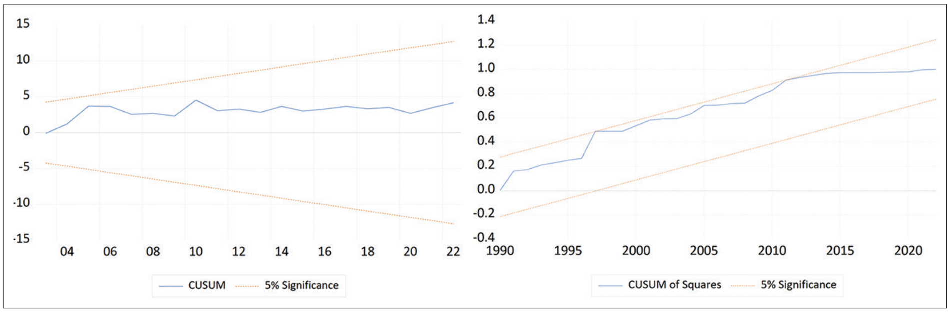


Figure 5: CUSUM and CUSUMSQ tests – CO_2 (Model 1). Source: Authors' calculation

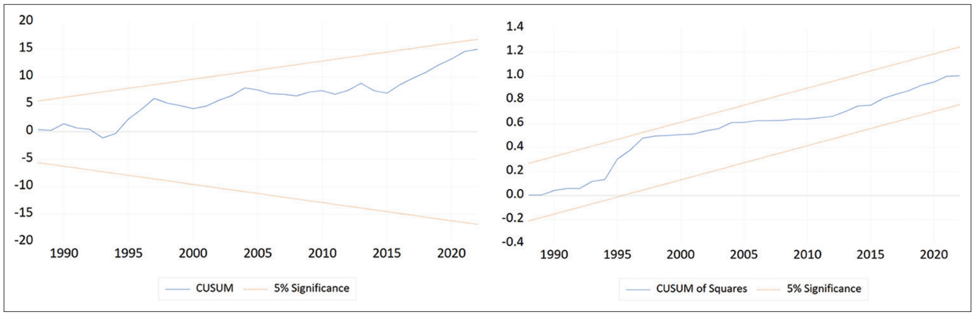


Table 7: ARDL model – CO_2 as dependent variable

Variable	Model 1	Model 2	Model 3
	Long-run coefficients		
Intercept	10.835	−9.028^a	−5.779^a
	(43.639)	(1.027)	(0.810)
ln GDP$_t$	−5.433	0.325	-
	(12.651)	(0.248)	
ln GDP^2_t	0.422	-	-
	(0.927)		
$(lnGDP_t - ln\overline{GDP})$	-	-	0.721^b
			(0.271)
$(lnGDP_t - ln\overline{GDP})^2$	-	-	0.395
			(0.721)
TO$_t$	0.0003	0.001	−0.002
	(0.004)	(0.003)	(0.003)
ln EC$_t$	0.716^a	0.746^a	0.509^a
	(0.145)	(0.123)	(0.108)
Joint-Significance	-	-	0.887
Bounds Test	5.069^b	6.173^a	5.352^b
	Short-run coefficients		
Δln GDP$_t$	−5.098^a	−0.895^b	-
	(0.849)	(0.375)	
$\Delta(lnGDP_t - ln\overline{GDP})$	-	-	−0.110
			(0.287)
$\Delta(lnGDP_t - ln\overline{GDP})^2$	-	-	1.161^b
			(0569)
Δ TO$_t$	-	-	0.003
			(0.003)
ECT$_{t-1}$	−0.729^a	−0.746^a	−0.703^a
	(0.124)	(0.127)	(0.116)
	Diagnostic tests		
LM {1}	[0.85]	[0.85]	[0.79]
LM {2}	[0.96]	[0.96]	[0.92]
ARCH {1}	[0.64]	[0.66]	[0.21]
ARCH {2}	[0.64]	[0.68]	[0.21]
JB	[0.00]	[0.00]	[0.79]
RESET	[0.72]	[0.63]	[0.89]

Model 1, Model 2, and Model 3, are the EKC testing approaches shown in equations (1), (2), and (3), respectively. ^{a,b,}and ^{c}denote significant at 1%, 5%, and 10%, respectively. Between ( ) and [ ] are standard errors and P-values, respectively. The lag length selected based on AIC. Source: Authors' calculation

income level remains below the threshold at which economic growth begins to enhance environmental quality. These findings align with those of several previous studies (e.g., Lacheheb et al., 2015; Sirag et al., 2018), which also reported no evidence supporting the EKC in similar contexts. Notwithstanding these studies relied only on one approach to test for the EKC hypothesis and the CO_2 emissions was used as a measure for the environmental degradation. In the same vein, our results are in line with those of Mrabet et al. (2017), who adopted Narayan and Narayan (2010) approach and found no evidence of the EKC hypothesis in the case of Qatar, given that our findings are robust even when different measure (CO_2) and different estimation techniques are used. Nevertheless, our findings stand in contrast to numerous earlier studies. For example, Awad (2019) reported evidence supporting the EKC hypothesis in a panel of African countries (including Sudan), based panel data analysis. This discrepancy may stem from methodological limitations, such as heterogeneity bias and reliance on the conventional EKC specification with CO_2 emissions as the sole environmental indicator. Similarly, Ike et al. (2020) confirmed the EKC hypothesis, but only for countries with high CO_2 emissions, and not only for those with lower emissions. Unlike Ike et al. (2020), the present study employs CFP, offering a more comprehensive assessment of environmental impact, along with three distinct approaches to test the EKC hypothesis. Furthermore, Sarkodie and Ozturk (2020) found evidence in favour of the EKC in Kenya using CO_2 emissions as their metric of environmental degradation. Charfeddine and Mrabet (2017), while adopting the ecological footprint as an indicator, still relied on the traditional EKC testing methodology and found support for the EKC only among oil-exporting countries. Nonetheless, Yilanci and Ozgur (2019) used the ecological footprint as an indicator for the environmental degradation and yet they found evidence supporting the EKC hypothesis in the G7 countries.[6] Their results

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[6] G7 countries are Canada, France, Germany, Italy, Japan, UK, and USA.

Figure 6: CUSUM and CUSUMSQ tests – CO_2 (Model 2). Source: Authors' calculation

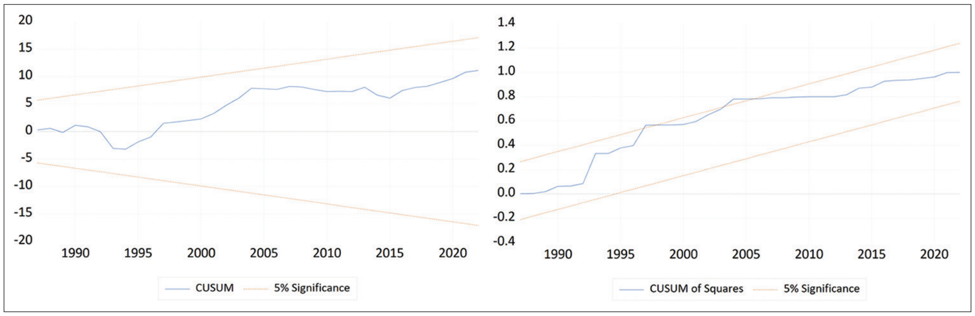
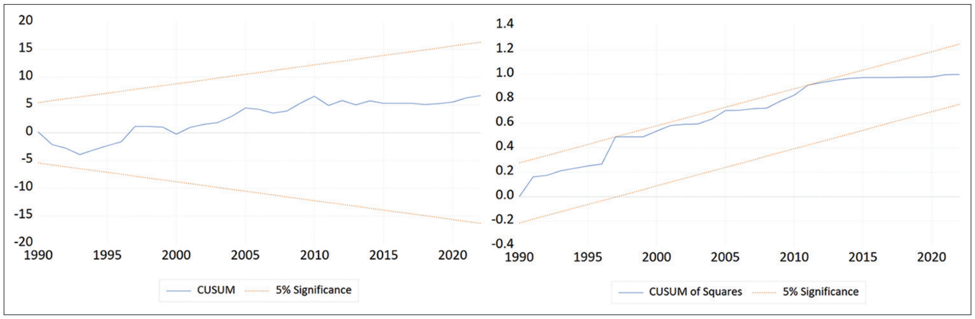


Figure 7: CUSUM and CUSUMSQ tests – CO_2 (Model 3). Source: Authors' calculation



are most likely to represent the reality in the industrialized nations, but in the less developed countries the story might be different. Although Mohamed et al. (2024) found evidence in favor of the EKC hypothesis in Malaysia and emphasized the role played by renewable energy in reducing CO_2 emissions and the ecological footprint, yet they relied simply on the conventional testing procedure of the EKC. In the same way, Chopra et al., (2024) validated the EKC hypothesis in the top five carbon emitters, USA, Russia, Japan, China, and India, using the CFP as a dependent variable and model GDP and its quadratic term.

The vast majority of the EKC literature have relied on a certain testing procedure, and to the best of our knowledge this is the only study that have used three different testing approaches in time series setting. Although the findings presented by this study may be somewhat limited in terms of the sample and data, however, it raises intriguing questions regarding the nature and extent of the relationship between economic growth and ecological degradation in several developing countries. The argument that developing economies are still in the process of damaging the environment and they are yet to reach the level that enables them to reduce the ecological degradation is in line with some empirical findings (Lacheheb, 2015; Sirag et al., 2018).

5. CONCLUSION AND POLICY IMPLICATIONS

As an input to the EKC hypothesis literature in the light of economic performance and its impact on the environment, our study investigated the relationship between economic growth measured using real GDP per capita, trade openness, primary energy consumption per capita, and environmental degradation in Sudan. In the literature, there are three main EKC testing procedures that jointly used by this paper. Also, the study used the carbon footprint as a measure for the environmental degradation, which is more appropriate compared to the CO_2 emissions. The ARDL cointegration approach is adopted as an appropriate estimation technique. In addition, the study accounts and test for structural changes in the data using unit root and cointegration tests that take structural breaks into consideration. The results of the traditional approach that involves using the GDP and GDP squared provided no evidence of the EKC hypothesis in Sudan. The second approach according to Narayan and Narayan (2010) revealed that when the long-run and short-run elasticities were compared, the EKC hypothesis was not present. Similarly, the outcomes of the approach introduced by Brown and McDonough (2016) failed to find any evidence for the existence of the EKC hypothesis. However, there is partial evidence that economic activities are strongly linked to environmental degradation, as GDP per capita and primary energy consumption are positively stimulating carbon footprint. The findings emerged from this study imply the absence of the EKC hypothesis in the case of Sudan. This indicates that the country's economic performance is posing a real pressure on the environment and the level of income is yet to reach the turning point beyond which GDP reduces the environmental damage. Also, the robustness analysis provided strong support to the main findings. Overall, the results imply that the absence of the EKC hypothesis in a developing country, such as Sudan, seems to be more realistic especially with the relatively low level of income and the lack of effective environmental policies.

The following recommendations are proposed for policy and future research. Strong environmental regulations need to be effectively enforced and continuously overseen to mitigate the ecological harm stemming from different economic activities and to safeguard resources for the benefit of future generations. In general, developing countries, such as Sudan, are in need of clear plans to internalize the costs of environmentally related negative externalities, which will account for the by-products of different economic activities. A possible limitation of this study is that we have used the aggregate carbon footprint as a measure for environmental degradation. Therefore, other elements of overall ecological footprint such as forest land, fishing grounds, built-up land, cropland, and grazing land, could be used by future research. Importantly, to provide a comprehensive picture and develop universal approach that is suitable for many developing countries, future studies related to other developing countries are required.

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REFERENCES

Ahmad, N., Du, L., Lu, J., Wang, J., Li, H.Z., Hashmi, M.Z. (2017), Modelling the CO_2 emissions and economic growth in Croatia: Is there any environmental Kuznets curve? Energy, 123, 164-172.

Al-Mulali, U., Weng-Wai, C., Sheau-Ting, L., Mohammed, A.H. (2015), Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. Ecological Indicators, 48, 315-323.

Altıntaş, H., Kassouri, Y. (2020), Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO_2 emissions? Ecological Indicators, 113, 106187.

Awad, A. (2019), Does economic integration damage or benefit the environment? Africa's experience. Energy Policy, 132, 991-999.

Awan, A., Alnour, M., Jahanger, A., Chukwuma, O.J. (2022), Do technological innovation and urbanization mitigate carbon dioxide emissions from the transport sector? Technology in Society, 71, 102128.

Bashir, M. F., MA, B., Hussain, H. I., Shahbaz, M., Koca, K., & Shahzadi, I. (2022). Evaluating environmental commitments to COP21 and the role of economic complexity, renewable energy, financial development, urbanization, and energy innovation: Empirical evidence from the RCEP countries. Renewable Energy, 184, 541–550.

Bölük, G., Mert, M. (2015), The renewable energy, growth and environmental Kuznets curve in Turkey: An ARDL approach. Renewable and Sustainable Energy Reviews, 52, 587-595.

Brown, S.P., McDonough, I.K. (2016), Using the environmental Kuznets curve to evaluate energy policy: Some practical considerations. Energy Policy, 98, 453-458.

Callan, S.J., Thomas, J.M. (2013), Environmental Economics and Management: Theory, Policy, and Applications. 6th ed. South-Western: Cengage Learning.

Charfeddine, L., Mrabet, Z. (2017), The impact of economic development and social-political factors on ecological footprint: A panel data analysis for 15 MENA countries. Renewable and Sustainable Energy Reviews, 76, 138-154.

Chen, Q., Taylor, D. (2020), Economic development and pollution emissions in Singapore: Evidence in support of the Environmental Kuznets Curve hypothesis and its implications for regional sustainability. Journal of Cleaner Production, 243, 118637.

Chopra, R., Rehman, M.A., Yadav, A., Bhardwaj, S. (2024), Revisiting the EKC framework concerning COP-28 carbon neutrality management: Evidence from Top-5 carbon embittering countries. Journal of Environmental Management, 356, 120690.

Destek, M.A., Sarkodie, S.A. (2019), Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development. Science of the Total Environment, 650, 2483-2489.

Devi, S., Gupta, N. (2019), Effects of inclusion of delay in the imposition of environmental tax on the emission of greenhouse gases. Chaos, Solitons and Fractals, 125, 41-53.

Dogan, E., Inglesi-Lotz, R. (2020), The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis: Evidence from European countries. Environmental Science and Pollution Research, 27, 12717-12724.

Dogan, E., Ulucak, R., Kocak, E., Isik, C. (2020), The use of ecological footprint in estimating the Environmental Kuznets Curve hypothesis for BRICST by considering cross-section dependence and heterogeneity. Science of the Total Environment, 723, 138063.

EIA. (2021), How Much of U.S. Energy Consumption and Electricity Generation Comes from Renewable Energy Sources? Available from: https://www.eia.gov/tools/faqs/faq.php?id=92&t=4#:~:text=How much of U.S. energy,about 20.1%25 of electricity generation

Engle, R.F., Granger, C.W. (1987), Co-integration and error correction: Representation, estimation, and testing. Econometrica: Journal of the Econometric Society, 55, 251-276.

Gregory, A.W., Hansen, B.E. (1996), Residual-based tests for cointegration in models with regime shifts. Journal of Econometrics, 70(1), 99-126.

Grossman, G.M., Krueger, A.B. (1991), Environmental impacts of a North American free trade agreement. Massachusetts, USA: National Bureau of Economic Research Cambridge.

Grossman, G.M., Krueger, A.B. (1995), Economic growth and the environment. The Quarterly Journal of Economics, 110(2), 353-377.

Gyamfi, B.A., Adedoyin, F.F., Bein, M.A., Bekun, F.V. (2021), Environmental implications of N-shaped environmental Kuznets curve for E7 countries. Environmental Science and Pollution Research, 28(25), 33072-33082.

Hanif, I., Gago-de-Santos, P. (2017), The importance of population control and macroeconomic stability to reducing environmental degradation: An empirical test of the environmental Kuznets curve for developing countries. Environmental Development, 23, 1-9.

Hatemi-j, A. (2008), Tests for cointegration with two unknown regime shifts with an application to financial market integration. Empirical Economics, 35(3), 497-505.

He, B.J., Wang, J., Zhu, J., Qi, J. (2022), Beating the urban heat: Situation, background, impacts and the way forward in China. Renewable and Sustainable Energy Reviews, 161, 112350.

IEA. (2022), Energy and Climate Change. Available from: https://www.iea.org/topics/climate-change

IEA. (2023), CO_2 Emissions in 2023. Executive Summary. Available from: https://www.iea.org/reports/co2-emissions-in-2023/executive-summary

Ike, G.N., Usman, O., Sarkodie, S.A. (2020), Testing the role of oil production in the environmental Kuznets curve of oil producing countries: New insights from Method of Moments Quantile Regression. Science of the Total Environment, 711, 135208.

Jiang, P., Yang, H., Ma, X. (2019), Coal production and consumption analysis, and forecasting of related carbon emission: Evidence from China. Carbon Management, 10(2), 189-208.

Kacprzyk, A., Kuchta, Z. (2020), Shining a new light on the environmental Kuznets curve for CO_2 emissions. Energy Economics, 87, 104704.

Kassouri, Y. (2021), Monitoring the spatial spillover effects of urbanization on water, built-up land and ecological footprints in sub-Saharan Africa. Journal of Environmental Management, 300, 113690.

Kearsley, A., Riddel, M. (2010), A further inquiry into the pollution haven hypothesis and the environmental Kuznets curve. Ecological

Economics, 69(4), 905-919.

Kocak, E., Alnour, M. (2022), Energy R&D expenditure, bioethanol consumption, and greenhouse gas emissions in the United States: Non-linear analysis and political implications. Journal of Cleaner Production, 374(7), 133887.

Kuznets, S. (1955), Economic growth and income inequality. The American Economic Review, 45(1), 1-28.

Lacheheb, M., Rahim, A.S.A., Sirag, A. (2015), Economic growth and CO_2 emissions: Investigating the environmental Kuznets curve hypothesis in Algeria. International Journal of Energy Economics and Policy, 5(4), 1125-1132.

Lau, L.S., Yii, K.J., Ng, C.F., Tan, Y.L., Yiew, T.H. (2025), Environmental Kuznets curve (EKC) hypothesis: A bibliometric review of the last three decades. Energy and Environment, 36(1), 93-131.

Lee, J., Strazicich, M.C. (2003), Minimum Lagrange multiplier unit root test with two structural breaks. Review of Economics and Statistics, 85(4), 1082-1089.

Lindmark, M. (2002), An EKC-pattern in historical perspective: Carbon dioxide emissions, technology, fuel prices and growth in Sweden 1870-1997. Ecological Economics, 42(1-2), 333-347.

Liu, Y., Lai, X. (2021), EKC and carbon footprint of cross-border waste transfer: Evidence from 134 countries. Ecological Indicators, 129, 107961.

Lorente, D.B., Alvarez-Herranz, A. (2016), An approach to the effect of energy innovation on environmental Kuznets curve: An introduction to inflection point. Bulletin of Energy Economics, 4(3), 224-233.

Mohamed, E.F., Abdullah, A., Jaaffar, A.H., Osabohien, R. (2024), Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint? Energy Strategy Reviews, 53, 101387.

Mongo, M., Belaïd, F., Ramdani, B. (2021), The effects of environmental innovations on CO_2 emissions: Empirical evidence from Europe. Environmental Science and Policy, 118, 1-9.

Moutinho, V., Varum, C., Madaleno, M. (2017), How economic growth affects emissions? An investigation of the environmental Kuznets curve in Portuguese and Spanish economic activity sectors. Energy Policy, 106, 326-344.

Mrabet, Z., AlSamara, M., Jarallah, S.H. (2017), The impact of economic development on environmental degradation in Qatar. Environmental and Ecological Statistics, 24(1), 7-38.

Narayan, P.K., Narayan, S. (2010), Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. Energy Policy, 38(1), 661-666.

Özokcu, S., Özdemir, Ö. (2017), Economic growth, energy, and environmental Kuznets curve. Renewable and Sustainable Energy Reviews, 72, 639-647.

Perone, G. (2024), The relationship between renewable energy production and CO_2 emissions in 27 OECD countries: A panel cointegration and Granger non-causality approach. Journal of Cleaner Production, 434, 139655.

Perron, P. (1997), Further evidence on breaking trend functions in macroeconomic variables. Journal of Econometrics, 80(2), 355-385.

Pesaran, M.H., Shin, Y., Smith, R.J. (2001), Bounds testing approaches to the analysis of level relationships. Journal of Applied Econometrics, 16(3), 289-326.

Petrović, P., & Lobanov, M. M. (2020). The impact of R&D expenditures on CO2 emissions: evidence from sixteen OECD countries. Journal of Cleaner Production, 248, 119187.

Ren, S., Du, M., Bu, W., & Lin, T. (2023). Assessing the impact of economic growth target constraints on environmental pollution: Does environmental decentralization matter? Journal of Environmental Management, 336(October 2022), 117618.

Sarkodie, S.A., Ozturk, I. (2020), Investigating the environmental Kuznets curve hypothesis in Kenya: A multivariate analysis. Renewable and Sustainable Energy Reviews, 117, 109481.

Sirag, A., Matemilola, B.T., Law, S.H., Bany-Ariffin, A.N. (2018), Does environmental Kuznets curve hypothesis exist? Evidence from dynamic panel threshold. Journal of Environmental Economics and Policy, 7(2), 145-165.

Solarin, S.A., Bello, M.O. (2018), Persistence of policy shocks to an environmental degradation index: The case of ecological footprint in 128 developed and developing countries. Ecological Indicators, 89, 35-44.

Stern, D.I. (2004), The rise and fall of the environmental Kuznets curve. World Development, 32(8), 1419-1439.

Sterpu, M., Soava, G., Mehedintu, A. (2018), Impact of economic growth and energy consumption on greenhouse gas emissions: Testing environmental curves hypotheses on EU countries. Sustainability, 10(9), 3327.

Uddin, G.A., Salahuddin, M., Alam, K., Gow, J. (2017), Ecological footprint and real income: Panel data evidence from the 27 highest emitting countries. Ecological Indicators, 77, 166-175.

Ullah, A., Khan, D. (2020), Testing environmental Kuznets curve hypothesis in the presence of green revolution: A cointegration analysis for Pakistan. Environmental Science and Pollution Research, 27, 11320-11336.

Ulucak, R., Bilgili, F. (2018), A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. Journal of Cleaner Production, 188, 144-157.

Ulucak, R., Lin, D. (2017), Persistence of policy shocks to Ecological Footprint of the USA. Ecological Indicators, 80, 337-343.

Wagner, M. (2015), The environmental Kuznets curve, cointegration and nonlinearity. Journal of Applied Econometrics, 30(6), 948-967.

Yilanci, V., Ozgur, O. (2019), Testing the environmental Kuznets curve for G7 countries: Evidence from a bootstrap panel causality test in rolling windows. Environmental Science and Pollution Research, 26(24), 24795-24805.

Zeraibi, A., Ahmed, Z., Shehzad, K., Murshed, M., Nathaniel, S.P., Mahmood, H. (2022), Revisiting the EKC hypothesis by assessing the complementarities between fiscal, monetary, and environmental development policies in China. Environmental Science and Pollution Research, 29(16), 23545-23560.