ERF WORKING PAPERS SERIES

Does the Inverted U-Shaped Kuznets Environmental Curve Hold for Sudan? Evidence from the ARDL Approach

Mohammed Elhaj Mustafa Ali
and Abdul-Hameed Elias Suliman

ECONOMIC RESEARCH FORUM
منتدى البحوث الاقتصادية

Working Paper No. 1777
May 2025

DOES THE INVERTED U-SHAPED KUZNETS ENVIRONMENTAL CURVE HOLD FOR SUDAN? EVIDENCE FROM THE ARDL APPROACH

Mohammed Elhaj Mustafa Ali[1] and Abdul-Hameed Elias Suliman[2]

Working Paper No. 1777

May 2025

Send correspondence to:
Mohammed Elhaj Mustafa Ali
University of Khartoum
mohdaj1976@gmail.com

[1] Development Studies and Research Institute (DSRI), University of Khartoum. Email: mohdaj1976@gmail.com
[2] Development Studies and Research Institute (DSRI), University of Khartoum. Email: abuhis@gmail.com

First published in 2025 by
The Economic Research Forum (ERF)
21 Al-Sad Al-Aaly Street
Dokki, Giza
Egypt
www.erf.org.eg

Abstract

This study primarily aims to test the applicability of the inverted U-shaped Environmental Kuznets Curve (EKC) hypothesis to Sudan using time series data from 1970 to 2022. The study is driven by the rise in greenhouse gas emissions—such as carbon dioxide (CO2) and methane (CH4)—during the last decades in which the country became an oil producer and exporter. To achieve this objective, the study employs the Autoregressive Distributed Lag (ARDL) co-integration technique, which is well-suited for analyzing short- and long-run relationships. Following the essential pre-tests, the analysis reveals a significant integrated relationship among the variables under consideration. The primary finding of the analysis is that the EKC in Sudan follows a U-shaped pattern. This implies a direct relationship between economic development and environmental deterioration, particularly in terms of CO2 emissions. The findings also highlight that the continuous growth in energy consumption, electricity production, and urbanization directly contributes to environmental degradation. Based on these results, the study proposes a number of recommendations, including policy interventions and behavioral changes, aimed at addressing the environmental imbalance identified in the analysis.

Keywords: Inverted U-shaped Environmental Kuznets, Greenhouse gas emissions, Sudan
JEL Classifications: Q5.

ملخص

تهدف هذه الدراسة إلى اختبار مدى إمكانية تطبيق فرضية منحنى كوزنتس البيئي التي يمثلها شكل حرف U المقلوب على السودان وذلك باستخدام بيانات سلاسل زمنية تغطي الفترة من 1970 إلى 2022. الدافع وراء هذه الدراسة هو الطفرة الكبيرة في انبعاثات الغازات المسببة للاحتباس الحراري العالمي، مثل ثاني أكسيد الكربون والميثان و التي زادت خلال العقود الأخيرة متزامنةً مع تحول البلاد إلى إنتاج وتصدير النفط. لتحقيق هذا الهدف، تستخدم الدراسة منهجية التكامل المشترك في إطار منهجية الانحدار الذاتي للفجوات الموزعة (ARDL) التي تُعد مناسبة لتحليل العلاقة بين المتغيرات في المديين القصيرة والطويل. بعد إجراء الاختبارات الأولية الحتمية من منظور القياس الاقتصادي، أماط التحليل اللثام عن وجود علاقة تكامل مشترك معنوية بين المتغيرات قيد الدراسة. النتيجة الأساسية للتحليل هي أن منحنى كوزنتس البيئي في السودان يتبع نمطا على شكل حرف U وليس حرف U المقلوب وهو ما يدلل على وجود علاقة مباشرة بين التنمية الاقتصادية والتدهور البيئي في السودان ممثلاً بزيادة انبعاثات ثاني أكسيد الكربون. كما أبرزت النتائج أيضا أن النمو المستمر في استهلاك الطاقة وإنتاج الكهرباء والتحضر يفاقم التدهور البيئي. بناءً على هذه النتائج، تقترح الدراسة عددا من التوصيات، بما في ذلك التدخلات باتباع سياسات معينة وكذلك تشجيع بعض التغييرات السلوكية بهدف معالجة الخلل البيئي الذي تم تحديده من خلال هذه الدراسة.

1. Introduction

The challenge of reversing environmental degradation and moving toward sustainability is one of the most pressing and heated issues in developed countries. In contrast, most developing countries remain secure havens for pollutants due to their flexibility and relaxed stance on environmentally harmful activities (Esty and Geradin, 1998; Lau et al., 2018). This is largely due to the fact that these countries prioritize economic growth and industrial development over environmental protection (Harrison, 1996; Peters and Hertwich, 2008; Zhang, 2008). Many economic activities in developing countries operate without strict regulations or enforcement, leading to high levels of pollution in the air, water, and soil (Khanam et al., 2023; Blackman and Harrington, 2018). Sudan is among the developing countries grappling with the dilemma of prioritizing economic growth and industrial development over environmental protection due to limited resources and competing priorities. This prioritization often leads to the exploitation of natural resources without proper sustainable planning, resulting in environmental degradation. In other words, the country's focus on dealing with poverty and economic growth has often come at the expense of environmental conservation efforts.

As a result, Sudan faces numerous environmental challenges such as deforestation, desertification, and air and water pollution. For instance, the total amount of carbon dioxide (CO2) emissions in the country increased from a negative growth rate (i.e., a negative carbon country) at the beginning of the 1990s to 7.8 percent in 2000 and then to 95 percent in 2005 (World Bank, 2024). From 2005 onwards, CO2 emissions continued to grow annually by more than 100 percent, reaching 340 percent in 2022 (World Bank, 2024). In the same manner, the average growth rate in per capita CO2 emissions jumped from 0.32 percent in the 1980s to 72 percent in the 1990s and to 92 percent in the 2000s (World Bank, 2024). This dramatic rise shows that Sudan is experiencing a troubling environmental trajectory. In other words, although Sudan's economic growth in the 2000s was impressive (Mustafa et al., 2019), it came at a significant ecological cost, implying that the long-term effects of climate change may eventually surpass the short-term economic gains.[3]

The implications of increased CO2 emissions on climate change and local ecosystems are profound and far-reaching. Rising CO2 levels contribute to global warming, leading to erratic weather patterns and intensified droughts, which can devastate agricultural productivity and threaten food security in the country. Additionally, local ecosystems may experience shifts in biodiversity as species struggle to adapt to rapidly changing conditions, resulting in habitat loss and potential extinction for vulnerable species. Furthermore, ecosystem alterations driven by rising CO2 levels

[3] According to Stern (2007), the cost of climate change due to CO2 discharges is equivalent to a five percent decrease in the annual GDP. This implies that the economic impact of climate change could significantly undermine overall economic growth. This alarming statistic serves as a clarion call for urgent action, highlighting how unchecked climate change has the potential to stifle economic growth and jeopardize future prosperity.

disrupt habitats, endanger species, and diminish biodiversity, in addition to affecting wildlife, ecosystem resilience, and the human communities relying on natural resources.

The late 1990s oil production and the boom-driven influx of foreign direct investment (FDI) may partially explain this jump in CO2 emissions in Sudan. Specifically, oil production led to increased fossil fuel consumption, releasing large amounts of CO2 into the atmosphere. Additionally, FDI in industries with outdated technologies exacerbated Sudan's carbon footprint by increasing its emissions. Moreover, the lack of strict regulations and enforcement regarding emissions from industries and vehicles has contributed to these sharp increases in CO2 and other greenhouse gases. The country's growing population and urbanization might have also played a role in the rise of emissions, as more people began using cars and consuming energy. Additionally, the clearing of forests for agriculture and urban development has led to a loss of biodiversity and increased carbon emissions, further contributing to the country's environmental challenges.

This accelerating environmental degradation in Sudan, a country often referred to as the world's food basket, underscores a critical crisis that extends far beyond its borders. Official reports from the Food and Agriculture Organization (FAO) and the World Food Program (WFP) highlight Sudan as one of the six key countries for global food supply. This is evident from Sudan's abundant arable land, diverse crop varieties, and optimal climate conditions, all of which solidify its crucial role in guaranteeing food security on a global scale. Moreover, Sudan's strategic location in Africa enables efficient food distribution to regions with shortages, significantly contributing to alleviating food scarcity worldwide. Given these remarkable agricultural advantages, it is imperative for Sudan to prioritize environmental conservation to foster sustainable development and avert possible agricultural challenges.

In this study, we use the Environmental Kuznets Curve (EKC) framework to assess whether Sudan’s policies are contributing to the improvement or exacerbation of the environment. To achieve this objective, we apply the Autoregressive Distributed Lag (ARDL) method to time series data spanning from 1970 to 2022. This methodology allows for the examination of long-term relationships between variables while accommodating the potential for short-term dynamics. Moreover, utilizing this technique helps capture both immediate fluctuations and enduring trends in the interplay between economic growth and environmental impacts, providing a comprehensive understanding of this complex relationship.

Using the EKC to study the environmental consequences of economic development in Sudan contributes to the literature in several respects. First, accurately assessing the relationship between economic growth and environmental degradation through the EKC supports informed decision-making by policymakers to promote agricultural productivity while safeguarding natural resources. Second, the EKC analysis not only helps identify critical points where environmental degradation has intensified in Sudan, but it also guides the implementation of targeted interventions that harmonize economic objectives with environmental preservation. Third, as Sudan navigates the challenges of economic development, embracing the EKC estimation becomes essential for fostering a harmonious balance between growth and environmental preservation, ultimately paving the way for a resilient and prosperous future.

The remainder of the paper is organized as follows. Section 2 discusses the foundational concepts and existing research on the EKC. Section 3 examines trends in environmental indicators in Sudan and constructs their relationship with economic development. Section 4 introduces the theoretical underpinning of the EKC framework and the ARDL method. Section 5 presents the study findings, leading to the conclusion in section 6.

2. Literature review

Theoretically, the EKC suggests that environmental degradation worsens as a country's income rises but then improves once a certain level of economic development is reached. This suggests that as countries become wealthier, they are more likely to prioritize environmental protection and sustainability. The EKC is named after Simon Kuznets (1955), who used this notion for the relationship between inequality and economic growth, arguing that as a country's income increases, inequality first worsens before eventually improving. Researchers have applied this theory to various environmental issues like greenhouse gas emissions, deforestation, water pollution, and biodiversity loss. Kruger and Grossman (1993) were the first to apply the EKC theory to environmental economics in their groundbreaking study in which they tested the relationship between sulfur dioxide (SO2) and per capita income. They find that in the initial stages of economic development, SO2 emissions increase as income rises. However, once a certain income level is reached, emissions begin to decrease as countries begin investing more in cleaner technologies and instigating environmental regulation (Kruger and Grossman,1993).

Grossman and Kruger's work laid the groundwork for later research on the EKC, which has led to different conclusions. Some suggest an inverted U-shaped relationship, while others suggest linear or U- and N-shaped relationships. These variations in the outcomes make it difficult to draw a single, overarching conclusion about the EKC. The circumstances surrounding these studies, such as the choice of a specific pollutant, the context, and the time frame under study, may contribute to these disparities. For instance, studies using longitudinal data in various contexts have yielded varying conclusions regarding the applicability of the EKC. Harbaugh et al. (2002) use an updated and revised panel data set on ambient air pollution in global cities to assess the strength of evidence for an inverted U-shaped relationship between national income and pollution. They evaluate the sensitivity of the pollution-income relationship to functional definitions, supplementary covariates, and changes between countries, cities, and years. These changes significantly influence the results, leading them to conclude that the dataset doesn’t provide much evidence for a U-shaped relationship. In the same way, Wang (2012) investigates the link between CO2 emissions from oil and GDP using panel data for 98 countries from 1971 to 2007. His empirical findings do not corroborate the exactness of the EKC concept. Apergis (2016) uses data on per capita CO2 emissions and per capita real GDP for 15 nations from 1960 to 2013 to verify the existence of the EKC at the panel and country levels. The author applies both panel-based and time-series-based cointegration methods. Based on the quantile cointegration technique, his findings show that the EKC hypothesis holds in 12 of the 15 countries.

In contrast, Wang et al. (2024) use global panel data from 147 countries from 1995 to 2018 to investigate the correlation between trade protection, economic growth, and environmental degradation, with a focus on the EKC hypothesis. Their research indicates that increasing income levels amplify the adverse effects of economic expansion on environmental degradation, whereas trade protectionism worsens this issue, especially in lower-income nations. Similarly, Cole (2004) investigates the Pollution Haven Hypothesis (PHH), which suggests the movement of "dirty" businesses from developed to developing regions, to explain the inverted U relationship of the EKC. He uses data on North-South trade flows for pollution-intensive products and estimates emissions for 10 pollutants. The study validates the PHH's presence but finds its impact to be limited and minor. Following the same argument, Tang (2015) analyzes the impact of registry listings on US bilateral trade flows, confirming a significant shift toward imports from less affluent economies. He argues that stricter environmental regulations may lead to pollution havens if environmental protection is seen as a normal good.

In certain instances, segmenting the longitudinal sample into groups with varying degrees of homogeneity or using a predictor other than GDP per capita frequently reveals the absence of agreement regarding the EKC. Lee et al. (2010) re-evaluate the EKC hypothesis on water pollution by employing the GMM method for 97 countries from 1980 to 2001, and they identify inverted U-shaped EKC relationships in the Americas and Europe but not in Africa, Asia, or Oceania. In the same way, Kaufmann et al. (1998) study the relationship between income and economic activity density on SO2 air concentration in 23 countries from 1974 to 1989. They find a U-shaped relationship between income and atmospheric SO2 concentration and an inverted U-shaped relationship between economic activity intensity and SO2 concentration. A study by Tenaw and Beyene (2021) looks at how natural resource wealth affects the link between the environment and development in 20 Sub-Saharan African countries from 1990 to 2015 using the EKC model with a focus on sustainability. Their findings confirm the presence of a modified EKC theory in Sub-Saharan Africa, which incorporated specific considerations for the region's natural resource abundance.

Canas et al. (2003) confirm the link between material input per capita and income in 16 developed countries. They find that the relationship followed both quadratic and cubic EKC curves, as well as an inverted-U quadratic pattern with a main upward trend. Perman and Stern (2003) evaluate the EKC hypothesis using a cointegration analysis on a panel dataset of SO2 emissions and GDP for 74 countries over a period of 31 years. They find that the data show stochastic trends, suggesting a concave relationship between SO2 emissions and income. However, the authors conclude that both individual and panel cointegration tests raise questions about the universal applicability of the EKC, making it a contentious notion. Stern and Common (2001) use a global sample to assess the relevance of the SO2 and EKC. They find that SO2 emissions per capita are a monotonic function of income in a global sample but an inverted-U-shaped function in high-income countries. However, upon assessing the model in terms of initial differences, the researchers find a monotonic EKC in both high-income and global samples.

Testing the EKC hypothesis by sector or local territories has also not led to a consensus on the phenomenon's validity, highlighting the need for more complex analyses. For instance, Htike et al. (2021) examine the EKC sectoral CO2 emissions in 86 developing and developed countries from 1990 to 2015. They discover that the EKC is applicable to three sectors: electricity and heat production, commercial services, and the energy industry's own use. Ehigiamusoe et al. (2021) study the impact of agricultural, industrial, financial, and service sectors on environmental pollution in Malaysia from 1980 to 2018 and find that these sectors have inverted U-shaped non-linear effects on CO2 and ecological footprints, while the financial sector has a U-shaped relationship. Using Pesaran's (2006) Common Correlated Effects (CCE) method, Apergis et al. (2017) assess the validity of the EKC hypothesis across 48 US states, finding that the hypothesis is applicable in only 10 states, whereas it is not valid for the remaining 38 states.

The variability in the results regarding the validity of the EKC is also apparent in studies conducted at a single country level. In other words, while some countries may display the expected inverted U-shape relationship between economic growth and environmental degradation, others can produce different outcomes, highlighting the complexity of this phenomenon. For instance, Sarkodie et al. (2020) test the EKC hypothesis in Kenya using an ARDL technique, a refined adaptation of partial least squares regression, and the U-test method. They find that the used models supported an inverted U-shaped curve, confirming its validity in Kenya. Beşe et al. (2020) employ the ARDL model to analyze the effect of economic growth on coal consumption in China and Australia, two nations significantly reliant on coal for energy. Their results validate the existence of an inverted U-shaped EKC for coal consumption.

Ahmad et al. (2017) study the EKC in Croatia from 1992 to 2011 using ARDL and VECM methodologies. Their results show an inverted U-shaped relationship between CO2 emissions and economic growth in the long term, confirming the EKC's validity. Meanwhile, Wang et al. (2016) examine the correlation between economic development and SO2 emissions in China to ascertain the validity of the EKC. Utilizing semi-parametric panel data analysis, their study finds that there is evidence of an inverted U-shaped relationship between GDP per capita and SO2 emissions. Fosten et al. (2012) examine the emissions dynamics concerning the EKC during periods of disequilibrium in the United Kingdom and reveal a real "inverted-U" relationship between CO2 and SO_2 per capita emissions and GDP per capita. Using the ARDL model, Tenaw (2021) look at how economic growth affected CO_2, CH_4, and nitrous oxide (N_2O) emissions in Ethiopia and validate the presence of an inverted U-shaped curve for CH_4 and N_2O emissions.

In the context of Sudan, the focus of this study, Mohamed (2018) uses yearly time series data and the OLS and ARDL methods to evaluate the role of energy and economic growth in explaining CO_2 emissions in Sudan from 1969 to 2015. His findings reveal a positively signed and statistically significant coefficient for both GDP per capita and squared GDP per capita variables, thereby refuting the EKC hypothesis. Eldowma et al. (2023) employ the ARDL bound testing methodology and additional econometric tools to investigate the correlation among population, energy consumption, CO_2, and economic growth in Sudan from 1971 to 2019. Their findings demonstrate substantial positive correlations among the total population, environmental degradation, and economic growth. Mohamed (2020) examines the influence of economic growth, agricultural expansion, and energy use on CH_4 and nitrous oxide (N_2O) emissions in Sudan. Using the EKC paradigm, he discovers a long-term equilibrium relationship between CH_4 and N_2O emissions, where economic development, trade openness, and FDI significantly influence CH_4 emissions. Energy consumption, agricultural expansion, and FDI all had a greater impact on N_2O emissions, while agricultural growth had no immediate effect. Additionally, the author confirms that the EKC is not applicable to CH_4 or N_2O emissions, with N_2O emissions being more affected by economic growth, agricultural growth, and energy use than CH_4 emissions.

Shahbaz et al. (2012) examine the correlation among CO_2 emissions, energy consumption, economic growth, and trade openness in Pakistan from 1971 to 2009. They identify a long-run relationship that validates the EKC notion. Esteve and Tamarit (2012) analyze the long-run relationship between per capita CO_2 emissions and per capita income in the Spanish economy from 1857 to 2007, incorporating threshold cointegration techniques to address a potential non-linear relationship. Their findings validate the non-linear relationship between the aforementioned factors, indicating the presence of an EKC in the Spanish context. Saboori et al. (2012) investigate the relationship between CO_2 and economic growth in Malaysia. Their study reveals a long-run relationship between CO_2 emissions and GDP in Malaysia, supporting the existence of an EKC. Using time series data from 1975 to 2005, Jalil and Mohmud (2009) investigate the existence of the EKC in China and find a quadratic relationship between GDP per capita and CO_2 emissions, supporting the EKC. Fodha and Zaghdoud (2010) find a long-term cointegrating link between the per capita emissions of CO_2 and SO_2 and GDP in Tunisia. They identify an inverted EKC U-shape between SO_2 emissions and GDP, with an income turning point estimated at around USD 1,200 or USD 3,700.

In contrast, Beşe and Kalayci (2021) evaluate the EKC hypothesis for Denmark, the United Kingdom, and Spain between 1960 and 2014. Their findings show that the EKC hypothesis is invalid for Denmark, the United Kingdom, and Spain, while the neutrality hypothesis is valid.

Akpan (2011) examine the applicability of the EKC to Nigeria by applying the ARDL to annual time series data from 1960 to 2008. Using CO2 emissions per capita as a proxy for environmental degradation, his results contradict the EKC theory. Instead, his results show an N-shaped relationship with a turning point at around USD 77.27, much below the dataset utilized in the analysis. El-Aasar and Hanafy (2020) examine the presence of the EKC in Egypt from 1971 to 2012. Their findings indicate that the EKC hypothesis is not applicable to greenhouse gas emissions in Egypt, both in the short and long run. Friedl and Getzner (2003) examine the correlation between economic development and CO2 emissions in Austria, a small, open, and industrialized nation. The authors examine whether an EKC relationship is applicable to a single country rather than focusing on panel or cross-sectional data from multiple countries. They discover a cubic (N-shaped) relationship between GDP and CO2 emissions that best fit the data for the period 1960-99. Moreover, their findings validate the established pollution haven hypothesis.

3. The trajectory of environmental performance in Sudan

Sudan’s environmental trajectory has undergone a profound transformation, as evidenced by the rapid growth in CO2 emissions over the last decades. Table 1 provides a comprehensive overview of Sudan’s total CO2 emissions in comparison to global and regional benchmarks. During the 1970s, Sudan’s emissions were negligible, averaging 3.97 Mt CO2e between 1970 and 1974. This positioned Sudan as a minimal contributor to global emissions, especially when compared to regions like Sub-Saharan Africa (318.03 Mt CO2e) and the Arab world (322.68 Mt CO2e). However, by the 2015-22 period, Sudan’s emissions had surged to 26.77 Mt CO2e, reflecting nearly a sevenfold increase. While Sudan's emissions are still lower than those of regions such as the Middle East and North Africa (MENA), which recorded emissions of 3,064.76 Mt CO2e during the same period, Sudan's growth rate significantly outpaces many of its neighbors. This rapid increase is closely tied to industrialization, fossil fuel dependency, and urbanization, highlighting the significant environmental trade-offs associated with Sudan’s economic development.

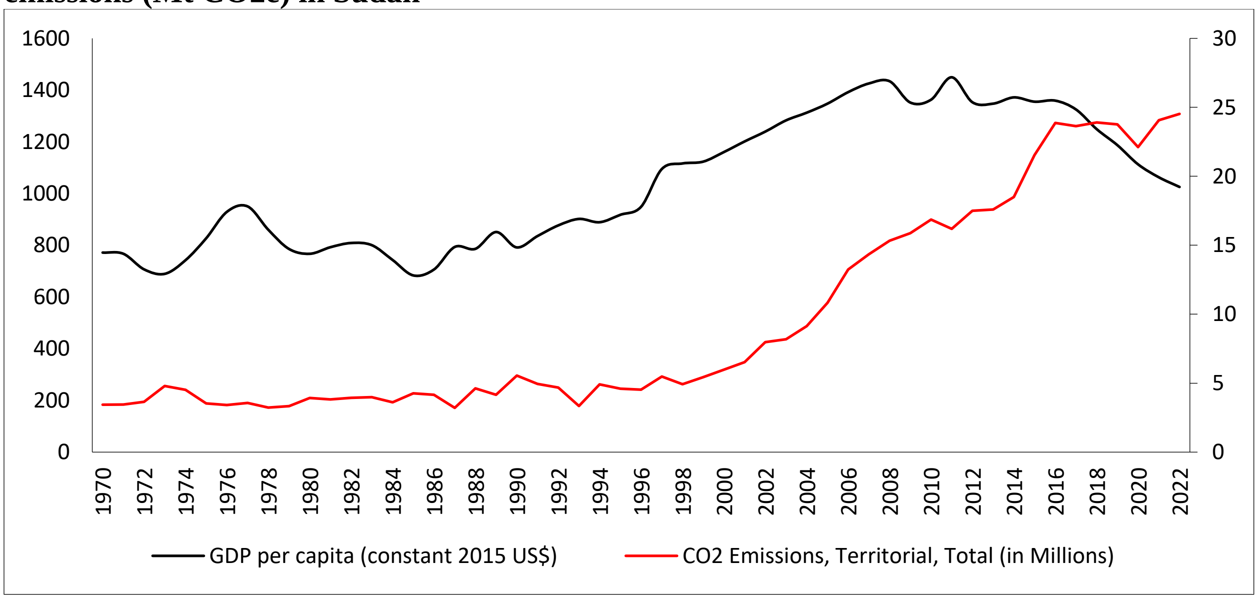
Table 1. Total CO2 emissions (in Mt CO2e) in Sudan with global and regional comparison

Year	World	SSA	MENA	Africa Western and Central	Africa Eastern and Southern	Arab World	Sudan
1970-74	-	318.03	433.04	75.17	242.86	322.68	3.96
1975-79	-	383.49	599.83	100.67	282.81	446.84	3.41
1980-84	-	413.52	688.33	100.57	312.95	534.31	3.85
1985-89	-	457.92	811.72	101.75	356.16	620.80	4.08
1990-94	22659.89	479.36	1014.47	110.11	369.24	742.55	4.68
1995-99	24304.34	548.40	1261.25	134.59	413.80	912.26	4.99
2000-04	26862.51	609.41	1525.94	151.34	458.07	1083.71	7.56
2005-09	31437.12	700.26	1976.27	149.17	551.09	1398.30	13.92
2010-14	35299.35	775.96	2408.68	182.48	593.47	1756.46	17.32
2015-22	42501.51	960.49	3064.76	257.41	703.07	2265.20	26.77

Source: World Development Indicators, World Bank (2024).

Figure 1 illustrates the relationship between GDP per capita and total CO2 emissions, capturing the evolving dynamics of Sudan's economic and environmental progress. The graph reveals a clear upward trajectory, demonstrating that as GDP per capita (in constant 2015 USD) increases, so do CO2 emissions. This trend reflects a U-shaped EKC, which deviates from the conventional inverted U-shaped pattern observed in many developed economies. In the case of Sudan, economic growth appears to amplify environmental degradation rather than mitigate it at higher income levels. This phenomenon is typical of developing nations during the early phases of industrialization, where economic priorities often overshadow environmental concerns. The absence of stringent environmental regulations and the reliance on carbon-intensive industries contribute to this pattern, suggesting that Sudan has not yet reached the turning point where economic growth leads to environmental improvement.

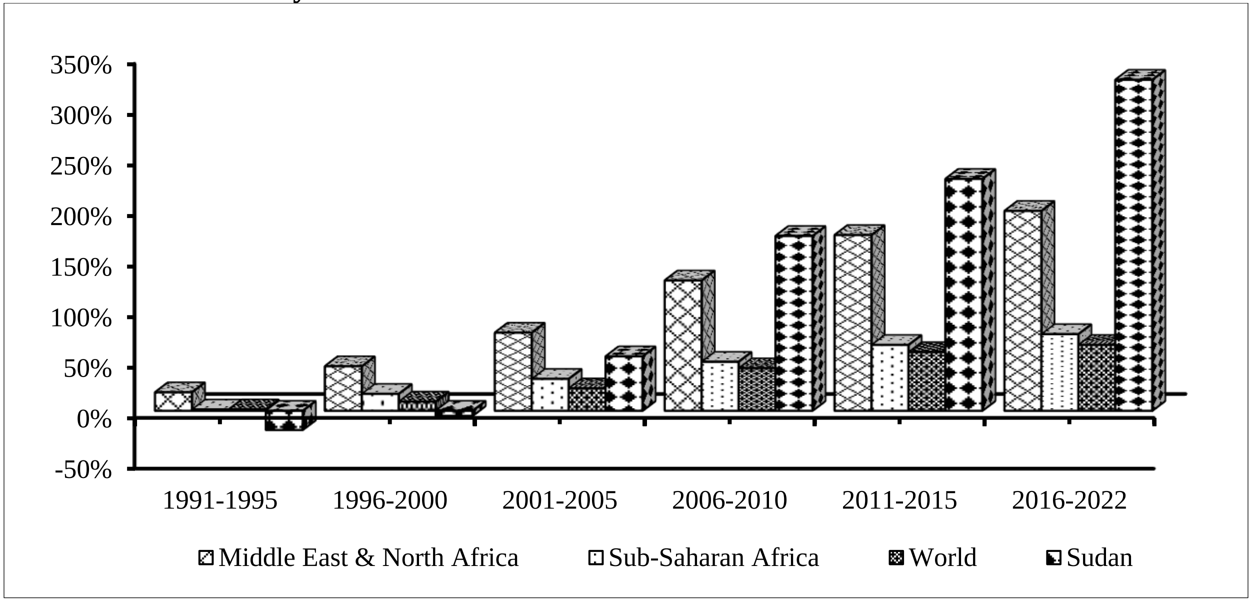
Figure 1. The interplay between GDP per capita (constant 2015 USD) and total CO2 emissions (Mt CO2e) in Sudan



Source: World Development Indicators, World Bank (2024).

Figure 2 highlights the percentage changes in CO2 emissions relative to the baseline year of 1990, offering a more granular perspective on Sudan's emissions growth. The data indicate an exponential rise, with emissions increasing by over 100 percent annually in some periods, culminating in a staggering 340 percent increase by 2022. This dramatic escalation coincides with Sudan's industrial boom and growing energy demands. The country's reliance on fossil fuels and biomass as primary energy sources has exacerbated this trend, reflecting the environmental cost of Sudan's economic development. The steep growth in emissions underscores the urgency of transitioning to cleaner energy alternatives and implementing policies to curb environmental degradation.

Figure 2. Changes of CO2 emissions in Sudan (as %) of current year with respect to emissions in baseline year 1990 emissions



Source: World Development Indicators, World Bank (2024).

Table 2 focuses on CO2 emissions per capita, comparing Sudan to other countries such as Saudi Arabia, Libya, Egypt, and its neighbors, Chad and Ethiopia. While Sudan's per capita emissions remain relatively modest—rising from 0.28 t CO2e in the 1970s to 0.52 t CO2e in 2020-22—they show a steady upward trajectory. This places Sudan ahead of its immediate neighbors, such as Ethiopia (0.167 t CO2e) and Chad (0.121 t CO2e), but far below more industrialized nations like Saudi Arabia (16.33 t CO2e) and Egypt (2.27 t CO2e). The relatively low emissions per capita can be attributed to Sudan's slower pace of industrialization compared to these nations. However, the steady increase reflects growing environmental pressures as urbanization and energy consumption intensify. The rise in per capita emissions is a stark reminder of Sudan's need for sustainable urban planning and investment in renewable energy sources to counteract these trends.

Table 2. CO2 emissions per capita (t CO2e/capita) in Sudan with some comparable countries

Year	Saudi Arabia	Libya	Egypt	Sudan	Eritrea	Chad	Ethiopia
1970-79	12.47	10.28	0.822	0.280	0.214	0.043	0.036
1980-89	12.89	7.700	1.367	0.208	0.168	0.036	0.037
1990-99	11.492	8.889	1.638	0.209	0.297	0.028	0.047
2000-09	13.90	9.381	2.161	0.359	0.228	0.041	0.073
2010-19	22.28	11.68	3.154	0.687	0.248	0.139	0.176
2020-22	16.33	8.515	2.268	0.516	0.213	0.121	0.167

Source: World Development Indicators, World Bank (2024).

As Sudan navigates its changing environment, the continuous increase in CO2 emissions highlights the urgent difficulties and opportunities present. Although its traditionally low emissions are ascribed to a more gradual industrialization relative to regional peers such as Saudi Arabia and Egypt, the rapid urbanization and escalating energy demand indicate a significant transformation. Addressing this trajectory will necessitate a concentrated effort toward sustainable urban development and significant expenditures in renewable energy resources. By implementing these techniques, Sudan may not only reduce its environmental effect but also establish itself as a regional leader in sustainable development, assuring a healthier future for both its people and the world.

4. Modeling and data

4.1. Model specification

This study employs the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) modeling framework as proposed by York et al. (2003) and Dietz and Rosa (1994, 1997) to evaluate the relevance of the EKC in Sudan. Both studies stated that the STIRPAT model enables researchers to analyze the connections between environmental consequences and human activities by disaggregating different driving elements. Following the lead of those authors, the STIRPAT model can be written in the usual notation as follows:

$$I_t = \alpha P_t^{\alpha} A_t^{\alpha} T_t^{\alpha} \varepsilon_t \tag{1}$$

where I_t represents the environmental quality; P represents inhabitants; A represents the affluence status experienced by the inhabitants; T represents the technology; t represents time, and ε is the normally distributed error term. The variables on the right-hand side can be expanded to incorporate the factors that the previous studies have agreed to include in models aiming at forecasting the status of environmental quality. In the context of this study, the terms I, P, and A can all serve as descriptors for CO2 emissions, urban population, and real GDP per capita, respectively. Moreover, the term T can be disaggregated to include energy consumption, energy production, domestic capital formation, and FDI. Thus, incorporating these variables and taking the logarithmic form, Equation (1) can be rewritten as follows:

$$lnCO2_t = \varphi_0 + \varphi_1 lnUPOP_t + \varphi_2 lnGDPPC_t + \varphi_3 lnGDPPC_t^2 + \varphi_4 lnENCO_t + \varphi_5 lnELEP_t + \varphi_6 lnGDK_t + \varphi_7 FDIGDP_t + \varphi_8 PRIV + \varepsilon_t \tag{2}$$

Where $CO2$ is CO2 emissions; $UPOP$ is urban population; $GDPPC$ is real GDP per capita; $ENCO$ is total energy consumption; $ELEP$ is electricity production; GDK is domestic capital formation; $FDIGDP$ is FDI as a percentage of GDP, $PRIV$ is a dummy variable representing the implementation of privatization policy taking value of 0 for the period from 1992 and onward and 0 otherwise; the φ_i $i = 1,2,3, \ldots, 8$ are the parameters to be estimated; and t and ε remained as defined before.

4.2. Estimation method

This study utilizes the ARDL model developed by Pesaran (2001) to examine the applicability of the EKC to the context of Sudan as represented by Equation (2). First, this approach enables a comprehensive assessment of the correlation between economic growth and environmental degradation in Sudan by overcoming the challenges posed by limited data availability. Second, the ARDL model can account for both short-run and long-run effects, providing a nuanced understanding of the relationship between economic development and environmental degradation. Third, the flexibility of this approach allows for the inclusion of multiple variables, such as population, FDI, and government policies, which can influence the relationship between economic development and environmental degradation. Overall, the use of the ARDL model enhances the rigor and accuracy of the analysis, offering valuable insights for policymakers and researchers interested in sustainable development in Sudan.

The essential step in estimating the ARDL cointegration model begins with ensuring that none of the variables is of order greater than one. This is crucial because if any variable is integrated of order two or higher, it can lead to misleading results and invalidate the cointegration analysis. Therefore, the analysis commences with conducting three-unit root tests: Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS), to evaluate the stationarity properties of the variables. This is crucial because integrating any variable of order two or higher can lead to misleading results and invalidate the cointegration analysis. If these tests indicate that all variables are stationary at level I(0) or integrated into order I(1), the next step is to determine the appropriate lag length for the ARDL model. This can be accomplished using six criteria, including the Akaike Information Criterion (AIC), the Schwartz Bayesian Criterion (SBC), and the Hannan-Quinn Information Criterion (HQIC), among others, which help in selecting the optimal lag structure for reliable estimation of the relationship between the variables.

Once we identify the optimal lag length, we can apply the ARDL bounds testing approach to assess the presence of a long-run relationship among the variables under consideration. This test is conducted by comparing the calculated F-statistic against critical values prepared by Pesaran (2001). If the F-statistic exceeds the upper bound critical value, we reject the null hypothesis of no long-run relationship (i.e., $\varphi_i = 0, i = 1,2,3, \dots ,8$) and accept the alternative hypothesis (i.e., $\varphi_i \neq 0, i = 1,2,3, \dots ,8$.), indicating the presence of such a relationship among the variables. Conversely, if the F-statistic is below the lower bound, we fail to reject the null hypothesis, suggesting that no long-term association exists. If the F-statistic falls within these bounds, we need to conduct further investigation to understand the dynamics between the variables.

Having confirmed the presence of a long-run relationship between the variables in the EKC model, the next step involves estimating both the short- and long-run relationships between them. We accomplish this by estimating the unrestricted error correction models, which allows for a comprehensive understanding of how these variables interact over time. Specifically, this approach identifies long-run relationships while allowing for short-run variations, which produces a more solid understanding of the model's dynamics. We will rewrite Equation (2) in an unrestricted form to accommodate the dynamics of short-run adjustments while retaining the long-run equilibrium relationship as follows:

$$
\begin{aligned}
\Delta CO2_t = \alpha_0 + \sum_{i=1}^{n} \alpha_{1i} \Delta lnGDPPC_{t-1} \\
+ \sum_{i=1}^{p} \alpha_{2i} \Delta lnGDPPC^2{}_{t-1} + \sum_{i=1}^{q} \alpha_{3i} \Delta lnGDK_{t-1} + \sum_{i=1}^{r} \alpha_{4i} \Delta lnUPOP_{t-1} \\
+ \sum_{i=1}^{s} \alpha_{5i} \Delta lnENCO_{t-1} + \sum_{i=1}^{v} \alpha_{6i} \Delta lnELEP_{t-1} + \sum_{i=1}^{w} \alpha_{7i} \Delta FDIGDP_{t-1} \\
+ \varphi_1 CO2_{t-1} + \varphi_2 lnGDPPC_{t-1} + \varphi_3 lnGDPPC^2{}_{t-1} + \varphi_4 lnGDK_{t-1} \\
+ \alpha_5 lnUPOP_{t-1} + \varphi_6 lnENCO_{t-1} + \varphi_7 lnELEP_{t-1} \\
+ \varphi_8 FDIGDP_{t-1} + \varphi_9 PRIV_{t-1} + \delta ECT_{t-1} + \varepsilon_t
\end{aligned} \tag{3}
$$

Where Δ is first difference operator; α_i $i = 1,2, \ldots,9$; n, p, q, r, s, v, and w are the lag length of the explanatory variables; ECT_{t-1} is the error correction term; δ is the coefficient of the error correction term, which plays a crucial role in this analysis, as it quantifies the speed at which the variables return to equilibrium after a short-run shock. A significant coefficient suggests a strong cointegration relationship between the variables and highlights the importance of correcting deviations in a timely manner Δ.

In Equation (3), $lnGDPPC$ and $lnGDPPC^2$ are the variables of interest, as they both depict the route of the EKC for the Sudan. Thus, understanding the parameters of these variables is crucial. If these parameters are zero (i.e., $\varphi_2 = \varphi_3 = 0$), it can be concluded that the GDP per capita does not significantly impact environmental quality (i.e., there is a flat relationship between lnCO2 and lnGDPPC). If the parameter of $lnGDPPC_t$ is greater than that of $lnGDPPC_t^2$ (i.e., $\varphi_2 > 0$ and $\varphi_3 < 0$) it can be concluded that increases in GDP per capita improve environmental quality, implying that the relationship between CO2 and economic development takes the form of an inverted U-shaped curve. Contrarily, if the GDP per capita parameter is smaller than the quadratic term, we can conclude that rising GDP per capita degrades environmental quality, suggesting a U-shaped relationship between CO2 and economic development.

The sign of the coefficient of the domestic capital formation variable is unknown (φ_4 =?) and needs empirical verification. This is due to the possibility that an increase in domestic capital could stem from increased capital accumulation in both direct and indirect ecologically sustainable industrial activities, which would subsequently lead to a reduction in CO2 emissions. In contrast, a rise in domestic capital formation might also be associated with traditional industries that rely heavily on fossil fuels, potentially increasing carbon emissions.

We expect the urban population variable to have a positive coefficient ($\varphi_6 > 0$). This indicates that growing urban populations will result in successive increases in CO2 emissions. In other words, as urban areas expand and develop, factors such as increased transportation, industrial activity, and energy consumption typically contribute to higher emissions levels. Similarly, the coefficient for the energy consumption variable is expected to be positive ($\varphi_6 > 0$) since increases in energy usage are projected to increase CO2 emissions. Intuitively, increased energy consumption typically correlates with higher levels of CO2 emissions, as more energy usage often leads to greater carbon output. Additionally, as firms invest in more energy-intensive technologies, the overall demand for energy is likely to rise, further reinforcing this positive relationship. Similarly, the electricity production variable's coefficient is expected to show a positive sign ($\varphi_7 > 0$). This is because higher energy production, particularly from fossil fuel sources, contributes significantly to carbon emissions.

Numerous studies, such as Grossman and Krueger (1993), Antweiler et al. (2001), and Miniesy and Tarek (2019), have demonstrated that FDI significantly influences the environmental quality of host countries. This argument frequently arises in the context of the pollution haven hypothesis, which contends that affluent countries send polluting companies to impoverished countries that are preoccupied with poverty alleviation and underdevelopment. However, some argue (Gokmenoglu and Taspinar, 2016; Blanco et al., 2013; Kisswani and Zaitouni, 2023) that FDI can enhance environmental standards in host countries, as companies may bring advanced technologies and practices that foster ecological sustainability. Additionally, the influx of FDI can enable governments to invest in better regulatory frameworks and infrastructure, thereby benefiting the economy and the environment. Therefore, the coefficient for the FDI variable is yet to be determined ($\varphi_8 = ?$). Many authors have posited that the adoption of specific economic policies could alter environmental circumstances (Li et al., 2024; Swyngedouw, 2018; Grubb et al., 2015; Dawson, 2011). Nevertheless, the success of these policies will be determined by the circumstances and scope of their implementation. Accordingly, in this study, we are uncertain about the impact of adopting privatization on environmental quality in Sudan ($\varphi_9 = ?$).

Finally, we perform numerous residual diagnostic tests, such as the Jarque-Bera test for normality, the Breusch-Godfrey test for autocorrelation, multicollinearity checks, a test for heteroscedasticity, and the Ramsey reset test for functional form specification, to ensure the model's robustness and provide confidence in the findings. Additionally, CUSUM and CUSUM squares tests are conducted to assess the stability of regression coefficients over time.

4.3. Data

The data used by this study primarily come from the World Bank Development Indicators, which are compiled and published by the World Bank. The World Bank's data include diverse economic, social, and environmental factors that offer valuable insights into the development of countries.

This data encompasses essential indicators such as CO2 emissions, GDP per capita, gross domestic capital, total population, and FDI as a percentage of GDP, providing a comprehensive view of economic and environmental aspects. Unfortunately, the World Bank development indicators do not report data on total energy consumption and electricity generation specifically for Sudan. As a result, we gathered information on total energy consumption and power output from the OIC Statistics database (OICStat), which covers 1,825 variables across 27 categories. Table 3 provides the definitions and sources of the variables used in this study.

Table 3. Variables definitions and data sources

Variable	Definition	Units of Measure	Time Period	Source
CO2	CO2 emissions	Metric ton	1970-2022	WDI
GDPPC	Gross domestic product per capita	Constant 2015 US$	1970-2022	WDI
UPOP	Total urban population	Head	1970-2022	WDI
GDK	Gross domestic capital formation	Constant 2015 US$	1970-2022	WDI
ENCO	Total final energy consumption	Million tons of oil equivalent	1970-2022	Seseric
ELEP	Electricity production	Billion kWh	1971-2022	Seseric
FDIGDP	Foreign direct investment as % of GDP	Percent	1970-2022	WDI
PRIV	Implementation of privatization policies	0 before 1992 and 1 otherwise	1970-2022	-

5. Empirical results

The main objective of this study is to verify the status of environmental conservation in Sudan by estimating the EKC using the ARDL method. Before proceeding with the analysis, it is essential to confirm that the variables included in the model, represented by Equation (2), exhibit stationarity up to order (1) at most. Table 4 displays the results of these ADF, PP, and KPSS tests for the underlying variables, both with an intercept and without a linear trend, as well as with an intercept and with a linear trend. The tests reveal a significant variation in the results. For instance, when examining the variables with intercepts and without linear trends, tests showed that lnUPOP, lnGDPPC, and lnGDK variables were stationary. In contrast, the remaining variables did not exhibit stationarity.

Table 4. Summary of ADF, PP, and KPSS unit roots tests

Variable	ADF Test		PP Test		KPSS	
With Intercept and Without Linear Trend						
	Level	1st Difference	Level	1st Difference	Level	1st Difference
ln(CO2)	0.366	-9.569***	0.261	-9.575***	0.780	0.215**
ln(GDPPC)	-1.454	-4.373***	-1.124	-4.191***	0.660*	0.468**
ln (UPOP)	-0.829	-2.034**	-4.035***	-2.071*	0.972	0.661**
ln(GDK)	-1.415	-3.887***	-1.021	-3.896***	0.160**	0.309**
ln(ENCO)	-0.112	-9.671***	-0.131	-10.70***	0.9630	0.181***
ln (ELEP)	0.066	-6.161***	-0.013	-6.207***	0.844	0.131***
FDIGDP	-1.794	-7.609***	-1.695	-7.609***	0.649	0.106***
With Intercept and Linear Trend						
ln (CO2)	-1.741	-9.651***	-2.144*	-9.721***	0.216**	0.093***
ln (GDPPC)	0.437	-4.578***	-0.056	-4.513***	0.132***	0.191***
ln (UPOP)	-1.787	-1.679	-1.920	-1.873	0.243**	0.138***
ln (GDK)	-1.176	-4.224***	-0.669	-4.256***	0.158**	0.109***
ln (ENCO)	-2.974**	-9.574***	-2.809**	-10.68***	0.156**	0.182***
ln (ELEP)	-1.346	-6.131***	-1.565	-6.168***	0.207**	0.118***
FDIGDP	-1.925	-7.603***	-1.938	-7.603***	0.117***	0.071***

*Notes: *, **, and *** represent the one percent, five percent, and 10 percent levels of significance, respectively.*

Likewise, when examining variables with intercepts and linear trends, the lnENCO and lnCO2 were stationary, while the rest of the variables showed non-stationarity. Notably, the KPSS test revealed that most variables with an intercept and linear trend satisfied the stationarity condition. However, when we apply these tests to the initial differences between the variables, the situation reverses. This is because all variables attained stationarity at higher significance levels. Typically, as long as the variables meet the stationarity condition between the level and the first differential below order (2) I, they do not present a major issue and align with the ARDL methodology chosen for this analysis.

This outcome sets the stage for the second preliminary step, which involves the determination of a suitable lag length for the variables included in the model. Table 5 presents the results of the test conducted to determine the appropriate lag length for the variables included in the model. Based on the results obtained, it is evident that the appropriate lag order is 3, as it has the highest log likelihood, lowest FPE, and lowest AIC value. Moreover, the sequential modified LR test statistic supports the validation of this lag order. Hence, lag order 3 is considered the best choice for the dataset under consideration because it consistently outperforms other lag orders based on different criteria. Specifically, the higher log-likelihood value indicates that the model with this lag order captures the data more accurately. Additionally, the lower FPE and AIC values suggest that this model is more efficient and provides a better fit to the data. The sequential modified LR test statistic further confirms the superiority of this lag order by showing that it is statistically significant in explaining the data dynamics.

Table 5. Lag selection criteria tests

Lag	LogL	LR	FPE	AIC	SC	HQ
0	134.4	NA	6.36e-13	-5.380	-5.065	-5.262
1	589.8	736.4	3.86e-20	-22.03	-19.20*	-20.96
2	662.5	92.86	3.37e-20	-22.41	-17.05	-20.39
3	765.6	96.50*	1.29e-20*	-24.07*	-16.19	-21.11*

*Notes: * indicates lag order selected by the criterion; LR: sequential modified LR test statistic (each test at the five percent level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion.*

Following this, we proceed to verify the existence of the long-run relationships between the variables using the ARDL-bound test approach. Table 6 presents the bound test results and the values of both the tabulated F statistic from Pesaran (2001) and the computed F statistic from the ARDL estimates. Upon comparison, it is evident that the computed F value (7.46) exceeds the tabulated F-statistic values, surpassing their upper bound at the one percent, five percent, and 10 percent levels of significance. Consequently, the findings support rejecting the null hypothesis that there is no long-run association between the variables and favor accepting the alternative hypothesis. Having confirmed the long-run relationship between the variables, the analysis proceeds to scrutinize the short- and long-term relationships within the model, employing the ARDL technique.

Table 6. Results of the bounds test

Computed F-statistic: 7.46						
Sample Size	**10%**		**5%**		**1%**	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
45	2.131	3.223	2.504	3.723	3.383	4.832
50	2.099	3.181	2.457	3.650	3.282	4.730
Asymptotic	1.920	2.890	2.170	3.210	2.730	3.900

*Notes: * I(0) and I(1) are the stationary and non-stationary bounds, respectively.*

Table 7 reports the long-run ARDL estimators for Equation (3). From an econometric standpoint, the table indicates that the coefficients of the variables display the anticipated sign and possess plausible magnitudes. The outcomes of the interest are the signs and magnitudes of the coefficients for the lnGDPPC and lnGDPPC-squared variables, with the coefficient for the lnGDPPC variable being negative (-9.552) and the coefficient for the lnGDPPC-squared variable being positive (0.763). The signs of these two variables are crucial due to their relevance in shaping the EKC. The coefficient for the linear lnGDPPC variable is negative and statistically significant at the five percent level, indicating a robust relationship. Conversely, the coefficient of the lnGDPPC-squared variable exhibits a positive sign and is statistically significant at the same level of significance. This outcome provides compelling evidence of a positive and significant correlation between growth in non-linear lnGDPPC and CO2 emissions. This suggests that the EKC exhibits a U-shaped pattern, indicating a direct association between an increase in GDP per capita and a rise in environmental degradation. More precisely, a one percent increase in GDP per capita causes CO2 emissions to rise annually by roughly 0.76 percent.

This finding contrasts with the conventional inverted U-shaped EKC proposed by Grossman and Kruger (1993) in their seminal work, which suggests that as an economy grows, environmental degradation initially increases but eventually declines after reaching a certain level of income. This also contradicts numerous studies that endorse the presence of an inverted U-shaped EKC across various contexts. However, this outcome aligns with the findings of numerous studies that validate the existence of the U-shaped EKC (Harbaugh et al., 2002; Akpan, 2011; Wang, 2012; El-Aasar and Hanafy, 2018). The environmental context of Sudan at the current stage of development deems this result satisfactory, especially given its shift toward higher greenhouse gas emissions. Since the early 1990s, Sudan has shifted from being a carbon-negative nation to experiencing a substantial rise in greenhouse gas emissions, indicating a notable environmental transformation. This argument can also be supported by the substantial gap between the magnitudes of the coefficients of the lnGDPPC and lnGDPPC-squared variables, highlighting the robustness of the analysis.

The coefficient of the total urban population variable (lnUPOP), which represents the impact of the urban population on environmental conservation, is negative and statistically significant. This outcome suggests that an increase in urban population leads to enhanced environmental conservation in the long run. This may seem counterintuitive at first glance, but the unique rural-to-urban migration patterns in Sudan may justify this outcome. In this context, migration primarily results from the movement of rural populations to cities rather than from urban population growth. In other words, this migration frequently led to the eviction of residents from large areas of the rural part, which represents an incubator for environmental reservation. Rural dwellers typically depend on natural resources such as logging for timber, charcoal production for fuel, and overgrazing for sustenance—all of which intensify environmental degradation and strain ecosystems. Therefore, we expect their migration from rural to urban areas to reduce environmental degradation. Moreover, urban areas often have better access to technology and resources for waste management and renewable energy; this shift could lead to improved ecological outcomes and a more balanced relationship between human activity and the environment.

As expected, the energy consumption variable (lnENCO) exhibits a negative and larger coefficient, signifying a robust positive correlation with CO_2 emissions. The estimated coefficient of 3.407 indicates that a one percent rise in energy consumption results in an approximate 3.41 percent annual increase in CO_2 emissions. This outcome demonstrates the country's extreme reliance on environmentally detrimental energy sources, such as fossil fuels and wood, alongside the inadequate use of clean and renewable energy alternatives like solar and wind power. This also aligns with numerous prior studies, such as Smith et al. (2018) and Brown and Jones (2019), which have documented the positive correlation between environmentally unfriendly energy usage and environmental degradation in Sudan.

Surprisingly, the findings suggest that increases in gross domestic capital (lnGDK) diminish CO_2. The coefficient of the variable, which showed a negative sign and a statistically significant magnitude ($p < 0.05$), supports a strong inverse relationship between domestic capital formation and CO_2. The value of 0.152 for the variable implies that a 0.15-unit increase in the growth rate of domestic capital results in approximately a 0.15 percent decrease in environmental degradation. It is noteworthy that the infrastructure sector, encompassing roads, bridges, and dams, accounts for the majority of domestic capital accumulation in Sudan. This may partially explain the emergence of domestic capital as a catalyst for environmental conservation. Moreover, Sudan's industrial sector predominantly features horizontally organized light industries like textile manufacturing and food processing, demonstrating lower environmental impacts compared to heavy industries. In other words, this industrial structure allows for a more sustainable approach to development, as light industries typically have a lower environmental footprint.

Table 7. Estimates of the ARDL Model (1, 2, 2, 2, 0, 0, 3, 3)

Dependent Variable: CO2				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
Long Run				
lnGDPPC(-1)	-9.552**	4.749	-2.011	0.055
lnUPOP(-1)	-0.434***	0.152	-2.861	0.008
lnENCO(-1)	3.407***	0.760	4.480	0.000
lnGDK	-0.152***	0.041	-3.693	0.001
lnGDPPP^2	0.763**	0.343	2.225	0.035
FDIGDP(-1)	0.009	0.012	0.843	0.407
lnELEP(-1)	-0.559**	0.220	-2.539	0.017
PRIV	-0.139***	0.019	-7.108	0.000
Short Run				
Δln(GDPPC)	-9.938***	1.034	-9.605	0.000
Δln(GDPPC(-1))	-0.257*	0.140	-1.823	0.077
Δln(UPOP)	-3.666**	1.348	-2.718	0.010
Δln(UPOP(-1))	5.966***	1.453	4.104	0.000
Δln(ENCO)	2.276***	0.151	15.01	0.000
Δln(ENCO(-1))	-1.308***	0.207	-6.314	0.000
Δ (FDIGDP)	-0.018***	0.007	-2.521	0.018
Δ (FDIGDP(-1))	-0.026***	0.007	-3.618	0.001
Δ (FDIGDP(-2))	-0.037***	0.007	-4.882	0.000
Δln(ELEP)	-0.521***	0.111	-4.665	0.000
Δln(ELEP(-1))	0.1222	0.094	1.300	0.202
Δln(ELEP(-2))	-0.281***	0.099	-2.830	0.007
ECT	-0.984***	0.154	-6.397	0.000
Constant	35.96**	16.26	2.212	0.036
Statistics Tests				
R-squared	0.944			
Adjusted R-squared	0.921			
S.E. of Regression	0.039			
Sum Squared Resid	0.052			
Log Likelihood	93.25			
F-statistic	42.54			
Prob (F-statistic)	0.000			

*Notes: ***, **, and *indicate statistical significance at the one percent, five percent, and 10 percent significance levels, respectively.*

Interestingly, the coefficient for the electricity production variable (lnELEP) is negative and statistically significant at the one percent level. This outcome suggests that augmenting electricity generation enhances environmental quality in Sudan. The coefficient of the variable 0.559 indicates that a one percent increase in electricity power results in an approximate 0.56 percent reduction in CO2. This outcome indicates that electricity generation in Sudan remains predominantly reliant on environmentally sustainable technologies, particularly hydropower, known for its minimal environmental impact. This result confirms the findings of many scholars who have highlighted the importance of investing in renewable energy sources to combat climate change.

The variable representing the impact of the 1992 economic reforms (PRIV) on environmental degradation shows a negative coefficient and is statistically significant at the five percent level. This indicates that the implementation of this program leads to environmental preservation by reducing CO2. Initiating this policy resulted in a 0.13 percent reduction in CO2 compared to the period before its implementation.

Overall, there is a significant level of agreement between the short- and long-run results. For example, the negative sign of the per capita GDP variable (lnGDPPC) supports the hypothesis of the U-shaped EKC confirmed in the long run. It is opposite to the sign of the non-linear coefficient of the squared per capita GDP (lnGDPPC2) that appeared with the long-run estimates. In contrast, the urban population variable has undergone a transformation, showing a positive and significant association with CO2 when lagged by one year. The fact that the coefficient of the lagged variable (5.966) is higher than the coefficient of the level variable (-3.666) suggests that urban population growth has a total short-run effect of making environmental degradation worse. This highlights the immediate effect that population dynamics have on environmental quality.

The coefficient of the energy consumption variable is positive and significant, establishing it as the primary source of CO2 in both the long and short term. In contrast, the coefficient of the FDI variable at both the level and the lags is associated with negative signs and is statistically significant at a one percent significance level. This result highlights that the FDI inflows play a crucial role in reducing environmental degradation. Yet, the low coefficient value of 0.019 indicates that the impact of FDI is minor in comparison to domestic capital. This outcome is expected as Sudan receives a relatively small proportion of foreign investment inflows (Ali, 2018). Furthermore, due to the country's political climate, foreign investors prefer to invest in the service sector, avoiding higher capital-intensive sectors (Ali, 2018). Whatever the case is, this outcome challenges the pollution haven hypothesis, which posits that rich nations transfer polluting investments to developing countries.

Finally, the impact of the electricity production variable on environmental quality in the short term mimics its effect in the long term. The negative and statistically significant coefficient associated with this variable implies that electricity generation plays a crucial role in mitigating CO2, highlighting the pivotal role of clean energy production in ensuring environmental sustainability.

The coefficient of the error correction term is negative and statistically significant, indicating that the system is able to adjust back toward equilibrium after a shock. This implies that the system corrects deviations from the long-term relationship over time, thereby strengthening the stability of the underlying model. Specifically, the error correction term of -0.984 indicates that each period corrects approximately 98.4 percent of the disequilibrium, emphasizing a strong tendency for the variables to return to their long-term relationship after any disturbances. This rapid adjustment underscores the robustness of the framework being analyzed.

Table 8. The residual diagnostic tests

Diagnostic test	Estimated Value	Probability
Normality Test (Jarque-Bera)	1.514	[0.4689]
Breusch-Godfrey Serial Correlation LM Test	[1]:F (01,24) = 0.8276	[0.3720]
	[2]:F (02,23) = 0.4229	[0.6606]
	[3]:F (03,22) = 1.0704	[0.3819]
ARCH Heteroskedasticity Test	[1]:F(01,44) = 1.1763	[0.2840]
	[2]:F(02,42) = 0.5667	[0.5716]
	[3]:F(03,40) = 1.4884	[0.2323]
Breusch-Pagan-Godfrey Heteroskedasticity Test	F(21,25) = 1.3090	[0.2578]
Harvey Heteroskedasticity Test	F(21,25) = 1.5566	[0.1445]
White Heteroskedasticity Test (Without Cross Terms)	F(21,25) = 1.6749	[0.1087]

The results of the statistical tests reported at the bottom of Table 8 indicate that the model fits the data well. These metrics suggest a strong relationship between the independent and dependent variables, supporting the hypotheses set forth in the research. Similarly, Table 8 reports the results of residual diagnostic tests, indicating a satisfactory fit of the model in this study. For example, the Jarque-Bera test, with a value of 1.514 and a p-value of 0.4698, confirms the normal distribution of the residuals, thereby reinforcing the validity of our findings. In the same way, the results of the Birch-Goodfrey serial correlation test at various time intervals show that the residuals are independent and do not display notable autocorrelation. This also enhances the reliability of the model by ensuring that the estimates are unbiased and not influenced by correlation over time, thereby strengthening the robustness of our conclusions.

The Breusch-Pagan-Godfrey, ARCH, and Harvey and White heteroskedasticity tests show that the model has a constant residual variance, which suggests that the homoscedasticity assumptions are true. This stability in residual variance enhances the reliability of the regression results and underscores the validity of the model's predictions. Moreover, the Ramsey-Rest test confirms the absence of specification errors in the model, signifying the accurate inclusion and modeling of all pertinent variables. The CUSUM and CUSUM square tests show that the model's coefficients are stable over the sample period. This can be inferred by the total lines of the sum of the recursive residuals staying within the critical limits as depicted by Figures 3 and 4. This stability is crucial as it ensures the accuracy of predictions and the model's reliability when used with future data, reducing the chance of substantial errors in reliability.

Figure 3. Plot of cumulative sum of recursive residuals

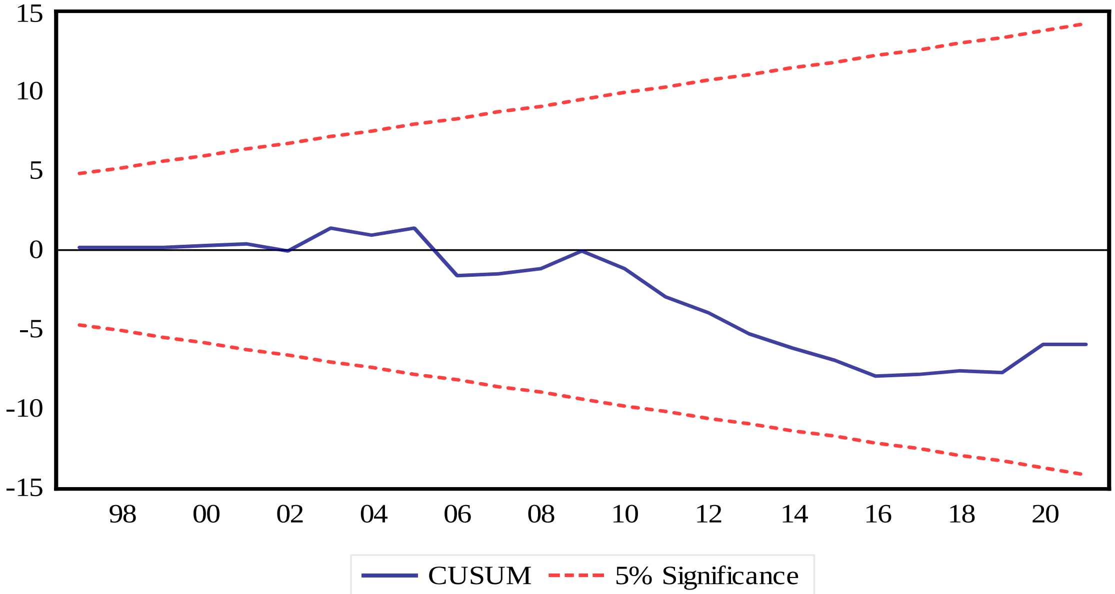
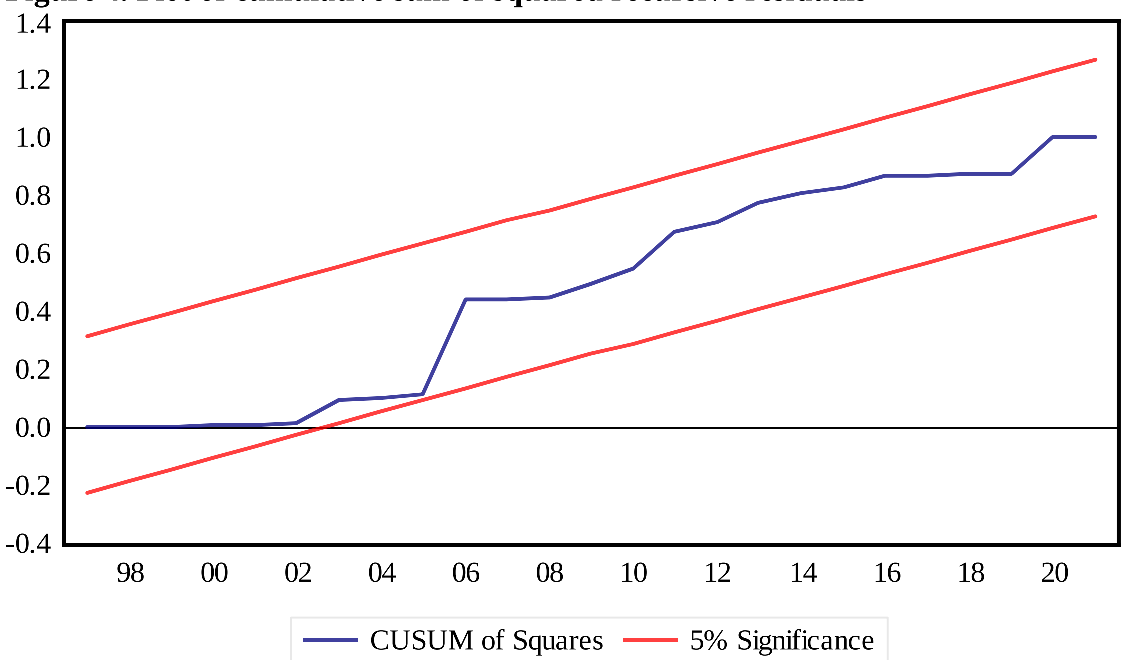


Figure 4. Plot of cumulative sum of squared recursive residuals



6. Conclusion

The primary aim of this study is to evaluate the relevance of the inverted U-shaped environmental Kuznets curve hypothesis to Sudan. Statistics reveal a great surge in the emissions of environmentally harmful gases such as CO2 and CH4 in the country. This is especially apparent in recent decades as Sudan has emerged as an oil producer and exporter. This transition has changed Sudan from being a carbon-negative country to one with triple-digit growth rates in greenhouse gas emissions. This deterioration in environmental quality signals a concern in a country where environmental preservation is essential for any developmental advancement. This study applies the ARDL method to data from 1970 to 2022 to analyze the applicability of the EKC to Sudan, thereby elucidating the trajectory of the country's environmental condition. Before applying the ARDL method, essential statistical tests such as unit root and co-integration tests were conducted to ensure the validity of the intended analysis.

The ARDL bounds test analysis reveals a clear co-integration relationship between the variables included in the analysis. The primary finding is that the EKC exhibits a U-shaped configuration. Most importantly, the results suggest that the coefficient of the squared GDP per capita is larger than the coefficient of its level, indicating a stronger non-linear relationship between economic development and environmental degradation. This relationship between economic growth and environmental quality, which is encapsulated by the U-shaped EKC, illustrates a critical phase in development where economic progress can initially come at the expense of environmental conservation.

The findings also reveal a robust and positive long-run association between increasing energy consumption and environmental degradation. This can be deduced from the coefficient of the variable, which was positive and very significant. Astonishingly, the coefficient of the electricity production variable exhibits a negative and significant sign, suggesting a positive contribution to environmental preservation. In the same way, the coefficient of the domestic capital variable was negative and statistically significant, indicating that increasing domestic capital accumulation improves environmental conservation. Similarly, the results reveal a negative and significant coefficient for the FDI variable, suggesting a long-run negative relationship with CO2. The coefficient of the dummy variable representing the implementation of the privatization and economic reform policy adopted in 1992 was negative and statistically significant. This signifies that the execution of this policy mitigates environmental degradation. The significant agreement between the short-and the long-run results findings indicates that the EKC in the Sudanese context demonstrates a U-shaped pattern. The sign of the GDP per capita coefficient in the short run, which is negative and statistically significant, further supports this finding. The coefficient of the energy consumption variable is negative and significant, signifying a robust correlation between CO2 and energy use. Moreover, the short-run finding also suggests that FDI and urban population growth mitigate environmental degradation.

In light of these findings, the study puts forward several recommendations to tackle the environmental challenges in Sudan. First, the country should promote the use of renewable energy sources like solar and wind power and decrease dependence on fossil fuels, thereby fostering a cleaner and more sustainable environment. In particular, the country should enforce stricter regulations on emissions from energy consumption and promote sustainable urban planning practices. This transition to renewable energy sources is crucial for decreasing dependence on fossil fuels, which significantly contribute to CO2 emissions. Second, policymakers must emphasize the significance of investing in green infrastructure and technology, such as energy-efficient buildings and sustainable transportation systems, to reduce CO2 emissions and increase energy efficiency. Third, promoting public transportation and carpooling is crucial to reducing reliance on fossil fuels, decreasing traffic congestion, and lowering carbon emissions, thereby promoting a more sustainable transportation system. This approach not only lessens individual carbon footprints but also encourages the use of more sustainable modes of transport. Finally, policymakers should work honestly on enhancing public awareness and education on the significance of environmental conservation and the impact of human activities on the environment. By fostering a greater understanding of environmental issues, individuals become more likely to adopt eco-friendly practices and support sustainable policies.

Implementing these recommendations effectively can guide Sudan toward rectifying environmental imbalances and fostering a healthier, more sustainable future for its citizens and the planet as a whole.

References

Ahmad, N., Du, L., Lu, J., Wang, J., Li, H. Z. and Hashmi, M. Z. (2017). Modelling the CO2 Emissions and Economic Growth in Croatia: Is There Any EKC? *Energy, 123,* pp.164-172.

Akpan, U. F. and Chuku, A. (2011). Economic Growth and Environmental Degradation in Nigeria: Beyond the EKC.

Ali, M. E. M. (2018). Impact of Foreign Direct Investment on Domestic Investment in Sudan:" Giving Hope Hypothesis." *Journal of Economic Cooperation and Development, 39(3),* pp.39-63.

Ali, M. E. M. (2018). Knowledge Spillovers from Foreign Direct Investment to Domestic Firms in Sudan. Published in Alabi, R.A., Gutowski, A., Hassan, N. M., Knedlik, T., Nour, S. S. O. M. and Wohlmuth, K. (2018). *Science, Technology and Innovation Policies for Inclusive Growth in Africa: General Issues and Country* Cases (Vol. 20). LIT Verlag Münster.

Antweiler, W., Copeland, B. R. and Taylor, M. S. (2001). Is Free Trade Good for the Environment? *American Economic Review, 91(4)*, pp.877-908.

Apergis, N. (2016). EKCs: New Evidence on Both Panel and Country-Level CO2 Emissions. *Energy Economics, 54,* pp.263-271.

Apergis, N., Christou, C. and Gupta, R. (2017). Are There EKCs for US State-Level CO2 Emissions? *Renewable and Sustainable Energy Reviews, 69*, pp.551-558.

Beşe, E. and Kalayci, S. (2021). EKC: Empirical Relationship Between Economic Growth, Energy Consumption, and CO2 Emissions: Evidence from 3 Developed Countries. *Panoeconomicus, 68(4),* pp.483-506.

Beşe, E., Friday, H. S. and Özden, C. (2020). Coal Consumption EKC in China and Australia: Evidence from ARDL Model. *Journal of Applied Business and Economics, 22(11).*

Blackman, A. and Harrington, W. (2018). The Use of Economic Incentives in Developing Countries: Lessons from International Experience with Industrial Air Pollution. *The Theory and Practice of Command and Control in Environmental Policy*, pp.199-238.

Blanco, L., Gonzalez, F. and Ruiz, I. (2013). The Impact of FDI on CO2 Emissions in Latin America. *Oxford Development Studies*, *41(1)*, pp.104-121.

Canas, A., Ferrao, P. and Conceicao, P. (2003). A New EKC? Relationship Between Direct Material Input and Income Per Capita: Evidence from Industrialised Countries. *Ecological Economics*, 46(2), pp.217-229.

Cole, M. A. (2004). Trade, the Pollution Haven Hypothesis and the EKC: Examining the Linkages. *Ecological Economics*, 48(1), pp.71-81.

Dawson, G. (2011). Free Markets, Property Rights and Climate Change: How to Privatize Climate Policy. *Libertarian Papers*, 3, p.1.

Dietz, T. and Rosa, E. A. (1994). Rethinking the Environmental Impacts of Population, Affluence and Technology. *Human Ecology Review, 1(2),* pp.277-300.

Dietz, T. and Rosa, E. A. (1997). Effects of Population and Affluence on CO2 Emissions. Proceedings of the National Academy of Sciences, 94(1), pp.175-179.

Ehigiamusoe, K. U., Lean, H. H. and Somasundram, S. (2022). Unveiling the Non-Linear Impact of Sectoral Output on Environmental Pollution in Malaysia. *Environmental Science and* Pollution Research, 29(5), pp.7465-7488.

El-Aasar, K. M. and Hanafy, S. A. (2018). Investigating the EKC Hypothesis in Egypt: The Role of Renewable Energy and Trade in Mitigating GHGs. *International Journal of Energy Economics and Policy, 8(3),* pp.177-184.

Eldowma, I. A., Zhang, G. and Su, B. (2023). The Nexus Between Electricity Consumption, CO2, and Economic Growth in Sudan (1971-2019). *Energy Policy,* 176, p.113510.

Esteve, V. and Tamarit, C. (2012). Threshold Cointegration and Nonlinear Adjustment Between CO2 and Income: The EKC in Spain, 1857-2007. *Energy Economics, 34(6),* pp.2148-2156.

Esty, D. C. and Geradin, D. (1998). Environmental Protection and International Competitiveness. *J. World Trade,* 32, p.5.

Fodha, M. and Zaghdoud, O. (2010). Economic Growth and Pollutant Emissions in Tunisia: An Empirical Analysis of the EKC. *Energy Policy, 38(2),* pp.1150-1156.

Fosten, J., Morley, B. and Taylor, T. (2012). Dynamic Misspecification in the EKC: Evidence from CO2 and SO2 Emissions in the United Kingdom. *Ecological Economics, 76,* pp.25-33.

Friedl, B. and Getzner, M. (2003). Determinants of CO2 Emissions in a Small Open Economy. Ecological Economics, 45(1), pp.133-148. Stern, D.I. and Common, M.S., 2001. Is There an EKC for Sulfur? *Journal of Environmental Economics and Management, 41(2),* pp.162-178.

Gökmenoğlu, K. and Taspinar, N. (2016). The Relationship Between CO2 Emissions, Energy Consumption, Economic Growth and FDI: The Case of Turkey. *The Journal of International Trade and Economic Development, 25(5),* pp.706-723.

Grossman, G. M. and Krueger, A. B. (1993). Environmental Impacts of a North American Free Trade Agreement. *The Mexico-US Free Trade Agreement, 11(2),* p.13.

Grubb, M., Sha, F., Spencer, T., Hughes, N., Zhang, Z. and Agnolucci, P. (2015). A Review of Chinese CO2 Emission Projections to 2030: The Role of Economic Structure and Policy. *Climate Policy, 15(sup1),* pp.S7-S39.

Harbaugh, W. T., Levinson, A., and Wilson, D. M. (2002). Reexamining the Empirical Evidence for an EKC. *Review of Economics and Statistics, 84(3),* pp.541-551.

Harrison, K. (1996). Passing the Buck: Federalism and Canadian Environmental Policy. UBC Press.

Htike, M. M., Shrestha, A., and Kakinaka, M. (2021). Investigating Whether the EKC Hypothesis Holds for Sectoral CO2 Emissions: Evidence from Developed and Developing Countries. *Environment, Development and Sustainability,* pp.1-28.

Jalil, A. and Mahmud, S. F. (2009). Environment Kuznets Curve for CO2 Emissions: A Cointegration Analysis for China. *Energy Policy, 37(12),* pp.5167-5172.

Kaufmann, R. K., Davidsdottir, B., Garnham, S. and Pauly, P. (1998). The Determinants of Atmospheric SO2 Concentrations: Reconsidering the EKC. *Ecological Economics, 25(2),* pp.209-220.

Khanam, Z., Sultana, F. M. and Mushtaq, F. (2023). Environmental Pollution Control Measures and Strategies: An Overview of Recent Developments. *Geospatial Analytics for Environmental Pollution Modeling: Analysis, Control and Management,* pp.385-414.

Kisswani, K. M. and Zaitouni, M. (2023). Does FDI Affect Environmental Degradation? Examining Pollution Haven and Pollution Halo Hypotheses Using ARDL Modelling. *Journal of the Asia Pacific Economy, 28(4),* pp.1406-1432.

Kuznets, S. (1955). Economic Growth and Income Inequality. *The American Economic Review, 45(1),* pp.1-28.

Lau, L. S., Choong, C. K. and Ng, C. F. (2018). Role of Institutional Quality on Environmental Kuznets Curve: A Comparative Study in Developed and Developing Countries. *In Advances in Pacific Basin Business*, *Economics and Finance (Vol. 6, pp. 223-247). Emerald Publishing Limited.*

Lee, C. C., Chiu, Y. B. and Sun, C. H. (2010). The EKC Hypothesis for Water Pollution: Do Regions Matter? *Energy policy*, *38(1),* pp.12-23.

Li, Q., Lin, C., Qin, S., and Xiao, Z. (2024). Does Privatization Come at the Cost of the Environment? *Available at SSRN 4982377.*

Miniesy, R. S. and Tarek, M. (2019). Is There Evidence of PHH in Developing Asia? *Journal of Chinese Economic and Foreign Trade Studies, 12(1),* pp.20-39.

Mohamed, E. S. (2018). Energy and Economic Factors Affecting CO2 in Sudan: An Empirical Econometric Analysis (1969-2015). *Journal of Economics Bibliography, 5(2),* pp.60-75.

Mohamed, E. S. E. (2020). Economic Growth, CH4 and N2O Emissions in Sudan: Where Should the Policy Focus Be? *Journal of Geoscience and Environment Protection*, *8*(10), p.202.

Mustafa, M. E., Elshakh, M. M., and Ebaidalla, E. M. (2019). Does Foreign Aid Promote Economic Growth in Sudan? Evidence from ARDL Bounds Testing Analysis. *Journal of Economic Cooperation and Development*, *40*(3).

Perman, R. and Stern, D. I. (2003). Evidence from Panel Unit Root and Cointegration Tests That the EKC Does Not Exist. *Australian Journal of Agricultural and Resource Economics, 47(3),* pp.325-347.

Pesaran, M. H., Shin, Y., and Smith, R. J. (2001). Bounds Testing Approaches to the Analysis of Level Relationships. *Journal of Applied Econometrics, 16(3),* pp.289-326.

Peters, G. P. and Hertwich, E. G. (2008). CO2 Embodied in International Trade with Implications for Global Climate Policy.

Saboori, B., Sulaiman, J. and Mohd, S. (2012). Economic Growth and CO2 Emissions in Malaysia: A Cointegration Analysis of the EKC. *Energy Policy, 51,* pp.184-191.

Sarkodie, S. A. and Ozturk, I. (2020). Investigating the Environmental Kuznets Curve Hypothesis in Kenya: A Multivariate Analysis. *Renewable and Sustainable Energy Reviews, 117,* p.109481.

Shahbaz, M., Lean, H. H., and Shabbir, M. S. (2012). EKC Hypothesis in Pakistan: Cointegration and Granger Causality. *Renewable and Sustainable Energy Reviews, 16(5),* pp.2947-2953.

Stern, N. (2007). Climate. Stern Review: The Economics of Climate Change. *New England Journal of Public Policy, 21(2*), p.4.

Swyngedouw, E. (2018). CO2 as Neoliberal Fetish: The Love of Crisis and the Depoliticized Immuno-Biopolitics of Climate Change Governance. Cahill, D.; Cooper, M.; Konings M.; Primrose, D. The Sage Handbook of Neoliberalism. *Londres: SAGE*, pp.295-307.

Tang, J. P. (2015). Pollution Havens and the Trade in Toxic Chemicals: Evidence from US Trade Flows. *Ecological Economics, 112,* pp.150-160.

Tenaw, D. and Beyene, A. D. (2021). Environmental Sustainability and Economic Development in Sub-Saharan Africa: A Modified EKC Hypothesis. *Renewable and Sustainable Energy Reviews, 143,* p.110897.

Tenaw, D. (2021). Getting into the Details: Structural Effects of Economic Growth on Environmental Pollution in Ethiopia. *Heliyon*, *7*(7).

Wang, K. M. (2012). Modelling the Nonlinear Relationship Between CO2 Emissions from Oil and Economic Growth. *Economic Modelling, 29(5),* pp.1537-1547.

Wang, Q., Wang, X., Li, R. and Jiang, X. (2024). Reinvestigating the EKC of Carbon Emissions and Ecological Footprint in 147 Countries: A Matter of Trade Protectionism. *Humanities and Social Sciences Communications*, *11(1)*, pp.1-17.

Wang, Y., Han, R. and Kubota, J. (2016). Is There an EKC for SO2 Emissions? A Semi-Parametric Panel Data Analysis for China. *Renewable and Sustainable Energy Reviews, 54*, pp.1182-1188.

World Bank (2024). World Development Indicators 2024. The World Bank.

York, R., Rosa, E. A. and Dietz, T. (2003). STIRPAT, IPAT and ImPACT: Analytic Tools for Unpacking the Driving Forces of Environmental Impacts. *Ecological Economics, 46(3)*, pp.351-365.

Zhang, Z. (2008). Asian Energy and Environmental Policy: Promoting Growth While Preserving the Environment. *Energy Policy, 36(10)*, pp.3905-3924.