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Assessing the Energy-Economy-Environment Nexus in Somalia: The Impact of Agricultural Value Added on CO_2 Emissions

Seadya Ahmed[1]*, Abdikafi Hassan Abdi[1,2], Muna Sodal[3], Omar Abdisalam Yusuf[1], Mohamud Hussein Mohamud[1]

[1]Faculty of Economics, SIMAD University, Mogadishu, Somalia, [2]Institute of Climate and Environment, SIMAD University, Mogadishu, Somalia, [3]School of Business, Kenyatta University, Nairobi, Kenya. *Email: seadya@simad.edu.so

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ABSTRACT

This study assesses the environmental impact of the agricultural sector's contribution to Somalia's economy within the energy-economy-environment nexus. While the agriculture sector is a central pillar of Somalia's economy, its environmental costs remain underexplored. By addressing this gap, the research utilizes time series data spanning from 1990 to 2020, including variables such as CO_2 emissions, real GDP, renewable energy use, agricultural value-added, and population growth. The data analysis employs the autoregressive distributed lag (ARDL) model, Canonical Cointegrating regression (CCR), dynamic ordinary least squares (DOLS), and fully modified ordinary least squares (FMOLS). The results reveal a strong positive relationship between economic growth and environmental degradation in Somalia, supporting the environmental Kuznets curve (EKC) viewpoint. While economic growth initially exacerbates environmental pollution, the effect diminishes as income levels rise. Renewable energy consumption significantly mitigates environmental degradation. However, agricultural value-added is found to increase environmental deterioration in the long-term. The findings suggest that Somalia's path to sustainable development will require concerted efforts to reform agricultural practices and embrace renewable energy adoption. Despite Somalia's considerable solar energy potential, owing to its abundant solar radiation, this resource remains underutilized. A strategic focus on expanding solar energy infrastructure could not only mitigate environmental harm but also enable the country to leapfrog traditional energy development, thereby driving economic growth and reducing pollution.

Keywords: Environmental Kuznets Curve, Economic Growth, Agricultural Value-Added, Renewable Energy, CO_2 Emissions, Sustainable Development

JEL Classifications: P18, Q18, Q56

1. INTRODUCTION

Climate change is one of the most pressing issues of the twenty-first century, driven mainly by the accumulation of greenhouse gases (GHGs) in the atmosphere, with carbon dioxide (CO_2) being the most significant contributor. This surge in CO_2 levels is largely attributed to the burning of fossil fuels, deforestation, and other unsustainable land-use practices (Dale et al., 2011; Raihan et al., 2022; Ramankutty et al., 2006; Smith et al., 2016). The increasing accumulation of CO_2 not only worsens climate change but also presents significant threats to environmental sustainability (Cramer et al., 2018; Hoegh-Guldberg et al., 2019). Consequently, mitigating the adverse effects of climate change has emerged as a primary focus for both domestic and global development endeavors (Adenle et al., 2017; Mikulewicz, 2018; Nath and Behera, 2011; Román et al., 2012). In recent decades, the intricate connection of rapid economic growth with environmental deterioration has been the focus of considerable scholarly discourse (Acheampong and Opoku, 2023; Ali et al., 2022; Ayad et al., 2023; Luo et al., 2023). Since 1950, fossil fuel consumption has increased more than eightfold, with a doubling of usage between 1980 and 2022, which indicates the environmental challenges associated with unsustainable resource utilization and unchecked economic expansion on a global scale (Ritchie and Rosado, 2024).

The agricultural sector, a key engine of economic growth in many countries, is also a significant source of CO_2 and other GHGs such as methane and nitrous oxide. Agricultural practices, whether sustainable or harmful, play a crucial role in the energy-economy-environment nexus, particularly in developing regions where agriculture is central to the economy (Abdi et al., 2024b). Recent studies by Pretty et al. (2018) and Fatima et al. (2024) suggest that agricultural value-added—the net output generated by the agricultural sector—can either increase or mitigate CO_2 emissions depending on the sustainability of these practices. While traditional agricultural practices often lead to deforestation, soil degradation, and GHG emissions (Altieri and Nicholls, 2017; Lal, 2003), research by Raihan et al. (2023), Raza et al. (2021), and Wang et al. (2020) demonstrates that aligning agricultural activities with sustainable methods can substantially reduce the sector's carbon footprint, thereby enhancing its contribution to both economic growth and environmental sustainability. Moreover, sustainable agricultural practices not only mitigate environmental impacts but also enhance productivity (Gomiero et al., 2011; Pretty et al., 2018; Shah and Wu, 2019; Snyder et al., 2014; Wu and Ma, 2015). However, population growth, especially in urban areas, complicates this nexus by increasing energy and resource use, thus exacerbating environmental degradation (Shakib et al., 2022). While population expansion initially worsens environmental quality, research indicates that sustainable practices and technological advancements can eventually stabilize or reduce its environmental impact (Cole and Neumayer, 2004; Liddle, 2014). This underscores the need to address agricultural practices within the broader context of sustainable development, as defined by the Brundtland Commission in 1987 and reviewed in Borowy (2013).

The reliance on fossil fuels and biomass for energy has been a critical driver of rising CO_2 emissions and other pollutants (Abbasi et al., 2022; Shahbaz et al., 2019). In Somalia, this dependency is exacerbated by the country's heavy use of traditional biomass, which contributes to deforestation and soil degradation, further intensifying environmental challenges (African Development Bank, 2015; Samatar et al., 2023; Warsame and Sarkodie, 2022). Although Somalia's global CO_2 emissions remain relatively low, at <0.03% of the total in 2021 (Federal Government of Somalia, 2021), the nation is still vulnerable to the effects of climate change. Over the past 25 years, Somalia has experienced steady economic growth, with its GDP expanding annually between 2.4% and 9.9%, aside from brief dips in 2013 and 2020 (World Bank Open Data, n.d.; Abdi et al., 2024). However, this growth has coincided with severe climate-related challenges (Marthews et al., 2019; Samatar et al., 2023). The agricultural sector, which contributes over 65% to GDP and employs about 80% of the population, plays a central role in Somalia's economy but also exacerbates environmental degradation (International Trade Administration, 2024; World Bank, 2018). Globally, agriculture emitted 9.3 billion tonnes of CO_2 equivalent (CO_2eq) in 2018 (FAO, 2018), and in Somalia, it is linked to deforestation, soil degradation, and unsustainable practices (IPCC, 2017; Kamyab et al., 2025). Between 2001 and 2021, Somalia lost 429,000 hectares of tree cover, generating 840,000 tons of CO_2eq emissions (Global Forest Watch, 2024), which depicts the environmental toll of traditional energy practices.

However, renewable energy offers a viable alternative for mitigating environmental impacts without compromising economic growth (Dincer and Rosen, 1999; Owusu and Asumadu-Sarkodie, 2016; Raihan and Tuspekova, 2022c). Studies show that renewable energy consumption lowers emissions and fosters sustainable development (Abdi et al., 2024b, 2023; Dincer, 2000; Lin and Moubarak, 2014; Magazzino et al., 2022; Saidi and Omri, 2020). In Sub-Saharan Africa (SSA), renewable energy presents a significant opportunity to leapfrog traditional energy development, but challenges such as high costs, low incomes, and policies favoring fossil fuels hinder its full potential (da Silva et al., 2018; Mohammed et al., 2013; Oluoch et al., 2021a, 2021b; Riti et al., 2022). Somalia, despite its substantial potential for solar energy, remains underutilized, with solar energy contributing only 11.9% to electricity generation in 2021 (Samatar et al., 2023). The barriers to greater renewable energy adoption in Somalia include high costs, insufficient infrastructure, limited technical expertise, and political instability (Samatar et al., 2023). These factors, combined with the continued reliance on biomass fuels and inefficient burning practices, perpetuate CO_2 emissions and environmental damage, emphasizing the need for a transition to cleaner energy sources (Samatar et al., 2023; Dubow, 2022; Warsame and Sarkodie, 2022).

As Somalia continues to develop and rebuild its economy, the potential for increased CO_2 emissions is a critical concern, especially if economic growth is not aligned with sustainable environmental practices. Given the significant environmental footprint of the agricultural sector and Somalia's recurring climate-related disasters, it is imperative to understand its impact on CO_2 emissions within the energy-economy-environment nexus. This paper, thus, seeks to explore the energy-economy-environment nexus in Somalia, with a particular focus on how agricultural value-added impacts the country's CO_2 emissions. By analyzing how economic growth, utilization of renewable energy, the contribution of the agricultural sector to the economy, and population dynamics impact CO_2 emissions, this study endeavors to illuminate how Somalia can harmonize economic development with environmental sustainability. Additionally, the study employs a range of econometric techniques, including the autoregressive distributed lag (ARDL), canonical cointegrating regression (CCR), dynamic ordinary least squares (DOLS), and fully modified ordinary least squares (FMOLS) methods, to ensure more robust and reliable results. Consequently, the findings of this research will inform strategies for reducing CO_2 emissions while supporting Somalia's efforts to rebuild the economy and achieve sustainable economic growth. The paper is structured as follows: Section 2 reviews the key theoretical and empirical studies. Section 3 explains the data sources and the econometric methods used. Section 4 presents the findings and analysis of the study, while the final section summarizes the conclusions and discusses relevant policy implications.

2. THEORETICAL AND EMPIRICAL REVIEW

Within the theoretical framework guiding this research, CO_2 emissions are identified as the environmental variable, capturing the ecological effects of the explanatory variables commonly included in relevant studies (Bibi and Jamil, 2021; Hussein and Warsame, 2023; Koc and Bulus, 2020; Nazir et al., 2018; Raihan et al., 2023; Raihan and Tuspekova, 2022c). In the context of the energy-economy-environment interplay, the Environmental Kuznets Curve (EKC) hypothesis, first proposed by Grossman and Krueger (1991), has been pivotal in framing the discourse surrounding the complex relationship linking rapid economic growth with environmental harm. The EKC concept posits that economic expansion initially results in ecological deterioration; yet, once income levels surpass a specific threshold, further growth results in environmental improvements (Acaravci and Ozturk, 2010; Dogan and Turkekul, 2016; Hussein and Warsame, 2023; Massagony and Budiono, 2023; Ozatac et al., 2017; Rana and Sharma, 2019; Dinda, 2004; Stern, 2004). This theory has been widely tested, with empirical studies producing mixed results. For instance, Apergis and Payne (2009) found evidence supporting the EKC, where economic growth initially exacerbates CO_2 emissions but eventually leads to environmental improvements as income levels increase in a panel of Central American countries. Similarly, Apergis and Ozturk (2015) confirm the EKC claim in an analysis of 14 Asian nations, indicating that higher income levels eventually lead to reduced emissions. However, other studies challenge the claim that economic expansion alone ensures environmental sustainability, which emphasizes the need for careful interventions to achieve the downward slope of the EKC (Al-Mulali et al., 2015; Begum et al., 2015; Koc and Bulus, 2020).

Moreover, the linkage between economic expansion and environmental impacts is increasingly acknowledged as more intricate than the EKC hypothesis suggests. Some research indicates that environmental degradation may persist even as countries become wealthier (Koc and Bulus, 2020; Samargandi, 2017). This suggests that economic growth without targeted environmental policies may not suffice to improve environmental outcomes in some regions (Bibi and Jamil, 2021; Dogan and Turkekul, 2016; Liu et al., 2017). In a country and region-specific studies, this complexity is particularly evident in developing countries, where economic expansion correlates with greater resource utilization and heightened environmental stress (Jalil and Mahmud, 2009). For instance, Sarkodie and Strezov (2018) examine the EKC proposition for the USA, Australia, Ghana, and, China over the period from 1971 to 2013, employing multiple analytical methods to analyze the relationship linking economic development, energy utilization, and environmental degradation. Their study supports the EKC notion in developed countries, where emissions decrease due to shifts towards less carbon-intensive industries, but finds that in developing and least-developed countries, emissions continue to rise with economic growth due to reliance on energy-intensive sectors and less stringent environmental regulations. In South Korea, Koc and Bulus (2020) identify an N-shaped link between GDP and emissions footprint, further challenging the EKC concept.

The findings from developed and developing countries and regions challenge EKC hypothesis. Liu et al. (2017), for instance, reveal that agricultural activities and the utilization of renewable energy reduce CO_2 emissions, whereas energy from non-renewable sources amplify it, thereby questioning the applicability of the EKC claim in four ASEAN countries— Indonesia, Thailand, Malaysia, and the Philippines—during the period from 1970 to 2013. Similarly, Begum et al. (2015) suggest that GDP growth has long-term positive influence on carbon emissions, rendering the EKC theory invalid for Malaysia. Yilanci and Pata (2020) conclude that the EKC proposition is not true for China, as the long-term impact of economic growth on the environment is more pronounced than the short-term impacts. Bibi and Jamil (2021) reveal that the findings for SSA do not support the EKC argument, highlighting regional disparities. Dogan and Turkekul (2016) also refute the EKC viewpoint in America showing that while real output reduces environmental degradation, the square of GDP increases emissions. Samargandi (2017) also finds no support for the EKC claim in Saudi Arabia, showing that economic expansion adds to CO_2 emissions, particularly in the industrial and service sectors, with technological innovation failing to mitigate emissions. Similarly, Al-Mulali et al. (2015) find that the EKC proposition does not apply to Vietnam, where economic growth consistently leads to increased pollution, driven by capital investments and fossil fuel consumption, with minimal mitigating effects from exports and energy from renewable sources.

The energy component of the nexus demonstrates the pivotal influence of energy use on economic activities and its dual impact as either a contributor to or mitigator of environmental pollution, depending on its type. Several studies have demonstrated that the utilization of renewable energy sources from wind, solar, and hydropower substantially lowers CO_2 emissions. For instance, the research of Omri and Nguyen (2014) found that in a sample of 64 countries, greater consumption of renewable energy was associated with diminished CO_2 emissions, while simultaneously promoting sustainable economic growth. Similarly, Saidi and Omri (2020) highlight the influence of renewable energy in decarbonizing the energy sector, as greater utilization of renewable sources led to a substantial decrease in CO_2 emissions and enhanced economic growth in fifteen countries with high renewable energy consumption. These results align with the findings of Dogan and Seker (2016) that revealed the use of renewable energy is negatively associated with CO_2 emissions in the European Union, which shows the effectiveness of renewable energy policies in curbing environmental harm. In addition, Abdi (2023) explores the influence of economic complexity and renewable energy consumption on carbon emissions across 41 SSA countries between 1999 and 2018. The study concludes that renewable energy consumption effectively reduces environmental pollution in both the short and long term.

Expanding on the role of specific economic sectors within this nexus, the influence of the agricultural-value-added on CO_2 emissions presents a particularly complex and mixed picture. Some of the empirics suggest that agriculture enhances environmental quality. For example, Wang et al. (2020) highlight that agricultural value-added acts as a mitigating factor in the G7 countries from

1996 to 2017, contrasting with the roles of globalization, natural resources, and financial development, which all contribute to higher emissions. Similarly, Raihan et al. (2023) reveal that in China, agricultural value-added reduces CO_2 emissions over both long and short-run. In Pakistan, Raza et al. (2021) suggest that the value of agricultural sector in the economy significantly diminishes emissions over time. Using time-series data from 1990 to 2020, (Abdi et al., 2024a) explored how agricultural value-added, renewable energy consumption, economic growth, and urbanization influence ecological footprints and CO_2 emissions. The findings from the ARDL bounds testing technique reveals that, over the long-term, agricultural value-added and renewable energy consumption play a significant role in lowering ecological footprints and CO_2 emissions. In the short term, agricultural value-added initially leads to an increase in these environmental indicators, while renewable energy consistently exerts a positive impact.

Conversely, other studies reveal the detrimental environmental impacts of agriculture. For instance, Raihan and Tuspekova (2022a) find that agricultural value-added increases carbon emissions in Brazil between 1990 and 2019. By the same token, Aydoğan and Vardar (2020) directly linked that the value of the agricultural sector adds to the economy, economic expansion, and utilization of non-renewable energy sources to CO_2 emissions, whereas renewable energy use and the quadratic term of GDP show an inverse relationship with environmental degradation. This supports the EKC hypothesis for Brazil, Turkey, China, Indonesia, India, Mexico, and Russia between 1990 and 2014. Raihan and Tuspekova (2022b) investigate the effects of economic growth, agricultural land expansion, and renewable energy utilization on CO_2 emissions from 1990 to 2018, confirming that while the increase of agricultural land and GDP damage the environment in Peru, use of energy from renewable sources reduces emissions. Similarly, Ali et al. (2017) significantly linked real GDP, foreign direct investment (FDI), energy use, trade liberalization, and financial advancement in Malaysia, while also uncovering a bidirectional relationship between environmental degradation and energy, further substantiating the EKC claim within the Malaysian context.

Furthermore, the findings regarding population growth within the energy-economy-environment nexus also present a mixed and nuanced picture. For instance, Owusu and Asumadu-Sarkodie (2016) find that in Ghana, population growth substantially affects CO_2 emissions, with a 1% addition to population leading to a 1.72% rise in carbon emissions from 1971 to 2013. Likewise, Dong et al. (2018) highlight that population and economic growth exert a direct and substantial impact on carbon emissions across various regions. However, the impact of population growth varies by region, as Alam et al. (2016) reports that although population growth significantly increases emissions in India and Brazil, it has no significant influence in Indonesia and China during the period from 1970 to 2012. Further studies, such as those by (Begum et al., 2015; Shaari et al., 2021), conclude that population growth does not substantially impact CO_2 emissions in Malaysia and nine other developing countries, respectively. Moreover, Dong et al. (2018) found that while population and economic growth significantly harm the environment, renewable energy adoption effectively reduces emissions, based on an analysis of 128 countries. Additionally, Ahmed et al. (2023), employing the nonlinear autoregressive distributed lag (NARDL) technique, found that increased population growth has a positive effect on CO_2 emissions.

Research in SSA further underlines the complex interplay between economic expansion, activities in the agricultural sector, renewable energy utilization, and environmental sustainability. Sarkodie (2018) confirms the EKC claim in 17 African countries from 1971 to 2013, indicating that economic growth initially worsens environmental deterioration but eventually enhances it once per capita GDP hits a critical threshold. The study also reveals a U-shaped relationship, with significant degradation at lower GDP levels and improvement only at higher GDP thresholds, driven by factors such as energy consumption and agricultural activities. Similarly, Tenaw and Beyene (2021) examine twenty SSA countries from 1990 to 2015, finding a modified EKC hypothesis where the environment-development linkage is contingent on natural resource endowment. Between 1990 and 2013, Demissew Beyene and Kotosz (2020) identify a bell-shaped correlation between CO_2 emissions and per capita income for 12 East African countries, which suggests that economic activities do not necessarily lead to increased emissions. More specifically, Al-Mulali et al. (2016) report that while the use of fossil fuel energy, GDP, and urbanization pollute the air over the short and long run, usage of renewable energy and financial development reduce pollution in the long term, confirming the presence of the EKC notion in Kenya during the period spanning 1980-2012 using the ARDL approach. Similarly, Moise (2023) indicates that agricultural productivity and trade openness are associated with elevated CO_2 emissions in Rwanda, while increased utilization of renewable energy and higher GDP levels significantly lower emissions.

In the context of Somalia, relevant research (Hussein and Warsame, 2023; Hussein and Mohamed, 2024; Mohamud and Mohamud, 2023; Warsame and Sarkodie, 2022) contributing to the broader understanding of the economy-energy-environment nexus in the SSA region is limited but growing. In their study, Hussein and Warsame (2023) support the relevancy of the EKC theory in Somalia using an ARDL technique and time series data from 1989 to 2020. Their study suggests that the country's GDP growth unfavorably affects the environment, whereas agricultural production and the squared term of economic growth are linked to lower pollution levels. Mohamud and Mohamud (2023) report that from 1990 to 2020, economic growth in Somalia significantly hampers environmental quality in the long term, whereas utilization of renewable energy lowers environmental emission over time. From 1985 to 2017, Warsame and Sarkodie (2022) find traditional energy demand and GDP growth in Somalia asymmetrically impact environmental deterioration. Additionally, Hussein and Mohamed (2024) identify that while renewable energy significantly enhanced Somalia's environmental well-being from 1990 to 2020, economic growth exacerbated environmental degradation, and globalization had mixed effects.

Based on the review of empirical studies in Somalia, it is evident that while significant progress has been made in understanding the energy-economy-environment nexus, certain critical gaps remain unaddressed. Previous research has predominantly focused on the impact of traditional energy utilization and economic growth on carbon emissions in Somalia. However, a notable gap in the literature is the lack of comprehensive analysis that considers the impact of agricultural value-added, utilization of renewable energy, and economic and population expansion on environmental degradation within the economy-environment-energy nexus in Somalia. While the value the agricultural sector adds to Somalia's economy is a critical component of the country's GDP, its specific role in influencing CO_2 emissions has not been adequately explored in conjunction with the other key variables this study considered. This research endeavors to bridge these gaps by incorporating how the value of the agricultural sector adds to the economy, economic expansion, renewable energy utilization, and population growth impact CO_2 emissions in Somalia in a single model. The results of this paper enhance the broader understanding of the factors driving and those mitigating environmental degradation in Somalia, add to the insights of how sector-specific dynamics shape environmental outcomes in less-developed contexts, and inform the creation of strategies that harmonize development with ecological sustainability.

3. MATERIALS AND METHODS

3.1. Data

This paper assesses the energy-economy-environment nexus in Somalia, with a particular emphasis on how the value from the agricultural sector to the economy impacts CO_2 emissions. The research is anchored in the EKC hypothesis. The analysis is based on data spanning 31 years, from 1990 to 2020, and includes essential variables that capture the connections between economic growth, renewable energy utilization, the value the agricultural sector contributes to the economy, and environmental impact. The specific measurements and data sources of these variables are detailed in Table 1. To stabilize variance across the dataset, all the variables in the series were logarithmically transformed.

Furthermore, Figure 1 shows the annual patterns of the factors examined in the study from 1990 to 2020. The graphs reveal distinct trends in the key variables analyzed in this study. CO_2 emissions show a consistent upward trend, indicating a steady increase in environmental impact with occasional minor fluctuations but an overall rise. Economic growth exhibits a steady upward trend, indicating consistent GDP growth with notable dips in the 90s, reflecting ongoing development and increased economic activities. Renewable energy consumption remains relatively stable, with minor fluctuations and periods of gradual increase, suggesting modest adoption without significant acceleration. Agriculture value added fluctuated at the beginning of the time of the study, with periods of growth and decline, hinting at variability influenced by factors like climate and economic conditions, but generally trending slightly upward. Population growth, on the other hand, demonstrates a smooth and steady increase, reflecting a consistent rise in population throughout the study period.

3.2. Model Specification

The empirical framework of this study assess the EKC notion within the context of Somalia. In this model, the dependent variable is CO_2, serving as a key indicator of environmental impact. The independent variables selected for this analysis include real GDP and its squared term, renewable energy utilization, agricultural value-added, and population growth. The model is structured as follows:

$$CO_{2t} = f(EG_t, EG_t^2, REC_t, AGV_t, PG_t) \quad (1)$$

The square of economic growth examines the non-linear effects predicted by the EKC hypothesis. This squared variable is essential for testing whether there is an inflection point beyond which further economic expansion reduces emissions, thus indicating the presence of an inverse relationship as the economy develops. Confirmation of a negative coefficient for the squared GDP term provides empirical evidence for the applicability of the EKC theory in the context of Somalia. The econometric model for this analysis is specified as:

$$CO_{2t} = \beta_0 + \beta_1 EG_t + \beta_2 EG_t^2 + \beta_3 REC_t + \beta_4 AGV_t + \beta_5 PG_t + e_t \quad (2)$$

Here β_1, β_3, β_4, and β_5 represent the coefficients associated with each independent variable, capturing their respective impacts on CO_2 emissions. The term β_0 denotes the intercept, while e_t represents the error term. To facilitate interpretation and ensure linearity in the relationships among the variables, Equation 3 below expresses the model in its logarithmic form:

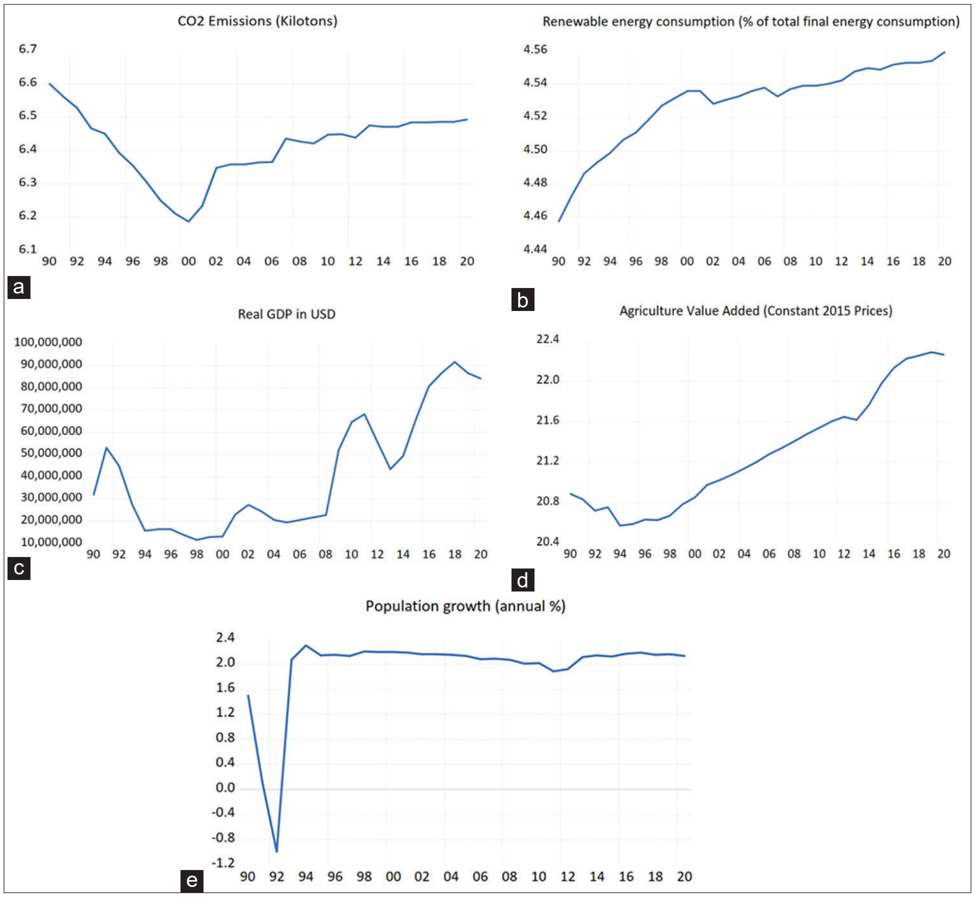
$$lnCO_{2t} = \beta_0 + \beta_1 lnEG_t + \beta_2 lnEG_t^2 + \beta_3 lnREC_t + \beta_4 lnAGV_t + \beta_5 lnPG_t + e_t \quad (3)$$

This stabilizes variance across the dataset, thereby improving the accuracy of coefficient estimation.

Table 1: Measurement and sources of the data

Variables	Measurements	Source of data	Code
CO_2 emissions	Kilotons	World Bank	$LNCO_2$
Economic growth	Real GDP in USD	SESRIC	LNEG
Squared economic growth	Real GDP in USD squared	SESRIC	LNEG2
Use of renewable energy	Renewable energy utilization (percentage of the total usage of final energy)	World Bank	LNREC
Agricultural value-added	Agriculture Value Added (Constant 2015 Prices, USD)	SESRIC	LNAGV
Population growth	Population growth (annual %)	World Bank	LNPG

Figure 1: Patterns of the variables in the study. (a) CO2 emissions. (b) Renewable energy consumption. (c) Economic growth. (d) Agriculture value added. (e) Population growth



3.3. ARDL Model

To prevent misleading results, this research began with stationarity tests of the data series before proceeding to estimate the ARDL model. Given the importance of establishing that the variance, autocorrelation, and mean structure of time series variables remain stable over time, the paper utilized the Phillips-Perron (PP) and Augmented Dickey-Fuller (ADF) tests to assess the stationarity of the variables.

Upon establishing that the variables exhibit a mix of I(0) and I(1) integration orders from the stationarity tests, the study proceeds to investigate the cointegration relationships using the ARDL F-bounds technique developed by (Pesaran et al., 2001). Equation 4 below expresses the econometric representation of the ARDL long-run model for this research:

$$\Delta lnCO_{2t} = \beta_0 + \beta_1 lnCO_{2t-1} + \beta_2 lnEG_{t-1} + \beta_3 lnEG^2_{t-1} + \beta_4 lnREC_{t-1} + \beta_5 lnAGV_{t-1} + \beta_6 lnPG_{t-1} + \sum_{i=1\,1}^{p} \Delta lnCO_{2t-i} + \sum_{i=1\,2}^{q} \Delta lnEG_{t-i} + \sum_{i=1\,3}^{q} \Delta lnEG^2_{t-i} + \sum_{i=1\,4}^{q} \Delta lnREC_{t-i} + \sum_{i=1\,5}^{q} \Delta lnAGV_{t-i} + \sum_{i=1\,6}^{q} \Delta lnPG_{t-i} + \varepsilon_t \quad (4)$$

The parameter Δ signifies the initial differencing, while q denotes the optimal number of lags. This paper employs the ARDL approach to investigate both short- and long-run dynamics between economic growth, consumption of renewable energies, agricultural practices, and environmental sustainability in Somalia. Upon confirming cointegration among the variables, Equation (4) is utilized to estimate the coefficients of the long-term. To assess the short-term effects, the study incorporates the Error Correction Term (ECT) as specified in Equation (5). This approach allows for a comprehensive understanding of both immediate and long-term effects within the energy-economy-environment nexus.

$$\Delta lnCO_{2t} = \beta_0 \sum_{i=1\,2}^{q} \Delta lnEG_{t-i} + \sum_{i=1\,3}^{q} \Delta lnEG^2_{t-i} + \sum_{i=1\,4}^{q} \Delta lnREC_{t-i} + \sum_{i=1\,5}^{q} \Delta lnAGV_{t-i} + \sum_{i=1\,6}^{q} \Delta lnPG_{t-i} + \Delta ECT_{t-1} + \varepsilon_t \quad (5)$$

The ECT coefficient, denoted as Θ, captures the speed of adjustment toward long-term equilibrium. To ensure the robustness of the estimated ARDL long-run coefficients, this study employed canonical cointegrating regression (CCR), dynamic ordinary least squares (DOLS), and fully modified ordinary least squares (FMOLS). These techniques are widely recognized in the literature for their ability to validate ARDL results by addressing common

Table 2: Descriptive statistics

Variables	lnCO_2	lnEG	lnEG^2	lnREC	lnAGV	lnPG
Mean	6.413156	17.31587	300.2761	4.528588	21.29449	1.936451
Median	6.438871	17.12563	293.2871	4.535820	21.20065	2.133500
Maximum	6.600034	18.33585	336.2034	4.559126	22.28736	2.302078
Minimum	6.187442	16.26179	264.4459	4.457830	20.57265	-0.991868
Std. Dev.	0.099461	0.671772	23.30203	0.024728	0.563638	0.664630
Skewness	−0.615183	0.078548	0.112670	−1.284644	0.440819	−3.576058
Kurtosis	2.906440	1.605002	1.604622	4.008612	1.939511	14.95016
Jarque-Bera	1.966632	2.545487	2.580566	9.840610	2.456652	250.5304
Probability	0.374069	0.280062	0.275193	0.007297	0.292782	0.000000
Sum	198.8078	536.7920	9308.560	140.3862	660.1293	60.02999
Sum Sq. Dev.	0.296774	13.53831	16289.53	0.018343	9.530638	13.25201
Observations	31	31	31	31	31	31
Correlations						
lnCO_2	1					
lnEG	0.7137	1				
lnEG^2	0.7091	0.9999	1	0.3645	0.8424	−0.1814
lnREC	−0.2277	0.3592	0.3645	1	0.7397	0.56804
lnAGV	0.4327	0.8394	0.8424	0.7397	1	0.2351
lnPG	−0.4224	−0.1861	−0.1814	0.5680	0.2351	1

Source: Findings from this research's analysis

econometric issues such as small sample bias, endogeneity, and serial correlation (Raihan et al., 2023). By employing these complementary methods, this research reinforces the validity of the long-term relationships identified within the energy-economy-environment nexus in Somalia.

4. RESULTS AND DISCUSSION

4.1. Descriptive Statistics

Table 2 summarizes the statistics of the key variables analyzed in this research. The findings show that agricultural value-added, GDP, and its squared term exhibit positive skewness, whereas CO_2 emissions, population, and renewable energy use are negatively skewed. The Jarque-Bera test indicates significant deviations from normality for renewable energy utilization and population, as evidenced by their low P-values. Additionally, the correlation matrix highlights a strong positive correlation between real GDP and CO_2 emissions, a moderate positive correlation with agricultural value-added, and a moderate negative correlation with population growth.

4.2. Stationarity Tests

Table 3 reports the outcomes of the stationarity tests. Most of the variables in the study are not stationary at their levels but become stationary after differencing as the ADF and PP test results indicate. However, utilization of renewable energy and population dynamics show stationarity at levels under both tests. These outcomes validate the choice of the ARDL model, which is particularly suitable for datasets comprising variables with mixed integration orders of zero and one.

4.3. F-bound Test

Table 4 shows the findings of the F-test and critical bound values, which assess the existence of a long-term relationship between the variables. The F-statistic of 12.04386 exceeds the upper bound critical value of 4.15 at the 1% significance level, signaling a strong long-term equilibrium cointegration between the variables.

Table 3: Results of the stationarity tests

Variables	ADF		PP	
	Levels	First difference	Levels	First difference
lnCO_2	−1.8891	−3.1973**	−1.9903	−3.1302**
lnEG	−1.4031	−3.7839***	−0.9026	−3.9646***
lnEG^2	−1.3886	−3.8145***	−0.8109	−3.9607***
lnREC	−5.8573***	−3.6817***	−5.8573***	−3.6682***
lnAGV	0.2539	−3.4134**	0.8948	−3.3087**
lnPG	−4.1409***	−8.1348***	−2.7007*	−7.2237***

*,**, and *** denote significance levels of 10%, 5%, and 1%, respectively

Table 4: F-test and critical bound values

F-Bounds test		Null hypothesis: No levels relationship		
Test statistic	Value	Significance (%)	I (0)	I (1)
F-statistic	12.04386	10	2.08	3
k	5	5	2.39	3.38
		2.5	2.7	3.73
		1	3.06	4.15

K represents the number of control variables

This outcome prompts the rejection of the null hypothesis of no long-term cointegration, further reinforcing the appropriateness of using the ARDL model in this research.

4.4. Short and Long-run Empirical Results

Table 5 details the estimated coefficients from the long and short-run ARDL analysis. The long-run analysis reveals that real GDP growth significantly raises environmental pollution in Somalia, confirming the presence of the EKC viewpoint. However, as economic growth advances, the rate of ecological degradation slows. Conversely, utilization of renewable energy significantly mitigates emissions, highlighting its critical role in reducing environmental degradation. Agricultural value-added, however, positively contributes to the carbon footprint over the long-term, suggesting that current agricultural practices in Somalia are detrimental to the environment.

Figure 2: CUSUM and CUSUMSQ plots

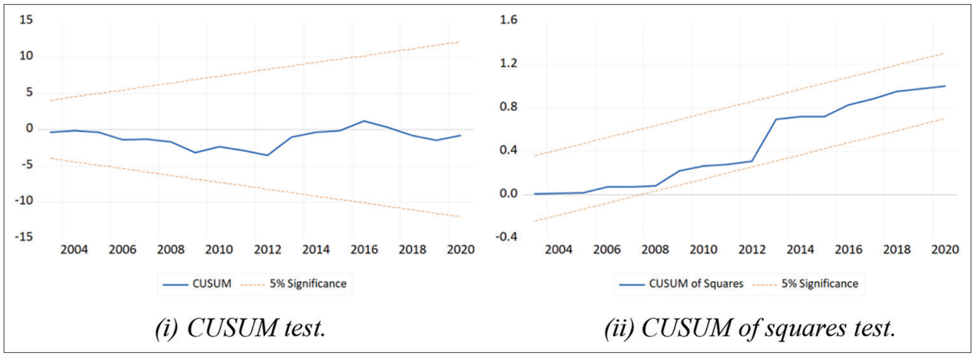


Table 5: Long and short-run empirical results

Variables	Long-run Coefficient	t-statistic	P-value	Short-run Coefficient	t-statistic	P-value
lnEG	4.996886	4.589782	0.0002	1.081223	3.156547	0.0055
$lnEG^2$	−0.143701	−4.570011	0.0002	−0.031180	−3.134831	0.0057
lnREC	−3.300735	−2.840525	0.0109	−4.964465	−12.28884	0.0000
lnAGV	0.216842	3.782138	0.0014	−0.090708	−2.678760	0.0153
lnPG	−0.000161	−0.006177	0.9951	−0.008604	−2.045171	0.0557
C	−26.58479	−2.288399	0.0344	-	-	-
ECT(−1)	−0.918243	-	-	−0.387887	−7.8787	0.0000
R^2						
Adjusted R^2			0.901211			

Source: Findings from this research's analysis

In the short run, economic growth exacerbates environmental degradation, though less intensely than in the long term, while renewable energy utilization remains an effective tool for immediate environmental quality enhancement. Interestingly, agricultural value-added shows a temporary detrimental effect on pollution, likely due to short-term factors such as seasonal agricultural variations. Population growth has an insignificant long-run effect on the environment but exerts a marginally negative impact in the short run, potentially reflecting short-term changes in energy demand or land use. The model's ECT is significant and negative, indicating a swift adjustment towards long-run equilibrium, with approximately 39% of short-run disequilibria corrected annually. The model exhibits a high level of explanatory power, as evidenced by its R-squared value and an adjusted R-squared.

The diagnostic tests in Table 6 indicate the absence of heteroskedasticity, serial correlation, non-normally distributed residuals, and omitted variable bias.

Stability tests depicted by the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMQ) plots in Figure 2, further show that the residuals remain within the 5% significance boundaries throughout the period analyzed.

The paper employed CCR, DOLS, and FMOLS methods, as shown in Table 7, to verify the robustness of the long-run ARDL findings. The consistency of the results across these methodologies reinforces the credibility of the findings of this research. Economic growth correlates positively with environmental pollution across all models, while the squared economic growth term confirms the EKC viewpoint. The renewable energy use consistently mitigates environmental harm, and agricultural value-added increases pollution, aligning with the ARDL outcomes.

Table 6: Post-estimation diagnostic tests

Tests	Coefficient	Probability
Heteroskedasticity (Breusch-Pagan-Godfrey)	0.520485	0.8649
Normality (Jarque-Bera)	0.542351	0.7625
Serial Correlation (Breusch-Godfrey)	1.009417	0.3291
Specification (Ramsey RESET)	0.173134	0.6825

Source: Findings from this research's analysis

4.5. Discussion of the Results

This study aimed to assess the energy-economy-environment nexus in Somalia, with a specific focus on understanding how agricultural value-added impacts the country's environmental pollution. By examining the impact of economic growth, renewable energy consumption, agricultural value-added, and population growth on CO_2 emissions, this study sought to provide insights into how Somalia can harmonize its economic development with environmental sustainability. The findings reveal a strong positive relationship between economic growth and environmental pollution in Somalia, supporting the Environmental Kuznets Curve (EKC) supposition. This result aligns with prior studies, such as those by (Abdi et al., 2024a; Aydoğan and Vardar, 2020; Sarkodie and Strezov, 2018), that identified similar dynamics in Somalia and other contexts, suggesting that while economic growth initially harms the environment, further economic expansion eventually promotes environmental health.

The use of renewable energy substantially lowers environmental degradation in Somalia, reinforcing the global consensus on

Table 7: CCR, DOLS, and FMOLS results

Variables	DOLS Coefficient	Probability	CCR Coefficient	Probability	FMOLS Coefficient	Probability
lnEG	2.695347	0.0317	2.196840	0.0113	2.156762	0.0046
lnEG2	−0.077400	0.0334	−0.062518	0.0124	−0.061253	0.0054
lnREC	−6.973303	0.0015	−4.015811	0.0000	−3.823685	0.0001
lnAGV	0.285979	0.0056	0.193000	0.0002	0.183140	0.0018
lnPG	−0.101802	0.2729	−0.001172	0.9573	−0.004038	0.7901
C	8.686205	0.4673	1.225071	0.8646	0.884797	0.8970
R2	0.992589		0.870909		0.867249	
Adjusted R^2	0.971416		0.844015		0.839593	

Source: Findings from this research's analysis

the prominence of renewable energy in reducing environmental impacts, as supported by studies like (Abdi et al., 2024a; Hussein and Mohamed, 2024; Mohamud and Mohamud, 2023; Omri and Nguyen, 2014; Saidi and Omri, 2020). This is particularly relevant for Somalia, where traditional biomass dominates energy use, contributing to deforestation and environmental degradation. Interestingly, the study found that the value the agricultural sectors adds to the economy prompts an increase in pollution levels in the long run, indicating that current agricultural practices in Somalia are detrimental to the environment. This contrasts with the results of some studies, such as Wang et al. (2020) in the G7 countries and (Abdi et al., 2024a; Hussein and Warsame, 2023; Raihan et al., 2023) in Somalia and China, where agriculture was found to promote environmental sustainability. However, the results align with research by (Raihan and Tuspekova, 2022b), which highlights that the agriculture sector contributes to environmental degradation in Peru. Lastly, Population growth has a slightly negative effect on Somalia's environmental pollution in the short term, but it shows an insignificant impact in the long term. This contrasts with studies in other countries, such as Alam et al. (2016), that found population growth significantly damaged the environment in Indonesia, Brazil, India, and China. The unique demographic and economic conditions in Somalia may explain this difference, indicating that while population growth does not currently drive emissions, it could become more significant as the country develops.

5. CONCLUSION AND POLICY RECOMMENDATIONS

This research set out to assess the energy-economy-environment nexus in Somalia, focusing on how agricultural value-added influences environmental pollution. By employing ARDL, CCR, DOLS, and FMOLS approaches and leveraging yearly time series data covering 1990-2020, the study provides significant insights into the dynamic interplay among these variables and their long-term implications for environmental sustainability in Somalia. The results confirm the EKC claim, demonstrating that economic growth exacerbates pollution at the beginning, but this relationship diminishes as income levels rise, eventually raising environmental quality. This suggests that while economic expansion drives environmental degradation in its early stages, further growth contributes to environmental health if managed properly. The use of renewable energy substantially lowers ecological footprint in Somalia, highlighting its crucial role in mitigating degradation. This aligns with global trends and reinforces the necessity for Somalia to transition from traditional biomass to more sustainable energy sources. Contrary to some global studies, the results indicate that agricultural value-added increases environmental pollution in Somalia. This finding points the current agricultural practices in Somalia deteriorates the environment, highlighting the urgent need for better sustainable practices. The findings indicate that population has marginal negative effect in the short run, which could be linked to specific socio-economic dynamics in Somalia, but the impact is insignificant in the long-term.

In conclusion, the study presents an understanding of the factors affecting environmental deterioration in Somalia and emphasizes the necessity of aligning economic growth with sustainable environmental practices. The results suggest that Somalia's path to sustainable development will require concerted efforts to reform agricultural practices and promote renewable energy adoption. The agricultural sector, which currently contributes to increasing pollution levels due to environmentally damaging practices, must undergo a transformation towards more sustainable methods. Implementing climate-smart agriculture, adopting renewable energy sources in farming, and promoting practices that enhance carbon sequestration could help reduce the sector's environmental impact while maintaining its economic contribution. In addition, this study highlights the urgent need for Somalia to embrace cleaner energy pathways as its economy expands, aligning with global efforts to combat environmental degradation. Despite Somalia's considerable solar energy potential, owing to its abundant solar radiation, this resource remains underutilized. A strategic focus on expanding solar energy infrastructure could not only mitigate environmental harm but also enable the country to leapfrog traditional energy development, thereby driving economic growth and reducing GHGs. Thus, the recommendation of this paper also call for targeted investments in renewable energy. These policy measures are vital for ensuring that Somalia balances economic development with environmental sustainability.

Future research should explore the effects of sustainable agricultural practices, like precision agriculture and agroforestry, on reducing emissions while boosting productivity. Additionally, studies should examine the impact of specific renewable energy sources on CO_2 emissions in Somalia. Lastly, the long-term impact of technological innovations in the agriculture and energy sectors on CO_2 emissions should be assessed to guide Somalia's environmental and economic strategies.

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