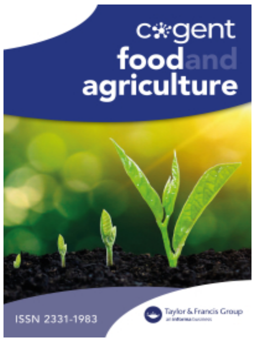

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The causal connection between CO_2 emissions and agricultural productivity in Somalia: evidence from an ARDL Bounds Testing Approach

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ABSTRACT

Agriculture is the backbone of Somalia's economy, accounting for over 75% of GDP and 93% of total revenue. Using an Autoregressive Distributed Lag (ARDL) model covering the period from 1990 through 2019, this study examines the relationship between CO_2 emissions and agricultural productivity in Somalia. The analysis shows that agricultural productivity (AGR), GDP per capita and renewable energy consumption (REC) significantly impact environmental degradation. In particular, higher agricultural productivity and higher GDP per capita are associated with lower environmental degradation, emphasising the importance of sustainable agricultural practices. Conversely, renewable energy consumption initially increases environmental degradation, possibly due to transition problems in introducing new technologies. The short-term results of the error correction model (ECM) show a significant negative relationship between agricultural productivity, GDP and environmental degradation. At the same time, renewable energy consumption has a positive short-term impact. The originality of this study lies in the fact that it focuses on the particular environmental and agricultural context of Somalia. This region has received less attention in the existing literature. The study proposes policy reforms that promote sustainable land management strategies, including agroforestry, crop rotation and conservation agriculture. These strategies, if implemented, will help restore soil health and reduce deforestation caused by unsustainable agricultural practices, offering a hopeful and optimistic outlook for the future of Somalia's agriculture and environment.

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Agriculture & Environmental Sciences; Economics; Environmental Economics

1. Introduction

In recent years, the agricultural industry in Africa has made positive progress in agricultural production. This growth highlights the potential for significant increases in agricultural productivity by introducing modern farming methods, improved infrastructure and strategic investments. However, the benefits of this progress must be weighed against the backdrop of increasing environmental pressures.

The agricultural sector not only contributes significantly to Somalia's GDP but is also the backbone of economic activity, exports and employment in Somalia. Livestock farming, particularly in the agricultural sector, continues to be the Somali economy's main driver. Agriculture is responsible for more than 75% of Somalia's GDP and an incredible 93% of the country's total exports (World Bank & Food and Agriculture Organization of the United Nations, 2018). Given Somalia's heavy reliance on agriculture, understanding the factors that impact agricultural productivity is critical to ensuring food security and economic stability.

Environmental degradation due to human activities refers to the degradation of natural resources such as water, oxygen and soil. The relationship between environmental factors and agricultural productivity has become an essential area of research in light of global climate change. One of the most pressing issues is the impact of carbon dioxide (CO_2) emissions on agricultural yields, especially in regions particularly vulnerable to climate variability. CO_2 emissions, mainly from industrial activities, deforestation and burning fossil

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fuels, have been linked to global warming. In the context of agriculture, increased CO_2 levels can have both positive and negative effects. Edoja et al. (2016) found a negative and significant short-term relationship between CO_2 emissions and agricultural productivity.

Agricultural productivity and carbon dioxide emissions are critical in Somalia due to their significant local and global impacts. An accelerated increase in carbon dioxide emissions causes global warming and climate change that threatens food production (Ayyildiz & Erdal, 2021). Somalia struggles with significant land degradation due to soil erosion, deforestation and overgrazing. These environmental stresses reduce agricultural productivity, further exacerbating food insecurity among the population (Food and Agriculture Organization [FAO], 2020). Agriculture in Somalia is vulnerable to climate change. The reduced crop yields and livestock productivity caused by increased carbon emissions can threaten livelihoods, increase poverty, and contribute to hunger as temperatures rise and the weather becomes volatile. Somalia must reduce carbon emissions and improve agricultural productivity to achieve its SDGs, which include SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

Furthermore, Somalia's agricultural productivity has far-reaching global and regional food security implications. This can lead to food shortages, increased global prices, and greater dependence on humanitarian aid due to droughts and poor harvests. Strengthening the resilience of agriculture in Somalia can help stabilise the global food supply. Reducing carbon emissions in countries vulnerable to climate change, such as Somalia, is essential. Despite Somalia's relatively low emissions, Somalia's climate challenges underscore the widespread global concern about the need for sustainable agricultural practices, climate change mitigation efforts, and adaptation measures to mitigate climate change. Agriculture significantly exacerbates global warming, especially livestock production (Pata, 2021). Conversely, climate change substantially impacts crops and livestock (Mendelsohn, 2009).

In addition, studying the links between CO_2 emissions and agricultural productivity provides valuable insights into broader environmental impacts, such as soil degradation and water scarcity. These factors are crucial for sustainable agricultural practices and environmental management. By addressing the environmental challenges associated with carbon emissions, Somalia can work towards the long-term sustainability of its agricultural sector (Ali Warsame & Hassan Abdi, 2023). Finally, empirical evidence on the causal relationships between CO_2 emissions and agricultural productivity is essential for formulating effective policy measures. Such findings can inform strategies to reduce carbon emissions and implement adaptation techniques to combat climate change. Policymakers can use this information to develop comprehensive plans that pursue both environmental and economic goals, ensuring a balanced approach to development (Hassan & Mohamed, 2024; Warsame et al., 2021).

Agriculture is the backbone of Somalia's economy, accounting for over 75% of GDP and 93% of total revenue (Warsame et al., 2021). Agriculture is a critical sector in Somalia, providing labour opportunities and income generation activities through crop sales. It is also a significant economic activity. More importantly, it is vital in meeting the population's food needs. Over 46% of the labour force is employed in agriculture, 25% in crop cultivation, and 9% in herding. The fishery subsector employs 4% of the workforce, and 9% is used in other agricultural-related activities, such as agro-processing and forestry (World Bank, 2018). For the past two decades, Somalia has been experiencing recurrent droughts and variations in rainfall patterns, which have substantially impacted agricultural output. The cumulative impact of many unsuccessful rainy seasons has reduced food production, resulting in a critical humanitarian crisis that escalated into famine in 2011, 2017, and 2022 in various regions of Somalia (World Bank, 2018) (World Bank & Food and Agriculture Organization of the United Nations, 2018). Simultaneously, Somalia has been dealing with significant environmental deterioration. With just 10.5% of its land area forested, the nation has encountered a concerning yearly deforestation rate of 429,000 hectares from 2000 to 2021, resulting in an average annual deforestation rate of 4.9% (World Bank, 2022). Deforestation and land degradation—currently expected to impact 23–30% of Somalia's total land—have resulted in the loss of 147,704 km^2 from 2000 to 2015. The degradation is caused by soil erosion, biological depletion, and gully erosion, exacerbated by the extensive use of firewood and charcoal for energy (World Bank, 2022). Considering agriculture's crucial role in Somalia's economy and the increasing environmental issues, it is essential to investigate the causal relationship between CO_2 emissions and agricultural output. Understanding these dynamics is essential for developing strategies that reduce environmental damage while improving agricultural output. This equitable strategy is essential for attaining environmental sustainability and enhanced food security in Somalia.

Several studies have already been conducted on the relationship between CO_2 emissions and agricultural productivity (Edoja et al., 2016; Rehman et al., 2019). However, these studies have focussed on countries other than Somalia. Given the particular environmental and agricultural challenges facing Somalia, examining the relationship in the country's specific context is crucial. In another study by Warsame et al. (2021), the autoregressive distributed lag (ARDL) technique was used to investigate the relationship between climate change and crop production in Somalia. Their study provided empirical evidence on how climate variables such as temperature and rainfall affect crop yields. However, the study focussed primarily on climate variables without examining the role of CO_2 emissions in detail. In addition, the study should have addressed the indirect socio-economic factors that could interact with CO_2 emissions and influence agricultural productivity. This study aims to fill a critical knowledge gap by examining the causal relationship between CO_2 emissions and Somalia's agricultural productivity using a time series of data from 1990 to 2019. The study's specific objectives are to investigate the long- and short-term relationships between agricultural productivity, energy consumption, GDP per capita and CO_2.

To achieve these research objectives, this study applies the Autoregressive Distributed Lag (ARDL) Bounds Testing Approach to explore the causal connection between CO_2 emissions and agricultural productivity in Somalia. The ARDL approach is particularly well-suited for this study because it offers several advantages over other econometric models. The ARDL model provides flexibility with the order of integration, as it can be applied regardless of whether the underlying variables are purely I(0), purely I(1), or a mixture of both. Another key advantage of the ARDL model is its ability to simultaneously estimate short-run and long-run dynamics, providing a comprehensive view of the relationship between variables. This is critical for understanding how CO_2 emissions and other factors impact agricultural productivity over different time horizons.

Our main findings indicate that, in the long run, agricultural productivity, GDP per capita, and renewable energy consumption significantly influence environmental degradation. Specifically, higher agricultural productivity and GDP per capita are associated with reduced environmental degradation, highlighting the importance of sustainable agricultural practices. Conversely, renewable energy consumption initially increases environmental degradation, likely due to transitional challenges in adopting new technologies. In the short run, the Error Correction Model (ECM) results show a significant negative relationship between agricultural productivity, GDP, and environmental degradation. At the same time, renewable energy consumption exhibits a positive short-term impact. These findings are crucial for policymakers, as they underscore the need for developing strategies that promote sustainable agricultural practices and investments in renewable energy infrastructure. This study offers valuable insights for designing effective adaptation and mitigation strategies to support sustainable agricultural development by providing empirical evidence on the environmental impacts of agricultural and economic activities in Somalia.

This study contributes several ways to the literature on environmental economics and agricultural productivity in Somalia. Firstly, the study fills an essential gap in the existing body of knowledge by including socio-economic parameters such as GDP per capita and energy consumption in the analysis. This allows a deeper understanding of how these variables interact with CO_2 emissions and affect agricultural production. Secondly, this study contributes to the existing empirical literature by presenting information on how renewable energy use interacts with agricultural production and environmental degradation. These results highlight the complexity associated with the transition to sustainable energy sources. Finally, the study's results provide policy-relevant insights applicable to Somalia and other developing countries facing similar environmental and agricultural challenges. Thus, the study is of global significance and contributes to a broader discourse on sustainable development in the agricultural sector.

The remainder of our paper is arranged as follows: The first section introduces the topic, followed by a review of the theoretical and empirical literature in section two. The methodology is presented in section three. Section four offers the empirical findings, while sections five and six discuss the study's results and conclusions.

2. Literature review

This literature review explores the interconnections among CO_2 emissions, agricultural production, economic development, and energy use. Understanding these connections is crucial and critical to addressing environmental challenges and promoting sustainable development, particularly in agricultural economies like Somalia. This understanding is the foundation for building a more sustainable future.

The agriculture sector significantly contributes to global greenhouse gas emissions, accounting for

14–30% of total emissions due to the extensive use of fossil fuels, fuel-driven equipment, irrigation, livestock production, and nitrogen-rich fertilisers (FAO). This sector can potentially reduce 80–88% of current CO_2 emissions through various measures, including improved soil and crop management, reducing tillage, and converting cultivated land to permanent crops (FAO). The Food and Agriculture Organization (FAO) emphasises that the agricultural sector holds substantial potential to decrease its emissions by adopting sustainable practices.

Human activities, particularly in power generation, residential, industrial, and transportation sectors, are primary drivers of CO_2 emissions. Economic activities involving the combustion of fossil fuels lead to increased greenhouse gas emissions, contributing significantly to climate change. In developing countries like Somalia, where agriculture is a critical part of the economy, the adverse effects of CO_2 emissions on agricultural productivity are particularly concerning. Climate change, driven by these emissions, affects crop yields and overall agricultural output, necessitating comprehensive studies to explore these dynamics (Warsame et al., 2021).

A previous study found that agricultural productivity significantly impacts CO_2. Rehman et al. (2019) demonstrate the relationship between carbon dioxide emissions and various factors such as cropped area, energy consumption, fertiliser offtake, gross domestic product per capita, distribution of improved seeds, total food grains, and water availability in Pakistan over the period from 1987 to 2017. An autoregressive distributed lag (ARDL) bounds-testing technique for cointegration was utilised to illustrate the causal relationships among the study variables based on long- and short-run analyses. The findings offer substantial long-term evidence that there is a positive and significant relationship between cropped area, energy consumption, and gross domestic product per capita with CO_2 emissions, highlighting the significance of our results.

Similarly, Raihan et al. (2022) explore the connections among economic growth, energy consumption, urban development, agricultural efficiency, and CO_2 emissions in Bangladesh. The study utilises the Dynamic Ordinary Least Squares (DOLS) method alongside the Autoregressive Distributed Lag (ARDL) bounds test, demonstrating that a decrease in agricultural productivity plays a significant role in the rise of CO_2 emissions. This finding highlights the importance of maintaining high agricultural productivity in reducing CO_2 emissions, stressing the necessity for policies that improve agricultural efficiency to tackle environmental issues in Bangladesh. In their study, Valin et al. (2013) examine the impact of various crop yield and livestock feed efficiency scenarios on greenhouse gas (GHG) emissions from agriculture and land use changes in developing nations. This study examines the mitigation linked to various productivity pathways through the global partial equilibrium model GLOBIOM. The results indicated the opposite effect of AGP on greenhouse gas emissions. Edoja et al. (2016) investigated the relationship between CO_2 emissions, agricultural production, and food security in Nigeria. The study examined annual time series data spanning from 1961 to 2010. The findings indicate an absence of a long-term relationship among the three variables. VAR estimations and impulse response functions reveal a significant and negative short-run relationship between CO_2 and AGP, indicating that CO_2 emissions decline in the short term as agricultural productivity rises.

The relationship between CO_2 emissions and economic growth has been extensively studied within the Environmental Kuznets Curve (EKC) framework. The EKC hypothesis posits that as economies grow, CO_2 emissions initially increase but eventually decrease as countries transition to cleaner technologies and more sustainable practices (Grossman & Krueger, 1995). This transition offers hope for a future where economic growth is not at the expense of the environment. However, empirical evidence remains mixed, particularly for developing countries where economic growth relies heavily on carbon-intensive energy sources. Some previous research has demonstrated that economic growth is linked to environmental degradation. For instance, Djellouli et al. (2022) examine the impact of non-renewable energy, renewable energy, economic development, and foreign direct investment on environmental deterioration in twenty chosen African nations from 2000 to 2015. the study adopted the Environmental Kuznets Curve theory and the Pollution Haven/Halo hypothesis. They found a positive relationship between economic growth and CO_2. Further, Kasperowicz (2015) used ECM estimation and suggested a negative long-run relationship between GDP and CO_2 emissions. Similarly, Stern (2004) suggests that as countries become more affluent, environmental quality initially declines but eventually improves. York et al. (2003) Investigate the main drivers of environmental deterioration, focusing on the roles of economic expansion, population, and technology. This study found economic growth to be a key driver of environmental degradation, but they acknowledged the roles of technology and population.

Energy consumption is a critical driver of CO_2 emissions, with the energy sector accounting for approximately 61.4% of total greenhouse gas emissions globally. The increasing energy demand, projected to rise by 56% between 2010 and 2040, underscores the need for sustainable energy solutions to mitigate CO_2 emissions. Renewable energy sources are crucial, offering significant potential to reduce CO_2 emissions by 50% by 2050. Renewable energy consumption is an essential factor in reducing environmental degradation. A study by Hu et al. (2018) analyses the impact of renewable energy consumption and commercial services trade on reducing carbon emissions in 25 developing nations from 1996 to 2012. The study showed that as more renewable energy sources are utilised, there is a decrease in environmental degradation.

Similarly, Djellouli et al. (2022) examine the impact of non-renewable, renewable energy, economic development, and foreign direct investment on environmental deterioration in twenty chosen African nations from 2000 to 2015. the study adopted the Environmental Kuznets Curve theory and the Pollution Haven/Halo hypothesis. They found that renewable energy consumption significantly reduces CO_2 emissions. Renewable energy cannot only provide the energy needed for industrialisation but also delay the degradation of the environment Cheng et al. (2019). Furthermore, consumption of renewable sources of energy may have a significant effect on reducing environmental degradation in a variety of countries, including Russia, Brazil, India, and China (Nassani et al., 2017). Kahia et al. (2019) investigated the correlation among renewable energy usage, economic development, foreign direct investment (FDI), trade, and carbon dioxide emissions in 12 nations of the Middle East and North Africa (MENA) from 1980 to 2012. Employing a Panel Vector Autoregressive model, the study found that renewable energy and international trade decreased carbon dioxide emissions.

In a similar tone, Pata and Naimoglu (2024) examine the impact of research and development investments in renewable and nuclear energy on CO_2 emissions in France from 1990 to 2020, applying the Fourier Autoregressive Distributed Lag (ARDL) approach to assess the impact of energy prices and technological advances on CO_2 emissions. It emphasises that while renewable and nuclear energy are alternatives to fossil fuels, technological progress in renewable energy significantly reduces carbon emissions. The study emphasises that rising energy costs could further accelerate the transition to renewable energy sources. Erdogan et al. (2023) examine the potential of renewable energy investments and technologies to promote carbon neutrality in the G7 countries. The authors apply sophisticated econometric methods, such as the cross-sectionally augmented Dickey-Fuller unit root test, the Durbin-Hausmann panel cointegration test, and the panel-augmented mean group estimator. The results conclude that investments in renewable energy and related technologies significantly reduce carbon emissions, while governance variables do not impact substantially. The study emphasises the importance of renewable energy for achieving carbon neutrality in the G7 countries.

An earlier study by Pata et al. (2023) examined the simultaneous effects of renewable energy, tourism, foreign direct investment (FDI) and trade openness on CO_2 emissions in six ASEAN countries within the framework of the ecological Kuznets curve (EKC) hypothesis. The study uses panel data from 1995 to 2018 and utilises the ARDL estimator and the Dumitrescu-Hurlin panel causality test. Their analysis shows that renewable energy has only a short-term impact on CO_2 emissions and no long-term impact, likely due to its underutilisation in ASEAN countries. Pata (2024) investigated the impact of energy policy uncertainty (ENPU) and climate policy uncertainty (CLPU) on carbon emissions and renewable electricity generation (REP) in China and the US. The study uses sophisticated econometric techniques to show that ENPU and CLPU increase carbon emissions in both countries. CLPU reduces REP, but ENPU has the opposite effect: it reduces REP in China but increases it in the US. The results show that climate and energy policy ambiguities hinder progress towards achieving the clean energy goals (SDG-7) and climate action (SDG-13). Similarly, Nor et al. (2024) scrutinise the relationship between environmental degradation and various variables, including renewable energy consumption, GDP, foreign direct investment and population. This study found that Somalia's renewable energy consumption and GDP have adverse and statistically significant effects on environmental degradation in the short and long term.

The literature highlights the relationships between CO_2 emissions, agricultural productivity, economic growth, and energy use. While existing studies provide valuable insights, there is a critical knowledge gap regarding the direct and indirect effects of CO_2 emissions on agricultural productivity in Somalia. This research aims to fill this gap by exploring these connections using the Autoregressive Distributed Lag (ARDL) Bounds Testing Approach. Considering environmental and socio-economic factors, this study will offer a foundation for developing effective adaptation and mitigation strategies, contributing to sustainable agricultural development in Somalia. This study differentiates itself from existing literature by concentrating specifically on Somalia, thoroughly analysing the direct and indirect impacts of CO_2 emissions, using an advanced analytical framework, and including socio-economic variables. Its contributions fill significant knowledge gaps and provide essential insights to guide policy and practice for sustainable agricultural development in Somalia.

2.1. Hypotheses

We develop our hypotheses based on the Environmental Kuznets Curve (EKC) theory, which suggests a relationship between economic development and environmental degradation.

H1. Agricultural productivity impacts environmental degradation in Somalia

H2. GDP per capita impacts environmental degradation in Somalia

H3. Renewable energy consumption impacts environmental degradation in Somalia

According to the EKC, CO_2 emissions in growing economies initially increase due to industrialisation but gradually decrease as nations adopt cleaner technologies and more sustainable practices (Grossman & Krueger, 1995). In Somalia, which faces significant socio-economic challenges, we examine how agricultural productivity, GDP per capita and renewable energy consumption affect environmental outcomes. For example, Edoja et al. (2016) investigated the relationship between CO_2 emissions, agricultural production and food security in Nigeria. The study analysed annual time series data from 1961 to 2010, showing no long-term relationship between the three variables. VAR estimates and impulse-response functions show a significant and negative short-term relationship between CO_2 and agricultural production, suggesting that CO_2 emissions decrease in the short term when agricultural productivity increases. In contrast, Kasperowicz (2015) and Stern (2004) indicate that GDP growth initially worsens environmental quality before improvements occur as countries become more prosperous. Similarly, Erdogan et al. (2023) examine the potential of investments in renewable energy and technologies to promote carbon neutrality in the Group of Seven (G7) countries. The authors apply sophisticated econometric methods, such as the cross-sectionally augmented Dickey-Fuller unit root test, the Durbin-Hausmann panel cointegration test, and the panel augmented mean group estimator. The results conclude that investments in renewable energy and related technologies significantly reduce carbon emissions, while governance variables have no significant impact. The study emphasises the importance of renewable energy in achieving carbon neutrality in the G7 countries.

The EKC framework is relevant given Somalia's dependence on agriculture, limited industrialisation, and growing interest in renewable energy. Given Somalia's dependence on agriculture, limited industrialisation and increasing interest in renewable energy, the EKC framework is applicable. We hypothesise that agricultural productivity may increase environmental degradation due to unsustainable practices, while GDP per capita may have a comparable impact without strict environmental regulations. However, the increasing use of renewable energy will mitigate these adverse effects by reducing dependence on traditional energy sources. Therefore, this study aims to analyse the impact of Somalia's economic activities on the environment.

Figures 1–4 indicate the trends in CO_2 emissions, Agricultural productivity, GDP per capita and energy consumption in Somalia.

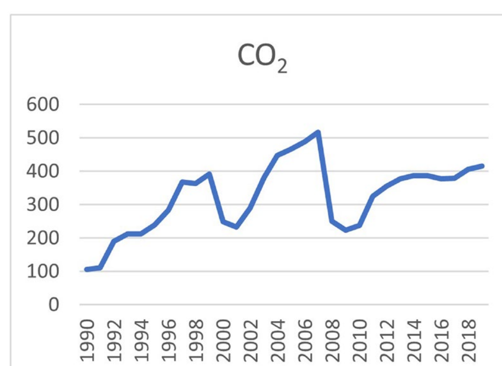

Figure 1. CO_2 emission.

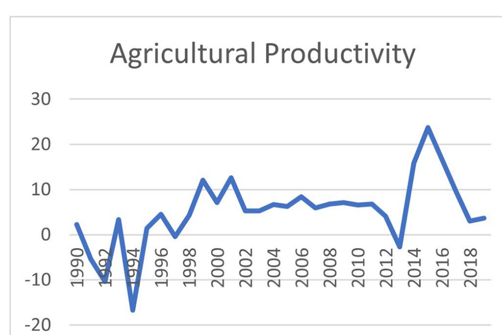

Figure 2. Agricultural productivity.

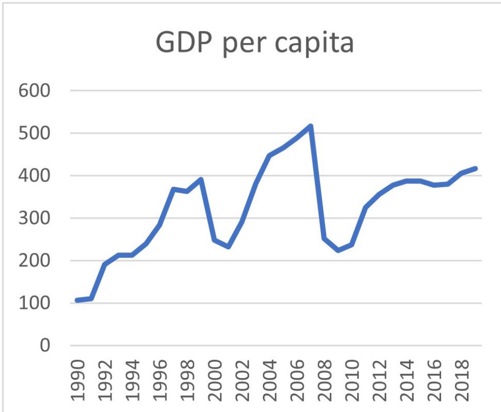

Figure 3. GDP per capita.

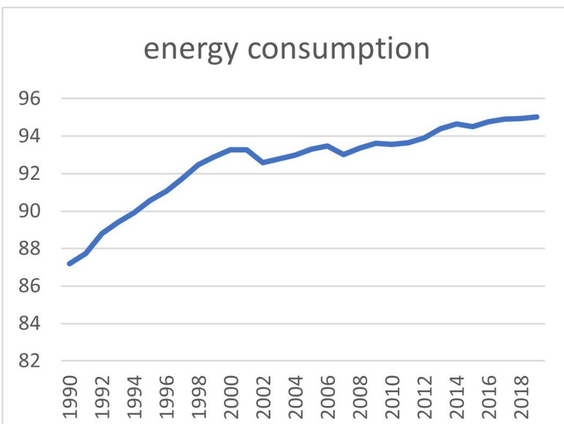

Figure 4. Energy consumption.

3. Data and methods

3.1. Data

This study uses annual time series data covering the period from 1990 to 2019. The period from 1990 provides an extensive 30-year time series that allows for accurate econometric analysis, especially for models such as ARDL, which require sufficient observations to examine long-term and short-term relationships effectively. This time span can include economic cycles, policy changes, and structural upheavals. The data comes from the World Bank and SESRIC. Table 1 provides a detailed overview of the variables used in the analysis and their corresponding explanations and data sources.

3.2. Model specification—Autoregressive Distributed Lag (ARDL) model

The ARDL model, introduced by Pesaran and Shin (1998), is a popular econometric technique used for modelling the relationship between variables, especially when the variables have different orders of integration (i.e. I(0) or I(1))—but not I(2). The ARDL model can handle short- and long-run dynamics between variables within the same framework, making it useful for time series analysis. The benefits of the ARDL bound test over the other traditional cointegration techniques are as follows: (i) it can be used when there is a mixed order of integration; (ii) it allows for the estimation of both long-run and short-run coefficients without requiring pre-testing for unit roots; (iii) it is applicable for the small sample size; (iv) accommodating different lag length; (v) autocorrelation problem is removed.

Table 1. Variable description and data sources.

Variables	Explanations	Data sources
Environmental Degradation (ED)	Represented by CO_2 emissions (in millions of tonnes).	World bank
Agricultural Productivity (AP)	Agriculture, value-added, constant 2015 prices, annual change (per cent).	SESRIC
Gross Domestic Product (GDP)	GDP per capita was constant in 2010 US dollars.	SESRIC
Energy consumption	(% of total final energy consumption)	SESRIC

Note. Table 1 provides an overview of the variables used in the study, along with their explanations and sources. The World Bank and SESRIC data ensures the reliability and consistency of the variables analysed.

The ARDL framework is often coupled with bounds testing, developed by Pesaran et al. (2001), to examine the presence of cointegration among the variables. The bounds test checks a long-run relationship (cointegration) between the variables. It compares an *F*-statistic against the lower bound I (0) and upper bound I(1) critical values, determining whether cointegration exists. When the calculated *F* statistic is below, the null hypothesis is not rejected; when the calculated F statistic is greater, the null hypothesis is rejected, which shows evidence of a long-run relationship among the variables. If cointegration is found, the long-run relationship can be estimated. At the same time, an error correction model (ECM) can be used to assess short-run adjustments to any deviation from the long-run equilibrium. In addition, after estimating the model, various diagnostic tests (e.g. serial correlation, heteroskedasticity, stability tests) should be performed to ensure the model's robustness.

This paper determines the relationship between the dependent and explanatory variables using ordinary least squares (OLS).

$$Y = f\left(ED, AP, REC, GDP\right) \tag{1}$$

$$ED_t = \beta_0 + \beta_1 AP_t + \beta_2 REC_t + \beta_3 GDP_t + \varepsilon \tag{2}$$

Where AP stands for agricultural productivity, ED for environmental degradation, REC for renewable energy consumption and GDP for gross domestic product.

We then undertake a cointegration analysis to examine the relationship between the following variables over time. We rewrite Eq. (2) into ARDL form as follows:

$$\Delta ED_t = \alpha_0 + \beta_1 ED_{t-1} + \beta_2 AP_{t-1} + \beta_3 REC_{t-1} + \beta_4 GDP_{t-1} + \sum_{i=0}^{q} \Delta\alpha_1 ED_{t-k} + \sum_{i=0}^{p} \Delta\alpha_2 AP_{t-k} + + \sum_{i=0}^{p} \Delta\alpha_3 REC_{t-k} + \sum_{i=0}^{p} \Delta\alpha_4 GDP_{t-k} + \varepsilon_t \tag{3}$$

To confirm the long-term relationship between the model variables, we use the two critical values of Pesaran et al. (2001) to reject the null hypothesis of no long-term cointegration if the obtained *F*-statistic exceeds the higher critical value. We do not reject the null hypothesis if the value of the *F*-statistic is below the lower critical values, indicating no long-term cointegration between the model variables.

Once the long-term relationship is established, the ARDL model derives the error correction model (ECM). It was derived by estimating the short-term parameters of the model by applying the ECM. Thus, incorporating the ECM model into our short-term parameters of the ARDL model would lead to equation (4) as follows:

$$\Delta \mathrm{ED_t} = \alpha_0 + \sum_{i=0}^{q} \Delta\beta_1 ED_{t-k} + \sum_{i=0}^{p} \Delta\beta_2 AP_{t-k} + \sum_{i=0}^{p} \Delta\beta_3 REC_{t-k} + \sum_{i=0}^{p} \Delta\beta_4 GDP_{t-k} + \lambda ECM_{t-1} + \varepsilon_t \tag{4}$$

The other variable definitions remain the same, with the exception of the error correction term (ECT). The ECT, a crucial factor in linking variables in the short run, must be negative and statistically significant.

4. Empirical findings

4.1. Summary statistics

The statistical values of the different normalities are shown in Table 2, together with the results of the summarised measurements across the variables. Each variable contains a total of 30 samples of time series data from Somalia from 1990 to 2019. Skewness values that are close to "0" indicate that all variables are normal. In addition, kurtosis was used to determine whether the series should be categorised as light or heavy-tailed compared to a normal distribution. Based on the empirical observations, all series are platykurtic as their values are less than 3.

In addition, environmental degradation had an average value of 0.063, with the highest and lowest values being 0.105 and 0.043, respectively. We found that the highest and lowest values for agricultural productivity were 23.7 and 16.65 respectively, while the mean value was 5.14. GDP averaged 322.53, with the highest and lowest GDP values in Somalia being 516.7 and 106.6 respectively. In addition, renewable energy consumption averaged 92.59, with the highest and lowest values for REC in Somalia being 95.03 and 87.20 respectively.

4.2. Unit root test results

The results of the unit root tests are summarised in Table 3, in which the Augmented Dickey-Fuller (ADF) and (Phillip-Perron) PP tests are used. The results of the ADF test show that all variables were stationary at the level except REC, which became stationary at first difference. In addition, the results of the PP test show that AP and REC were stationary at level, while ED and GDP were not stationary at level but became stationary after first difference. The unit root tests indicate that the series is stationary at different levels, either at the level or at first order integration, either I(0) or I(1). This makes it suitable for use with the ARDL bounds cointegration approach. In addition, the results of the unit root test are shown in Table 3. The results show that we could not reject the null hypothesis that the series are non-stationary when the unit root test was performed at the level with the presence of a regime shift. Nevertheless, we performed a first-order integration, i.e. I(1), with the predicted break dates 1979, 1980, 2001 and 2010.

Table 2. Summary statistics.

	ED	AP	GDP Per Capita	REC
Mean	0.063206	5.143000	322.5347	92.59304
Median	0.055974	5.635000	359.6750	93.27000
Maximum	0.105785	23.71000	516.7000	95.03000
Minimum	0.042826	−16.65000	106.6400	87.20322
Std. Dev.	0.019350	7.652142	106.0342	2.135771
Skewness	1.179834	−0.458931	−0.244277	−1.117222
Kurtosis	3.079989	4.738252	2.311829	3.339145
Jarque-Bera	6.968038	4.829985	0.890331	6.384695
Probability	0.030684	0.089368	0.640718	0.041075
Obs (no of years)	30	30	30	30

Table 3. The result of the unit root test.

	ADF			PP		
Variables	*T*-statistics	prob	Order	*T*-statistics	prob	Order
ED	−4.6577	0.0057***	I (0)	−2.8625	0.0627*	I (1)
AP	−7.5337	0.0000***	I (1)	−3.1449	0.0342*	I (0)
REC	−4.4696	0.0141***	I (0)	−4.2628	0.0024***	I (0)
GDP per capita	−2.6991	0.0872*	I (0)	−4.6294	0.0010***	I (1)

Notes. *, **, *** denote significance at 10%, 5% and 1%, respectively.

4.3. Results of the cointegration tests

Once we have established the stationarity of the series, we use the ARDL Bounds test to assess cointegration. We used the information criterion (IC), the Schwarz-Bayes criterion (SBC) and the Akaike criterion (AIC) to determine the optimal lag length for the cointegration study. The AIC showed that two lags were most effective. The *F*-statistic was calculated using an acceptable lag length determined by the Akaike criterion (AIC). The ARDL bounds test was performed to examine the cointegration relationship between the variables and the results are presented in Table 4. The results are presented such that when the estimated value of the *F*-test exceeds the values of both bounds (lower and upper bounds), the existence of a long-run association between the variables is established. The results show that the approximate value of the *F*-statistic (10.61109) over 10%, 5%, 2.5% and 1% of the decisive upper bound is of the order of zero and one, respectively, rejecting the null hypothesis and establishing a long-run association between the variables.

Table 4. ARDL bounds test results.

F-Bounds test		Null Hypothesis: No levels of relationship		
Test statistic	Value	Signif	I(0)	I(1)
			Asymptotic: $n = 1000$	
F-statistic	10.61109	10%	2.72	3.77
k	3	5%	3.23	4.35
		2.5%	3.69	4.89
		1%	4.29	5.61

Table 5. Long –run coefficients.

Levels equation				
Case 3: unrestricted constant and no trend				
Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
AP	−0.000653	0.000252	−2.590038	0.0237
GDP per capita	−3.27E-05	1.09E-05	−2.986769	0.0113
REC	−0.004810	0.001017	−4.731212	0.0005

4.4. Long –run result

The long-term relationship between carbon emissions (CO_2), agricultural productivity (AP), GDP per capita and renewable energy consumption (REC) was analysed. As the estimates in Table 5 show, the regression analysis provides valuable insights into the long-term dynamics between critical variables and environmental degradation in Somalia. The results show that environmental degradation is negatively affected by agricultural productivity (AP), GDP per capita and renewable energy consumption (REC).

The analysis shows a negative and statistically significant correlation between agricultural productivity and environmental degradation, with a significance level of 5%. Specifically, a 1% increase in agricultural productivity leads to a 0.000653% decrease in environmental degradation in Somalia in the long term. This indicates that higher agricultural productivity reduces environmental degradation, likely due to adopting more sustainable agricultural practices. Thus, H1 is accepted, and the result is consistent with those of Edoja et al. (2016) and Raihan et al. (2022). Similarly, the study shows a negative and statistically significant correlation between GDP and environmental degradation, with a significance level of 5%.

A 1% increase in GDP per capita leads to a 0.0000327% decrease in environmental degradation in Somalia in the long term. Economic growth leads to a slight decrease in environmental degradation due to increased investment in cleaner technologies and more sustainable development methods. Thus, H2 is accepted, and the result is consistent with Kasperowicz (2015) and Stern (2004). The most remarkable result is the strongly negative and statistically significant relationship between renewable energy consumption and environmental degradation, with a significance level of 1%. A 1% increase in renewable energy consumption leads to a 0.00481% decrease in environmental degradation in Somalia in the long term. This emphasises the significant environmental benefits of increased renewable energy use, which can lead to a cleaner and more sustainable ecosystem. Thus, H3 is accepted, and the result is in line with Djellouli et al. (2022), Cheng et al. (2019), Nassani et al. (2017) and Kahia et al. (2019).

These findings emphasise the urgent need for balanced policy interventions that promote economic

Table 6. Error Correction Model (ECM).

ARDL Error Correction Regression
Dependent Variable: D(ED)
Selected Model: ARDL (2, 3, 4, 1)
Case 3: Unrestricted Constant and No Trend
ECM Regression
Case 3: Unrestricted Constant and No Trend

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
C	0.171776	0.023577	7.285851	0.0000
D(ED(−1))	0.204773	0.065683	3.117614	0.0089
D(AP)	−0.000115	1.78E-05	−6.490910	0.0000
D(AP(−1))	9.24E-05	2.32E-05	3.984620	0.0018
D(AP(−2))	9.11E-05	1.82E-05	5.007607	0.0003
D(GDP PER CAPITA)	−2.87E-06	2.01E-06	−1.426550	0.1792
D(GDP PER CAPITA(−1))	5.23E-06	1.94E-06	2.702044	0.0192
D(GDP PER CAPITA(−2))	7.17E-06	2.07E-06	3.460164	0.0047
D(GDP PER CAPITA(−3))	6.69E-06	2.07E-06	3.226712	0.0073
D(REC)	−0.006264	0.000584	−10.72332	0.0000
CointEq(−1)*	−0.330033	0.045310	−7.283916	0.0000

Table 7. Diagnostic and stability test results.

Test	*F*-statistics	Prob. Value
Autocorrelation	12.61989646103419	0.1323
Heteroscedasticity	1.3822	0.2910
Normality		0.6545
CUSUMQ	Stable	

growth and agricultural productivity while ensuring increased use of renewable energy to address the complex relationship between economic development and environmental sustainability.

4.5. Short –run result

Table 6 illustrates the ECM-induced short-term adjustments. Agricultural productivity and GDP have a statistically significant negative short-term relationship with the dependent variable, while renewable energy consumption has a positive relationship. The negative error correction term is statistically significant. Negative (ECM-1) means that the variables must be corrected by 0.0048% to return to long-term equilibrium.

4.6. Diagnostic and stability tests

We have performed several diagnostic tests to further verify the stability and robustness of our model. It is crucial to ensure the absence of autocorrelation, heteroscedasticity and non-normality and to confirm the correct specification of the model. The expectation is that all test statistics are statistically non-significant to confirm the robustness of the model.

The results presented in Table 7 show that the Breusch–Godfrey LM test for autocorrelation provides no evidence of autocorrelation as the *F*-statistic is not statistically significant. The Breusch–Pagan–Godfrey test for heteroscedasticity also shows a statistically insignificant *F*-statistic, which indicates that there is no heteroscedasticity between the error terms. The Jarque–Bera test for normality confirms that the variables are normally distributed. In addition, the CUSUM square test shows the stability of the model. Overall, the diagnostic tests confirm that the model is free of heteroscedasticity and serial correlation and has been correctly specified, which ensures its robustness.

5. Results discussion

Agriculture is the most important source of income for a large part of the Somali population. It plays a vital role in the Somali economy and contributes significantly to the country's GDP. Livestock farming and the agricultural sector in particular continue to be the main drivers of the Somali economy. Agriculture is responsible for more than 75% of Somalia's GDP and an incredible 93% of the country's total exports. Indeed, according to the Global Development Centre (GDC) in Somalia, a country that is among the least affected countries in the world by this phenomenon, environmental issues, particularly climate change, are the biggest problems. This study measures the relationship between CO_2 emissions and agricultural productivity in Somalia. The ARDL model is applied to analyse the relationship between the latent variables econometrically. The long-run coefficients show essential implications for environmental degradation (ED) and related policies.

Agricultural productivity shows a significant negative impact with a coefficient of -0.000653, which is significant at the 5% level (*p*-value = 0.0237). This means that higher agricultural productivity is associated with lower environmental degradation. Specifically, a 1% increase in agricultural productivity leads to a 0.000653% decrease in environmental degradation in Somalia in the long term. This indicates that higher agricultural productivity reduces environmental degradation, likely due to adopting more sustainable agricultural practices. This negative relationship emphasises our responsibility and obligation to adopt sustainable agricultural practices such as efficient water use, soil conservation and reduced reliance on chemical inputs to protect and conserve natural resources and mitigate environmental degradation.

GDP per capita has a significant negative impact on environmental degradation with a coefficient of −3.27E-05, which is significant at the 5% level

(p-value = 0.0113). This means that environmental degradation decreases slightly with increasing GDP per capita. A 1% increase in GDP per capita leads to a long-term decrease in environmental degradation in Somalia of 0.0000327. Economic growth leads to a slight decrease in environmental degradation due to increased investment in cleaner technologies and more sustainable development practices. This negative relationship suggests that when accompanied by investment in cleaner technologies and sustainable practises, economic growth can lead to better environmental outcomes. Higher GDP per capita often reflects better infrastructure, more efficient resource utilisation and greater capacity for environmental protection measures. Therefore, promoting economic growth with a focus on sustainability can help curb environmental degradation. To ensure economic growth, efforts to increase GDP per capita should include investment in green technologies, stricter environmental regulations and sustainable development initiatives.

In addition, renewable energy consumption has a significant negative impact, with a coefficient of −0.004810, which is highly significant at the 1% level (p-value = 0.0005). This means that a higher renewable energy consumption is associated with a lower environmental impact. A 1% increase in renewable energy consumption leads to a 0.00481% decrease in environmental degradation in Somalia in the long term. This emphasises the significant environmental benefits of increased renewable energy use, which can lead to a cleaner and more sustainable ecosystem. This negative relationship suggests that using renewable energy sources such as solar, wind and hydropower significantly reduce dependence on fossil fuels, contributing to environmental pollution and degradation. The potential of renewable energy to dramatically reduce environmental degradation is inspiring and should motivate further investment and adoption of these technologies.

6. Conclusion and policy implications

This paper analyses the relationship between CO_2 emissions and agricultural productivity in Somalia. The long-term regression results show that environmental degradation is negatively affected by agricultural productivity (AGR), GDP per capita and renewable energy consumption (REC). The analysis shows a negative and statistically significant correlation between agricultural productivity and environmental degradation with a significance level of 5%. Specifically, a 1% increase in agricultural productivity leads to a 0.000653% decrease in environmental degradation in Somalia in the long term. This indicates that higher agricultural productivity reduces environmental degradation, which is likely due to the adoption of more sustainable agricultural practises.

The study also shows a negative and statistically significant correlation between GDP and environmental degradation, with a significance level of 5%. A 1% increase in GDP per capita leads to a 0.0000327% decrease in environmental degradation in Somalia in the long term. Economic growth leads to a slight decrease in environmental degradation due to increased investment in cleaner technologies and more sustainable development practises. The most remarkable result is the strong negative and statistically significant relationship between renewable energy consumption and environmental degradation with a significance level of 1%. A 1% increase in renewable energy consumption leads to a 0.00481% decrease in environmental degradation in Somalia in the long term. This emphasises the significant environmental benefits of increased renewable energy use, which can lead to a cleaner and more sustainable ecosystem.

The short-term results of the error correction model (ECM) indicate that agricultural productivity and GDP show a statistically significant negative correlation with environmental degradation in the short term. Specifically, the coefficient D(AP) is −0.000115 and D(GDP_PER_CAPITA) is −2.87E-06, which hurts environmental degradation. In contrast, renewable energy consumption (D(REC)), with a coefficient of −0.006264, positively relates to the dependent variable in the short term, indicating that a short-term increase in renewable energy consumption may initially lead to higher environmental degradation, possibly due to transition phases or implementation problems.

The findings of this study have several important policy implications for addressing environmental degradation in Somalia. The study proposes policy reforms that promote sustainable land management strategies, including agroforestry, crop rotation and conservation agriculture. These strategies will help restore soil health and reduce deforestation caused by unsustainable agricultural practices. The study also recommends various policy measures to reduce carbon emissions, including investment in research and development, a trading scheme, a clean energy strategy, and further legislative measures to reduce carbon emissions. These projects aim to reduce carbon emissions, promote sustainable energy practices and stimulate innovation in clean technologies.

In addition, it is crucial to reduce carbon emissions by increasing the use of renewable resources for power generation, including hydropower, ocean energy, geothermal energy, wind energy and solar energy. In Somalia, the government and policymakers must prioritise using renewable energy sources. In addition, government funding for renewable energy infrastructure could be increased. Somalia must reduce the cost of renewable energy and limit the use of fossil fuels in industry, businesses and households, as renewable energy can help reduce emissions. The study emphasises the importance of raising farmers' awareness of the negative impacts of unsustainable practices. Training initiatives must be implemented to educate people about sustainable agricultural practices and conservation benefits.

A major limitation of this study is that it focuses solely on CO_2 emissions, agricultural productivity, economic growth and energy consumption, potentially ignoring other relevant factors. Future research should integrate additional variables such as technological advances, soil health and regional policy differences to analyse CO_2 emissions and agricultural productivity comprehensively.

Authors contributions

The authors contributed significantly to this article's conception, design and development. Bile Abdisalan Nor was responsible for the article's first draft, introduction, literature review, econometric methodology, data collection, analysis, writing the discussion section, reviewing the manuscript, revising it critically for intellectual content and the final approval of the version to be published. Azhar Mohamad wrote and updated the introduction, reviewed and edited the manuscript, revising it critically for intellectual content and the final approval of the version to be published.

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Data availability statement

The data used in this study are not publicly available but can be requested from the corresponding author, Bile Abdisalan Nor, b.abdisalannor@gmail.com

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