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Article

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Fostering a Sustainable Future in Somalia: Examining the Effects of Industrialization, Energy Consumption, and Urbanization on Environmental Sustainability

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ABSTRACT

While existing research has extensively explored the individual impacts of energy consumption, industrialization, and urbanization on environmental sustainability, there remains a notable gap in understanding the synergistic effects of these factors within the context of rapidly developing regions, such as Somalia. Therefore, this study explores the impacts of energy consumption, industrialization, and urbanization on environmental sustainability in Somalia from 1990 to 2020. The long-run linkage among the variables of the study was confirmed using the bounds-testing approach. The findings from the ARDL model indicate that economic growth, energy consumption, and trade openness significantly exacerbate environmental pollution in Somalia in the short- and long-run. Conversely, while industrialization and urbanization reduce environmental pollution both the short- and long-run, urbanization does not demonstrate a statistically significant impact. The long-run findings of the study were validated using the DOLS and FMOLS approaches. The Granger causality analysis reveals unidirectional causalities from environmental pollution to GDP per capita, industrialization, and trade openness, as well as from energy consumption to environmental degradation. However, no causal linkage is detected between urbanization and environmental pollution within Somalia. Based on the results of the study, we propose the promotion of renewable energy sources, green industrialization strategies, urban planning and sustainable development, and enhanced monitoring and regulation to effectively address environmental degradation.

Keywords: Energy Consumption, Industrialization, Urbanization, Economic Growth, Trade Openness, Environmental Pollution
JEL Classifications: C32, Q01, Q43, Q56, O55

1. INTRODUCTION

Over the past few decades, the rapid increase in energy consumption, industrialization, and urbanization has severely deteriorated the environment and challenged global sustainability. The profound and disturbing impacts of environmental degradation have significantly altered the earth's geographical spaces, raising alarms among environmental stakeholders and activists (Munir et al., 2020). Energy consumption, driven by fossil fuels such as coal, oil, and petroleum, is a significant contributor to global carbon emissions, which are primary agents of air pollution and climate change (Abdi, 2023; Jalil and Mahmud, 2009; Khan et al., 2020). During the 20th century, the earth's surface temperature rose by approximately 0.6°C due to escalating greenhouse gas (GHG) concentrations and other human activities, intensifying climate change (Abdi et al., 2023a; Zhang et al., 2022). Increasing levels of atmospheric CO_2, which constitute more than 75% of GHG emissions, pose a significant threat to nature and the planet (Mert and Bölük, 2016). Concurrently, the processes of industrialization introduce a plethora of pollutants through the discharge of industrial effluents and emissions, which degrade air, water, and soil quality (He et al., 2019). Urbanization further exacerbates this scenario by straining the existing infrastructural capacities to manage waste and emissions, leading to more concentrated pollution levels in densely populated areas (Poumanyvong and Kaneko, 2010). The reduction of GHG and carbon emissions to foster a low-carbon economy has become a key priority across the globe, aligning with the Sustainable Development Goals (SDGs) (Sun and Ouyang, 2016).

Rapid economic growth frequently leads to increased energy consumption, which serves as a vital engine of economic activity. However, it significantly contributes to environmental pollution through the emission of GHGs and other contaminants (Balsalobre-Lorente et al., 2018). This increase in energy consumption can unexpectedly strain energy resources and exacerbate CO_2 emissions, further intensified by population growth and economic expansion (Liu et al., 2023). The CO_2 emissions from energy consumption in newly industrialized countries have significantly increased since the 1990s in comparison to industrialized countries (Kasman and Duman, 2015). Environmental scientists contend that energy usage is the primary source of CO_2 emissions, which are a key contributor to the level of GHGs in the atmosphere and the resulting effects of climate change and global warming (Ozturk et al., 2016). The relationship between economic growth and environmental impact follows the paradigm of the Environmental Kuznets Curve (EKC), which posits that while economic growth initially leads to environmental degradation, the trend can reverse as economies reach and surpass a certain income threshold, facilitating investments in greener technologies and stricter regulatory frameworks (Churchill et al., 2018; Sarkodie and Strezov, 2019).

In addition, industrialization has profoundly influenced sustainability, significantly affecting economic growth and environmental quality. Although it has catalyzed positive economic developments since the Industrial Revolution, it has also markedly increased environmental pollution (Carvalho et al., 2018). The Industrial Revolution that began in 1750 introduced a variety of synthetic compounds and heavy metals into the environment through the mechanization of production processes, which significantly impacted the environment today (Ahmed et al., 2022). Since the dawn of the industrial era, GHG concentrations have risen sharply, culminating in atmospheric CO_2 levels reaching 409.8 ppm (parts per million) in 2019—higher than any other time in at least the past 800,000 years (Lindsey, 2020). Moreover, the rapid expansion of industries has escalated the consumption of fossil fuels, resulting in widespread pollution. Notably, industrial activities are among the primary sources of particulate matter and noxious gases that compromise air quality and contribute to climate change (Liu and Bae, 2018). This negative impact is primarily due to the fact that industries, particularly in developing economies are the largest consumers of energy and often rely on inefficient technologies (Li et al., 2016). According to the IPCC (2014), industrial activities and the combustion of fossil fuels account for 78% of the total increase in carbon emissions globally from 1970 to 2010. The proliferation of pollutants from manufacturing activities has significantly contributed to climate change and atmospheric deterioration, adversely affecting the livelihoods of many communities (Abdi et al., 2023b; Ali Warsame and Hassan Abdi, 2023).

Urbanization is a prominent global trend that has significant environmental implications, particularly concerning pollution levels. As populations shift from rural to urban settings, the concentration of activities that generate pollutants increases, exacerbating the quality of air, water, and soil (Zhang et al., 2022). In recent decades, there has been a significant increase in population and economic growth, leading to a higher demand for global resources and causing environmental degradation (Nasrollahi et al., 2020). Rapid urbanization significantly increases energy consumption and exacerbates environmental concerns, particularly by driving substantial rises in global CO_2 emissions associated with extensive urban expansion (Abdi, 2023). Urban areas, due to their high density of vehicular traffic, rising construction, industrial activities, and energy consumption, become hotspots for various pollutants, including particulate matter, nitrogen oxides (NO_2), and sulfur dioxide, all of which pose serious health risks to urban dwellers (Liu and Bae, 2018). According to IRENA (2016), cities worldwide are responsible for more than two-thirds of global energy consumption and contribute to 70% of energy-related CO_2 emissions. Research indicates that the spatial expansion of cities and the associated industrial and transport emissions significantly contribute to urban air pollution (Li et al., 2019). Moreover, the intensification of urbanization has been linked to higher noise pollution levels, further degrading the living conditions in urban settings.

Africa is acutely susceptible to the ramifications of climate change, with temperature increases exceeding 1.5°C posing significant risks to its economies, agriculture, infrastructure, water, and food systems (African Development Bank, 2021). Despite contributing less than 3% to historical and current global emissions, the continent—and Somalia, in particular—faces severe climate-related consequences. In Somalia, distinct weather patterns—including droughts, locust infestations, floods, and soil erosion—are prevalent (Abdi et al., 2024a). The primary culprit for environmental degradation is deforestation, spurred by the production of charcoal for domestic and export purposes (Ali Warsame and Hassan Abdi, 2023). Industrialization in Somalia is at a nascent stage, largely because of the prolonged period of civil unrest and governance challenges that have hindered large-scale industrial development. The manufacturing sector is relatively small, with most industries centered around the production of light consumer goods, which contributes to the country's overall modest industrial footprint. In addition, urbanization in Somalia has been rapidly accelerating, especially in major cities like Mogadishu, Hargeisa, and Bosaso. This is due to a combination of factors, including internal displacement due to conflicts and environmental factors, and the return of diaspora Somalis investing in the country. The rapid urban growth has outpaced the development of adequate infrastructure and services, leading to challenges in waste management, water supply, and sanitation that exacerbate environmental pollution.

Moreover, traditional biomass sources, like firewood and charcoal, account for 82% of energy consumption, a statistic dominating both urban and rural household energy usage (Ali Warsame and Hassan Abdi, 2023). The use of traditional biomass has contributed to environmental issues such as deforestation and desertification. Presently, a meager 10% of Somalia's energy derives from renewable sources, with the country accounting for less than 0.003% of worldwide GHG emissions, primarily from land use, agriculture, and deforestation (Abdi et al., 2024b; Warsame et al., 2023). Figure 1 presents the trends in CO_2 emissions per capita and energy use per person in Somalia over a period from 1991 to 2022. The CO_2 emissions per capita show that emissions started at a peak in 1991 and then sharply decreased, suggesting a significant reduction in per capita carbon emissions following the onset of civil unrest that led to the breakdown of central governance. In addition, energy consumption mirrors the pattern seen in CO_2 emissions, with a sharp fall in the early 1990s, plateauing through the early 2000s before gradually decreasing further. The continued but more gradual decline in emissions and energy usage could be indicative of a country with limited industrial activity and reliance on biomass, which is generally less carbon-intensive compared to fossil fuels. The simultaneous reduction in both CO_2 emissions and energy consumption per capita could be a result of several factors. These might include the degradation of infrastructure, limited industrial activity, and the displacement of populations due to ongoing conflict and instability.

Mitigating the adverse environmental impacts of industrialization requires stringent regulatory frameworks, innovative pollution control technologies, and a shift toward sustainable manufacturing practices. This is especially pertinent in an era where urban and industrial growth is inevitable, yet the need for sustainable practices is paramount (He et al., 2019; Jalil and Mahmud, 2009; Poumanyvong and Kaneko, 2010). Although several studies have investigated factors that affect environmental pollution in the sub-Saharan Africa (SSA) region, there are few studies that focus on the case of Somalia (Ali Warsame and Hassan Abdi, 2023; Warsame et al., 2023). The prospect of industrialization is evident in many countries in SSA, as evidenced by the declining share of agriculture in total employment (Abdi, 2023). The studies that investigated the effects of industrialization in the SSA, particularly in Somalia, are lacking. Therefore, this study explores the effects of energy consumption, industrialization, and urbanization on environmental pollution in Somalia from 1990 to 2020. The study contributes to the literature in these ways. This research enhances the scholarly discourse by offering novel insights into the effects of industrialization on environmental degradation in Somalia—a subject previously unexplored. Employing a robust econometric framework, this study utilizes an array of techniques, such as unit root tests, bounds testing, and the autoregressive distributed lag (ARDL) model, alongside Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) methods, to ensure the reliability of the results. Furthermore, it applies Granger causality to elucidate the directional relationship between the variables.

The rest of the paper proceeds as follows: Section two presents the literature review; section three outlines the data sources and econometric methodology employed; section four discusses the empirical analysis; and the final section concludes with policy implications.

2. LITERATURE REVIEW

Recent empirical studies have rigorously linked environmental pollution to economic growth, energy consumption, industrialization, and urbanization across various regions. By employing a range of advanced econometric techniques, the literature has predominantly used various pollution indicators such as GHGs, CO_2 emissions, and ecological footprints (Majumder et al., 2022; Ozturk et al., 2016; Warsame et al., 2023). This section summarizes the relevant research on explanatory variables and environmental pollution.

2.1. Economic Growth and Environmental Pollution

Numerous studies have employed cross-country data to explore the relationship between economic growth and environmental pollution. In a panel analysis spanning from 1985 to 2018, Osuntuyi and Lean (2022) explored the complex interconnections between economic growth, energy consumption, and environmental degradation, utilizing an array of econometric models including, FMOLS, DOLS, PMG, and CCEMG. They revealed that while economic growth tends to alleviate environmental degradation in more affluent nations, an increase in education levels surprisingly corresponds with environmental harm in poorer countries. Abdi (2023) examined the impacts of economic complexity and renewable energy on carbon emissions across 41 sub-Saharan African countries from 1999 to 2018. Using PMG cointegration analysis, the study found that both economic growth and urbanization significantly exacerbate environmental degradation over time. Furthering the analysis of the BRICS and Next-11 countries, Majumder et al. (2022) employed an extensive econometric approach, finding support for the EKC in BRICS nations, where economic growth initially exacerbates but later improves environmental quality. In addition, Wang and Zhang (2021) analyzed how renewable energy and high oil prices help decouple economic growth from carbon emissions, particularly in higher-income countries. Their findings indicate that trade openness reduces carbon emissions in high- and upper-middle-income countries but has negative impact in lower-income countries, which tend to increase emissions.

In a country-level analysis, Balli et al. (2020) conducted an analysis using time series data to assess the interactions among GDP growth, energy consumption, and CO_2 emissions in Turkey. Their findings indicate a direct correlation where GDP and energy usage increases are associated with significant rises in environmental deterioration. Chol (2020), through an ARDL model analysis, identified a reinforcing relationship between economic expansion and environmental pollution in China. The study emphasized the environmental sacrifices accompanying China's economic surge. Furthering this research, Abdi et al. (2024b) utilized ARDL model and dynamic OLS to show that, in the long-term, agricultural value-added and renewable energy consumption play a crucial role in mitigating both ecological footprints and CO2 emissions. However, economic growth demonstrates a complex impact: it significantly contributes to an increase in ecological footprints over the long-run, while simultaneously leading to a reduction in CO2 emissions in both the short- and long-term. . Collectively, these studies concur on the multifaceted effects of economic dynamics on environmental pollution, providing critical insights for policymaking aimed at sustainable economic development.

2.2. Energy Consumption and Environmental Pollution

Recent investigations across different regions consistently highlight a robust association between energy utilization and environmental deterioration. Appiah (2018) focused on Ghana, applying the ARDL and Granger causality models to data spanning from 1960 to 2015, confirming a long-run relationship between GDP, energy consumption, and CO_2 emissions, with unidirectional causality from energy usage to increased emissions. By utilizing a similar approach, Chol (2020) found that heightened energy consumption directly escalates pollution levels. Khan et al. (2020) extended this analysis to Pakistan, using time series data from 1965 to 2015. Through the ARDL technique, the estimates reveal that both short-run and long-run increases in energy consumption and economic growth elevate CO_2 emissions. In a broader regional analysis, Appiah et al. (2021) explored these linkages within sub-Saharan Africa from 1990 to 2016 through AMG, CCEMG, and DCCEMG estimation methods, documenting a significant positive impact of energy use on CO_2 emissions. Sharma et al. (2021) assessed emerging Asian economies and discovered that while energy consumption's interaction with linear per capita income significantly boosts carbon emissions in the long-run, its interaction with squared per capita income yields an insignificant effect.

Furthermore, Wen et al. (2021) analyzed the nexus among energy consumption, economic growth, and CO_2 emissions in South Asian economies from 1985 to 2018. By applying the FMOLS technique, they noted that environmental quality declines due to non-renewable energy use. Ozcan et al. (2020) investigated this triad within OECD countries, concluding that economic growth and energy consumption patterns play a pivotal role in enhancing environmental performance. Khan et al. (2020) investigated the impact of innovation and energy usage using time series data on China's consumption-based carbon emissions. The findings illustrated that while innovation tends to enhance environmental quality, energy use exacerbate CO_2 emissions. Similarly, Zaidi et al. (2019) explored the dynamics between energy consumption, economic growth, globalization, and CO_2 emissions within the APEC countries. This study highlighted that globalization adversely affects CO_2 levels, while energy use significantly detracts from environmental sustainability. Lastly, Alajlan and Alreshaidi (2022) examined Saudi Arabia through panel time-series ARDL analysis from 1985 to 2019, highlighting that economic growth fosters increased energy consumption, which in turn raises CO_2 emissions.

2.3. Industrialization and Environmental Pollution

The impact of industrialization on environmental sustainability has been extensively studied across various regions. Mentel et al. (2022) focused on sub-Saharan Africa, utilizing the Generalized Method of Moments (GMM) to assess the impact of industrialization on environmental sustainability. They discovered that industrial expansion substantially increases carbon emissions. Similarly, Azam et al. (2022) explored these dynamics within OPEC countries using the Hausman test and Granger causality approaches. Their findings revealed a bidirectional causality between industrialization and environmental pollution, where rapid industrial activities escalate pollution levels. In South Asia, Sumaira and Siddique (2023) analyzed the interplay between energy consumption, industrialization, and environmental degradation using cointegration and causality tests. Their research confirmed the presence of bidirectional causality and long-term co-integration between industrialization and environmental contamination, suggesting a persistent, reciprocal relationship. Furthermore, Dogan and Inglesi-Lotz (2020) explored the influence of economic structures on validating the EKC hypothesis in European countries over the period from 1980 to 2014. Their research highlighted that a greater industrial share leads to reduced emissions, a result attributed to the sector's adoption and integration of energy-efficient and environmentally sustainable technologies. Similarly, Claire and Widyawati (2023) focused on ASEAN countries from 1990 to 2019, employing the PMG method to reveal that renewable energy significantly mediates the negative effects of industrialization on CO_2 emissions. In Nigeria, Musa et al. (2021) utilized Modified Toda and Yamamoto causality methods from 1982 to 2018 to demonstrate a unidirectional causal relationship where economic and industrial expansion leads to increased CO_2 emissions.

2.4. Urbanization and Environmental Pollution

In Somalia, Warsame et al. (2023) explored urbanization and environmental degradation using ARDL, KRLS, and VECM models over the data period 1985–2016. Their findings indicate that urbanization exacerbates environmental degradation in the long run, although globalization appears to temporarily enhance environmental quality. This pattern is echoed in Pakistan, where Abbasi et al. (2021) and Ullah et al. (2020) analyzed the effects of urbanization from 1980 to 2018, both finding that urbanization significantly elevated CO_2 emissions. Further broadening the scope, Dong et al. (2019) analyzed the impact of urbanization on carbon emissions in a developed nation using a threshold regression model from 1960 to 2013. They discovered a double-threshold effect where urbanization initially increases emissions but eventually reduces them as urbanization progresses. Adding to the Asian context, Ali et al. (2019) explored the impact of urbanization on CO_2 emissions in Pakistan from 1972 to 2014 using ARDL–VECM methods and found a significant increase in emissions due to urbanization. Ahmad et al. (2019) further examined urbanization, energy consumption, and economic development on CO_2 emissions in China. The authors identified that urbanization and growth in the construction sector have significantly and positively impacted the increase in energy consumption. Furthermore, Khan et al. (2019) assessed how energy consumption, globalization, innovation, and economic growth impact environmental sustainability in Pakistan. The results revealed a mixed impact where innovation and potentially urbanization improve environmental conditions, whereas globalization, energy consumption, and economic expansion contribute positively to CO_2 emissions, thereby posing challenges to environmental sustainability.

The prevailing literature predominantly indicates that economic growth, energy consumption, industrialization, and urbanization adversely impact environmental quality. However, some discrepancies exist, with a few studies suggesting that economic development, industrialization, and urbanization may enhance environmental conditions. This divergence highlights the need for further investigation into this subject across different geographical contexts. Accordingly, this study aims to explore the effects of these variables on environmental pollution, specifically in Somalia, a context yet unexamined in this field. Thus, this research seeks to fill the gap in the literature concerning Somalia and provide insights that could inform both policy and practice regarding sustainable development in similar settings.

3. MATERIALS AND METHODS

3.1. Data Sources and Descriptions

The present study aims to examine the effects of energy consumption, industrialization, and urbanization on environmental pollution in Somalia. To carry out this investigation, data ranging from 1990 to 2020 were gathered from diverse sources, including the Organization of Islamic Cooperation (OIC-SESRIC), the World Bank, and Ourworldindata. Subsequently, a time series analysis was constructed based on these datasets. The study took into account six variables, namely energy consumption (EC), carbon dioxide emissions (CO_2), trade openness (TO), industrialization (IND), real GDP per capita (GDPPC), and urbanization (URB). To address potential issues with non-normality, heteroscedasticity, and miss-specified functional form, all variables were transformed into logarithmic form. Table 1 presents the variables, symbols, units of measurements, and data sources. In addition, trends of the sampled variables throughout the study period are presented in Figure 2.

3.2. The Econometric Model

The ARDL approach is used to test for the presence of long-run co-integration among the variables in the sample. The ARDL method is preferred over other co-integration methods for several reasons. Firstly, it can be applied to small sample sizes and does not necessitate long time-series data. Secondly, ARDL can handle variables that are integrated at level I(0) and first difference I(1) but not at the second difference I(2). Thirdly, unlike previous methods, it simultaneously models both long-run and short-run co-integration between the variables (Pesaran et al., 2001). Finally, the unrestricted structure of the technique allows for the best representation of the data-generating process and lag order within the general-to-specific framework. Rearranging the parameters of the ARDL model helps to reduce endogeneity and residual serial correlation (Pesaran et al., 1999). Based on the empirical work of Sarkodie and Adams (2018), Abdi (2023), Warsame et al. (2023), and Azam et al. (2022), the following linear equation is employed to illustrate the relationship between energy consumption, industrialization, urbanization, and environmental pollution in Somalia as presented in Eq (1):

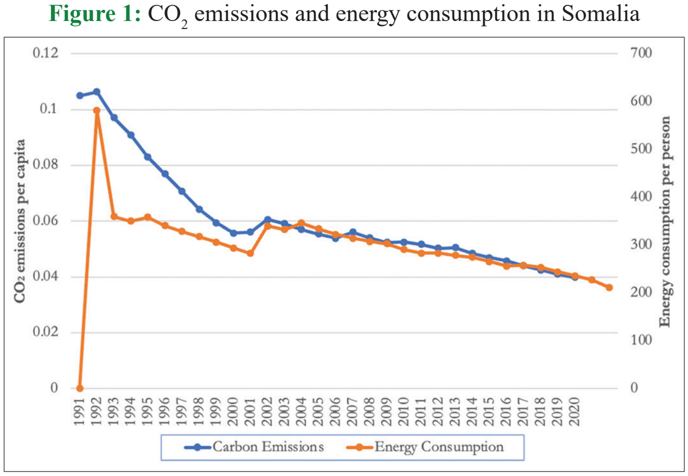
$$lnCO_{2t} = \beta_0 + \beta_1\, lnGDPPC_t + \beta_2\, lnEC_t + \beta_3\, lnIND_t + \beta_4\, lnTO_t + \beta_5\, lnURB_t + \varepsilon_t \quad (1)$$

Where $lnCO_2$ is the explained variable, while $lnGDPPC$, $lnEC$, $lnIND$, $lnTO$, and $lnURB$ stand for the explanatory variables, ε represents the error term, and t indicates the time. β_0 is the constant term while β_1, β_2, β_3, β_4, and β_5 are the elasticities to be estimated. The ARDL cointegration equation can be written as:

$$\begin{aligned}\Delta ln\mathrm{CO}_{2_t} = {} & \alpha_0 + \beta_1 ln\mathrm{CO}_{2_{t-1}} + \beta_2 lnGDPPC_{t-1} + \beta_3 lnEC_{t-1} \\ & + \beta_4 lnIND_{t-1} + \beta_5 lnTO_{t-1} + \beta_6 lnURB_{t-1} + \\ & \sum_{i=0\,1}^{p} \Delta ln\mathrm{CO}_{2_{t-i}} + \sum_{i=0\,2}^{q} \Delta lnGDPPC_{t-i} + \sum_{i=0\,3}^{q} \Delta lnEC_{t-i} \\ & + \sum_{i=0\,4}^{q} \Delta lnIND_{t-i} + \sum_{i=0\,5}^{q} \Delta lnTO_{t-i} \\ & + \sum_{i=0\,6}^{q} \Delta lnURB_{t-i} + ECT_{t-1} + \varepsilon_t \end{aligned} \quad (2)$$

where α_0 is the constant, β_1 - β_6 are the long-run elasticities, $\gamma_1 - \gamma_6$ are the coefficients of the short-run variables, p and q indicates the optimal lags of the explained variable and the regressors, Δ is the sign of first difference showing short-run variables and φ indicates the error correction term (ECT) coefficient. Thus, the ARDL cointegration approach begins with bound testing. The null hypothesis (H_0: $\beta_1=\beta_2=\beta_3=\beta_4=\beta_5=\beta_6=0$) implies that in the long-run variables are not cointegrated while the alternative hypothesis (H_1: $\beta_1\neq\beta_2\neq\beta_3\neq\beta_4\neq\beta_5\neq\beta_6\neq0$) suggests that in the long-run variables are cointegrated. The null hypothesis was evaluated using critical values and Wald-F statistics. If the Wald-F statistics exceed the upper bound critical values, it means that the null hypothesis is rejected, indicating a long-term relationship between the variables. Conversely, if the Wald-F statistics are below the upper bound critical values, the null hypothesis is retained.

Figure 1: CO_2 emissions and energy consumption in Somalia



Data sources: World Bank (2020). Our world in data (2021)

4. EMPIRICAL ANALYSIS AND DISCUSSION

4.1. Descriptive Summary

The descriptive statistics for the series provide an explanation of the data characteristics, as presented in Table 2. The outcomes indicate the means for the following variables: carbon emissions (−1.223), GDP per capita (2.506), energy consumption (2.477), industrialization (7.807), trade openness (1.402), and urbanization (1.561). Additionally, industrialization, energy consumption, and GDP per capita stand out with the highest values, reaching 8.41, 2.76, and 2.75, respectively. Notably, trade openness exhibits the largest standard deviation of 0.426, indicating significant deviations

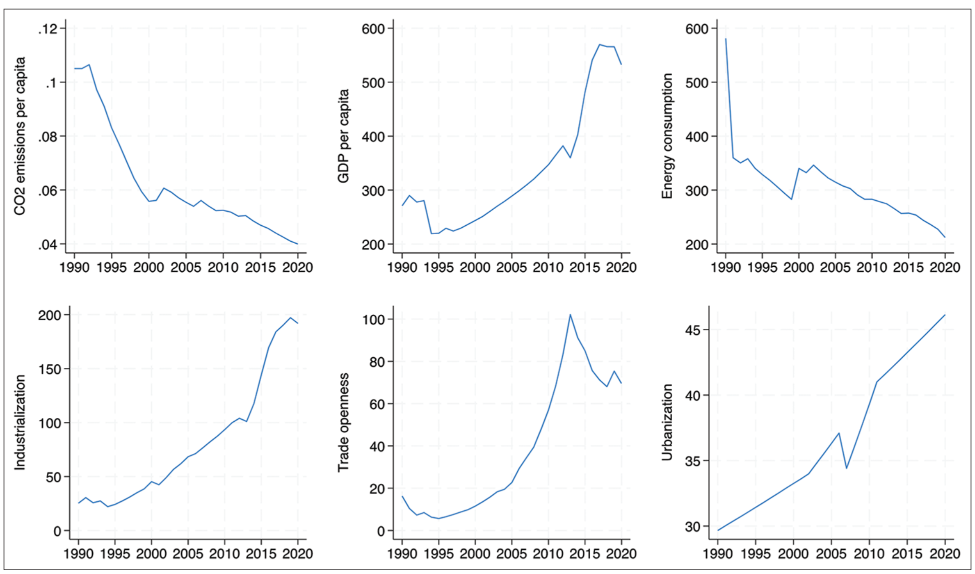
Table 1: Variables and data sources

Variable	Symbol	Description	Source
Carbon emissions	CO_2	CO_2 emissions (metric tons per capita)	WDI
Economic growth	GDPPC	GDP per Capita (Constant 2015 Prices)	SESRIC
Energy consumption	EC	Primary energy consumption per capita (kWh/person)	Ourworldindata
Industrialization	IND	Manufacturing, Value Added, Constant 2015 Prices	SESRIC
Trade openness	TO	Import plus export divided by GDP	SESRIC
Urbanization	URB	Urban population (% of total population)	WDI

Table 2: Descriptive summary and correlation matrix

	$\ln CO_2$	lnGDPPC	lnEC	lnIND	lnTO	lnURB
Segment A: Characteristic of the data						
Mean	−1.223	2.506	2.477	7.807	1.402	1.561
Maximum	−0.972	2.755	2.764	8.294	2.009	1.664
Minimum	−1.399	2.340	2.326	7.346	0.750	1.472
Standard Deviation	0.123	0.133	0.080	0.307	0.426	0.061
Skewness	0.796	0.682	1.108	0.093	−0.042	0.256
Kurtosis	2.613	2.271	6.434	1.757	1.470	1.670
Jarque-Bera	3.468	3.095	21.584	2.038	3.030	2.622
Probability	0.176	0.212	0.000	0.360	0.219	0.269
Observations	31	31	31	31	31	31
Segment B: Pairwise correlation matrix						
$\ln CO_2$	1.000					
lnGDPPC	−0.704	1.000				
lnEC	0.818	−0.703	1.000			
lnIND	−0.908	0.924	−0.800	1.000		
lnTO	−0.806	0.870	−0.655	0.939	1.000	
lnURB	−0.896	0.907	−0.836	0.974	0.927	1.000

Figure 2: Trends of the study variables



from the mean in its average values. It is worth mentioning that trade openness is the only variable with a negative skewness, while all other variables are positively skewed. On the other hand, the correlation analysis demonstrated in Table 2 indicates that GDP per capita is negatively correlated to CO_2 emissions, while energy consumption is positively correlated to CO_2 emissions. However, as industrial production increases, CO_2 emissions decrease by −0.908. The correlation between CO_2 emissions and trade openness is −0.806, suggesting a negative correlation. In addition, urbanization shows a negative correlation, suggesting that as the urban population increases, emissions decrease by −0.896.

4.2. Unit Root Test

The regular trending of time series data challenges the assumption of stationarity. To address this, we employ the Augmented Dickey-Fuller (ADF) and Philips-Perron (PP) tests to investigate the unit root of the variables of interest. This helps us avoid any misleading findings. The unit root results are presented in Table 3. CO_2 emissions, energy consumption, GDP per capita, industrial production, trade openness, and urban population show mixed orders of integration at level I(0) and first difference I(1). Considering the nature of our data, the ARDL technique is appropriate. None of the variables demonstrate stationarity at

Table 3: Unit root test results

Variables	ADF		PP	
	Level			
	Constant	Constant with trend	Constant	Constant with trend
$lnCO_2$	−2.055	−3.805**	−1.643	−1.531
lnGDPPC	−0.009	−3.077	0.407	−2.166
lnEC	−3.980***	−6.913***	−3.695***	−5.951***
lnIND	0.125	−4.442***	0.126	−2.597
lnTO	−1.02	−1.517	−0.467	−3.04
lnURB	0.086	−2.464	0.598	−2.455
	At first difference			
	Constant	Constant with trend	Constant	Constant with trend
$\Delta lnCO_2$	−3.310**	−3.539*	−3.299**	−3.539*
ΔlnGDPPC	−4.008***	−4.386***	−4.051***	−4.403***
ΔlnEC	−11.255***	−10.697***	−11.621***	−11.278***
ΔlnIND	−5.469***	−5.589***	−5.470***	−5.589***
ΔlnTO	−3.894***	−3.574*	−3.926***	−3.549*
ΔlnURB	−5.474***	−5.420***	−6.078***	−6.800***

The significance levels of 1%, 5%, and 10% are represented by ***, **, and *, respectively

Table 4: Bounds testing outcomes

Model	F-statistic	Signif.	Bounds test critical values		Decision
			k=5		
			I (0)	I (1)	
$lnCO_2=f$(lnGDPPC, lnEC, lnIND, lnTO, lnURB)	13.307	1%	4.071	5.741	Cointegration
		5%	2.899	4.143	
		10%	2.386	3.479	

Table 5: Long-run and short-run outcomes

Variable	Coefficient	Std. Error	t-Statistic
Long-run estimates			
Constant	0.069	0.283	0.242
lnGDPPC	0.179***	0.052	3.455
lnEC	0.215***	0.057	3.793
lnIND	−0.165***	0.033	−5.004
lnTO	0.033**	0.011	2.855
lnURB	−0.153	0.122	−1.253
Short-run estimates			
Constant	−0.055**	0.019	−−2.857
$\Delta lnCO_{2t-1}$	0.169	0.115	1.474
$\Delta lnGDPPC_{t-1}$	0.426***	0.081	5.284
$\Delta lnGDPPC_{t-2}$	−0.082	0.098	−0.835
$\Delta lnEC_{t-1}$	0.348***	0.072	4.840
$\Delta lnEC_{t-2}$	0.203***	0.037	5.434
$\Delta lnIND_{t-1}$	−0.375***	0.066	−5.678
$\Delta lnIND_{t-2}$	0.014	0.070	0.204
ΔlnTO	0.054*	0.029	1.860
ΔlnURB	−0.389**	0.141	−2.753
$\Delta lnURB_{t-1}$	0.187	0.148	1.263
ECT_{t-1}	−0.075**	0.027	−2.818

the second difference level I(2). Subsequently, we examine the presence of long-run co-integration and the elasticity of their coefficients.

4.3. Co-integration Test

We investigate the possibility of long-term co-integration between CO_2 emissions and a set of independent variables such as energy consumption, GDP per capita, industrialization, trade openness, and urban population. The bound test method was utilized to examine this relationship. Table 4 presents the results of the bound testing approach. At a significance level of 5%, the F-bound test statistic (13.307) exceeds the upper-bound critical value (4.143). This suggests that CO_2 emissions and the independent variables under study have a long-term connection.

4.4. Long-run and Short-run Estimates

In Table 5, the empirical findings of the study unveil significant relationships among the explanatory and dependent variables, with varying levels of statistical significance observed across different factors. Notably, while urbanization did not exhibit statistical significance, the other variables demonstrated noteworthy impacts on environmental pollution in Somalia over the long-run. Firstly, the coefficient of GDP per capita emerges as a pivotal factor, indicating a substantial influence on environmental pollution. A 1% increase in GDP per capita corresponds to a 0.179% increase in CO_2 emissions. Our findings align with the prior findings of Alajlan and Alreshaidi (2022) and Abdi (2023), who have reported that an increase in GDP leads to an increase in CO_2 emissions in both the short- and long-run. This indicates the consequence of economic growth fueled by heightened consumption, investment, and transportation levels, which ultimately contribute to a decline in environmental quality within the Somali context. Furthermore, the study reveals a compelling relationship between energy consumption and environmental pollution in Somalia. A 1% increase in energy consumption correlates with a substantial 2.15% rise in environmental pollution. This is comparable to Chol (2020) and Raihan and Tuspekova (2022), who found that increased energy consumption exacerbates CO_2 emissions in Russia. Energy consumption is primarily derived from the burning of fossil fuels and the burning of trees for coal consumption. These activities directly impact the quality of soil, ecosystems and the exploitation of natural resources.

Additionally, industrialization emerges as a mitigating factor, with a percentage increase in industrial activity resulting in a −0.165% reduction in CO_2 emissions. This aligns with the findings of Dogan and Inglesi-Lotz (2020), who discovered that a higher proportion of industrial activity correlates with decreased emissions in Europe. However, it contradicts the findings of Azam et al. (2022), Mentel et al. (2022), and Sumaira and Siddique (2023), who reveal that industrialization greatly contributes to environmental deterioration. This finding demonstrates the potential for industrial development to be coupled with environmental sustainability measures, which offer avenues for mitigating pollution. However, trade openness presents a contrasting narrative, with a 1% increase in trade openness corresponding to a 0.033% degradation in environmental quality. This statistically significant result, observed at the 5% level, highlights the complex linkage between economic policies and environmental outcomes. Ragoubi and Mighri (2021) have documented the direct impact of trade openness on CO_2 emissions. This finding supports the notion that trade openness plays a constructive role in expanding economic activity and energy consumption, thereby leading to higher greenhouse gas emissions. Albeit not statistically significant, the effects of urbanization on CO_2 emissions in Somalia are adverse. Correspondingly, Deng and Mendelsohn (2021) have concluded that urbanization has a detrimental impact on air quality in the U.S.

In addition, the short-run results are presented in Table 5. The previous year's CO_2 has positively impacted the current environmental pollution, although it was insignificant. Moreover, the prior year's GDP per capita effect on current CO_2 emissions is positive and statistically significant. This means that a 1% change in economic growth results in a 0.426% increase in carbon emissions in the short-run. Furthermore, the analysis shows that a percentage change in previous years' energy consumption leads to a 0.348% and 0.203% rise in carbon emissions, with a significant effect. Similarly, a 1% change in the short-run industrial value-added leads to a −0.375% decline in CO_2 emissions, which is also statistically significant. The impact of trade openness on carbon emissions is positive and significant at the 10% threshold level. This suggests that a percentage change in trade openness leads to a 0.054% increase in carbon emissions in the short term. Additionally, the research finds that urbanization has a negative effect on carbon emissions. Specifically, a 1% change in urban population leads to a 0.389% decrease in carbon emissions in the short-run, and this effect is statistically significant at a 5% level. Moreover, the ECT reveals that the deviation from long-term equilibrium is gradually corrected through partial short-term adjustments. According to Table 5, the estimated value of ECT has a statistically significant and negative coefficient of −0.075. This indicates that the long-term equilibrium adjusts at a rate of 7.5% annually in response to the disequilibrium caused by short-term shocks.

Table 6: Diagnostic test results

Type	Statistic
Serial correlation – LM test	2.937 (0.2302)
Heteroscedasticity – BPG test	13.93 (0.5308)
Normality – Jarque-Bera test	0.867 (0.6480)
Ramsey RESET test	1.781 (0.1002)

4.5. Diagnostic Tests

After evaluating the long- and short-run coefficients of the ARDL model, a series of diagnostic tests were conducted, as demonstrated in Table 6. These tests included assessments for serial correlation (Breusch-Godfrey test), heteroscedasticity (Breusch-Pagan test), model misspecification (Ramsey reset test), and normality. No diagnostic issues were detected, indicating that the model used in this study is free from misspecification problems. Moreover, it is essential to highlight that the models utilized in the study exhibit stability, as evidenced by the analysis of CUSUM and CUSUM of square tests, illustrated in Figure 3. These stability tests offer additional reassurance that the parameters of the models remain dependable for analytical endeavors.

4.6. Sensitivity Analysis

The study employed various cointegration techniques to confirm the long-term estimates of the ARDL approach. The implementation of DOLS and FMOLS is showcased in Table 7. Both models consistently demonstrate a similar direction as the main results. Specifically, GDP per capita and trade openness indicate positive associations with CO_2 levels. Moreover, energy consumption exhibits a positive relationship in both models, although it lacks statistical significance for the FMOLS approach. Conversely, industrialization consistently displays a statistically significant negative association with environmental pollution in Somalia. However, the relationship between urbanization and CO_2 levels varies slightly between models,

Figure 3: CUSUM and CUSUM of squares tests

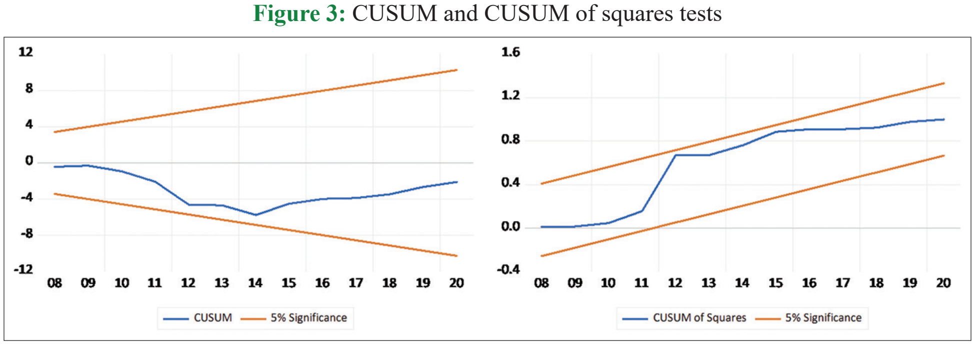


Table 7: Long-run estimates of DOLS and FMOLS

Variable	DOLS			FMOLS		
	Coefficient	Standard Error	t-Statistic	Coefficient	Standard Error	t-Statistic
Constant	1.966***	0.458	4.289	2.583***	0.742	3.480
lnGDPPC	0.688***	0.197	3.496	0.586***	0.072	8.146
lnEC	0.358**	0.119	3.000	0.004	0.149	0.024
lnIND	−0.616***	0.074	−8.286	−0.676***	0.061	−11.029
lnTO	0.143***	0.035	4.060	0.083***	0.029	2.814
lnURB	−0.769**	0.286	−2.694	−0.083	0.316	−0.261

Table 8: Granger causality results

Null Hypothesis	Obs	F-Statistic	Prob.
$lnGDPPC \neq lnCO_2$	29	1.42441	0.2603
$lnCO_2 \neq lnGDPPC$		4.62049	0.0201
$lnEC \neq lnCO_2$	29	9.71329	0.0008
$lnCO_2 \neq lnEC$		0.04487	0.9562
$lnIND \neq lnCO_2$	29	0.51133	0.6061
$lnCO_2 \neq lnIND$		5.43879	0.0113
$lnTO \neq lnCO_2$	29	0.26090	0.7725
$lnCO_2 \neq lnTO$		2.77977	0.0821
$lnURB \neq lnCO_2$	29	1.78443	0.1895
$lnCO_2 \neq lnURB$		0.56531	0.5756

with a negative and statistically significant association in the DOLS model and a non-significant effect in the FMOLS model. These combined results offer comprehensive insights into the directional impact of various factors on environmental pollution across different econometric models.

4.7. Granger Causality Analysis

Following the analysis of long-run estimates using various methodologies, we proceeded to investigate Granger causality among the variables of interest, the results of which are detailed in Table 8. The findings indicate a one-way causal relationship from CO_2 emissions to GDP per capita, suggesting that CO_2 emissions Granger cause GDP per capita, while the reverse causality is not observed. This implies that economic growth may stem from CO_2 emissions generated through energy consumption in the production process. Additionally, a unidirectional causality from energy consumption to carbon emissions was observed, indicating that the utilization of energy from fossil fuels leads to carbon emissions as a result of chemical reactions during combustion. Furthermore, the Granger causality between industrialization and CO_2 emissions suggests a one-way causal linkage from CO_2 emissions to industrialization, implying that industrialization does not cause carbon emissions, but rather, carbon emissions drive industrialization. Conversely, in the case of trade openness and CO_2 emissions, a unidirectional causality from CO_2 emissions to trade openness was identified, indicating that while trade openness does not directly cause carbon emissions, carbon emissions influence trade openness. Lastly, our analysis found no evidence of bidirectional causality between urbanization and carbon emissions in Somalia.

5. CONCLUSION AND POLICY RECOMMENDATIONS

Understanding the dynamics of energy usage, manufacturing activities, and the consumption patterns of the urban population on environmental quality is crucial for devising effective policies aimed at achieving environmental sustainability in Somalia. Thus, this study employed time series data from 1990 to 2020 to analyze the impact of energy consumption, industrialization, and urbanization on environmental pollution in Somalia. The integration order of the dataset was determined using the ADF and PP unit root tests. The bounds-testing approach was used to ascertain the long-run association among the variables of interest. The ARDL test results unveil the pivotal role of economic growth, energy consumption, and trade openness as significant determinants of environmental degradation in Somalia, exerting influence both in the short- and long-run. Conversely, industrialization emerges as a key factor driving the reduction of carbon dioxide emissions, exerting its impact over both short- and long-run horizons. Similarly, urbanization demonstrates a positive effect on environmental quality, manifesting benefits in both the short- and long-run, albeit with insignificance observed in the latter. To confirm the long-run estimates of the ARDL approach, the study implemented the DOLS and FMOLS techniques. Moreover, the Granger causality analysis unveils one-way causal relationships from environmental pollution to GDP per capita, industrialization, and trade openness as well as from energy consumption to environmental degradation. However, no causal connection is identified between urbanization and environmental pollution within the context of Somalia.

To enhance environmental sustainability in Somalia, policymakers should prioritize several key policy recommendations based on the findings of this study. Firstly, there is a pressing need to promote renewable energy sources to mitigate the significant impact of energy consumption on environmental degradation. Initiatives incentivizing investment in solar, wind, and hydroelectric power can help reduce reliance on fossil fuels and curb pollution. Secondly, green industrialization strategies should be implemented to harness the potential of industrialization in reducing carbon dioxide emissions. This involves advocating for eco-friendly production processes, encouraging the adoption of clean technologies, and enforcing stringent environmental regulations to minimize industrial pollution. Additionally, efforts should be directed toward sustainable urban planning and development despite the insignificance of urbanization in the long-run. Measures such as enhancing public transportation systems, promoting energy-efficient buildings, and implementing waste management strategies can mitigate the environmental impact of urbanization. Lastly, governments should prioritize enhanced monitoring and regulation by strengthening the enforcement of environmental laws, establishing robust monitoring systems to track pollution levels, and collaborating with international organizations to access expertise and resources for effective environmental management. By implementing these policy recommendations, Somalia can move towards achieving environmental sustainability while fostering economic growth and improving the well-being of its citizens.

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