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Transitioning to sustainable energy and enhanced environmental quality in Somalia through renewable energy, globalisation and trade openness

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A balanced approach that combines trade policies, renewable energy promotion, and robust environmental regulations is crucial for improving ecological sustainability. Although the literature suggests that trade openness facilitates the transfer of cleaner energy technologies to developing nations, existing empirical studies have produced inconclusive results, particularly in Somalia's context. Therefore, this study explores the dynamic relationships between renewable energy, trade openness, economic growth, globalisation, and environmental degradation using annual time-series data from 1990 to 2019. Employing advanced econometric methods, including the autoregressive distributed lag (ARDL) model and dynamic OLS analyses, the findings reveal significant long-run cointegration among the variables. The essential insights of this study affirm that renewable energy strengthens environmental quality in both the short- and long-run, which stipulates its potential as a sustainable solution for Somalia. Conversely, trade openness has a detrimental impact on environmental quality in both the short- and long-run. While globalisation hinders environmental quality in the short-run, economic growth improves it. In addition, variance decomposition analysis highlighted that environmental deterioration was mainly self-perpetuating, accounting for 49% of the fluctuations. Additionally, variations in renewable energy sources are closely linked to environmental degradation, reinforcing the importance of adopting clean energy sources. Considering these findings, this study proposes establishing clear renewable energy strategies, leveraging globalisation for sustainable investments, and enforcing stringent environmental regulations that balance the benefits of trade openness. These observations provide a valuable framework for future research to examine sector-specific interventions and the long-term impacts of trade and energy policies on fragile economies.

Keywords Renewable energy, Trade openness, Globalisation, Environmental degradation, Clean energy, Sustainable growth

Pursuing sustainable development has become a global imperative as nations grapple with the dual challenges of economic growth and environmental preservation. Owing to heightened production levels, the combustion of non-renewable energy sources has led to an increase in greenhouse gas (GHG) emissions, which is a critical factor in global climate change[1,2]. Anthropogenic activities such as high GHG emissions, poor agricultural practices, transportation, and population growth are the primary causes of ecological deterioration, which risks health and sustainable development[3–6]. The Intergovernmental Panel on Climate Change[7] has highlighted that activities such as desertification, deforestation, and global warming have environmental implications. Carbon dioxide (CO_2) represents the most significant portion of GHGs, making it a primary environmental pollutant of concern[6,8,9]. Economic growth driven by trade openness and industrialisation can exacerbate environmental pollution and contribute to climate change through increased industrial activities and consumption[10,11].

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Environmental scientists, researchers, and policymakers have convened to deploy cutting-edge mitigation strategies in response to grave concerns posed by the ongoing rise in global temperatures[12]. The Kyoto Protocol and COP21 are major international climate agreements that address environmental challenges, with participating nations committed to reducing CO_2 emissions to diminish global temperature by 2 °C[13].

Several factors influence environmental quality, including globalisation, trade openness, economic growth, and renewable energy. Although energy generation and use are essential for economic growth, they present challenges, including environmental pollution, which impede ecological sustainability[14]. In 2019, the combined manufacturing, energy, transport, and building sectors were responsible for approximately 79% of the global GHG emissions, whereas agriculture, forestry, and land use accounted for 22%[7]. Energy economics research has identified energy consumption and economic growth as the foremost contributors to environmental conditions[10,11,15,16]. Grossman and Krueger[17] hypothesised an inverted U-shaped link between real growth and ecological deterioration. This phenomenon is commonly referred to as the Environmental Kuznets Curve (EKC) hypothesis, named after Kuznets[18]. Numerous studies have validated the Environmental Kuznets Curve (EKC) hypothesis, indicating that economies heavily reliant on fossil fuels often experience environmental degradation in the early stages of development. At a certain threshold level, adopting better technologies may enhance environmental quality[1,5]. The impact of trade openness on economic growth and environmental sustainability has recently become a prominent subject of academic research[19,20]. Trade liberalisation accelerates economic growth and affects pollution levels by allowing countries to leverage their comparative advantages through resource transfer[10].

Trade openness enhances energy usage through industrial exports and imports of goods, such as automobiles and industrial inputs[5,14]. In countries with advanced technological innovation and strong institutional frameworks, trade liberalisation positively impacts environmental quality, whereas the challenge of reducing emissions is more significant in less industrialised nations[21]. Many scholars affirm that the environmental implications of trade openness vary based on the scale, technique, or composite effects[8,15,22]. More precisely, free trade has a scale effect because an increased trade volume leads to higher production and energy consumption, resulting in elevated CO_2 emissions[4,23]. In addition, the composition effect suggests that trade increases can affect pollution levels, depending on whether a nation's comparative advantage involves trading goods from energy-intensive sectors. According to the technology effect, trade flows among countries enhance competitiveness, efficiency, and the adoption of environmentally friendly technologies in production, thereby reducing environmental degradation. A recent study by Jahanger[24] suggested that the composition effect is the most crucial factor in regulating carbon emissions because the impacts of size and technique are insufficient. Shahzad et al.[8] demonstrate that the benefits of improved technologies and effective environmental policies outweigh the negative effects of scale and composition on the environment. Depending on which of the three effects is prominent, the overall impact of trade openness on the environment is unclear, although scale and composition impacts are typically dominant in developing countries.

The escalation of global warming owing to fossil fuel use has heightened the global focus on sustainable development, stressing the necessity of adopting cleaner energy sources[25]. According to the International Energy Agency (IEA, 2020), there has been an increase in energy-related CO_2 emissions in developing countries compared with industrialised economies. Numerous studies have emphasised the critical need for developing countries to transition from their existing energy infrastructure to renewable energy to address climate change, enhance energy security, and foster economic growth[10,20,26,27]. Using alternative energy sources may help reduce CO_2 emissions, which comprise more than 60% of total GHG emissions[10]. Recent projections indicate that by 2025, renewable energy will surpass coal in power generation and is expected to account for 50% of global electricity production by mid-century[3,25]. Moreover, renewable energy sources play a significant role in attaining energy security by reducing nations' reliance on imported fossil fuels[28]. However, the inadequate energy infrastructures of developing nations have been unable to grow, which has slowed down the shift of these nations' energy usage from non-renewable to renewable sources[2]. Dauda et al.[15] proposed updating energy consumption policies to increase the proportion of renewable energy sources and reduce environmental pollution.

African nations emit the least GHGs compared to industrialised countries, although the continent is most severely affected by environmental changes[29]. Renewable energy technologies are particularly beneficial for African countries because they offer environmentally friendly solutions for electricity generation and address issues such as limited energy access in remote rural areas, poverty, and climate change susceptibility[29]. Because the volatility of oil and gas prices is high, African countries need to alter their energy policies towards renewables by utilising their abundance of natural resources[1]. Promoting sustainable energy is critical because trade contributes to 20% of global environmental pollution[12]. The existence of an African Continental Free Trade Area (AfCFTA) could facilitate trade between member countries and yield large economic gains[30]. Somalia experiences energy instability because most families rely primarily on traditional biomass for cooking[31]. The fulfilment of energy needs via charcoal and firewood utilisation has affected forest resources, resulting in overgrazing, arable land loss, and desertification[32]. By diversifying its energy mix and embracing clean technologies, the country's vast, untapped renewable energy potential, including wind, solar, and hydroelectric resources, could serve as an opportunity to leapfrog carbon-intensive development paths and reduce the costs associated with energy imports.

While scholarly discourse has extensively investigated the environmental degradation arising from the rapid expansion of trade openness, empirical studies have displayed inconsistent findings[14,22,33–35]. To the best of our knowledge, there has been relatively little emphasis on investigating the interdependence between trade openness, renewable energy, economic growth, globalisation, and environmental sustainability in Somalia. Despite Somalia's significant reliance on trade, which forms a large part of its GDP through imports and exports, the impact of trade activities on its sustainable development journey remains a critical research question[19]. Empirical studies predict that adopting renewable-energy technology is more feasible in nations with greater trade openness[12,28]. In contrast to similar studies, the central objective of this investigation was to pinpoint the impacts of trade openness, renewable energy consumption, economic growth, and globalisation on environmental degradation in Somalia using annual data from 1990 to 2019. Accordingly, the present investigation enhances the existing literature in these unique ways. First, it attempts to evaluate the effects of increased trade openness concurrently, the promotion of renewable energy, globalisation, and economic growth on CO_2 emissions in a single framework in Somalia. A few studies, including Warsame et al.[32,] on the renewable energy-environmental degradation nexus in Somalia have failed to consider trade openness. The country depends heavily on the export of agricultural and livestock products, and most consumed goods are imported. In addition, to infer consistent outcomes, this empirical study uses various econometric techniques, including unit root analysis, bounds testing, the Johansen cointegration approach, the autoregressive distributed lag (ARDL) model, dynamic OLS, and variance decomposition. Finally, the findings can inform evidence-based policies that align economic progress with environmental protection, thus charting a course towards a more sustainable future for Somalia.

The remainder of this paper is structured as follows. The second section reviews related theoretical and empirical literature. In the third section, the methodology details the research approach, data collection, and analytical methods. The fourth section presents the results and discusses outcomes. Finally, the study concludes with relevant policy suggestions.

Theoretical and empirical literature

Theoretically, the literature relies on the pollution haven hypothesis 'PHH' and the factor endowment hypothesis 'FEH' to explain the association between trade openness and the environment[8,36]. The PHH posit that developing nations with loose environmental regulations become hubs for pollution-intensive production, attracting multinational firms to transfer their highly polluting industries to these areas. Manufacturing costs are substantially lower in nations with laxer environmental restrictions, thereby accommodating companies with more detrimental environmental consequences[15]. Effective environmental regulations, technological transfers, and knowledge spillovers can mitigate carbon-intensive trade activities[37]. On the other hand, the FEH suggests that a nation's trade patterns are influenced by its resource endowments, leading to the specialisation and export of goods that capitalise on abundant local resources. Developing countries like Somalia, where natural resources are abundant, tend to specialise in resource-intensive manufacturing. This specialisation and increased trade can accelerate environmental degradation due to the higher resource consumption and potential pollution associated with these industries.

With the global imperative to combat climate change, the intersection of trade openness, economic growth, environmental sustainability, and globalisation has garnered increasing attention in contemporary literature. Among the top emitters of emerging economies, Ertugrul et al.[38] reveal that the vital long-run determinants of environmental degradation are economic growth, energy use, and trade openness. Notably, existing empirical studies covering factors influencing environmental quality have concluded various outcomes, which can be attributed to divergence in the methodologies, variables adopted, and development levels of the respective nations. Drawing on various academic sources, this review explores the complex effects of trade openness, renewable energy consumption, economic growth, and globalisation on the carbon emissions landscape.

Trade openness and carbon emissions

Trade openness can facilitate the diffusion of cutting-edge cleaner technologies and best practices, resulting in improved environmental performance[39]. Using a panel nonlinear ARDL from 1990 to 2017, Qamruzzaman and Jianguo[27] reveal that adopting renewable energy would result from economies' openness to trade. Similarly, expanding the import of renewable energy equipment may accelerate the deployment of renewable energy sources in South Asian economies[35]. Recent studies by Adebayo et al.[10] and Shahbaz et al.[40] discovered that trade openness reduces environmental degradation in the U.S. and Sweden. However, Han et al.[14] demonstrated that trade strongly promotes non-renewable energy consumption while only slightly strengthening renewable energy usage. Regarding multilateral trade agreements, Dou et al.[41] assessed the effects of imports and exports on environmental quality separately. This study indicates a contrasting impact of trade on environmental pollution. While exports significantly reduce CO_2 emissions, imports have been found to increase environmental degradation. Additionally, they demonstrate that trade openness indirectly affects environmental degradation due to size, technological, and structural factors. Naranpanawa[42] does not find a long-run causal relationship between trade openness and environmental degradation in several cointegration settings. However, this study suggests that a rise in trade openness would increase CO_2 emissions in Sri Lanka in the short run. In the top renewable energy-consuming countries, international trade has no apparent effect on environmental pollution[23].

However, investigations have revealed that the advantages of trade openness are not sufficient to cut emissions[12]. Many studies suggest that countries with higher trade openness experience increased carbon emissions owing to the production and consumption of pollution-intensive products. For instance, Wenlong et al.[6] reveal that while trade openness adversely affects environmental quality, improvements in energy efficiency and technological progress have beneficial impacts. As international trade contributes to environmental deterioration, it poses significant challenges to achieving sustainable development[5,43]. Using the ARDL bounds testing approach, Abokyi et al.[36,] Nurgazina et al.[11,] and Shahzad et al.[8] concur that trade openness, in conjunction with increased energy consumption, raises environmental pollution in Ghana, Malaysia, and Pakistan. Sun et al.[44] reported that increased international trade and specialisation in the Belt and Road nations may engender environmental deterioration. Using panel data spanning 122 countries from 1990 to 2014, Wang et al.[45] discovered that increased economic activity resulting from trade openness may result in higher carbon emissions. Similarly, You et al.[46] discovered that CO_2 emissions in the U.S. were accelerated by high openness and economic growth. Additionally, Hdom and Fuinhas[47] used FMOLS and DOLS cointegration models to conclude that natural gas and trade openness exacerbate environmental degradation in Brazil. In sub-Saharan

Africa, Sun et al.[30] exhibited that increased trade openness is related to increased environmental deterioration, although its scale diminishes over time.

Renewable energy consumption and carbon emissions

By reducing the reliance on fossil fuels, integrating renewable energy sources holds promise for both economic development and carbon emission reduction[43]. Muhammad et al.[37] show that renewable energy is constructively connected with economic growth but adversely correlates with CO_2 emissions in 23 OECD countries. Using the DOLS estimator, Dogan and Seker[23] demonstrated that although non-renewable energy worsens the environment, renewable energy and trade reduce carbon emissions. Zafar et al.[12] revealed that switching to renewable energy, supported by policies encouraging trade openness and sustainable economic development, enhances environmental quality. Additionally, Destek and Sinha[48] used panel data from 24 OECD nations to show that accelerating the use of renewable energy decreases the ecological footprint, whereas the utilisation of non-renewable energy accelerates environmental deterioration. Using various cointegration approaches, You et al.[46] and Ahmed et al.[49] found that the long-term use of renewable energy helped improve environmental quality in the U.S. and Somalia, respectively. Utilising renewable energy has a detrimental effect on environmental degradation in the top renewable energy countries[23]. Wavelet analysis by Adebayo et al.[3] suggests that using renewable energy in Portugal reduces CO_2 levels in the medium and long run. Moreover, Inglesi-Lotz and Dogan[1] discovered that in sub-Saharan Africa, while renewable energy contributes to reducing environmental pollution, the consumption of non-renewables exacerbates it. In 25 African nations, using renewable energy reduces CO_2 emissions[50].

However, the efficacy of renewable energy is influenced by various factors. Adams and Acheampong[29] discovered that increasing the proportion of renewable energy sources in the energy mix requires considerable democratic changes, which may assist in reducing environmental pollution. Warsame et al.[32] reported that strong governance, which boosts renewable energy policies, also increases environmental quality. According to Hussain et al.[22], political stability, applying laws, regulatory excellence, and suppressing corruption are significant features that affect investments in renewable energy in BRI nations. Correspondingly, renewable energy investments, technological advancements, and eco-innovation have substantially reduced GHG emissions[34,51,52]. In addition, Murshed[2] examined the nonlinear effects of ICT trade on the potential for a transition to renewable energy sources and the reduction of environmental pollution in South Asian nations. Their findings show that ICT trade directly boosts the use and share of renewable energy, lowers energy intensity, promotes the use of cleaner cooking fuels, and lowers CO_2 emissions. Along with clean energy technologies, Dauda et al.[15] and Abdi[26] recently revealed that human capital and economic complexity lower environmental deterioration in various African countries. Moreover, Thi et al.[20] used the FMOLS, DOLS, and system-GMM estimators to illustrate that innovation and renewable energy lower emissions, whereas international tourism increases environmental deterioration. Jamil et al.[53] reported that the effect of renewable energy on CO_2 emissions was statistically negligible in G-20 countries.

Economic growth and carbon emissions

Economic growth often corresponds to increased energy consumption and carbon emissions, as exemplified by the Environmental Kuznets Curve (EKC) hypothesis[12,39]. Empirical evidence for the EKC regarding CO_2 emissions is mixed, and the threshold varies across countries and pollutants. According to the EKC theory, environmental degradation first worsens as economic growth advances,however, at a certain point, environmental deterioration starts to decline with increases in economic growth[54]. Jamel and Maktouf[55], using annual panel data from 40 European nations, revealed bidirectional Granger causality between economic growth and environmental pollution. Similarly, Ohlan[56] established a favourable and significant connection between real GDP per capita, population density, and environmental pollution. Similar outcomes from Warsame et al.[32] and Abdi[26] state that environmental deterioration is an aftermath of economic expansion in both the short and long run. Ali et al. (2022) showed an unfavourable effect of economic growth on environmental degradation in India only in the short run. In addition, Dogan and Seker[23] discovered that economic growth and non-renewable energy use increase environmental pollution in the top renewable energy countries. Similarly, Adebayo et al.[57] and Ansari et al.[4] suggest that economic expansion hampers environmental quality.

Additionally, Jahanger et al.[58] used spectral causal analysis to show that economic growth causes long-term environmental degradation in Mexico. In sub-Saharan Africa, Adebayo and Acheampong[59] noticed that for most quantiles, there is a positive feedback relationship between economic growth and CO_2 emissions. While rapid economic growth may lead to increased emissions, some empirical findings assert that it leverages the potential of renewable energy to achieve economic prosperity while limiting carbon emissions. For example, Hdom and Fuinhas[47] revealed that economic growth and renewable energy sources reduce environmental deterioration. Alam and Murad[33] demonstrated that economic growth substantially enhances renewable energy consumption in the long run but not in the short run. By adopting a quantile-on-quantile approach, Adebayo et al.[10] noted that most quantiles present a negative relationship between economic growth and environmental pollution. In G7 nations, Ahmad et al.[60] revealed an inverted U-shaped association between ecological footprints and economic growth. Adding to this discussion, Yuhuan et al.[61] similarly highlighted that industrial growth contributes to CO_2 emissions, but fostering industrial competition and renewable energy mitigates these effects by promoting innovation and sustainability.

Globalisation and carbon emissions

The literature asserts that global interconnectedness accelerates opportunities for technology transfer, knowledge sharing, and diffusion of cleaner production processes across borders. Based on data from 74 developing nations, economic and social globalisation substantially mitigate environmental degradation[62]. Similarly, Ahmad et al.[60]

demonstrated that eco-innovation and financial globalisation diminish the ecological footprint of G7 nations. Using heterogeneous panel cointegration methods, Tahir et al.[9] claim that globalisation has the capacity to reduce emissions in South Asian countries. Using a sample of top renewable energy-consuming countries, Ansari et al.[4] found that renewable energy usage, globalisation, and urbanisation have reduced ecological footprints. According to Pata and Yilanci[16], energy use accelerates environmental deterioration in G7 nations, whereas globalisation significantly decreases it. Yuping et al.[13] provide insights into the dynamic relationship between renewable energy use, globalisation, and carbon emissions in Argentina, emphasising that globalisation and clean energy reduce environmental degradation. This result is supported by Awan et al.[63], who discovered that globalisation minimises environmental deterioration in MENA nations. Warsame et al.[64] state that although globalisation positively impacts environmental quality in the short run, it accelerates environmental degradation in the long run.

However, increased movement of goods and services can result in higher transportation-related emissions. Using the augmented ARDL approach, Pata and Caglar[5] indicated that globalisation has a rising influence on the use of natural resources and environmental pollution in China. By contrast, Jahanger et al.[62] reported that globalisation has a two-fold threshold impact on human capital rather than monotonously reducing or boosting carbon productivity in China. According to Pata[25], globalisation in the BRIC countries increases pollution indicators, even though clean energy production significantly reduces environmental stress. As Nathaniel et al.[65] reported, environmental deterioration is accelerating in LACC nations because of globalisation. Using the quantile-on-quantile technique, Adebayo and Acheampong[59] demonstrate a positive feedback relationship between globalisation and carbon emissions at all quantiles. Wen et al.[54] used the FMOLS approach in South Asian economies and found that globalisation was positively correlated with CO_2 emissions. Chien et al.[52] used the quantile ARDL to establish that globalisation is a significant factor in Pakistan's rising environmental degradation. Using a comparable framework, Jahanger et al.[58] examine the heterogeneous effects of globalisation in Mexico at various CO_2 levels. The results demonstrate that globalisation, which increases the ratio of environmental degradation, only affects the higher quantiles of CO_2 emissions.

Materials and methods
Data sources and descriptions
This study comprehensively explores the effects of trade openness and renewable energy use on environmental degradation in Somalia using data from 1990 to 2019. The data for analysis were extracted from the World Bank, KOF, and SESRIC databases. The study variables included environmental pollution, renewable energy, trade openness, globalisation, and economic growth. Natural logarithm transformations of all variables were performed to eliminate potential heteroscedasticity issues. Environmental degradation has been measured using various factors, such as GHG emissions, deforestation, and other indicators. In the present study, environmental quality was measured using CO_2 emission levels. Notably, elevated CO_2 emissions worldwide have impeded environmental quality. According to Warsame et al.[64] and Saint Akadiri et al.[66], globalisation significantly contributes to environmental pollution. Therefore, globalisation and economic growth were used as control variables to consider their significant roles in increasing CO_2 emissions. The sampling period was determined based on data availability.

Table 1 provides the data, symbols, measurement units, and their sources. As shown in Fig. 1a–e, the trends of environmental degradation, real GDP per capita, globalisation, renewable energy consumption, and trade openness are depicted over the sampled period. Environmental degradation marked a decline in the early 1990s, followed by a steady increase in recent years. In addition, Real GDP per capita exhibits consistent growth, which reflects economic progress despite early volatility. Globalisation demonstrates fluctuations, with a sharp rise after 2010, indicating deeper integration into global markets. Likewise, renewable energy consumption steadily increases, which aligns with global sustainable energy efforts. As an indication of Somalia's growing participation in international markets, trade openness displays an upward trajectory. Moreover, the flow of the analysis is illustrated in Fig. 2.

Econometric methodology
The ARDL approach was implemented to achieve this objective. This method performs better than other cointegration techniques in various ways. First, the ARDL may be utilised with small sample sizes and may not require lengthy time-series data. Second, the variables of different integration orders may be regressed using the ARDL if it does not integrate them in the second difference, I(2). Third, unlike earlier techniques, it simultaneously regresses the variables' short- and long-run cointegration[67]. On the other hand, the Johansen cointegration method complements ARDL by focusing on multivariate systems of equations to identify long-run equilibrium relationships among multiple variables. Unlike ARDL, which allows for single-equation analysis, the

Variable	Code	Description	Source
Environmental degradation	lnED	Carbon dioxide emissions (kilotons)	World Bank
Economic growth	lnRGDPC	Real gross domestic product per capita	SESRIC
Globalisation	lnGL	KOF Globalisation index	KOF
Renewable energy	lnRE	% of total final energy consumption	World Bank
Trade openness	lnTO	Import plus export divided by GDP	SESRIC

Table 1. Data sources and description.

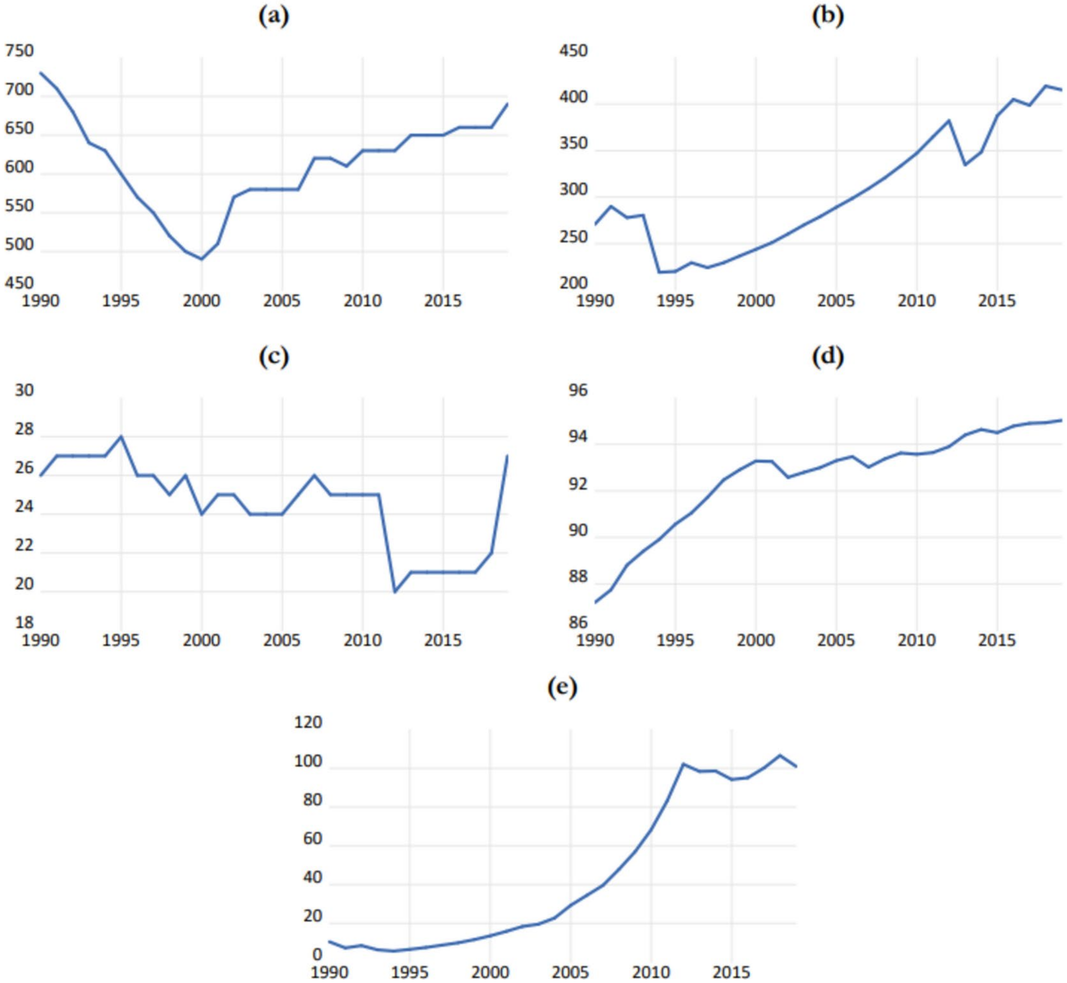


Fig. 1. Trend of variables: (**a**) Environmental degradation (**b**) Real GDP per capita (**c**) Globalisation (**d**) Renewable energy consumption (**e**) Trade openness.

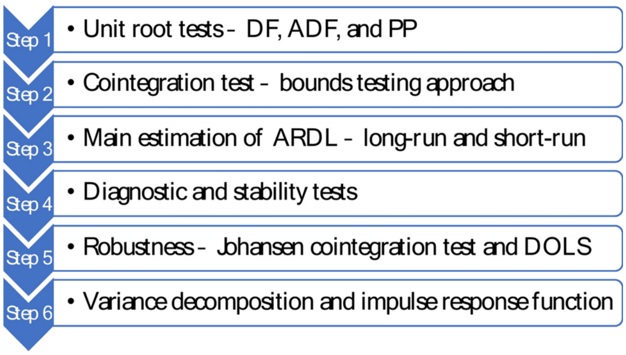


Fig. 2. The flow of the analysis.

Johansen method is particularly useful when the researcher aims to analyse interdependencies among variables within a system. It uses trace and maximum eigenvalue tests to determine the number of cointegration vectors. Following Pata and Caglar[5], Ghazouani et al.[68], and Yurtkuran[69], the ARDL cointegration equation in this study is written as follows:

$$lnED_t = \beta_0 + \beta_1 lnRGDPC_t + \beta_2 lnGL_t + \beta_3 lnRE_t + \beta_4 lnTO_t + \varepsilon_t \quad (1)$$

where $lnED_t$ is the log of environmental degradation in year t, $lnRE_t$ is the log of renewable energy in year t, $lnTO_t$ is the log of trade openness in year t, $lnGL_t$ is the log of globalisation in year t, $lnRGDPC_t$ is the log of Real GDP per capita and ε_t is the disturbance term in time t. Utilising Eq. (2), we develop our ARDL equation as follows:

$$\begin{aligned}\Delta lnED_t =& \alpha_0 + \sum_{i=0}^{p} \Delta\alpha_1 lnED_{t-k} + \sum_{i=0}^{p} \Delta\alpha_2 lnRGDPC_{t-k} + \sum_{i=0}^{p} \Delta\alpha_3 lnGL_{t-k} \\ &+ \sum_{i=0}^{p} \Delta\alpha_4 lnRE_{t-k} + \sum_{i=0}^{p} \Delta\alpha_5 lnTO_{t-k} + \beta_1 lnED_{t-1} \\ &+ \beta_2 lnRGDPC_{t-1} + \beta_3 lnGL_{t-1} + \beta_4 lnRE_{t-1} + \beta_5 LnTO_{t-1} + \emptyset ECT_{t-1} + \varepsilon_t\end{aligned} \quad (2)$$

where the α's are the coefficients of the short-tun, and α_0 is the constant, β's denote the coefficients of the long-run variables, Δ symbolises the operator of the first difference, p represents the number of lags, ε is the disturbance error term, ECT and $\varnothing$ represent the error correction term and its coefficient, respectively. Because determining the long-run cointegration of the dependent and explanatory variables is crucial in ARDL modelling, we regress Eq. (2) using the ordinary least squares (OLS) technique. The Wald F-statistic is used to compare the alternative hypothesis (H_a), which states that there is cointegration between the variables, to the null hypothesis (H_0), which states that there is no cointegration among the variables in Somalia. This hypothesis is formulated as follows:

$H_0: \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$ | H_0: the variables are not cointegrated.
$H_a: \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$| H_a: the variables are cointegrated.

Empirical analysis and discussion

Table 2 lists the summary statistics and correlations between the sampled parameters. The results indicate that the highest mean value is possessed by environmental degradation, at approximately 6.4, while globalisation has the lowest (3.19). In addition, all variables are less volatile, except trade openness, which shows the highest volatility, as shown by the standard deviation. Table 2 shows the correlations of the variables of interest. We observed a positive association between environmental pollution and fundamental variables such as economic growth and trade openness. At the same time, a negative relationship exists between environmental pollution and globalisation and between environmental pollution and renewable energy. Moreover, renewable energy and trade openness positively correlate with economic growth, whereas growth and globalisation are negatively correlated. Similarly, we find that renewable energy and trade openness are adversely related to globalisation. Finally, a positive correlation was established between renewable energy and trade openness.

Prior to model analysis, we tested the stationarity of the variables of interest. Testing the order of integration of the variables is essential for producing robust and unbiased results as well as for selecting the appropriate method for our data. The stationarity results of the Augmented Dickey-Fuller (ADF), Dickey-Fuller (DF), and Phillips-Perron (PP) tests (Table 3) revealed that all parameters contained a unit root problem at level I(0), except for globalisation in ADF. However, in the first difference, I(1), all the variables are stationary, implying that the integration process of the parameters is of mixed order.

Variable	lnED	lnRGDPC	lnGL	lnRE	lnTO
Panel A: Descriptive analysis					
Mean	6.413	5.698	3.196	4.528	3.305
Median	6.438	5.668	3.219	4.536	3.251
Maximum	6.593	6.039	3.332	4.554	4.669
Minimum	6.194	5.390	2.996	4.468	1.728
Std. Dev	0.101	0.206	0.095	0.023	1.067
Skewness	− 0.51	0.130	− 0.734	− 1.16	− 0.01
Kurtosis	2.685	1.817	2.356	3.425	1.435
Jarque–Bera	1.446	1.834	3.209	6.894	3.062
Probability	0.485	0.400	0.201	0.032	0.216
Panel B: Correlation analysis					
lnED	1				
lnRGDPC	0.598	1			
lnGL	− 0.13	− 0.631	1		
lnRE	− 0.2	0.594	− 0.662	1	
lnTO	0.341	0.914	− 0.742	0.818	1

Table 2. Descriptive and correlation analysis.

Variable	DF	ADF	PP
Series at I(0)			
lnED	− 1.720	− 2.658	− 2.344
lnRGDPC	− 1.952	− 2.305	− 2.406
lnGL	− 2.359	− 4.961***	− 2.055
lnRE	− 1.653	− 3.418*	− 2.918
lnTO	− 1.227	− 1.136	− 2.931
Series at I(1)			
ΔlnED	− 3.563**	− 3.425*	− 3.462*
ΔlnRGDPC	− 3.769**	− 3.926**	− 5.539***
ΔlnGL	− 4.816***	− 4.741***	− 4.741***
ΔlnRE	− 3.975***	− 3.825**	− 3.839**
ΔlnTO	− 3.689***	− 4.559***	− 4.559***

Table 3. Unit root tests. Δ where is the first-difference variable. *, **, and *** exhibit the significance level of 10%, 5%, and 1%, respectively. The t-statistics reported are trends and intercepts.

Variable	Coefficient	Std. Error	t-Statistic
Long-run elasticities			
lnRGDPC	0.068	0.224	0.304
lnGL	− 0.201	0.225	− 0.893
lnRE	− 7.429***	1.761	− 4.219
lnTO	0.147**	0.065	2.27
Constant	39.893***	9.134	4.368
Short-run elasticities			
ΔlnRGDPC	− 0.151***	0.045	− 3.356
ΔlnGL	0.098**	0.043	2.276
ΔlnRE	− 8.302***	0.66	− 12.577
ΔlnTO	0.052***	0.019	2.811
ECT (− 1)	− 0.276***	0.038	− 7.273
F-bound test statistics	8.032		
Upper bound critical value at 1% significance level	− 6.56		

Table 4. Bound test and coefficient elasticity results. Notes: *, **, and *** exhibit the significance level of 10%, 5%, and 1%, respectively.

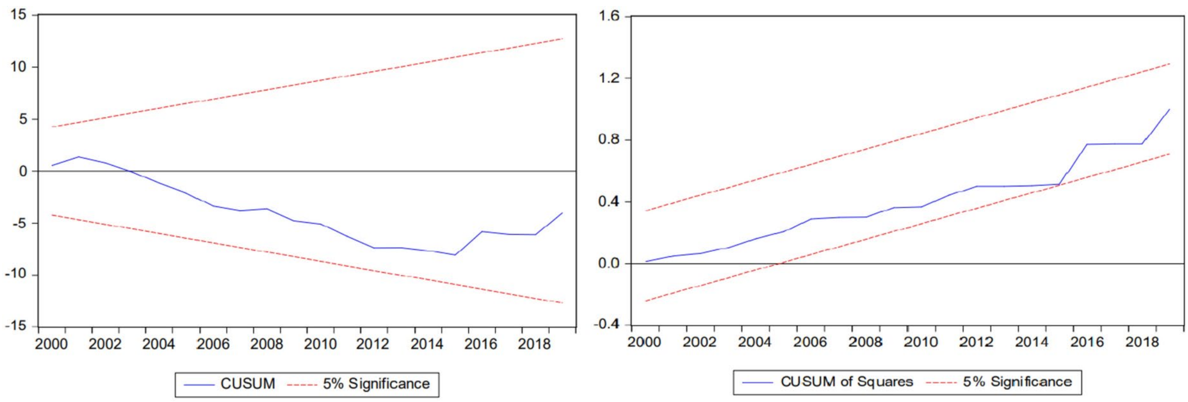
Having determined the integration order of the parameters of interest, we examined the existence of long-run cointegration among the investigated variables. The ARDL-bound test was used for the analyses. This method was selected as the most appropriate cointegration method because of the mixed order of integration of the sampled variables, as indicated by the unit root test results. The results of the bounds test, displayed in Table 3, underscore the presence of long-run cointegration between environmental degradation and the sampled explanatory variables of economic growth, globalisation, renewable energy, and trade openness.

The results for the long- and short-run coefficient elasticities are presented in Table 4. According to their empirical findings, a 1% increase in renewable energy reduces environmental degradation by approximately 7.4% in the long run. Similarly, although it is statistically insignificant, globalisation inhibits environmental degradation in Somalia in the long run. In contrast, trade openness and economic growth contribute to long-term environmental degradation in Somalia despite the statistical insignificance of economic growth. A percentage increase in trade openness leads to an increase in environmental degradation of approximately 0.14% in the long run. Furthermore, renewable energy is adversely related to environmental degradation in the short term. However, a 1% increase in globalisation and trade openness increases environmental degradation by approximately 0.09% and 0.052% in the short run. Economic growth enhances environmental quality in the short run, and a percentage increase in growth reduces environmental degradation by approximately 0.15% in the short-run in Somalia. Moreover, the coefficient of ECT is -0.27, which is negative and statistically significant. This implies that environmental degradation converges to long-run equilibrium at a speed of adjustment of approximately 27% annually via changes in globalisation, economic growth, renewable energy, and trade openness.

Tests for serial correlation, heteroscedasticity, functional misspecification, normality, and model stability were performed to check stability and residual diagnostics. No evidence of serial correlation or heteroscedasticity was observed. The functional form of the model was correctly specified, and the normality test revealed that the data were identically and normally distributed, as presented in Table 5. Using the CUSUM and CUSUM

Test	Statistic
Adjusted R-square	0.974
Reset test	2.108 [0.163]
Heteroskedasticity test	0.493 [0.781]
Serial correlation test	0.237 [0.689]
Normality	0.679 (0.712)

Table 5. Diagnostic tests. T-statistics values are in (…) parenthesis. P-values are in […].



(a) CUSUM test

(b) CUSUM of Squares test

Fig. 3. Model stability tests.

Hypothesis	Test Statistic	5% critical value	P-value
Trace test			
r ≤ 0	78.897	69.818	0.007
r ≤ 1	53.437	47.856	0.013
r ≤ 2	32.927	29.797	0.021
r ≤ 3	16.384	15.494	0.036
r ≤ 4	1.2346	3.8414	0.266
Maximum Eigenvalue test			
r ≤ 0	25.459	33.876	0.354
r ≤ 1	20.510	27.584	0.306
r ≤ 2	16.542	21.131	0.194
r ≤ 3	15.149	14.264	0.036
r ≤ 4	1.2346	3.8414	0.266

Table 6. Johansen cointegration method.

of Squares tests, the results of the model stability tests are depicted in Fig. 3a,b, indicating the adequacy of the model's fit. Moreover, the goodness of fit of the model was adequate, as indicated by the adjusted R-squared value (0.97), where 97% of the variation in environmental degradation was accounted for by the sampled explanatory variables: renewable energy, globalisation, trade openness, and economic growth.

Tables 6 and 7 disclose the results of the multivariate cointegration method and dynamic ordinary least squares (DOLS), performed as robustness for the ARDL bound test. The Johansen cointegration method underscores the presence of long-run cointegration among environmental degradation and the explanatory variables of interest in the trace test. However, no cointegration was detected among the sampled variables in the maximum eigenvalues. Moreover, the DOLS results showed that renewable energy mitigates environmental degradation in Somalia, whereas trade openness hampers it in the long run. Economic growth and globalisation are insignificant. Nevertheless, the DOLS robustly verified the long-run results of the bounds test. Illustratively, the long-run ARDL and DOLS outcomes are presented in Fig. 4.

In addition to the bound test, an innovative accounting approach was utilised to address the dynamic contribution of each parameter to environmental degradation in Somalia. This approach included the impulse

Variable	Coefficient	Std. Error	t-Statistic
lnRGDPC	0.118	0.282	0.418
lnGL	− 0.351	0.269	− 1.304
lnRE	− 9.265***	1.783	− 5.196
lnTO	0.128*	0.063	2.022
Constant	48.422***	8.679	5.578
R^2	0.993		
Adjusted R^2	0.966		

Table 7. Dynamic Ordinary Least Squares (DOLS). Notes: *, **, and *** exhibit the significance level of 10%, 5%, and 1%, respectively.

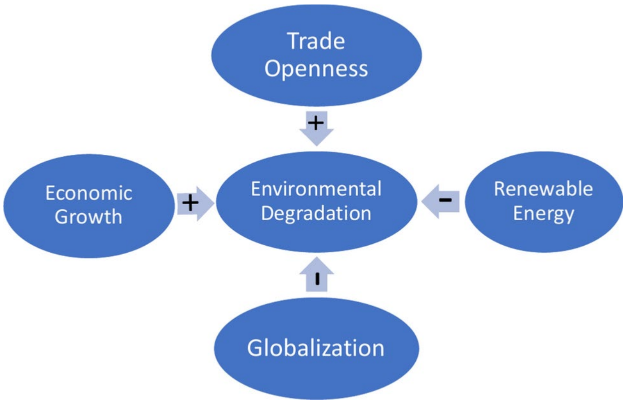


Fig. 4. Long-run ARDL and DOLS outcomes.

response function and variance decomposition using 10 periods prior to the sample period. The results of the variance decomposition, shown in Table 8, revealed that 49% of future fluctuations in environmental degradation could be attributed to the variable itself. Economic growth, globalisation, renewable energy, and trade openness were responsible for 25.7%, 9.7%, 6.9%, and 8.5% of these fluctuations, respectively. Our results further indicated that the contribution of economic growth to the shock was the highest at 41.3%, followed by globalisation (21.7%), renewable energy (18.8%), trade openness (12.7%), and environmental degradation (5.3%). Additionally, it was observed that globalisation's contribution to its shocks was as high as 58.5%, followed by renewable energy (14.13%) and economic growth (12.5%). Moreover, future oscillations in renewable energy are predominantly explained by environmental degradation (42.7%), followed by economic growth (29.3%) and renewable energy (14.07%). Future changes in economic expansion are primarily explained by economic growth and globalisation. A striking finding of this study is that historical changes in trade openness are primarily driven by globalisation (43.8%). As countries become more globalised, they are expected to become more open in terms of trade. Additionally, renewable energy and trade openness accounted for 38.08% and 12.26% of historical fluctuations in trade openness, respectively.

On the other hand, a 1 standard deviation shock in economic growth leads to an increase in environmental degradation in the first six periods, but the response becomes negative from periods 7 to 9. Environmental degradation responded negatively to a 1 standard deviation shock in renewable energy from Periods 1 to 3; however, from Period 4, the response turned positive. However, a 1 standard deviation shock in trade openness results in positive environmental degradation in all ten periods, except for period 1, which is insignificant. Finally, environmental degradation responds positively to the 1 standard deviation shock of globalisation, except in periods (1 and 6), which are statistically insignificant. Moreover, the study further illustrated the impulse response functions (IRF) of the variables, as shown in Fig. 5a–d. The IRF results illustrate the dynamic responses of environmental degradation to shocks in key variables: economic growth, renewable energy, trade openness, and globalisation. Panel (a) displays a positive response of environmental degradation to a shock in GDP per capita, which suggests that initial economic growth may exacerbate environmental degradation. Panel (b) features a negative response of environmental degradation to renewable energy. However, Panel (c) reveals a positive response of environmental degradation to trade openness. Finally, Panel (d) establishes a mixed response of environmental degradation to globalisation, which indicates that globalization can both enhance and hinder environmental sustainability depending on specific circumstances.

Discussion of the results

Traditional biomass energy consumption, mainly charcoal and firewood, constitutes 80–90% of the final energy consumption in Somalia, which has an unfavourable effect on the environment[32]. The negative association

Period	S.E	lnED	lnRGDPC	lnGL	lnRE	lnTO
Variance Decomposition of lnED:						
1	0.027	100.000	0.000	0.000	0.000	0.000
2	0.040	91.376	5.940	0.097	2.577	0.007
3	0.046	76.529	20.046	0.970	1.952	0.501
4	0.050	64.690	29.508	1.227	1.682	2.890
5	0.052	60.077	31.286	1.293	1.798	5.543
6	0.053	58.384	30.643	1.296	1.967	7.707
7	0.054	57.145	29.984	1.579	2.369	8.921
8	0.055	55.273	29.067	2.989	3.335	9.334
9	0.056	52.383	27.530	6.005	4.976	9.104
10	0.058	49.022	25.740	9.729	6.940	8.566
Variance Decomposition of lnRGDPC:						
1	0.045	3.100	96.899	0.000	0.000	0.000
2	0.070	4.894	66.673	12.240	7.397	8.794
3	0.073	7.064	62.846	11.508	7.552	11.027
4	0.075	7.599	60.673	11.081	7.777	12.867
5	0.076	7.455	58.697	10.974	8.427	14.446
6	0.078	7.087	55.652	11.911	10.006	15.341
7	0.081	6.626	51.837	14.047	12.198	15.290
8	0.085	6.148	47.769	16.916	14.620	14.545
9	0.088	5.722	44.092	19.690	16.899	13.593
10	0.091	5.385	41.304	21.709	18.833	12.766
Variance Decomposition of lnGL:						
1	0.068	17.402	0.732	70.063	9.364	2.437
2	0.079	15.477	2.288	66.605	9.884	5.743
3	0.086	13.831	8.898	60.831	8.915	7.523
4	0.089	12.911	14.727	56.376	8.270	7.714
5	0.092	11.989	16.228	55.960	8.599	7.221
6	0.098	10.689	14.629	58.263	9.963	6.452
7	0.105	9.534	12.854	60.153	11.457	5.999
8	0.111	8.878	12.401	60.376	12.354	5.989
9	0.113	8.609	13.109	59.476	12.634	6.169
10	0.114	8.505	14.130	58.550	12.551	6.262
Variance Decomposition of lnRE:						
1	0.002	70.371	4.002	0.000	25.626	0.000
2	0.004	67.323	8.109	10.016	13.784	0.766
3	0.004	58.372	17.802	11.528	11.457	0.839
4	0.005	50.839	26.274	12.325	9.7849	0.775
5	0.006	47.705	30.403	11.748	9.4302	0.712
6	0.006	46.411	31.433	11.401	10.065	0.687
7	0.006	45.224	31.029	11.850	11.229	0.666
8	0.006	44.057	30.262	12.584	12.445	0.649
9	0.006	43.212	29.671	13.063	13.415	0.637
10	0.006	42.739	29.360	13.189	14.079	0.631
Variance Decomposition of lnTO:						
1	0.100	1.335	8.270	0.000	16.870	73.522
2	0.134	1.895	4.767	12.683	20.468	60.185
3	0.183	2.265	2.879	28.151	27.820	38.882
4	0.224	2.153	1.947	37.810	30.644	27.443
5	0.269	1.888	1.608	44.206	32.861	19.435
6	0.304	1.724	2.051	46.640	34.325	15.257
7	0.328	1.622	2.847	46.726	35.635	13.167
8	0.341	1.547	3.654	45.723	36.798	12.276
9	0.346	1.497	4.190	44.587	37.668	12.055
10	0.350	1.496	4.349	43.799	38.085	12.269

Table 8. Variance decomposition.

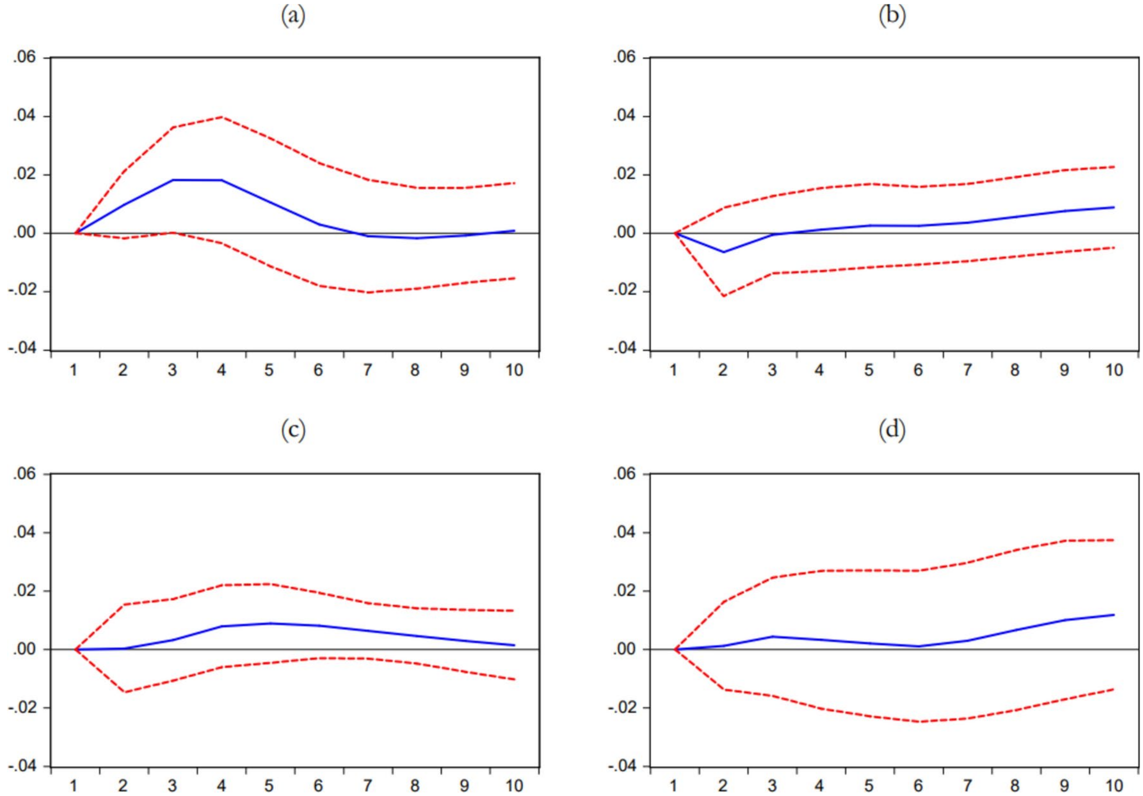


Fig. 5. Impulse Response Function: (**a**) Response of lnED to lnRGDPC (**b**) Response of lnED to lnRE (**c**) Response of lnED to lnTO (**d**) Response of lnED to lnGLO.

between environmental degradation and renewable energy, both in the short and long run, indicates a reduction in environmental degradation through the adverse effects of renewable energy on environmental deterioration. In other words, the findings underscore that incorporating renewable energy technologies and the extraction and consumption of clean energy into the energy mix enhances the environmental quality in Somalia. This result is consistent with the findings of Warsame et al.[32,] who found that renewable energy reduces deforestation in Somalia. Several other studies, such as Sarkodie and Adams[70] in South Africa and Chien et al.[71] in a panel of Asian countries, have reported that renewable energy improves environmental quality. Abdi[26] documented that renewable energy stimulates environmental quality in sub-Saharan African countries. However, the findings of our study are contrary to the previous results of Mahjabeen et al.[72] in eight developing countries (D-8) and Bölük and Mert[73] in a panel of European Union countries which found that renewable energy impedes environmental quality. The adoption of renewable energy sources, as indicated in our study, plays a pivotal role in achieving SDG 7 (Affordable and Clean Energy) by ensuring access to affordable, reliable, sustainable, and modern energy for all. Furthermore, the climate mitigation strategies stressed in this analysis directly contribute to SDG 13 (Climate Action) by strengthening resilience and adaptive capacity to climate-related hazards and integrating climate change measures into national policies.

Additionally, it was observed that trade openness adversely affects environmental quality in Somalia by increasing CO_2 emissions. Trade openness can potentially mitigate environmental degradation by promoting technological innovation and information diffusion, which are favourable to environmental quality. In contrast, Somalia, a low-income country with a less diversified economy, imports final goods intended for consumption, which impedes environmental quality[19,74]. The positive effect of trade openness on environmental degradation is in line with Shahzad et al.[8] in Pakistan, Pata and Caglar[5] in China, Adebayo et al.[57] in India, and Abokyi et al.[36] in Ghana but contradicts Zafar et al.[12] in emerging countries. However, economic growth is inconsequential in the long run, but it improves the quality of the environment in the short run. This result is consistent with previous studies by Och[75] and Warsame et al.[64], who observed that economic growth improved environmental quality in Mongolia and Somalia, respectively. In addition, globalisation is insignificant in the long run but adversely affects environmental quality in the short run. This result contrasts with that of Destek[76], who found that globalisation has no significant effect on environmental pollution in Latvia and the Slovak Republic.

Conclusion and policy recommendations

The literature predominantly concurs that renewable energy enhances environmental quality, although the effects of trade openness vary depending on the nature of the traded products. Although improved technology transfer and economic growth can enhance environmental quality, trade openness may harm the environment through increased pollution and resource extraction. This study offers new insights into how renewable energy and trade openness, along with economic growth and globalisation, affect environmental degradation in Somalia. Utilising annual time-series data from 1990 to 2019, this study employs the ARDL cointegration technique and innovative accounting systems, including the impulse response function and variance decomposition. The empirical results indicate that renewable energy, trade openness, economic growth, and globalisation are co-integrated with environmental degradation in Somalia in the long term. Renewable energy significantly improves environmental quality in the short and long terms, whereas trade openness hinders environmental quality in both periods. In the short run, economic growth and globalisation have significant negative and positive effects on environmental degradation, although their long-run effects are statistically insignificant. Various econometric methods confirm the robustness of the results. Nevertheless, the variance decomposition results emphasise that environmental degradation is primarily influenced by itself, accounting for 49% of the fluctuations. Economic growth contributed 41.3% to its own changes, followed by globalisation, renewable energy, and trade openness. Future fluctuations in renewable energy will be largely driven by environmental degradation (42.7%), economic growth, and renewable energy. Changes in trade openness are primarily explained by globalisation (43.8%), with significant contributions from renewable energy and trade openness. Globalisation strongly influenced these changes (58.5%), followed by renewable energy and economic growth.

Based on our findings, we offer several policy recommendations for balancing the competing priorities of mitigating CO_2 emissions while fostering sustainable economic development in Somalia. First, policymakers should establish a national renewable energy strategy with clear time-bound targets to increase the share of renewable energy sources in the energy mix. This can be achieved by allocating sufficient resources and incentives to facilitate the development and deployment of renewable energy technologies, focusing on decentralisation and off-grid solutions. Second, this study illustrates the necessity of incorporating clean energy policies (SDG 7) and climate resilience frameworks (SDG 13) to achieve sustainable economic growth and environmental sustainability. Policymakers should prioritize initiatives that simultaneously address energy access and climate adaptation to meet these global targets. Third, governments should leverage globalisation to attract foreign direct investment (FDI) in clean and sustainable industries. They should also develop comprehensive foreign investment strategies encouraging environmentally responsible investment and technology transfer. They should also foster partnerships with international donors and organisations to secure funding and technical expertise for renewable energy projects. Fourth, the authorities should balance the benefits of trade openness with stringent environmental regulations and standards to ensure that economic growth does not occur at the expense of the environment. Moreover, they must strengthen enforcement mechanisms and penalties for non-compliance with environmental regulations. Finally, because many households predominantly consume traditional biomass energy sources, policymakers should launch nationwide public awareness campaigns to educate citizens about the benefits of adopting clean energy. They should engage civil society organisations and media outlets to disseminate information on sustainable practices.

Building on this research, future studies should explore additional determinants of environmental pollution in Somalia. It includes a detailed analysis of specific trade policies and an examination of how tariffs, quotas, and regulations influence environmental outcomes. In addition, a deeper division into disaggregated renewable energy sources is crucial. Investigating the distinct impacts of solar, wind, hydroelectric, and biomass energy can reveal their individual and collective effectiveness in mitigating environmental degradation. Such studies can provide a more comprehensive understanding of the dynamics of economic factors and environmental soundness in Somalia.

Data availability

The datasets used and/or analysed in the current study are available at https://data.worldbank.org/country/somalia, https://www.sesric.org/query.php, https://kof.ethz.ch/en/data/kof-time-series-database.html.

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Author contributions

Abdikafi Hassan Abdi: conceptualisation, writing the introduction and literature review, and improving and editing the original draft. Abdimalik Ali Warsame: data collection, analysis, and writing of the discussion section. Mohamed Okash Sugow: Writing the literature review and policy implications. Hassan Abdikadir Hussein: Writing the methodology section. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
This study followed the ethical practices of the writing process. We declare that this manuscript is original, has not been published previously, and is not currently under consideration for publication elsewhere.

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