Abdi *et al. Discover Environment* (2026) 4:507
https://doi.org/10.1007/s44274-026-01057-9

Discover Environment

RESEARCH Open Access

Testing the load capacity curve hypothesis accounting for energy consumption and water use pressure in climate-vulnerable Somalia

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Abstract

Sustainability assessments in climate-vulnerable economies require metrics that extend beyond emissions to evaluate whether ecological demand remains within the regenerative limits of biocapacity. In Somalia, recurrent droughts and increasing pressure on limited freshwater resources have heightened concerns about the country's ability to sustain ecological balance under growing economic and demographic pressures. Against this backdrop, this study provides the first empirical test of the Load Capacity Curve (LCC) hypothesis for Somalia over the period 1990–2022 by examining the effects of economic growth, energy consumption, urbanization, gross fixed capital formation, and water-use pressure on the load capacity factor (LCF). To accommodate the smooth structural change characteristic of a climate-exposed economy, the analysis employs a Fourier autoregressive distributed lag (FARDL) model, complemented by Fourier-ADF and Fourier-LM unit-root tests, and cumulative Fourier Granger causality analysis. Alternative long-run estimations corroborate the LCC hypothesis. Economic growth is associated with a decline in the LCF, while the significant positive coefficient on its squared term indicates an attenuation of this adverse association as income rises. Energy consumption, urbanization, and water-use pressure are significantly negatively associated with the LCF in the long-run, whereas capital formation shows a significant negative association with the LCF in the short-run. Fourier Granger causality tests reveal unidirectional causality running from economic growth and its squared term to the LCF, bidirectional causality between the LCF and water-use pressure, capital formation, and energy consumption, and no significant causal linkage with urbanization. The findings provide policy-relevant evidence on ecological sustainability in Somalia.

Keywords: Load capacity curve, Economic growth, Water use, Water stress, Energy consumption, Capital formation

1 Introduction

Economic development depends fundamentally on natural systems that provide food, freshwater, energy, raw materials, and ecosystem services essential for production and human well-being. However, rapid economic expansion, urbanization, population growth, and changing consumption patterns have intensified pressure on forests, agricultural land, freshwater resources, and biodiversity [8, 23, 39]. According to the Global

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Footprint Network [20], humanity currently consumes natural resources approximately 80% faster than the Earth can regenerate them. Moreover, freshwater scarcity is becoming an increasingly critical global challenge, with the number of countries experiencing water scarcity projected to rise substantially by 2050, particularly in sub-Saharan Africa because of rapid population growth and declining freshwater availability [3, 8]. These environmental challenges demonstrate that sustainability extends beyond pollution reduction to preserving the ecological capacity that supports long-term development. Accordingly, increasing attention has been given to comprehensive indicators that evaluate both the demand placed on ecosystems and their ability to regenerate. Among these, the load capacity factor (LCF) has emerged as a comprehensive measure of environmental sustainability by integrating ecological footprint with biocapacity [23, 36, 49].

The balance between ecological demand and the regenerative capacity of ecosystems is continuously influenced by economic transformations. During the early stages of development, rising income stimulates industrialization, infrastructure expansion, and resource-intensive production. These activities increase the demand for energy, land, water, and other natural resources, thereby placing greater pressure on ecological systems [18, 46]. Economic expansion at this stage is also commonly accompanied by fossil-fuel dependence and intensive resource extraction. As a result, ecological demand often grows faster than ecosystems can regenerate [21, 36]. As economies mature, technological innovation, cleaner production methods, renewable energy adoption, and stronger environmental institutions can gradually reduce this trade-off [31, 48]. These changes improve resource-use efficiency and lower ecological pressure, which allows economic development to become increasingly compatible with environmental sustainability [7, 10]. This dynamic forms the basis of the load capacity curve (LCC) hypothesis, which proposes that economic growth initially weakens ecological sustainability but eventually strengthens it once countries reach a sufficiently advanced stage of development [34]. However, whether this transition occurs depends on the pace of technological progress and the effectiveness of environmental governance in mitigating the ecological pressures associated with economic expansion [18, 27].

Remaining within ecological limits is influenced by the country's energy system, urbanization, and productive capital accumulation. These structural dimensions determine the intensity of resource extraction, the efficiency of resource utilization, and the ability of ecosystems to regenerate under increasing development pressures [18, 49]. Among them, the energy system represents one of the most influential determinants of environmental sustainability because virtually all production and consumption activities depend on energy inputs [7]. Reliance on fossil fuels increases carbon emissions, accelerates resource depletion, and intensifies ecological pressure, whereas expanding renewable energy improves resource-use efficiency, lowers dependence on exhaustible resources, and enhances ecosystem resilience [3, 10, 36]. In addition, rapid and unplanned urban expansion increases demand for housing, transport, energy, and public services, placing additional pressure on land, water, and other natural resources [49]. Conversely, compact urban planning, technological innovation, and efficient infrastructure can reduce resource intensity and enhance environmental performance [18, 27]. The environmental implications of capital accumulation are equally dependent on the quality of investment. Capital formation directed toward carbon-intensive industries and conventional infrastructure can lock economies into environmentally unsustainable development pathways. By contrast, investment in renewable energy technologies, resource-efficient production systems, and climate-resilient infrastructure strengthens environmental sustainability by increasing productivity while reducing ecological pressure [7, 42].

Water constitutes one of the most fundamental forms of natural capital because it sustains ecosystem functioning, biological productivity, and the regenerative processes that determine ecological carrying capacity. Unlike many other natural resources, water underpins virtually every ecosystem service, supporting biodiversity, maintaining forests and wetlands, regulating nutrient cycles, and sustaining agricultural and industrial production [8, 23]. Growing evidence indicates that increasing pressure on freshwater resources has become one of the principal constraints to sustainable development. Rising population, climate change, urban expansion, and changing consumption patterns have intensified water stress in many regions, with Sub-Saharan Africa projected to experience one of the fastest declines in per capita freshwater availability over the coming decades [8]. Water is also central to the water-energy-food nexus, where decisions affecting one resource inevitably influence the others [50]. Water shortages reduce agricultural productivity, increase energy requirements for water extraction and irrigation, weaken food security, and amplify ecological degradation, while inefficient water allocation further intensifies pressure on ecosystems [22, 40]. Since agriculture accounts for approximately 70% of global freshwater withdrawals and remains the dominant consumer of blue and green water resources, improving agricultural water management is essential for reducing ecological pressure while maintaining food production [30].

Despite the continued degradation of its ecological resource base, Somalia illustrates the tension between economic development and ecological sustainability, with economic recovery remaining dependent on natural capital [4, 47]. Agriculture and livestock continue to underpin livelihoods, employment, and economic activity, which makes growth highly dependent on productive land, water availability, healthy rangelands, and favorable climatic conditions. However, recurrent droughts, prolonged conflict, land degradation, widespread deforestation, and weak environmental governance have substantially reduced ecosystem resilience and the regenerative capacity of natural resources [33, 47]. Reflecting these pressures, Somalia has remained in ecological deficit since the mid-1980s, as the country's ecological footprint persistently exceeds its available biocapacity [31]. Figure 1 illustrates the declining ecological balance over the study period. Moreover, forest resources have also declined considerably, with forest cover falling from approximately 13% to below 10% of total land area and an estimated 2.2 million hectares lost, largely because of unsustainable charcoal production and biomass extraction [33]. Unlike the industrialization-led urban transition experienced in many developing countries, urban expansion in Somalia has been driven largely by conflict- and drought-induced displacement [5]. Meanwhile, limited access to modern energy has sustained heavy dependence on fuelwood and charcoal [1].

Despite the growing body of research on environmental sustainability, several important gaps remain. Although the LCC hypothesis has been examined across a range of developed and emerging economies, empirical evidence remains geographically concentrated [18, 46, 48], with little evidence from climate-vulnerable countries such as Somalia. Moreover, existing environmental studies on Somalia have relied primarily on CO_2

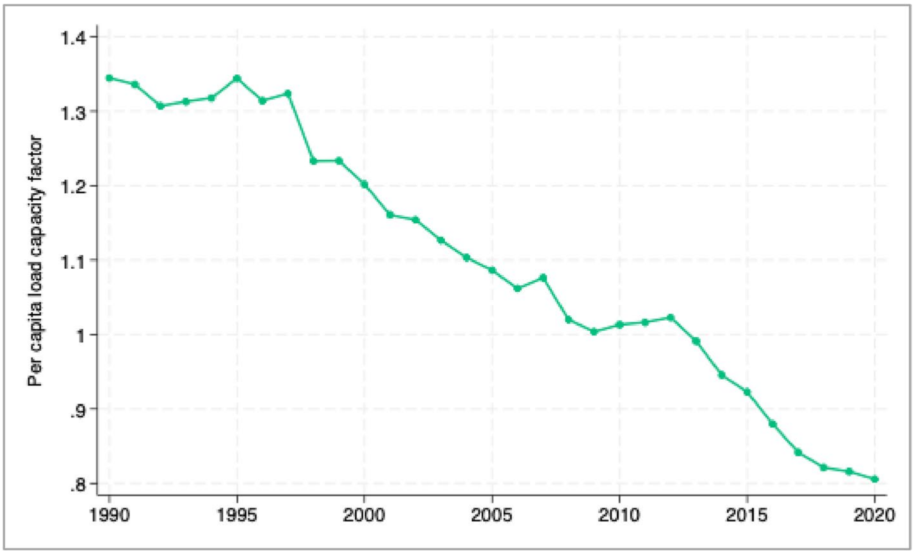

Fig. 1 Trends of per capita load capacity factor in Somalia (1990–2020)

emissions, ecological footprint, or deforestation as proxies for environmental quality [5, 31, 33]. A recent study has employed the LCF without examining the validity of the LCC hypothesis or the role of water use as a determinant of ecological sustainability [4]. Furthermore, little attention has been given to modelling ecological capacity while explicitly accounting for the gradual structural changes that characterize economies affected by prolonged political instability, climatic shocks, and post-conflict reconstruction. To address these gaps, this study investigates the determinants of LCF in Somalia by testing the LCC hypothesis while simultaneously examining the effects of energy consumption, gross fixed capital formation, urbanization, and agricultural water use within a unified empirical framework. Methodologically, the study applies the Fourier autoregressive distributed lag (FARDL) approach, complemented by Fourier unit-root and Fourier Granger causality analyses, to accommodate smooth structural changes and provide robust evidence on causal relationships among the variables. By extending the LCF literature to one of the world's most climate-vulnerable economies, this study provides new empirical evidence and policy insights for advancing environmental sustainability.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature, Sect. 3 describes the data and methodology, Sect. 4 presents and discusses the empirical findings, and Sect. 5 concludes with policy implications and recommendations.

2 Literature review

The relationship between economic growth and environmental quality has increasingly been examined through the LCC hypothesis, although empirical evidence remains inconclusive. Several studies support the hypothesis. Wu et al. [48] confirmed a U-shaped relationship between economic growth and the LCF across the E−7 economies. Similar evidence was reported by Duran and Saqib [14] for the G20 economies and by Caglar et al. [11], Kinnunen et al. [27], and Ridwan et al. [39] for Türkiye, Finland, and the United States, respectively. These studies suggest that the environmental costs of economic expansion can eventually be reversed as economies undergo technological progress, adopt cleaner energy systems, and strengthen environmental policies. However, several studies challenge the universality of the LCC hypothesis. Ergene et al. [18] found that economic growth persistently reduced the LCF in China, attributing this outcome to continued coal dependence and energy-intensive industrialization. Likewise, Xu et al. [49] reported that economic growth reduced the LCF in Brazil, while Pata et al. [34] rejected the LCC hypothesis for Portugal despite finding that renewable energy improved environmental sustainability. Uche [46] also rejected the hypothesis for South Africa under conventional ARDL estimation, although quantile analysis indicated that higher income levels may improve environmental sustainability under favorable ecological conditions. Evidence based on CO_2 emissions likewise indicates that the growth–environment relationship is heterogeneous. Tachega et al. [45] found that the Environmental Kuznets Curve was supported in some African income groups but not others.

Evidence on the environmental effects of capital formation remains limited for the LCF, with most studies relying on material footprints, ecological footprints, or CO_2 emissions. Conceptual evidence suggests that investment itself can generate substantial environmental pressure because capital goods embody large amounts of carbon and material use. Södersten et al. [42] indicated that capital formation accounts for a considerable share of global embodied carbon emissions, while Södersten et al. [43] demonstrated that conventional material-footprint measures substantially underestimate the environmental burden of capital goods by excluding the resources embodied in their production. Empirical findings, however, remain inconclusive. Idroes et al. [25] found that capital formation reduced CO_2 emissions across North African economies. Bekoe et al. [9] reported similar long-run evidence for Ghana, where newly installed capital initially increased emissions but reduced them over time as installed capital became more energy efficient. Sarfraz et al. [41] reported that capital formation intensified CO_2 emissions in the G7 economies. Similar inconsistencies emerge for urbanization. Using the LCF, Zhu et al. [52] found that urbanization reduced environmental sustainability across the E−7 economies, whereas Xu et al. [49] reported no significant long-run effect in Brazil. Likewise, Ridwan et al. [39] showed that rapid urbanization reduced the LCF across BIMSTEC countries by increasing pressure on natural resources and land use. Evidence based on the ecological footprint by Al-Mulali and Ozturk [6] indicates that urbanization significantly increased ecological pressure across MENA countries. Similarly, Hossain [24] showed that urbanization influenced CO_2 emissions differently across newly industrialized economies.

The environmental effects of energy consumption depend fundamentally on the composition of the energy mix. Evidence based on the LCF consistently reports that renewable energy enhances environmental sustainability. Apergis et al. [7] found that renewable energy increased the LCF in the United States, whereas non-renewable energy reduced both the LCF and ecological sustainability. Similar findings were reported by Hakkak et al. [21] for Russia, Bekun et al. [10] for the MINT economies, and Pata et al. [35] for the United States, where biomass energy significantly improved the LCF despite exhibiting no long-run relationship with CO_2 emissions or the ecological footprint. Likewise, Pata et al. [34] showed that renewable energy consumption and energy-related research and development strengthened the LCF in Portugal, although the study rejected the LCC hypothesis. By contrast, Pata and Balsalobre-Lorente [36] found that aggregate energy consumption reduced the LCF in Türkiye, attributing this outcome to the country's continued dependence on fossil fuels. Evidence based on CO_2 emissions reaches similar conclusions. Khan et al. [26], Nasreen et al. [32], and Ozturk and Acaravci [37] found that higher energy consumption significantly increased carbon emissions in Pakistan, South Asian economies, and Türkiye, respectively. Liu et al. [28], however, demonstrated that improvements in energy efficiency significantly reduced emissions in the United States by lowering the energy intensity of production.

Growing water demand, population expansion, and climate change have intensified pressure on freshwater resources. Hoekstra and Wiedmann [23] argued that water scarcity has become a global environmental constraint, with blue and grey water footprints already exceeding sustainable limits in many river basins. Empirical evidence likewise indicates that unsustainable water use contributes to environmental degradation. Hamed et al. [22] found that greater agricultural production and energy consumption increased CO_2 emissions across MENA countries, although improvements in crop water productivity did not produce statistically significant environmental gains. Similarly, Saidmamatov et al. [40] reported that water stress significantly increased CO_2 emissions in Central Asia. At the sectoral level, Zhang et al. [51] showed that agricultural water consumption expanded rapidly in China because of economic growth, increasing crop yields, and fertilizer use, while Chen et al. [12] found that excessive water resource consumption worsened environmental degradation in Ghana. Likewise, Dastranj et al. [13] demonstrated that integrated water-use optimization and emissions reduction substantially improved environmental carrying capacity under future climate scenarios. Evidence from the water–energy nexus further suggests that water conservation can generate significant environmental benefits. Zhang et al. [50] and Feng et al. [19] found that improving irrigation efficiency and optimizing water allocation reduced both water consumption and the carbon footprint of agricultural production. Similarly, Su et al. [44] demonstrated that integrated land and water allocation can simultaneously reduce agricultural water use and carbon emissions without compromising food security.

Despite the growing body of international evidence, empirical research on ecological capacity in Somalia remains scarce. Existing studies have primarily examined environmental degradation using CO_2 emissions, the ecological footprint, or deforestation, while only one recent study has employed the LCF as a comprehensive measure of environmental sustainability [4]. Mohamed et al. [31] confirmed the EKC hypothesis using the ecological footprint and showed that urbanization increases ecological pressure. Osman et al. [33] found that gross fixed capital formation mitigates deforestation, while economic and population growth accelerate forest loss. Likewise, Abdullahi and Ahmed [5] reported that urbanization remains a major driver of environmental degradation. More recently, Abdi et al. [4] provided one of the few LCF-based assessments for Somalia. However, this emerging literature has not examined whether the LCC hypothesis holds in Somalia, nor has it investigated the role of water use on environmental sustainability within an LCF framework. Accordingly, this study extends the existing literature by testing the LCC for Somalia while simultaneously evaluating the effects of these key macroeconomic and structural determinants on the LCF. In doing so, it provides new evidence for a country where LCF-based research remains limited despite increasing environmental pressures.

3 Methodology

3.1 Data and variables

The empirical analysis uses annual time-series data for Somalia covering the period 1990–2022. This sample period is determined by the common availability of all variables and represents the longest consistent time series for the empirical analysis. The LCF is employed as the proxy for ecological sustainability because it measures the balance between biocapacity and ecological footprint [4]. The explanatory variables include economic growth, energy consumption, agricultural water withdrawal, gross fixed capital formation, and urbanization. Their selection is informed by the environmental sustainability literature examining the effects of economic growth and the LCC hypothesis [36, 49], energy consumption [1], water use and stress [22, 40], domestic investment [9, 42], and urbanization [2, 39]. To examine the LCC hypothesis, the squared term of GDP per capita is included in the empirical model. As a robustness check, agricultural water withdrawal is replaced with water stress (SDG Indicator 6.4.2) to determine whether the estimated relationships are sensitive to alternative measures of water resource conditions. Annual data are obtained primarily from the World Development Indicators (WDI), the Global Footprint Network (GFN), the Food and Agriculture Organization (FAO), and Our World in Data (OWID). Table 1 reports the definitions, measurement units, and data sources for all variables.

3.2 Econometric approach and the model specification

The empirical analysis proceeds in several stages. First, the autoregressive distributed lag (ARDL) framework developed by Pesaran et al. [38] is employed to examine the long-run relationship between environmental sustainability, economic growth, energy consumption, agricultural water withdrawal, domestic investment, and urbanization. The ARDL approach is appropriate because it accommodates variables integrated of order I(0) and I(1), performs well in relatively small samples, and jointly estimates the short-run dynamics and long-run equilibrium relationship [31]. In addition, the optimal lag structure is determined using the Akaike Information Criterion (AIC).

Table 1 Variables, symbols, descriptions and sources

Variable	Code	Description	Source
Load capacity factor	LCF	BiocapPerCap/EFConsPerCap	GFN
Economic growth	GDPC	GDP per capita (constant 2015 US$)	WDI
Energy consumption	$GDPC^2$	Primary energy consumption per capita (kWh/person)	Our World in Data
Agricultural water usage	AW	Agricultural water withdrawal (% of total renewable water resources)	FAO
Water Stress	WS	SDG 6.4.2 Water Stress (%)	FAO
Capital formation	GCF	Gross capital formation (constant 2015 US$)	WDI
Urbanization	URB	Urban population (% of total population)	WDI

Following the empirical LCF literature that tests the LCC hypothesis, particularly Pata and Balsalobre-Lorente [36], Xu et al. [49], Wu et al. [48], Ergene et al. [18], and Kinnunen et al. [27], the empirical model is specified as follows:

$$LCF = \beta_0 + \beta_1 GDPC_t + \beta_2 GDPC_t^2 + \beta_3 EC_t + \beta_4 AW_t + \beta_5 GCF_t + \beta_6 URB_t + \beta_t \quad (1)$$

where LCF denotes the load capacity factor; $GDPC$ and $GDPC^2$ represent economic growth and its squared term, respectively; EC is energy consumption; AW denotes agricultural water withdrawal; GCF represents gross fixed capital formation; URB is urbanization; and ε_t is the stochastic error term. The coefficients $\beta_1 - \beta_6$ measure the long-run effects of the explanatory variables on environmental sustainability. To assess the robustness of the empirical findings, agricultural water withdrawal is replaced with water stress (WS) as an alternative measure of water resource conditions. To reduce scale differences among the variables and facilitate elasticity interpretation, all variables are transformed into their natural logarithms. The log-linear specification is therefore expressed as

$$lnLCF_t = \beta_0 + \beta_1 lnGDPC_t + \beta_2 lnGDPC^2{}_t + \beta_3 lnEC_t + \beta_4 lnAW_t + \beta_5 lnGCF_t + \beta_6 lnURB_t + \varepsilon_t \quad (2)$$

The ARDL bounds testing procedure is implemented using the following conditional error-correction specification:

$$\begin{aligned}
\Delta lnLCF_t &= \beta_0 + \beta_1 lnLCF_{t-1} + \beta_2 lnGDPC_{t-1} \\
&+ \beta_3 lnGDPC^2{}_{t-1} + \beta_4 lnEC_{t-1} + \beta_5 lnAW_{t-1} \\
&+ \beta_6 lnGCF_{t-1} + \beta_7 lnURB_{t-1} \\
&+ \sum_{i=1}^{p} \lambda_1 \Delta lnLCF_{t-i} + \sum_{i=1}^{q} \lambda_2 \Delta lnGDPC_{t-i} \\
&+ \sum_{i=1}^{q} \lambda_3 \Delta lnGDPC^2{}_{t-i} + \sum_{i=1}^{q} \lambda_4 \Delta lnEC_{t-i} \\
&+ \sum_{i=1}^{q} \lambda_5 \Delta lnAW_{t-i} + \sum_{i=1}^{q} \lambda_6 \Delta lnGCF_{t-i} + \sum_{i=1}^{q} \lambda_7 \Delta lnURB_{t-i} + \varepsilon_t
\end{aligned} \quad (3)$$

In Eq. (3), the coefficients associated with the lagged level variables represent the long-run relationship, whereas the differenced variables capture the short-run dynamics. The ARDL bounds test evaluates the null hypothesis of no cointegration against the alternative of a long-run equilibrium relationship. The calculated Wald F-statistic is compared with the corresponding lower and upper critical bounds. A value exceeding the upper bound confirms cointegration, whereas a value below the lower bound indicates the absence of a long-run relationship. Once cointegration is established, the corresponding error-correction model (ECM) is estimated to examine the short-run dynamics and the speed of adjustment toward the long-run equilibrium:

$$\Delta lnLCF_t = \beta_0 + \sum_{i=1}^{p} \lambda_1 \Delta lnLCF_{t-i} + \sum_{i=1}^{q} \lambda_2 \Delta lnGDPC_{t-i} + \sum_{i=1}^{q} \lambda_3 \Delta lnGDPC^2{}_{t-i} + \sum_{i=1}^{q} \lambda_4 \Delta lnEC_{t-i} + \sum_{i=1}^{q} \lambda_5 \Delta lnAW_{t-i} + \sum_{i=1}^{q} \lambda_6 \Delta lnGCF_{t-i} + \sum_{i=1}^{q} \lambda_7 \Delta lnURB_{t-i} + \rho ECT_{t-1} + \varepsilon_t \quad (4)$$

where ECT_{t-1} is the lagged error-correction term. A negative and statistically significant coefficient confirms convergence toward the long-run equilibrium.

Although the conventional ARDL framework accommodates mixed orders of integration and jointly estimates the short- and long-run relationships, it assumes parameter stability over the sample period. To account for gradual structural changes, this study employs the Fourier ARDL approach, which extends the ARDL model by incorporating low-frequency sine and cosine terms that approximate structural changes of unknown timing and form [16]. The Fourier approximation is expressed as

$$d(t) = \sum_{j=1}^{n} a_j \sin\left(\frac{2\pi jt}{T}\right) + \sum_{j=1}^{n} b_j \cos\left(\frac{2\pi jt}{T}\right) \quad (5)$$

Following Ludlow and Enders [15], a single frequency is adopted, yielding

$$d(t) = \gamma_1 \sin\left(\frac{2\pi jt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi jt}{T}\right) \quad (6)$$

The Fourier terms are incorporated into the ARDL framework as follows:

$$\Delta lnLCF_t = \beta_0 + \beta_1 lnLCF_{t-1} + \beta_2 lnGDPC_{t-1} + \beta_3 lnGDPC^2{}_{t-1} + \beta_4 lnEC_{t-1} + \beta_5 lnAW_{t-1} + \beta_6 lnGCF_{t-1} + \beta_7 lnURB_{t-1} \sum_{i=1}^{p} \lambda_1 \Delta lnLCF_{t-i} + \sum_{i=1}^{q} \lambda_2 \Delta lnGDPC_{t-i} + \sum_{i=1}^{q} \lambda_3 \Delta lnGDPC^2{}_{t-i} + \sum_{i=1}^{q} \lambda_4 \Delta lnEC_{t-i} + \sum_{i=1}^{q} \lambda_5 \Delta lnAW_{t-i} + \sum_{i=1}^{q} \lambda_6 \Delta lnGCF_{t-i} + \sum_{i=1}^{q} \lambda_7 \Delta lnURB_{t-i} + \gamma_1 \sin\left(\frac{2\pi jt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi jt}{T}\right) + \varepsilon_t \quad (7)$$

Stationarity is examined using the Fourier Augmented Dickey–Fuller (Fourier-ADF) test of Enders and Lee [16], which accounts for smooth structural changes. The test is specified as.

$$\Delta Y_t = \alpha_0 + \alpha_1 t + \gamma_1 \sin\left(\frac{2\pi jt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi jt}{T}\right) + \delta \gamma_{t-1} + \sum_{i=1}^{p} \phi \Delta Y_{t-1} + \varepsilon_t \quad (8)$$

Finally, the cumulative Fourier-frequency Granger causality test of Enders and Jones [17] is employed to examine the direction of causality while accounting for smooth structural changes. The test is specified as

$$Y_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i Y_{t-i} + \sum_{i=1}^{q} \beta_i X_{t-i} + \sum_{j=1}^{k^*} \left[\gamma_{1j} \sin\left(\frac{2\pi jt}{T}\right) + \gamma_{2j} \cos\left(\frac{2\pi jt}{T}\right)\right] + \varepsilon_t \quad (9)$$

Table 2 Descriptive statistics and pairwise correlations

	lnLCF	lnGDPC	lnGDPC^2	lnEC	lnAW	lnWS	lnGCF	lnURB
Panel A: Summary statistics								
Mean	0.048	5.743	33.068	1.196	2.978	3.073	19.987	15.202
Maximum	0.299	6.228	38.782	1.857	3.105	3.200	21.367	16.069
Minimum	− 0.309	5.349	28.614	0.812	2.226	2.330	19.336	14.484
Std. Dev	0.192	0.295	3.412	0.282	0.244	0.242	0.596	0.493
Kurtosis	1.932	1.695	1.711	2.923	5.219	5.184	2.579	1.882
Probability	0.334	0.229	0.217	0.305	0.000	0.000	0.093	0.382
Observations	33	33	33	33	33	33	33	33
Panel B: Correlation analysis								
lnLCF	1.000							
lnGDPC	− 0.934							
lnGDPC^2	− 0.935	1.000	1.000					
lnEC	− 0.875	0.798	0.798	1.000				
lnAW	− 0.647	0.418	0.418	0.428	1.000			
lnWS	− 0.649	0.420	0.420	0.430		1.000		
lnGCF	− 0.933	0.947	0.949	0.889	0.357	0.359	1.000	
lnURB	− 0.994	0.915	0.916	0.871	0.693	0.695	0.910	1.000

Table 3 Fourier-ADF and Fourier-LM unit-root test results

Variable	Fourier-ADF Statistic	Sig	Fourier-ADF Status	Fourier-LM Statistic	Sig	Fourier-LM Status
lnLCF	− 3.717	10%	I(1)	2.674	Not significant	I(1)
lnGDPC	− 5.353	1%	I(0)	− 3.294	Not significant	I(1)
lnGDPC^2	− 7.458	1%	I(0)	− 3.228	Not significant	I(1)
lnAW	− 5.302	1%	I(0)	− 5.836	1%	I(0)
lnWS	− 5.304	1%	I(0)	− 5.837	1%	I(0)
lnGFCF	− 2.491	Not significant	I(1)	− 1.646	Not significant	I(1)
lnURB	− 4.569	5%	I(0)	0.753	Not significant	I(1)
lnEC	− 5.504	1%	I(0)	− 1.927	Not significant	I(1)

$$X_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{i=1}^{q} \beta_i Y_{t-i} + \sum_{j=1}^{k^*} \left[\gamma_{1j} \sin\left(\frac{2\pi jt}{T}\right) + \gamma_{2j} \cos\left(\frac{2\pi jt}{T}\right) \right] + \varepsilon_t \tag{10}$$

where k^* denotes the optimal cumulative Fourier frequency jointly selected with the lag order using the AIC. Significant lagged coefficients indicate the existence of Granger causality.

4 Results and discussion

4.1 Descriptive statistics and correlation analysis

Table 2 reports the descriptive statistics for all variables included in the analysis. The LCF has a mean value of 0.048 and ranges from − 0.309 to 0.299, which reveals substantial fluctuations in Somalia's ecological balance over the study period. Gross fixed capital formation exhibits the largest dispersion among the explanatory variables, consistent with the pronounced variation in domestic investment during the country's economic transition. By comparison, both water-use indicators vary more gradually over time, while economic growth, energy consumption, and urbanization display sufficient variability to capture long-run structural changes. The Jarque–Bera statistics indicate that most variables satisfy the normality assumption, whereas the two water-use indicators depart from normality because of their relatively high kurtosis. This does not pose an econometric concern because the Fourier ARDL approach does not require the explanatory variables to be normally distributed.

Table 2 also presents the pairwise correlation coefficients among the variables. The LCF is negatively correlated with economic growth, squared economic growth, energy consumption, urbanization, gross fixed capital formation, and both measures of water use. The strongest association is observed for urbanization, followed by economic growth and domestic investment. These unconditional correlations reveal that periods characterized by faster economic expansion, increasing urbanization, higher investment, greater energy demand, and intensified water withdrawals have generally coincided with lower ecological capacity in Somalia. The explanatory variables are also positively correlated with one another, which is expected given the simultaneous evolution of economic growth, investment, urban development, and resource use during the reconstruction period. Since these coefficients only describe bivariate linear relationships, they should not be interpreted as evidence of causality. The magnitude, direction, and persistence of these relationships are therefore examined more rigorously in the subsequent econometric analysis.

4.2 Unit-root and cointegration analysis

Table 3 reports the results of the Fourier-ADF and Fourier-LM unit-root tests, both of which accommodate smooth structural shifts without requiring the timing or form of structural changes to be specified a priori. This feature is particularly appropriate for Somalia, where prolonged conflict and recurrent economic disruptions may generate gradual rather than abrupt changes in macroeconomic time series. The Fourier-ADF test indicates that economic growth, squared economic growth, both water-use indicators, urbanization, and energy consumption are stationary at levels, whereas the LCF and gross fixed capital formation become stationary only after first differencing. Similarly, the Fourier-LM test identifies both water-use indicators as level stationary and classifies the LCF together with urbanization as integrated of order one. Although the Fourier-LM statistics for economic growth, squared economic growth, gross fixed capital formation, and energy consumption do not provide conclusive evidence of level stationarity, neither test identifies any variable as integrated beyond the first order. Thus, the combined evidence confirms that the variables exhibit a mixture of I(0) and I(1) processes,

Table 4 Fourier ARDL bounds tests for cointegration

Model	*F*-statistic	*k*	10% level		5% level		1% level		Decision
			I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
Model I (lnAW)	6.927	6	2.3	3.3	2.6	3.6	3.3	4.4	Cointegrated
Model II (lnWS)	6.897	6	2.3	3.3	2.6	3.6	3.3	4.4	Cointegrated

Table 5 Conventional ARDL benchmark estimates

Model	$\Delta lnLCF_t$	Coeff	Std. Error	t-stat	95% Confidence Interval	
ECT	$lnLCF_{t-1}$	− 1.275***	0.337	− 3.79	− 1.982	− 0.568
Long-run estimates	lnGDPC	− 3.198***	1.104	− 2.90	− 5.517	− 0.880
	$lnGDPC^2$	0.282**	0.101	2.8	0.07	0.494
	lnEC	− 0.111*	0.054	− 2.05	− 0.225	0.003
	lnAW	− 0.003	0.056	− 0.06	− 0.121	0.114
	lnGCF	− 0.015	0.041	− 0.36	− 0.100	0.07
	lnURB	− 0.868***	0.232	− 3.74	− 1.356	− 0.380
Short-run dynamics	$\Delta lnLCF_{t-1}$	0.468	0.29	1.61	− 0.142	1.078
	$\Delta lnLCF_{t-2}$	0.541**	0.244	2.21	0.028	1.055
	$\Delta lnGDPC_t$	− 4.078*	2.052	− 1.99	− 8.389	0.233
	$\Delta lnGDPC^2_t$	0.360*	0.184	1.95	− 0.028	0.747
	$\Delta lnEC_t$	0.08	0.067	1.19	− 0.061	0.222
	$\Delta lnAW_t$	− 0.004	0.071	− 0.06	− 0.153	0.145
	$\Delta lnGCF_t$	− 0.019	0.05	− 0.37	− 0.125	0.087
	$\Delta lnURB_t$	− 2.662**	0.949	− 2.81	− 4.655	− 0.669
	Constant	16.195**	6.934	2.34	1.628	30.763
Diagnostics	R^2	0.659	Breusch–Godfrey LM (F)		2.940 (0.0805)	
	Adjusted R^2	0.450	Heteroskedasticity (χ^2)		30.000 (0.4140)	
	Root MSE	0.0161	Skewness (χ^2)		15.680 (0.4036)	
			Kurtosis (χ^2)		0.050 (0.8285)	
			IM (χ^2)		45.730 (0.4417)	

which satisfies the integration requirements of the Fourier ARDL approach and justifies its application.

Table 4 presents the results of the Fourier ARDL bounds test for cointegration. The estimated F-statistic of 6.927 in the baseline specification exceeds the upper-bound critical values at the 10%, 5%, and 1% significance levels, leading to the rejection of the null hypothesis of no long-run relationship. This finding confirms the existence of a stable equilibrium relationship between the LCF and its determinants, namely economic growth, agricultural water use, urbanization, energy consumption, and gross fixed capital formation. To verify that this conclusion is not driven by the choice of water-use proxy, the model was re-estimated using the alternative water-stress indicator while maintaining the same specification. The corresponding F-statistic of 6.897 likewise exceeds the upper-bound critical value at the 1% significance level, yielding the same inference. The close agreement between the two specifications demonstrates that the evidence of cointegration is insensitive to the measurement of water use, which provides a robust basis for estimating the long-run coefficients and the associated short-run error-correction dynamics.

4.3 ARDL estimation

Before accounting for smooth structural changes through the Fourier ARDL framework, a conventional ARDL model was estimated to provide a benchmark for comparison. As reported in Table 5, the ECT is negative and highly significant, which confirms the existence of a stable long-run equilibrium relationship among the variables. The magnitude

Table 6 Fourier ARDL long-run and short-run estimates

Variable	Model I: Main	Model II: Robustness
Long-run elasticities		
lnGDPC	− 2.637488**	− 2.680675**
	(1.130560)	(1.137163)
$lnGDPC^2$	0.210136*	0.213966*
	(0.098910)	(0.099419)
lnEC	− 0.238514*	− 0.234626*
	(0.128902)	(0.127955)
lnLnAW	− 0.210151**	
	(0.093970)	
lnWS		− 0.210031*
		(0.094668)
lnGCF	0.032682	0.032847
	(0.056578)	(0.056927)
lnURB	− 0.609643***	− 0.618789***
	(0.178889)	(0.179089)
Short-run dynamics		
ΔlnGDPC	− 0.489124	− 0.521184
	(0.800261)	(0.801716)
$\Delta lnGDPC_{t-1}$	2.917498***	2.916936***
	(0.888652)	(0.889943)
$\Delta lnGDPC^2$	0.028767	0.031665
	(0.071349)	(0.071476)
$\Delta lnGDPC^2_{t-1}$	− 0.261660***	− 0.261515***
	(0.079137)	(0.079251)
ΔlnEC	0.041414	0.042124
	(0.034911)	(0.034981)
$\Delta lnEC_{t-1}$	0.112907***	0.111094***
	(0.029088)	(0.029066)
ΔlnAW	− 1.378432***	
	(0.280464)	
ΔlnWS		− 1.389942***
		(0.285647)
$\Delta lnAW_{t-1}$	− 0.520946***	
	(0.180114)	
$\Delta lnWS_{t-1}$		− 0.535119***
		(0.184367)
ΔlnGCF	− 0.083179**	− 0.082244**
	(0.029165)	(0.029211)
ΔlnURB	− 1.677495***	− 1.676372***
	(0.206878)	(0.207127)
COS	0.013428***	0.013157***
	(0.003272)	(0.003261)
SIN	0.002616	0.002571
	(0.003401)	(0.003403)
ECT_{t-1}	−1.449972***	−1.447777***
	(0.149386)	(0.149477)
Constant	25.38362***	25.73259***
	(2.615096)	(2.656684)
Adjusted R^2	0.821	0.820

standard error are in parenthesis. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively of the adjustment coefficient indicates that deviations from the long-run equilibrium are corrected rapidly, with some overshooting during the adjustment process.

Under the ARDL specification, the long-run coefficients suggest that economic growth initially weakens the LCF, while the positive squared-income term points to a possible U-shaped relationship. This pattern offers an initial indication in favour of the LCC hypothesis, although stronger inference is explored for the Fourier specification, which explicitly accommodates smooth structural change. Energy consumption and urbanization are also negatively associated with the LCF, whereas agricultural water withdrawal and capital formation are statistically insignificant. In the short-run, the income terms and urbanization remain significant, while energy consumption, water use, and capital formation do not. The significant second lag of the dependent variable further indicates persistence in short-run ecological adjustment.

The diagnostic tests indicate that the ARDL model is econometrically adequate, with no evidence of serial correlation, heteroskedasticity, or residual misspecification. Nevertheless, because the conventional ARDL model assumes parameter stability over time, it may not adequately capture the gradual structural changes associated with the prolonged political instability, economic reconstruction, and recurrent climate shocks in Somalia. The Fourier ARDL model addresses this limitation by explicitly incorporating smooth structural shifts.

4.4 Fourier ARDL estimation

Table 6 reports the long-run and short-run estimates obtained from the Fourier ARDL model. Model I uses agricultural water withdrawal as the primary measure of water use, whereas Model II replaces it with the SDG 6.4.2 water-stress indicator to assess the robustness of the estimated relationships. The close correspondence between the two specifications indicates that the estimated long-run elasticities and short-run dynamics are insensitive to the choice of water-use measure. Consequently, the discussion focuses on the underlying economic and environmental mechanisms rather than the differences between the two models, which are minimal. In both specifications, the cosine term is positive and statistically significant, whereas the sine term is statistically insignificant. The significance of the cosine component indicates the presence of smooth structural changes and nonlinear deterministic shifts over the sample period.

The Fourier ARDL estimates indicate a nonlinear long-run relationship between economic growth and ecological sustainability in Somalia. The negative coefficient on income and the positive coefficient on its squared term support the LCC hypothesis. This suggests that economic growth is associated with a decline in the LCF at lower income levels, while this adverse association weakens as income increases. Importantly, the coefficient on the linear income term should not be interpreted independently as a constant elasticity because the ecological effect of economic growth is jointly determined by the linear and quadratic income terms. In the main model, the estimated coefficients for the linear and quadratic income terms are − 2.637 and 0.210, respectively, while the robustness model produces highly comparable estimates of − 2.681 and 0.214. The negative linear coefficient and positive quadratic coefficient indicate that the adverse association between economic growth and the LCF gradually weakens as income increases, consistent with the nonlinear LCC hypothesis. In the short-run, the contemporaneous changes in income and its squared term are statistically insignificant, whereas their lagged changes are both highly significant with opposite signs.

These findings are consistent with Somalia remaining at a relatively early stage of economic development, where expanding production, infrastructure development, energy demand, and resource utilization may exert greater pressure on ecological resources than the environmental benefits associated with technological progress and improved resource efficiency. Although the positive quadratic term suggests that the adverse association weakens as income rises, the estimated relationship indicates that this transition has not yet become evident during the study period. This interpretation is consistent with post-conflict economic recovery in Somalia, characterized by expanding construction, transport, livestock production, and trade alongside continued reliance on imported fossil fuels, limited renewable-energy deployment, and relatively weak environmental governance. The findings align with studies supporting the LCC hypothesis in the E−7 economies [48], Türkiye [11], Finland [27], and the G20 economies [14], all of which report that the adverse environmental association of economic growth weakens as economies advance through technological progress, renewable-energy adoption, and stronger environmental institutions. However, the findings contrast with those reported for China [18] and South Africa [46], where the LCC hypothesis was not supported.

The long-run estimates indicate that energy consumption is negatively associated with LCF in Somalia, which suggests that greater energy use coincides with lower ecological sustainability over time. This relationship is plausible given the structure of the country's energy sector, where electricity generation is largely supplied by imported diesel generators, while household energy demand continues to rely heavily on charcoal and fuelwood. Such an energy profile is generally associated with greater ecological pressure through increased dependence on fossil fuels and continued exploitation of forest resources. In contrast, the short-run estimates reveal no significant contemporaneous effect of changes in energy consumption on the LCF, although the lagged change exhibits a positive and statistically significant association. This pattern suggests that the environmental consequences of changes in energy use may not materialize immediately and could reflect short-term adjustment processes, seasonal fluctuations, or delayed responses in production and resource utilization before the longer-run ecological costs become apparent. The long-run findings align with Pata and Balsalobre-Lorente [36], Xu et al. [49], and Abdi and Hashi [1], who likewise reported that conventional energy consumption is associated with lower environmental sustainability. However, other studies, such as Apergis et al. [7], Hakkak et al. [21], Abdi et al. [3], and Bekun et al. [10], found that renewable energy improves the LCF. A plausible explanation for these differences is the composition of national energy systems. Nevertheless, Somalia remains heavily dependent on fossil fuels and traditional biomass.

Notably, the long-run estimates indicate that agricultural water withdrawal (Model I) and water stress (Model II) are both negatively associated with LCF in Somalia. This suggests that increasing pressure on freshwater resources coincides with lower ecological sustainability. The short-run estimates reinforce this finding, as contemporaneous and lagged changes in agricultural water withdrawal and water stress exert significant negative effects on the LCF. These results suggest that increasing pressure on freshwater resources is associated with both immediate and persistent reductions in ecological sustainability. This relationship is plausible in Somalia, where recurrent droughts, highly variable rainfall, limited water-storage and irrigation infrastructure, and a heavy dependence on rain-fed agriculture increase the vulnerability of ecosystems to water scarcity. Greater agricultural water withdrawal may intensify pressure on already scarce freshwater resources, while rising water stress reflects growing competition among agricultural, domestic, and ecological water demands. Consequently, increasing pressure on water resources is likely to reduce ecological carrying capacity and intensify environmental stress. These findings are comparable to those of Saidmamatov et al. [40] and Chen et al. [12], who found that increasing water stress was associated with greater environmental degradation. They indicated the role of water management in this relationship. Moreover, Zhang et al. [51] reported that intensive agricultural water use contributed to rising water pressure. These results imply that the environmental consequences of water use depend not only on water availability but also on the efficiency of water management, institutional capacity, and climatic conditions. In Somalia, where freshwater resources are naturally scarce and water-management infrastructure remains underdeveloped.

Gross fixed capital formation does not exhibit a discernible long-run relationship with ecological sustainability in Somalia during the study period. However, the short-run estimates reveal a significant negative association, which indicates that increases in investment are accompanied by a temporary decline in the LCF. This short-run pattern is plausible because capital formation in Somalia is largely concentrated in infrastructure development, construction, transport, and other resource-intensive activities that initially require substantial material and energy inputs. Over time, however, these effects may diminish as investments become operational, which may explain the absence of a significant long-run relationship. The insignificant long-run coefficient differs from Osman et al. [33], who found that capital formation reduced deforestation in Somalia, and Idroes et al. [25], who reported that capital formation improved environmental quality in North African economies. The short-run finding is in contrast to Bekoe et al. [9], who reported that domestic investment improves environmental quality. It also contrasts with Sarfraz et al. [41] and Liu et al. [29], who found that capital formation increased environmental degradation in the long-run. These mixed findings suggest that the environmental implications of capital formation depend not only on the scale

Table 7 Post-estimation diagnostic tests

Test type	Main model	Robustness model
Serial correlation—LM Test	2.7980	2.7925
	(0.1199)	(0.1203)
Heteroskedasticity Test	12.165	12.064
	(0.9103)	(0.9138)
Normality Test	0.9133	0.9870
	(0.6334)	(0.6104)
CUSUM test	Stable	Stable
CUSUM of Square	Stable	Stable
Ramsey RESET Test	0.4182	0.4105
	(0.5339)	(0.5377)

p-values are reported in parentheses

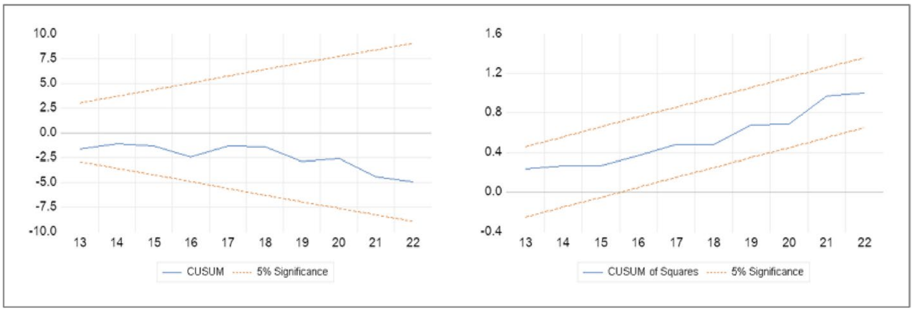

Fig. 2 Model I

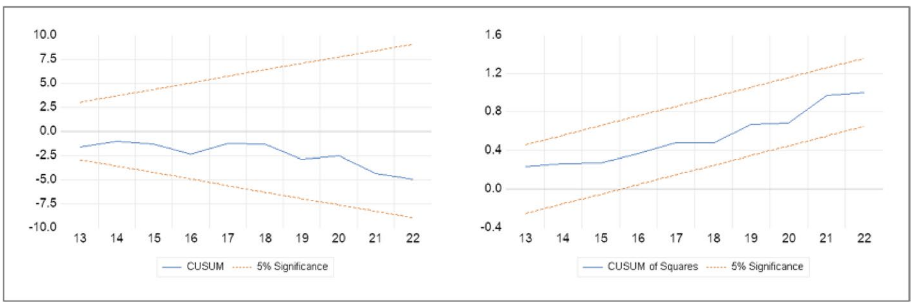

Fig. 3 Model II

Table 8 Cumulative Fourier Granger-causality results

Tested Direction	Test Statistic	P-value	Direction of Causality
lnGDPC → lnLCF	16.691	0.000	1%
lnLCF → lnGDPC	0.001	0.978	Not signif
$\ln GDPC^2$ → lnLCF	17.832	0.000	1%
lnLCF → $\ln GDPC^2$	0.000	0.991	Not signif
lnEC → lnLCF	4.685	0.060	10%
lnLCF → lnEC	37.529	0.000	1%
lnAW → lnLCF	39.957	0.000	1%
lnLCF → lnAW	150.739	0.000	1%
lnWS → lnLCF	39.957	0.000	1%
lnLCF → lnWS	150.588	0.000	1%
lnGCF → lnLCF	54.271	0.000	1%
lnLCF → lnGCF	8.766	0.009	1%
lnURB → lnLCF	0.03	0.861	Not signif
lnLCF → lnURB	2.232	0.159	Not signif

of investment but also on its composition, technological characteristics, and the stage at which its effects are evaluated.

The long-run estimates also indicate that urbanization is negatively associated with LCF in Somalia, which suggests that increasing urban expansion coincides with lower ecological sustainability. The short-run estimates reinforce this finding, revealing a larger and statistically significant negative association between changes in urbanization and the LCF. This relationship is plausible in the Somali context, where rapid urban expansion has largely occurred in the absence of adequate urban planning, environmental regulation, and supporting infrastructure. Population displacement, post-conflict reconstruction, and the concentration of economic activities in urban centers have increased demand for housing, transport, energy, water, and other natural resources, while waste management and sanitation systems have remained relatively underdeveloped. Consequently, urban growth is likely to coincide with greater pressure on ecological resources and a decline in ecological sustainability. These findings are broadly consistent with previous evidence showing that rapid urbanization tends to reduce ecological sustainability by increasing pressure on natural resources and land use [6, 52]. They also align with recent evidence from Somalia, where urbanization has been identified as an important driver of environmental degradation [2, 5, 31]. However, the results differ from Xu et al. [49], who found no significant long-run relationship between urbanization and the LCF in Brazil. These differences likely reflect variations in urban development patterns, institutional capacity, and infrastructure provision.

Table 7 presents the diagnostic test results for the estimated Fourier ARDL models, while Figs. 2 and 3 display the CUSUM and CUSUM of Squares (CUSUMSQ) stability tests, respectively. The Breusch–Godfrey LM test indicates no evidence of serial correlation, while the heteroskedasticity test confirms that the residuals are homoscedastic. The Jarque–Bera test suggests that the residuals are normally distributed, and the Ramsey RESET test provides no evidence of functional-form misspecification. As shown in Figs. 2 and 3, the CUSUM and CUSUMSQ statistics remain within the 5% critical bounds throughout the sample period, which confirms the stability of the estimated coefficients and the absence of structural instability. The diagnostic statistics are highly comparable across the main and robustness specifications.

4.5 Fourier Granger causality analysis

Table 8 reports the results of the cumulative Fourier Granger causality test, which extends the conventional Granger causality framework by incorporating Fourier terms to account for smooth structural changes [17]. The results indicate a unidirectional causal relationship running from economic growth and its squared term to the LCF, while no evidence is found for reverse causality. This finding suggests that changes in income provide useful predictive information for future ecological sustainability. Therefore, the causality results complement the Fourier ARDL estimates by reinforcing the role of economic growth as an important determinant of ecological sustainability in Somalia. In contrast, no causal relationship is detected between urbanization and the LCF in either direction, which implies that although urbanization exhibits a significant long-run association with ecological sustainability, it does not possess additional predictive power within the Granger-causality framework.

The results further reveal bidirectional causality between the LCF and both measures of water-use pressure, namely agricultural water withdrawal and water stress, indicating a dynamic feedback relationship in which changes in freshwater pressure and ecological sustainability mutually influence one another over time. Similarly, bidirectional causality is observed between capital formation and the LCF. Energy consumption also exhibits feedback with ecological sustainability, although the causal relationship from energy consumption to the LCF is statistically weaker (10% significance level) than the reverse direction. These findings are broadly consistent with Bekoe et al. [9] and Sarfraz et al. [41], who reported feedback relationships between investment and environmental quality, as well as Hamed et al. [22] and Saidmamatov et al. [40], who documented dynamic interactions between water-resource variables and environmental outcomes.

5 Conclusion and policy recommendations

As Somalia continues to pursue economic recovery amid persistent environmental and climate-related challenges, understanding the factors that influence ecological sustainability is increasingly important. This study contributes to the emerging LCF literature by providing one of the first comprehensive assessments of the LCC hypothesis in Somalia over the period 1990–2022, while explicitly incorporating water-resource pressure into the analytical framework. By employing the Fourier ARDL and Fourier Granger causality approaches, the study accounts for the gradual structural changes associated with conflict, economic reconstruction, and climate variability, which provides more reliable evidence than conventional linear time-series models. The use of alternative water-use indicators further strengthens the robustness of the empirical findings and demonstrates the importance of considering different dimensions of freshwater pressure when evaluating ecological sustainability. Notably, this study extends the empirical literature on the determinants of ecological sustainability by exploring the interconnected roles of economic development, resource use, energy systems, investment, and urban transformation in influencing ecological capacity in climate-vulnerable economies.

In light of the findings, several policy recommendations emerge. First, Somalia's economic recovery should integrate environmental safeguards through stronger land-use planning, environmental regulation, and resource-efficient production to decouple economic growth from ecological degradation. Second, the energy transition should reduce dependence on diesel and traditional biomass by expanding solar and wind energy and improving the regulation of private electricity providers. Third, sustainable urban planning should prioritize waste management, water and sanitation services, and institutional capacity to manage rapid urban expansion. Fourth, integrated water resources management should strengthen rainwater harvesting, efficient irrigation, groundwater monitoring, and watershed restoration to reduce water stress. Fifth, investment policies should prioritize renewable energy, climate-resilient agriculture, sustainable water infrastructure, and environmentally efficient technologies rather than simply increasing investment. Finally, the bidirectional relationships among ecological sustainability, water use, energy consumption, and investment suggest that these sectors should be addressed through coordinated policy frameworks rather than isolated interventions.

While this study provides important evidence on the determinants of ecological sustainability in Somalia, several limitations should be acknowledged. First, the analysis is constrained by data availability, limiting the inclusion of potentially important environmental, institutional, and climatic factors. Second, the use of annual data may obscure short-term and seasonal variations in water use, energy consumption, and ecological conditions. Third, the relatively small sample, combined with multiple explanatory variables, lagged terms, and Fourier components, reduces the available degrees of freedom and increases the sensitivity of the estimates to model specification and lag selection. Fourth, the aggregate water-use indicators do not capture spatial heterogeneity in groundwater depletion, irrigation efficiency, or competing water demands across regions and sectors. Finally, although the Fourier ARDL approach effectively models gradual structural change, it is less suited to capturing abrupt shocks arising from armed conflict, severe droughts, population displacement, or sudden policy interventions. Future research should exploit higher-frequency and spatially disaggregated data, incorporate broader institutional and environmental indicators, and employ complementary nonlinear or identification-based approaches to better capture structural shifts and strengthen the robustness of empirical evidence.

Acknowledgements
The authors would like to express their sincere appreciation to SIMAD University, Somalia, for providing the institutional support necessary to conduct this research.

Author contributions
A.H.A. conceptualized and designed the study, developed the methodological framework, conducted the empirical analysis, and drafted the manuscript. A.A.M. contributed to the literature review, data compilation, and refinement of the empirical analysis. A.M.H. contributed to drafting the introduction and assisted in structuring and interpreting the results. All authors read and approved the final manuscript.

Funding
This research was supported by SIMAD University, Somalia.

Data availability
The raw data underlying the findings of this study are available from the corresponding author, Abdikafi Hassan Abdi, upon reasonable request. Requests for data access may be directed to the corresponding author at abdikafihasan79@gmail.com.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 28 May 2026 Accepted: 10 September 2026
Published online: 15 September 2026

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