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Education for sustainable development in Somalia: do economic growth, energy consumption, and population density affect ecological footprints?

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Received: 6 December 2024 / Accepted: 14 March 2025
Published online: 16 April 2025

Abstract
Somalia faces severe environmental challenges, including overdependence on nonrenewable energy, deforestation, and rapid population growth, exacerbated by poor governance and weak institutional capacity. As one of the most climate-vulnerable nations, Somalia's environmental sustainability is crucial for its long-term economic and social stability. Given this background, this study examines the dynamic impact of economic growth, energy consumption, education, and population density on Somalia's ecological footprint using annual data from 1990 to 2020. Employing ARDL and DOLS models, the findings confirm a long-run cointegration relationship among the scrutinized variables. The results indicate that energy consumption significantly increases ecological pressures. In contrast, education mitigates environmental impacts. Additionally, population density is found to intensify ecological stress in both the short and long run. Unlike many countries, Somalia does not exhibit the Environmental Kuznets Curve hypothesis, highlighting the urgent need for targeted policy interventions. By considering these outcomes, this study proposes adopting renewable energy, integrating environmental education, and implementing sustainable urban and economic strategies to alleviate ecological pressures and ensure long-term environmental sustainability. Moreover, the findings provide critical insights for policymakers in Somalia and other developing economies facing similar environmental challenges.

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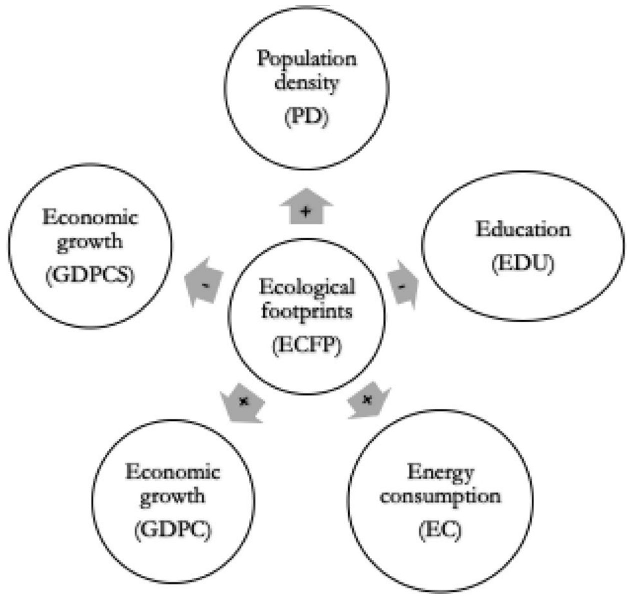
Graphical abstract



Keywords Ecological footprint · Education · Economic growth · Energy consumption · Population density · Sustainable development

Abbreviations

SDGs	Sustainable Development Goals
UN	United Nations
GFN	Global Footprint Network
PP	Phillips–Perron
ADF	Augmented Dickey–Fuller
ARDL	Autoregressive distributed lag
EKC	Environmental Kuznets Curve
ICRG	International Country Risk Guide
ECF	Ecological footprint
DOLS	Dynamic ordinary least squares

1 Introduction

Every country faces the challenge of balancing economic growth and environmental protection [1–4]. Many economic models have traditionally emphasized rapid growth, often ignoring long-term environmental costs such as habitat loss and climate change [5]. The ecological footprint, a gauge of how human activities—from agriculture to building infrastructure—affect the environment, provides a clear alert that we are depleting resources far quicker than the Earth can regenerate [6]. According to current estimates, we consume approximately 1.75 times more than the planet can sustainably provide, which implies that our demand for resources exceeds the Earth's capacity to recover [6]. The strain on natural systems only increases as cities and industries grow. Urbanization, industrial growth, and increased energy consumption are necessary for development but also strain the planet's limited resources [7, 8].

There is a growing global recognition of the importance of clean air, water, and ecosystems, as these are more than just environmental concerns; they also affect our quality of life and health. Addressing these challenges is critical not only for slowing climate change but also for promoting global well-being and meeting the Sustainable Development Goals that nations worldwide strive to achieve [9]. Today's environmental economics literature examines factors driving ecological decline, such as sectoral, social, political, and macroeconomic influences. Although economic growth fosters development, it often places significant stress on natural resources and ecosystems, creating a challenging gap between growth and sustainability goals [1, 10]. To lessen environmental damage and foster sustainability, countries have begun implementing emission reduction, renewable energy adoption, and regulatory frameworks [11]. These efforts reflect a global recognition of the importance of striking a balance between economic goals and preserving environmental quality for future generations.

Overgrazing and cutting trees for charcoal production are the mainstays in the depletion of natural resources. Apart from causing soil erosion and loss of vegetation, these directly lead to a quickening of the degradation process, which makes the environment even more vulnerable [12]. As a result, contamination of the environment appears as a key concern, which increases Somalia's vulnerability to climate change by reducing the country's ability to respond effectively to altered ecological conditions [13]. Figure 1 illustrates Somalia's change from having a solid ecological reserve to plunging the country into an ecological deficit from 1961 to 2022. In the earlier years, the biocapacity of Somalia, as represented by the green line, was considerably higher compared to the ecological footprint, represented by the red line. The difference between this means the natural environment of Somalia was more than adequate to supply the needs of its population for resources and the absorbing waste produced, thus creating a substantial ecological reserve. Over time, however, both biocapacity and ecological footprint started to decline, with biocapacity–the resources available–decreasing more steeply than the ecological footprint, the resources used. The ecological footprint has exceeded biocapacity since about 2014, which resulted in an ecological deficit. Since then, Somalia has used more resources than the environment can replenish, which reflects a trend of increasing overexploitation and stress on the environment. This trend illustrates Somalia's possible challenges in pursuing sustainability and pressures on its natural resources.

Human capital encapsulates the accumulation of competencies and knowledge acquired through education, contributing to enhanced productivity. It reflects both the duration of formal schooling and the potential economic and social benefits derived from education [14, 15]. Though there are a relatively limited number of studies on human capital and its relationship to environmental impact, education does seem to influence environmental awareness and behaviours in a variety of ways [16]. For instance, education expands one's opportunities for acquiring multiple sources of information that may ease the perceptions that citizens develop about complex environmental problems and may, therefore, increase the likelihood of embracing renewable energy solutions [16, 17]. People with higher education and income levels are also more engaged in recycling activities compared to their lower-educated or lower-income peers [18]. Moreover, education fosters a deeper understanding of sustainable practices, encouraging individuals to adopt environmentally responsible behaviours in both personal and professional spheres [19]. Improper waste management due to lack of awareness can lead to serious environmental issues, including water contamination and pollution.

As population density increases, so does the demand for essential resources like food, water, shelter, and energy. This heightened demand places significant pressure on already scarce resources. Higher population density often

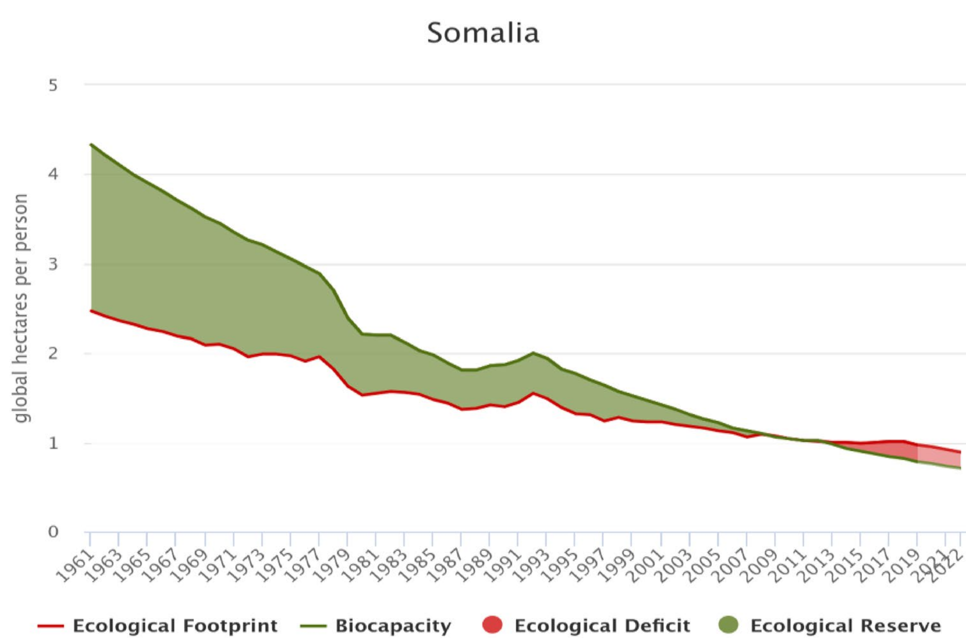


Fig. 1 Ecological footprint and biocapacity in Somalia (1961–2022). Data source: Global Footprint Network (2022)

contributes to a range of environmental issues, including climate change, pollution, and the depletion of natural resources [20–22]. While greater population density can foster economic development and innovation, it also intensifies environmental challenges such as increased emissions, reduced agricultural productivity [23], declining soil fertility [24], and higher rates of waste generation, deforestation, and overall environmental degradation [25]. Densely populated areas are responsible for consuming a disproportionate share of global resources, utilizing approximately 75% of the world's natural resources [26, 27], over 66% of global energy, and nearly 70% of total greenhouse gas (GHG) emissions [28]. This depicts the imminence of sustainable development strategies to mitigate the adverse environmental impacts of increasing population density.

Historically, it was believed that carbon dioxide (CO_2) emissions were considered the best estimate of environmental decay. According to Al-Mulali et al. [29] and Abdi et al. [30], CO_2 is a poor proxy variable as it presents only one dimension of the issue. In addition, Lu [31] criticizes the sole use of atmospheric CO_2 and pollution as inadequate proxies since they cannot represent the impact of economic activities on all natural resources. This narrow approach tends to skip important components of environmental decay, such as mining, deforestation, and agriculture. Given these limitations, some researchers, such as Danish et al. [32], encourage incorporating more comprehensive measures in quantifying environmental harm. An example is the ecological footprint, which can be described as the capacity of all biologically productive land and water to absorb waste and regenerate the resources that human civilization consumes [33–35]. This wider measure provides a broad perspective on environmental sustainability. Much research into environmental sustainability has focused on the interrelationship that exists between energy consumption, carbon emissions, and renewable energy sources such as geothermal, natural gas, coal, and biomass that are regarded as key drivers of attaining carbon neutrality [36–38]. While these studies add rich knowledge to sustainable energy alternatives, most fail to consider other vital drivers of environmental degradation, especially in developing countries like Somalia.

While every nation encounters economic development and environmental conservation obstacles, the characteristics and magnitude of these issues vary by location. Somalia exhibits several ecological issues similar to other emerging countries, including significant reliance on nonrenewable energy sources, deforestation, and resource overexploitation [1, 13]. However, the particularities of the socio-economic and institutional context of Somalia enhance its environmental vulnerability. Unlike many sub-Saharan African countries, the protracted political instability and limited governance structures that have characterized Somalia make enforcing environmental regulations and resource management a particular challenge [12, 39]. On the other hand, Somalia is resourceful in terms of solar and wind resources, which creates a unique opportunity for transitioning toward renewable energy – a potential advantage it shares with its neighbours in the Horn of Africa. According to Hussein and Mohamed [40], in contrast with countries like Kenya or Ethiopia, which have made considerable advances in renewable energy investments, the progress of Somalia remains very limited because of weak infrastructure and investment barriers. Furthermore, Somalia's increasing population density mirrors trends in densely populated developing countries, where demographic pressures affect environmental resources [41]. However, Somalia's urban design and resource efficiency programs are subpar compared to those of comparable nations, which exacerbates ecological challenges.

Most research on Somalia's environmental challenges has primarily examined deforestation and CO_2 emissions as proxies for ecological deterioration [13, 40, 42]. However, this narrow focus overlooks the country's broader and more complex environmental issues. A limited number of studies [1], Mohamed et al. [43] have adopted the ecological footprint as a comprehensive measure of environmental degradation. Yet, these studies often fail to capture the critical role of education in fostering environmental awareness and sustainable practices. Education serves as a catalyst for sustainable development by enhancing personal skills and knowledge essential for addressing emerging ecological challenges. Integrating education into the discourse provides a more comprehensive understanding of sustainability issues at the national level. This study seeks to bridge this gap by assessing the impact of education, population density, energy consumption, and economic growth on Somalia's ecological footprint from 1990 to 2020. Specifically, it addresses the following research questions:

(1) How does education influence Somalia's ecological footprint?
(2) What are the short- and long-run effects of population density on ecological pressures?
(3) What role does energy consumption play in environmental degradation?
(4) Does Somalia's economic growth align with the Environmental Kuznets Curve hypothesis?

By addressing these questions, this study contributes to the literature by examining the dynamic interactions between these variables and Somalia's ecological footprint. Remarkably, the findings will provide insights for policymakers on the need to prioritize education for environmental awareness, promote renewable energy adoption to mitigate ecological pressures, and implement population management strategies to alleviate resource strain.

The study is organized as follows: the second section analyzes relevant literature, the third section defines methodology and model, the fourth section presents results and discussion, and the fifth section concludes and makes recommendations.

2 Literature review

In the past few decades, many studies have discussed how economic growth, energy use, education, and population density affect environmental quality. These studies, performed across different areas and times, have applied diverse economic models and methods. This part summarizes critical studies and presents key points from the existing research.

2.1 Economic growth and environmental sustainability nexus

The relationship between income and environmental degradation, particularly in terms of ecological footprint, has been examined in various studies, with mixed results on whether it follows the Environmental Kuznets Curve (EKC) hypothesis. Some research supports the EKC, which proposes that environmental degradation increases initially as a country's income grows. However, the trend reverses after reaching a certain income level, and the environment improves. For example, Aşıcı and Acar [44] observed this inverted U-shape in 116 countries from 2004 to 2008. Their findings suggest that while income growth initially leads to more environmental pressure, it eventually results in less degradation as economies mature. Similarly, Destek et al. [45] found the EKC relationship in EU countries, which suggests that as nations become wealthier, their ecological impact rises, but this reverses once a certain level of income is reached. Other studies, like that of Wang and Dong [46] in sub-Saharan Africa and Destek and Sarkodie [47] in newly industrialized countries, also support the idea that economic growth increases ecological footprint in the early stages, but this growth slows down or leads to a decrease in environmental impact as countries develop further. Uddin et al. [48] found similar results in several Asian economies, where growth initially worsens environmental outcomes but later leads to improvements. In Somalia, Mohamed et al. [43] confirmed the existence of the EKC hypothesis.

On the other hand, some studies do not find explicit support for the EKC hypothesis. Uddin et al. [49] analyzed the 27 countries with the highest emissions. They found that as income grew, the ecological footprint continued to rise without indicating a turning point where economic growth leads to environmental improvement. Ozcan et al. [50] examined Turkey and found a feedback loop between income and ecological footprint but no evidence supporting the EKC. Aydin et al. [51], in their study of 26 EU countries from 1990 to 2013, also found no confirmation of the EKC using the panel smooth transition regression (PSTR) model. Contrastingly, Eweade et al. [52] found that GDP and trade openness worsen the ecological footprint in the UK. In Africa, Sarkodie [53] observed a U-shaped relationship rather than an inverted U-shaped one, which suggests that economic growth may continue to worsen environmental conditions in some countries. Ulucak and Bilgili [54] also found that the EKC only applied in specific countries. This proposes that the relationship between income and environmental degradation is not uniform across different regions. Similarly, Abdi et al. [30] found that rising economic growth contributes to environmental deterioration, leading to a notable increase in ecological footprints and CO_2 emissions. Damak and Eweade [55] and Eweade et al. [56, 57] propose that heightened economic expansion correlates with amplified ecological decline. Similarly, Usman et al. [58] reveal that economic growth initially boosts the load capacity factor, but its squared term leads to environmental degradation in China.

2.2 Energy consumption and environmental sustainability nexus

A significant body of research shows that high energy consumption, especially from fossil fuels, has a clear impact on the ecological footprint and environmental health of various countries. In Qatar, Charfeddine [59] found that increased energy use directly raises the ecological footprint, a pattern often seen in high-energy economies. Yilanci and Pata [60] identified a similar trend in China, where the combination of economic growth and energy consumption continues to push up the country's ecological footprint. In Mexico, Eweade et al. [56, 57] further revealed that fossil fuel consumption and economic growth drive environmental deterioration, whereas FDI enhances environmental quality, with asymmetric effects showing that positive shocks in fossil fuel consumption intensify ecological pressures. Looking across Europe, Neagu and Teodoru [61] found evidence that higher energy use generally leads to more GHG emissions. In the United States, Shahzad et al. [62] reveal that reliance on fossil fuels consistently expands the ecological footprint, regardless of the country's economic condition, which underlines how traditional energy sources place a lasting strain on the environment. Shahbaz et al. [63] have also established a linear relationship between energy use and CO_2 emissions in Japan, postulating that even for the advanced economies, environmental pressures will persist with increasing energy demand. Idroes et al. [64] found similar trend in Indonesia. Eweade et al. [56, 57] revealed that economic growth and energy consumption exacerbate ecological footprint.

Other studies detail how economic growth and urbanization affect this energy-environment relationship. For example, using the case of France, Can and Gozgor [65] find that even economic growth and energy use are linked to increased CO_2 emissions within a short-run context. The findings also support the EKC hypothesis. According to Hardi et al. [66], increasing energy consumption in Indonesia has triggered an upward ecological footprint movement, especially in informal sectors, and such a situation necessitates shifting to renewable energy sources. Bekun et al. [67] studied renewable versus nonrenewable energy and found that nonrenewable energy sources, in particular, have a detrimental effect on environmental sustainability. Adebayo et al. [2, 3] reported a similar trend in MINT countries (Mexico, Indonesia, Nigeria, and Turkey), where rising energy consumption has been a major driver of CO_2 emissions in recent decades. On the other hand, Eweade et al. [52] argue that globalization, renewable energy, and increased transportation energy use are coupled with lower ecological harm. Adebayo et al. [68] found that solar energy innovation, digitalization, and economic globalization reduce ecological degradation in the U.S., while natural resource extraction worsens it. Using Quantile-on-Quantile Kernel-Based Regularized Least Squares (QQKRLS) and Wavelet Quantile Regression (WQR), they confirmed the positive role of renewable energy. Similarly, Li et al. [69] showed that renewable energy mitigates Costa Rica's ecological footprint while corruption harms it in the short term.

2.3 Education and environmental sustainability nexus

Empirical evidence reveals that human capital, or stock of skills and knowledge obtained through education, fosters pro-environmental behaviour, economic development, and compliance with environmental regulations. Xu et al. [70] examined individual environmental decisions in China and determined the positive influence of education on such decisions,educated consumers in their sample showed a predisposition toward spending more on eco-labelled seafood, thereby contributing to marine sustainability. Lan et al. [71] further asserted that human capital speeds up technological capability, an important factor considered necessary in adopting green technology applicable to improving environmental quality. Bano et al. [72] reiterate that human capital enhances productivity and efficiency in energy use, as well as response to the use of green technologies in industry, households, and transportation. Similarly, Desha et al. [73] indicated that a higher education level increases the probability of compliance with environmental laws. The authors conclude that human capital contributes to higher levels of regulatory compliance.

Human capital also contributes to resource conservation and reduction in emissions. In this line of difference, Salim et al. [74] argue that human capital decreases energy use, while Mahmood et al. [75] and Bano et al. [72] in Pakistan reveal the mitigating role of human capital on emissions. Shukla [76] also links human capital with general economic growth that may foster sustainable growth paths. However, scant scholarly attention is being paid to the direct linkage between human capital and ecological footprint. This relationship was investigated by Hassan et al. [77] by supporting the EKC hypothesis, which postulates that the ecological footprint is positively related to natural resources. However, they found an insignificant impact of human capital on the ecological footprint in Pakistan. Their results further indicate a deterring role of urbanization on ecological footprint. Likewise, Danish et al. [14] noticed that economic growth boosts the ecological footprint,however, human capital does not significantly influence Pakistan's ecological footprint.

2.4 Population density and environmental sustainability nexus

The relationship between population density and environmental degradation has been a focal point in environmental studies. Many studies suggest that higher population density exacerbates environmental pressures by increasing resource demand and contributing to pollution and waste. For example, Rahman and Alam [41] found that in Bangladesh, high population density correlates strongly with resource depletion and deforestation, overwhelming local ecosystems. Similarly, Muhammad et al. [78] emphasized that population density intensifies challenges associated with the growing demand for energy, industry, and transportation, which further strains environmental resources. Conversely, some studies argue that population density can lead to resource efficiency and reduced ecological footprints under the right conditions. Hussain et al. [79] found that in Pakistan, higher population density resulted in lower environmental impacts when the population was more evenly distributed and accompanied by policies promoting efficient resource use. Much of the existing literature focuses on urbanization rather than population density. Studies like Shahbaz et al. [80] and Bello et al. [81] demonstrate that urban growth often increases CO_2 emissions and ecological footprints, particularly in rapidly industrializing nations. However, Ahmed et al. [82] and Nathaniel and Khan [83] exhibit that urbanization can mitigate these adverse effects when coupled with renewable energy use and sustainable practices.

The literature on the linkage between economic growth and CO_2 emissions provides mixed evidence regarding whether income growth eventually improves environmental conditions, as suggested by the EKC hypothesis. While some studies observe an inverted U-shaped relationship where environmental degradation initially rises with income but later declines, others, particularly in high-emission or developing regions, do not find such patterns. Moreover, population density has generally been associated with increased ecological strain and higher energy use, although sustainable urban planning can help mitigate these effects. Notably, most studies rely on CO_2 emissions as the primary indicator of environmental degradation, which fails to capture the broader ecological impacts encompassed by the ecological footprint, such as resource depletion and land use changes. Furthermore, although human capital has been linked to environmental awareness and the adoption of green technologies, limited research has examined its direct impact on the ecological footprint. This study makes a novel contribution by shifting the focus from urbanization to population density and employing ecological footprint as a comprehensive measure of environmental degradation. Unlike previous studies, this analysis captures the broader ecological challenges while exploring the effects of economic growth, energy consumption, education, and population density in Somalia's context.

3 Materials and methods

3.1 Sampling data

This study conducts a comprehensive analysis of annual time series data to examine the socioeconomic determinants of ecological footprints in Somalia from 1990 to 2020. This period represents a critical phase of transformation, marked by significant shifts in urbanization, population dynamics, and energy consumption patterns, providing a robust foundation for assessing the country's environmental trajectory. The selected timeframe aligns with key global sustainability initiatives, including the Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs). This allows for a broader contextualization of Somalia's progress toward environmental sustainability. Furthermore, data availability from reputable sources such as UNESCO, the Global Footprint Network, and the World Development Indicators ensures the reliability and accuracy of key variables. Nevertheless, the primary variable of interest, ecological footprint (ECFP), represents the environmental demand imposed by a population [16]. This variable reflects the combined effect of resource consumption and waste assimilation on the environment.

Several explanatory variables are included to explore the drivers of ecological footprint: economic growth, energy consumption, education, and population density. Economic growth provides a standardized measure of income and its potential link to environmental pressure [47, 50]. Moreover, energy consumption indicates the energy requirements of the population and its sustainability implications [7]. Education serves as a proxy for human capital and the potential impact of environmental awareness on the ecological footprint [72, 75]. Finally, population density reflects demographic pressure on natural resources, often associated with heightened environmental impact [41, 79]. The data for these variables are sourced from the Global Footprint Network (GFN), World Development Indicators (WDI), Our World in Data, and UNESCO. Table 1 provides an overview of the variables used in the study, including their definitions, measurement units, and respective data sources. It is worth mentioning that Fig. 2 provides a visual depiction of the analysis process.

3.2 Econometric model specification

This study utilizes an EKC model as a basis, expanding on the original framework by Grossman and Krueger [84] and later applied by Egbetokun et al. [85] and Mohamed et al. [43]. The EKC hypothesis posits that as economic development progresses, environmental degradation first intensifies and then decreases, which illustrates an inverted U-shaped relationship. This model will capture this relationship using ecological footprint (ECFP) as a dependent variable and income (proxied by GDP per capita) along with its square term to represent non-linearity. Including additional variables allows

Table 1 Variables, symbols, descriptions and sources

Variable	Code	Description	Source
Explained variable			
Ecological footprints	ECFP	Ecological footprint (gha)	GFN
Explanatory variable			
Economic growth	GDPC	GDP per capita (constant 2015 US$)	WDI
Energy consumption	EC	Primary energy consumption per capita (kWh/person)	Ourworldindata
Education	EDU	School age population, secondary education, both sexes (number)	UNESCO
Population density	PD	People per square kilometer of land	WDI

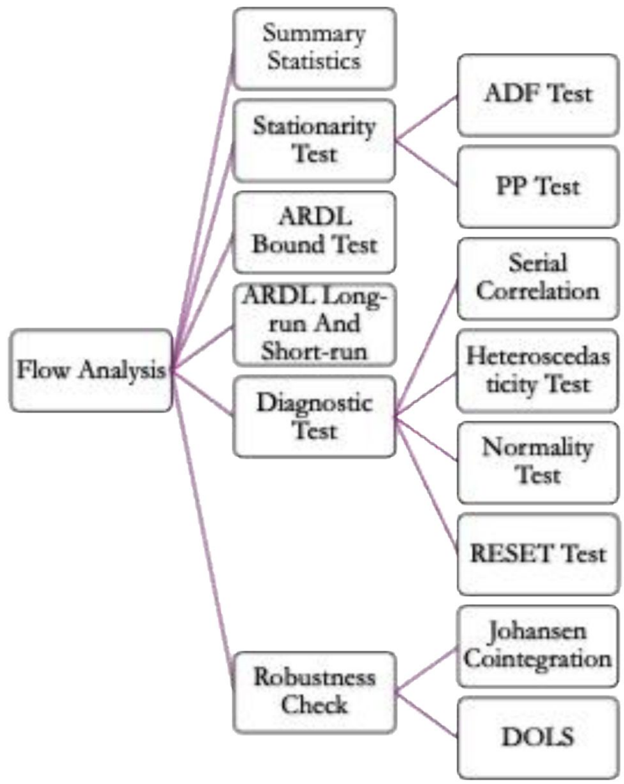


Fig. 2 Flow of the analysis

for a more comprehensive analysis of the socio-environmental determinants of environmental quality. The baseline equation is formulated as follows:

$$ECFP_t = \alpha_0 + \alpha_1 GDPC_t + \alpha_2 GDPC_t^2 + \alpha_3 X_t + \varepsilon_t \quad (1)$$

where $ECFP_t$ represents the ecological footprint at time t, serving as an indicator of environmental impact. The variable $GDPC_t$ denotes GDP per capita, capturing the effect of income on environmental degradation, while $GDPC_t^2$, the squared term of GDP per capita, tests the EKC hypothesis by introducing a non-linear relationship. X_t represents additional exogenous variables relevant to environmental outcomes, and ε_t is the stochastic disturbance term accounting for random variation in the model. To enhance interpretability, a natural logarithmic transformation is applied to all variables, which allows for elasticity-based interpretations. This transformation leads to the following revised model:

$$lnECFP_t = \alpha_0 + \alpha_1 lnGDPC_t + \alpha_2 lnGDPC_t^2 + \alpha_3 lnEC_t + \alpha_4 lnEDU_t + \alpha_5 lnPD_t + \varepsilon_t \quad (2)$$

where energy consumption, $lnEC_t$, representing the impact of energy use on the environment; education, $lnEDU_t$, reflecting the role of human capital and environmental awareness; and population density, $lnPD_t$, which shows the pressure of population growth on environmental resources. In testing the EKC hypothesis, the model posits that the coefficient of $lnGDPC_t$ should be positive, which indicates that economic growth initially exacerbates environmental degradation. Conversely, the coefficient of $lnGDPC_t^2$ is expected to be negative if the EKC holds, which suggests that at higher levels of income, environmental degradation starts to decline. Integrating additional exogenous variables such as energy consumption, education, and population density strengthens the model's ability to examine a range of factors influencing ecological footprint.

The approach developed by Pesaran et al. [86] is adopted in this study for cointegration analysis due to the methodological advantages of the ARDL model, which align well with the study's objectives. Firstly, the ARDL model facilitates the simultaneous estimation of both short-run and long-run coefficients, which provides a comprehensive framework to examine the dynamic relationships among variables over time. This dual estimation captures both immediate and persistent effects, which allows for a deeper temporal interaction analysis and a better understanding of the transitional dynamics that characterize the relationships under study. Another advantage of the ARDL approach is its suitability for small sample sizes, unlike other cointegration techniques that typically require larger datasets to produce reliable estimates. This feature makes the ARDL model particularly relevant to this study, where data limitations may otherwise constrain the application of alternative methods. Additionally, the ARDL framework's bounds-testing approach allows for the inclusion of variables with mixed stationarity levels. Specifically, it accommodates variables that are either stationary at level I(0) or integrated of order one I(1), without the need for pre-testing each variable's integration level. Although the ARDL model does not support variables integrated at the second difference, I(2). Building on Eq. (2), the conditional ARDL model is specified as follows to capture both short-run dynamics and long-run relationships among the variables:

$$\begin{aligned}\Delta lnECFP_t = {}& \alpha_0 + \alpha_1 lnECFP_{t-1} + \alpha_2 lnGDPC_{t-1} + \alpha_3 lnGDPC^2_{t-1} + \alpha_4 lnEC_{t-1} + \alpha_5 lnEDU_{t-1} \\ & + \alpha_6 lnPD_{t-1} + \sum_{i=1}^{p} \gamma_1 \Delta lnECFP_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta lnGDPC_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta lnGDPC^2_{t-i} \\ & + \sum_{i=1}^{q} \gamma_4 \Delta lnEC_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta lnEDU_{t-i} + \sum_{i=1}^{q} \gamma_6 \Delta lnPD_{t-i} + \varepsilon_t\end{aligned} \tag{3}$$

In this model, α_0 represents the intercept, the parameters α_1 to α_6 indicate the long-run impact of each variable on ecological footprint, the parameters γ_1 to γ_6 reflect the short-run impact of the explanatory variables on ecological footprint . Here, p and q denote the optimal lag lengths for the dependent and independent variables, respectively, while Δ indicates the variables that are included to capture short-run effects. To assess the presence of a stable long-run relationship among the variables, a bounds test is conducted using an F-statistic to test the null hypothesis of no long-run relationship. Specifically, the null hypothesis is that ($H_0 : \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = \alpha_6 = \alpha_7 = 0$) against the alternative hypothesis of cointegration ($H_a : \alpha_1 \neq \alpha_2 \neq \alpha_3 = \alpha_4 \neq \alpha_5 \neq \alpha_6 \neq \alpha_7 \neq 0$). If the F-statistic exceeds the upper critical bound (I(1)), a long-run relationship is confirmed. Conversely, if It falls below the lower critical bound (I(0)), no long-run relationship exists. If the F-statistic lies between these bounds, the result is inconclusive. To address this, cointegration tests are first performed using Eqs. (3). Subsequently, the study explores short-run dynamics by applying error correction models (ECM) to examine the relationship between the independent variables and the ecological footprint. In this context, the error correction term (ECT), η, measures the speed at which the model returns to equilibrium after short-term deviations. The error correction framework can then be expressed by modifying Eqs. (3) as follows:

$$\begin{aligned}\Delta lnECFP_t = {}& \alpha_0 + \sum_{i=1}^{p} \gamma_1 \Delta lnECFP_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta lnGDPC_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta lnGDPC^2_{t-i} \\ & + \sum_{i=1}^{q} \gamma_4 \Delta lnEC_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta lnEDU_{t-i} + \sum_{i=1}^{q} \gamma_6 \Delta lnPD_{t-i} + \eta ECT_{t-1} + \varepsilon_t\end{aligned} \tag{4}$$

Table 2 Descriptive statistics

	lnECFP	lnGDPC	lnGDPC^2	lnEC	lnEDU	lnPD
Mean	2.79	5.771	33.401	5.706	13.861	2.788
Maximum	2.808	6.345	40.259	6.365	14.331	3.272
Minimum	2.777	5.39	29.056	5.357	13.196	2.327
SD	0.01	0.308	3.617	0.186	0.233	0.289
Jarque–Bera	1.647	3.095	3.43	21.585	0.949	1.914
Probability	0.439	0.213	0.18	0	0.622	0.384
Observations	31	31	31	31	31	31

Table 3 Correlation matrix

	lnECFP	lnGDPC	lnGDPC^2	lnEC	lnEDU	lnPD
lnECFP	1.000					
lnGDPC	0.933	1.000				
lnGDPC^2	0.931	1.000	1.000			
lnEC	− 0.789	− 0.703	− 0.707	1.000		
lnEDU	0.891	0.847	0.851	− 0.950	1.000	
lnPD	0.978	0.878	0.876	− 0.806	0.876	1.000

4 Empirical results and discussion

4.1 Summary statistics and correlation outcomes

The descriptive statistics in Table 2 summarize the key characteristics of the variables in the study, including mean, minimum, maximum, standard deviation, and normality measures. Among the variables, the squared GDP per capita demonstrate the highest average value at 33.401, while population density has the lowest mean at 2.788. The maximum and minimum values of squared GDP per capita (40.259) and ecological footprint (2.777), respectively, highlight the range of economic activities and ecological impacts within the sample period. The relatively low standard deviation of the ecological footprint at 0.010 suggests stable ecological implications over time, while the higher variability in GDP per capita squared reflects the dynamic economic growth within the study period. The Jarque–Bera test results confirm the normality of most variables, except for energy consumption.

On the other hand, Table 3 presents the correlation matrix, which reveals the associations between the study variables. All variables, except for energy consumption, present a positive correlation with the ecological footprint, which indicates that factors like GDP per capita, population density, and education may amplify environmental impacts. Energy consumption, however, exhibits a negative correlation with other variables, which suggests that increased energy use might be associated with lower ecological impacts, possibly due to the nature of energy sources or efficiency measures in place.

4.2 Unit root tests and cointegration findings

Time-series data may include trends that could produce erroneous estimations. In order to address the non-stationarity problems that typically occur in time-series data, we employed the Philips Perron (PP), Augmented Dickey–Fuller (ADF), Dickey–Fuller Min-t, and Zivot–Andrews test. According to the null hypothesis (H_0), the series has a unit root, in contrast to the alternative hypothesis (H_1) of both tests, which holds that the series is stationary. The PP, ADF, Dickey-Fuller Min-t, and Zivot-Andrews unit root test results indicate that the series is stationary at different orders of integration, as presented in Table 4. The results of both tests show that, with the exception of energy consumption, every series at I(0) has a unit root. Nevertheless, following I(1), every variable became stationary. The results support the suitability of the ARDL approach and suggest that we move on to the cointegration analysis of the study since they show that the stationarity of the variables exhibits different orders of integration, i.e., I(0) and I(1).

After confirming that the variables meet the unit root requirements, we proceeded to investigate the long-run cointegration relationship between economic growth, energy consumption, education, population density, and ecological

Table 4 Unit root tests

Variable	PP		ADF		Zivot-Andrews	
	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept	Break data
lnECFP	0.9964	− 2.2426	0.9578	− 2.23	− 4.5037*	2016
ΔlnECFP	− 5.1519***	− 5.3698***	− 5.1521***	− 5.3698***	− 6.0860*	1998
lnGDPC	0.4076	− 2.1657	− 0.0092	− 3.0767	− 4.4147*	2014
ΔlnGDPC	− 4.0513***	− 4.4029***	− 4.008***	− 4.3856***	− 5.1279	1996
lnGDPC^2	0.4529	− 2.0561	− 0.0498	− 2.9981	− 4.5967*	2014
ΔlnGDPC^2	− 3.8654***	− 4.235**	− 3.8554***	− 4.2126**	− 4.8224	1996
lnEC	− 3.6954***	− 5.951***	− 3.9796***	− 6.913***	− 19.0718*	2000
ΔlnEC	− 11.6206***	− 11.2784***	− 11.2547***	− 10.6966***	− 12.4118*	2000
lnEDU	− 2.2936	− 4.4624***	− 2.3605	− 4.3107***	− 7.9552	2014
ΔlnEDU	− 11.9577***	− 21.6986***	− 2.5205	− 25.5976***	− 6.9444*	2008
lnPD	1.027	− 4.2624**	− 0.6218	− 3.978**	− 4.1331**	2009
ΔlnPD	− 4.9818***	− 4.6577***	− 4.2158***	− 3.8162**	− 4.7529*	2013

	Innovative outlier			
	Level Intercept	Break data	Intercept and trend	Break data
lnECFP	− 0.9671	1997	− 4.1746	2010
ΔlnECFP	− 5.9769*	1995	− 5.8124*	1995
lnGDPC	− 1.6708	2014	− 10.6685*	2013
ΔlnGDPC	6.9320*	1994	− 5.5579*	1994
lnGDPC^2	− 1.7992	2014	− 10.4121*	2013
ΔlnGDPC^2	− 5.7505*	1994	− 5.3171**	2017
lnEC	− 6.8398*	2012	− 20.0873*	1999
ΔlnEC	− 11.1779*	2019	− 12.1167*	1999
lnEDU	− 6.2086*	2010	− 8.6094*	2013
ΔlnEDU	− 37.1479*	2008	− 33.4091*	2008
lnPD	− 4.7803**	2012	− 6.9666*	2009
ΔlnPD	− 4.145	2012	− 16.2158*	2015

Δ represents the first difference. *, **, and * denote significance at the 1%, 5%, and 10% levels, respectively

Table 5 F-bound test

F-statistics	Significance level	Critical values	
		K = 5	
		I(0)	I(1)
9.953697	1%	4.537	6.370
	5%	3.125	4.608
	10%	2.578	3.858

The Wald F-statistics are evaluated against the critical values specified by Narayan (2005). Here, K denotes the number of explanatory variables

footprint. The results of the Wald F-statistic, along with the critical values, are presented in Table 5. The findings reveal that economic growth, energy consumption, education, and population density share a long-run cointegration with ecological footprint. This affirms that these variables move together over time. In this context, we reject the null hypothesis of no cointegration and accept the alternative hypothesis of cointegration. Our Wald F-statistic of 9.95 exceeds the critical value of 6.37 at the 1% significance level, which provides strong evidence of a long-term relationship between the dependent and explanatory variables. This validation of cointegration allows us to proceed with further analysis of both the short-run and long-run dynamics among the variables.

4.3 Long-run and short-run ARDL outcomes

The analysis will adopt the general-to-specific approach of Krolzig and Hendry. [87] within the ARDL framework to identify the order of integration for the variables and specify the optimal lag length of the models. This method automatically resolves serial correlation and model stability issues since the error term becomes uncorrelated and the parameters stabilize by systematically removing those variables with the highest p-values. Given the smaller number of observations in the dataset, two lags were initially explored in this analysis, though one lag length was selected. The findings of this study indicate that the relationship between income and ecological footprint in Somalia does not provide statistically significant evidence for the EKC hypothesis. While the coefficients for GDP and GDP squared exhibit the expected positive and negative signs, respectively, their insignificance suggests that economic growth alone may not bring about significant improvements in environmental quality in Somalia. This contrasts with the findings of Aşıcı and Acar [44] and Destek et al. [45], who observed the EKC relationship in samples of developed countries where economic growth initially increased environmental pressure but eventually led to ecological improvement as income levels reached a critical threshold. However, Somalia's lack of significant results could be due to its unique economic and institutional challenges, which suggests that Somalia may not have reached the stage of economic maturity needed to see these EKC dynamics unfold.

However, the results of this study reveal that energy consumption significantly contributes to the ecological footprint in Somalia, with a 1% increase in energy consumption leading to a 0.004% increase in the ecological footprint. This finding is consistent with a significant body of research highlighting the environmental strain associated with high energy use, particularly from fossil fuels. Charfeddine [59] observed a similar pattern in Qatar, where increased energy consumption directly raised the ecological footprint. Similar to our results, Yilanci and Pata [60] reported that the combined effects of economic growth and rising energy demand have substantially increased China's ecological footprint. For developing economies like Somalia, this reliance on nonrenewable energy sources could continue exacerbating environmental challenges. Given Somalia's limited infrastructure for cleaner energy, the country may face persistent environmental pressures as energy demands grow.

The long-run results in Table 6 show that education has a negative impact on the ecological footprint in Somalia, where a 1% increase in education results in a 0.005% reduction in ecological footprint. This outcome suggests that education contributes to environmental improvements by raising awareness about sustainable practices and fostering environmentally responsible behaviors. These findings are in line with Xu et al. [70], who found that higher levels of

Table 6 Long-run and short-run relationship

Long-run coefficients			
Variables	Coefficients	SE	t-Statistics
lnGDPC	0.014	0.054	0.261
$lnGDPC^2$	− 0.001	0.004	− 0.125
lnEC	0.004**	0.002	2.056
lnEDU	− 0.005**	0.003	− 2.136
lnPD	0.012***	0.004	3.053
Constant	1.271***	0.161	7.874
Short-run coefficients			
Variable	Coefficient	SE	t-Statistic
$\Delta lnECFP_{t-1}$	− 0.347*	0.177	− 1.959
ΔlnGDPC	0.137*	0.067	2.045
$\Delta lnGDPC^2$	− 0.011*	0.006	− 1.868
$\Delta lnEC_{t-1}$	0.005	0.005	1.008
ΔlnEDU	0.013	0.011	1.133
$\Delta lnEDU_{t-1}$	0.034***	0.009	3.556
ΔlnPD	0.147***	0.041	3.597
ECT_{t-1}	− 0.003***	0.001	− 3.122

Δ represents the first difference. *, **, and * denote significance at the 1%, 5%, and 10% levels, respectively education positively influence pro-environmental decisions in China, with educated individuals more likely to support sustainable consumption choices. Similarly, Lan et al. [71] highlighted the role of human capital in accelerating technological advancements, which are essential for adopting green technologies and reducing environmental impact. In the context of regulatory compliance, Desha et al. [73] demonstrated that individuals with higher education levels show a greater tendency to comply with environmental laws. However, the impact of education on ecological footprint in Somalia appears narrower compared to findings in regions with more robust environmental education and infrastructure, which indicates that more resources may be needed to ensure the effectiveness of education in fully transforming environmental behaviors in Somalia.

Conversely, population density exhibits a positive long-run impact on the ecological footprint in Somalia, with a 1% increase in population density resulting in a 0.012% increase in ecological footprint. This relationship presents the environmental pressures associated with higher population density, as densely populated areas often face increased resource consumption, waste generation, and strain on ecological systems. These findings align with Shahbaz et al. [80] and Bello et al. [81], who noted that as urban populations grow, their energy demands and emissions rise, further intensifying environmental impact. In the context of developing regions like the Next-11 countries, Rahman and Alam [41] supported the idea that increased population density typically places a burden on the environment. In contrast to our findings, Hussain et al. [79] revealed that higher population density can alleviate ecological pressures. In Somalia, the positive effect of population density on ecological footprint reflects more traditional environmental stresses without the mitigating efficiencies observed in other contexts. The country's limited infrastructure and urban planning may prevent the potential benefits of higher density, such as shared resources and optimized public services, from reducing per capita ecological burdens.

The short-run results illustrate the immediate and dynamic effects of various factors on Somalia's ecological footprint, as well as the adjustment toward long-run equilibrium. The lagged dependent variable, change in ecological footprint, has a negative coefficient of -0.347 at the 10% significance level. For GDP per capita, the short-run results show a positive impact on ecological footprint, with a coefficient of 0.137. This suggests that short-run increases in income drive up the ecological footprint, likely due to increased consumption and economic activity. However, the squared term of GDP per capita has a negative coefficient of -0.011, which indicates a potential decrease in ecological footprint at higher income levels, though this effect is statistically significant at 10% level. These findings hint at an EKC relationship in the short-run, where initial income growth may intensify environmental pressures before potentially reversing as income levels increase. Moreover, the lagged term of education presents a significant positive effect on ecological footprint, with a coefficient of 0.034. This suggests that the environmental benefits of education take time to manifest, which imply that as environmental awareness and knowledge spread, there are delayed but meaningful improvements in sustainable behaviors that help reduce the ecological footprint. However, population density demonstrates a strong and significant positive effect on ecological footprint in the short-run, with a coefficient of 0.147. This indicates that population density increases place additional strain on environmental resources, likely due to intensified consumption, waste generation, and resource demand in densely populated areas. Finally, the ECT has a highly significant negative coefficient of -0.003, confirming that the model adjusts back to the long-run equilibrium, albeit slowly.

4.4 Diagnostic tests

Several diagnostic and model stability tests, as shown in Table 7, confirm the robustness of the results. The adjusted R-squared values, close to 80%, indicate that the selected regressors—economic growth, energy consumption, education, and population density—explain nearly 80% of the variation in ecological footprint. Diagnostic tests reveal no issues with serial correlation, ensuring that model errors are uncorrelated. The heteroskedasticity test confirms constant error

Table 7 Diagnostic tests

Test type	Statistic (p-value)
Serial correlation LM test	0.0015 (0.9695)
Heteroskedasticity test	11.911 (0.1552)
Normality test	0.204 (0.903)
RESET test	0.430 (0.6716)
Adjusted R^2	0.781

The values in parentheses indicate the p-values

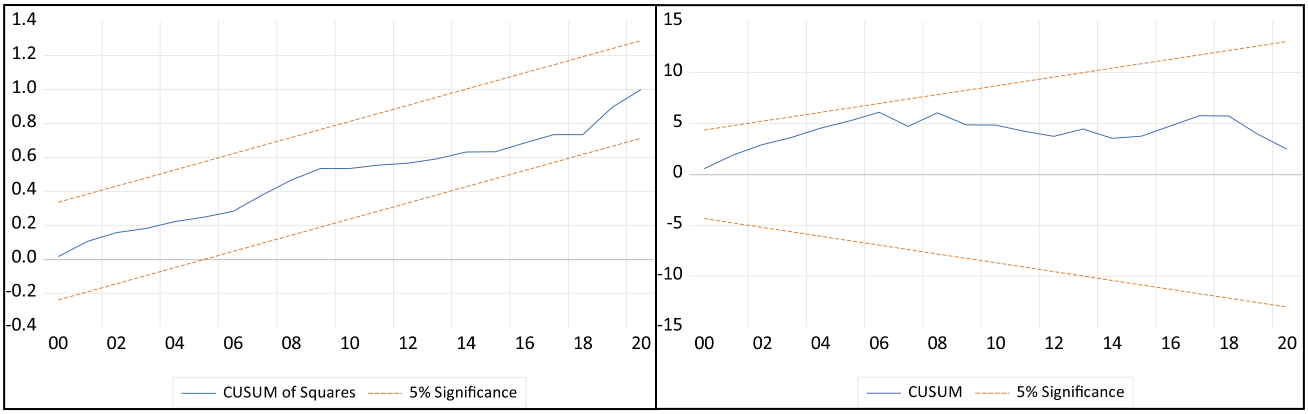


Fig. 3 Stability tests

Table 8 Johansen cointegration outcomes

Unrestricted cointegration rank test (trace)				
Hypothesized No. of CE(s)	Eigenvalue	Trace statistic	0.05 Critical value	Prob
None *	0.990	293.516	95.754	0.000
At most 1 *	0.880	165.350	69.819	0.000
At most 2 *	0.773	106.038	47.856	0.000
At most 3 *	0.707	64.510	29.797	0.000
At most 4 *	0.571	30.170	15.495	0.000
At most 5 *	0.207	6.489	3.841	0.011
Unrestricted cointegration rank test (maximum Eigenvalue)				
Hypothesized No. of CE(s)	Eigenvalue	Max-Eigen statistic	0.05 Critical value	Prob
None *	0.990	128.165	40.078	0.000
At most 1 *	0.880	59.312	33.877	0.000
At most 2 *	0.773	41.528	27.584	0.000
At most 3 *	0.707	34.340	21.132	0.000
At most 4 *	0.571	23.681	14.265	0.001
At most 5 *	0.207	6.489	3.841	0.011

Table 9 Robustness analysis using the DOLS technique

Variable	Coefficient	SE	t-Statistic	Prob
lnGDPC	0.017	0.118	0.141	0.890
lnGDPC^2	0.000	0.010	0.043	0.966
lnEC	0.010	0.005	2.041	0.062
lnEDU	− 0.013	0.006	− 2.268	0.041
lnPD	0.023	0.009	2.423	0.031
Constant	2.734	0.361	7.570	0.000

variance, which indicates no heteroskedasticity. Additionally, the Jarque–Bera test shows that the data are normally distributed. The absence of functional form misspecification further enhances the model's reliability. As depicted in Fig. 3, the stability tests, including CUSUM and CUSUMSQ of recursive residuals, indicate that the models remain stable over time, which validating the robustness of the findings.

4.5 Robustness analysis of the results

To further validate the robustness of the findings, we employ the Johansen and Juselius (J&J) cointegration test and the DOLS approach. The J&J cointegration test serves to confirm the existence of long-term cointegration among the variables, while the DOLS method provides an additional check on the estimated parameters from the ARDL technique. The DOLS method is used to tackle potential endogeneity problems and provide more precise estimates in models where the variables are cointegrated. The results, presented in Tables 8 and 9, respectively, reinforce the robustness of the ARDL findings by confirming the presence of long-term relationships between ecological footprint, economic growth, energy consumption, education, and population density. The J&J cointegration test results, as shown in Table 8, indicate significant trace and maximum eigenvalue statistics across all hypothesized cointegrating equations at the 0.05 level. On the other hand, the robustness of the ARDL estimates is further confirmed through the DOLS approach, detailed in Table 9. The DOLS results show that economic growth, energy consumption, education, and population density have consistent effects on ecological footprint, which is in line with the ARDL results. Specifically, the coefficient of GDP per capita and its squared term are not statistically significant, aligning with the ARDL long-run cointegration findings. In addition, energy consumption and population density increase ecological strain. However, education maintains its negative impacts.

4.6 Toda-Yamamoto causality test

The findings of the Toda-Yamamoto causality test in Table 10 highlight the complex interconnections among the ecological footprint, economic growth, energy consumption, education, and population density. The findings demonstrate that population density exerts a statistically significant causal influence on economic growth, energy consumption, education, and ecological footprint, thereby serving a pivotal role in the advancement of environmental sustainability, macroeconomic performance, and human capital accumulation. Moreover, the proliferation of civilizations necessitates the improvement of knowledge and a rise in energy consumption. The ecological footprint is also found to have a significant impact on education, suggesting the potential for a feedback cycle between human development indicators and environmental degradation. Additionally, the empirical evidence indicates that education and economic growth are critical determinants of population density, which is indicative of their impact on demographic transitions. The findings also indicate that economic growth has a substantial impact on energy consumption, whereas other explanatory variables, such as education and ecological imprint, do not seem to have a significant causal effect on energy demand. The absence of causality from energy consumption to other macroeconomic and demographic variables suggests that energy utilization alone does not independently stimulate economic or demographic transformations.

5 Conclusion and policy recommendations

This study aims to investigate the short-run and long-run dynamics between ecological footprint, economic growth, energy consumption, education, and population density in Somalia using annual data from 1990 to 2020. This study employed advanced econometric methodologies to unravel these relationships, utilizing unit root tests to confirm the stationarity of the variables and validate the use of the ARDL bounds testing approach. Additional robustness checks, such as the Johansen and Juselius cointegration test and the DOLS method, substantiated the findings. The causality analysis further revealed the directional influences among these variables. The study results demonstrate that the GDP per capita and its square term in Somalia have the same signs in the long-run but are insignificant. In the short-run, the

Table 10 Results of the Toda-Yamamoto causality

Variables	lnECFP	lnGDPPC	lnEC	lnEDU	lnPD
lnECFP		1.002	2.616	4.307*	0.961
lnGDPPC	1.312		6.924*	22.829*	13.056*
lnEC	0.674	0.148		1.383	0.312
lnEDU	1.404	0.018	0.022		6.039*
lnPD	10.134*	5.122**	4.603**	6.833	

ecological footprint increases with GDP per capita, while higher income levels may attain an inflexion point. Energy consumption contributes to environmental degradation, while education contributes to sustainability. Ecological footprint is positively correlated with population density. The ECT depicts gradual long-run equilibrium correction at 0.3% per year.

Based on the findings, this study recommends several policy measures to balance economic growth and ecological sustainability in Somalia. Transitioning to renewable energy sources, such as solar and wind power, is essential to mitigate the environmental impact of energy consumption while enhancing energy security. Integrating environmental education into school curricula and community awareness campaigns can foster sustainable practices and long-term ecological benefits. Addressing the pressures of population density through sustainable urban planning and rural development initiatives is critical to managing resource use efficiently. Encouraging green economic growth strategies, including investments in eco-friendly technologies and sustainable industries, can align development objectives with environmental goals. Furthermore, strengthening governance and regulatory frameworks is vital for the effective implementation and enforcement of these policies, with community engagement ensuring culturally relevant and widely supported solutions. Together, these measures can guide Somalia toward a sustainable development pathway.

This study has certain limitations that warrant further exploration in future research. The constrained data availability restricted a more comprehensive analysis of the issue. Expanding the range of variables in future studies could provide deeper insights into environmental challenges. Additionally, the study's focus on Somalia limits the generalizability of its findings to other contexts. Comparative analyses of neighboring countries or similar economies could offer a broader understanding of regional sustainability dynamics. Lastly, the statistical approach employed relies on historical data, which may not fully capture emerging trends such as the impacts of climate change and technological advancements. Incorporating predictive modeling in future research could enhance adaptability to evolving conditions and inform more forward-looking policy recommendations.

Author contributions Abdikafi Hassan Abdi: conceptualisation, data collection, writing the original draft, the introduction, discussion section, reviewing, and editing the whole manuscript. Abdisalan Aden Mohamed: data analysis and writing methodology section. Mohamed Abdukadir Mohamed: contributed to writing the introduction and literature review.

Funding This research was supported by SIMAD University, Somalia.

Data availability The datasets used and/or analyzed during the current study are available from the author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval and consent to participate 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.

Consent for publication Not applicable.

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