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Unraveling the environmental Kuznets curve in IGAD countries: interplay between ecological footprint, economic growth, renewable energy, and globalization

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Abstract

Climate change has become a global phenomenon; hence, mitigating environmental pollution and degradation are crucial for addressing climate change consequences. A paradigm shift from fossil fuel to clean energy sources is suggested to reduce environmental pollution without compromising economic growth. This study assesses the validity of the environmental Kuznets curve (EKC) hypothesis by incorporating the impacts of renewable energy, population density, and globalization on ecological footprint in IGAD member nations. A battery of econometric techniques, such as Pedroni, Kao, and Johansen Fisher cointegration methods, heterogeneous panel methods, and Dumitrescu-Hurlin panel causality tests are utilized. Before the formal analysis, we performed a cross-sectional dependence test; and it was observed that the data are cross-sectional dependent. Hence, the second-generation unit root test is utilized which confirms that all the interested variables are stationary at the first difference I (1). The empirical results of cointegration methods indicate that explanatory variables are cointegrated into the ecological footprint in the long run. Moreover, the PMG—which provides consistent results as evidenced by the Hausman test—underscored that globalization, population density, and renewable energy mitigate ecological footprint in the long run even though renewable energy is insignificant. An increase in economic growth is associated with a deterioration of environmental pollution, while squared growth is linked to a reduction in pollution. This evidence supports the existence of the EKC theory, which posits an inverted U-shaped relationship between economic expansion and ecological footprint. Besides, unidirectional causalities are detected from ecological footprint to population density, renewable energy, economic growth, and squared economic growth but not the other way around. In light of the empirical results, several policy recommendations are proposed.

1. Introduction

Environmental concerns, including climate change and its enduring consequences, have become ubiquitous worldwide, notably in both developing and least-developed countries. A synergy of human anthropogenic activities and economic growth processes has led to these environmental challenges (Mendonça *et al* 2020, Warsame *et al* 2024). It, consequently, engenders catastrophic impacts on the environment, economies, and human lifestyles due to the dearth of effective regulation. This led to heightened global consciousness regarding environmental concerns that have been instrumental in facilitating the synchronization of international initiatives to reduce emissions, for instance, the Kyoto Protocol, the Paris Agreement, and the inception of the Sustainable Development Goals (SDGs), including but not limited to seeking to champion the adoption of sustainable energy technologies, boost eco-friendly agricultural practices, and confront the multifaceted issues posed by climate change and its far-reaching consequences. A profound interconnection is apparent between environmental pollution, economic growth, globalization, urbanization, and energy consumption which have a substantial impact on various indicators of human development, gender equality, employment, income, livelihoods, and skill development (Sarkodie and Ozturk 2020).

The interplay between economic activities and their impact on environmental degradation has emerged as a highly compelling subject of investigation for scholars. A central concept that has garnered extensive attention in exploring the association between income levels and environmental pollution is the theory of the Environmental Kuznets Curve (EKC) hypothesis originated from the seminal work of Grossman and Krueger (1991). Panayotou (1993) laid the foundation for the EKC hypothesis. According to the EKC hypothesis, there is a relationship between environmental degradation and economic growth. Initially, as economies grow, environmental degradation and pollution tend to worsen. However, after reaching a threshold point, further economic growth can lead to environmental improvements. This shift happens as resources are allocated to enhance living standards, promote cleaner energy sources, and support a healthier ecological environment. As a result, the relationship between economic growth and environmental quality takes the shape of an inverted U-shaped curve (Panayotou 1993). Thus, the EKC hypothesis has been extensively examined in numerous studies, with CO_2 emissions commonly employed as the measurement of environmental pollution (Chen *et al* 2019, Munir *et al* 2020). Nevertheless, more recent investigations have adopted the ecological footprint (EF) as an alternative measure of environmental pollution to evaluate the EKC hypothesis (Liu *et al* 2018, Yilanci and Korkut Pata 2020). This transition is motivated by the EF's capability to quantify the extent to which human resource consumption exceeds environmental boundaries (Yilanci and Korkut Pata 2020).

The EKC hypothesis has received substantial validation from a preponderance of scholarly studies, showing that when economies reach a certain level of development it becomes possible to reduce the ecological footprint. However, this reduction is usually not possible in the early stages of economic growth. Table 1 illustrates the studies that validated the EKC hypothesis in both cross-country and single-country studies (Alam *et al* 2016, Yang *et al* 2017, Egbetokun *et al* 2020, Yasin *et al* 2020, Zeraibi *et al* 2021, Hussein and Warsame 2023). Conversely, numerous prior studies have levied criticism on the EKC hypothesis, contending that it lacks universality across economies. Moreover, recent critiques of the traditional inverted U-shaped EKC suggest the existence of an N-shaped relationship with a second turning point (Allard *et al* 2018, Churchill *et al* 2018, Rej and Nag 2022) showing that environmental degradation may initially decrease with rising income but increase again at higher income levels. Studies have also identified the possibility of an inverted N-shaped EKC (Özokcu and Özdemir 2017a, Bandyopadhyay *et al* 2022, Abbasi *et al* 2023). This pattern suggests that, in advanced economies, heightened consumption and production may lead to renewed environmental strain. These findings highlight the need for more nuanced interpretations of the relationship between economic growth and environmental impact.

Consequently, these studies have underscored the notion that attaining the necessary threshold of economic development for diminishing the ecological footprint may not guarantee its actual reduction. Thus, further economic growth may instead result in an escalation of the ecological footprint level (Çakmak and Acar 2022). Some other studies that do not confirm the EKC hypothesis are also presented in table 1, organized for both panel and single-country studies (Ahmed and Long 2012, Al-Mulali, Saboori *et al* 2015, Baek 2015, Özokcu and Özdemir 2017b, Zambrano-Monserrate *et al* 2018, Yilanci and Korkut Pata 2020).

On the other hand, globalization is a multifaceted and intricate phenomenon that encompasses aspects of economics, politics, ideology, culture, as well as the environment (Warsame *et al* 2023). Globalization's pervasive impact is channeled primarily through economic channels, most notably the influx of foreign direct investments. This phenomenon can incite a 'technique effect,' which, in the context of environmental preservation, leads to the acquisition and implementation of cutting-edge technologies for the management of environmental pollution (Zaidi *et al* 2019). Furthermore, the emergence of globalization is intertwined with the rapid industrialization witnessed in various regions. This development corresponds to heightened energy demands, the transference of knowledge and technology, the amplification of international trade and economic investments, and the expansion of agricultural production (Ibrahiem and Hanafy 2020). However, many studies pointed out that the advantages of globalization will significantly enhance economic growth and attenuate environmental pollution through technical knowledge and advanced technology (Saud *et al* 2020). Conversely, some other studies documented that globalization may lead to natural resource exploitation heightens the environment (Dogan and Seker 2016, Ibrahiem and Hanafy 2020). Therefore, the implications of globalization on the environment can be dichotomous, signifying both detrimental and beneficial contingent upon the rigorousness of regulatory measures (Sarkodie and Adams 2018).

Renewable energy consumption (REC) is generally acknowledged as an effective approach to addressing the dual concerns of energy security and the reduction of emissions. Clean energy represents an augmenting sustainable energy resource that warrants active promotion to facilitate future sustainable development (Warsame 2023). Furthermore, it is worth noting that renewable energy is regarded as environmentally sustainable and economically viable. This is due to its ability to minimize the adverse effects of climate change, mitigate environmental deterioration, and decrease poverty by supplying electricity access to remote areas

Table 1. Environmental kuznets curve literature table.

Author(s)	Country(ies)	Period	Method	Results
(Yasin *et al* 2020)	53 developed countries and 57 less developed countries	1996–2016	Generalized Method of Moments (GMM)	Supported the EKC hypothesis
(Zeraibi *et al* 2021)	Southeast Asian Countries	1985–2016	Panel regression analysis	Supported the EKC hypothesis
(Alam *et al* 2016)	Developing countries	1970–2012	ARDL	Supported the EKC hypothesis
(Adzawla *et al* 2019)	Sub-Saharan Africa	1970–2012	Vector Autoregressive and Ordinary Least Square regression	Supported the EKC hypothesis
(Yang *et al* 2017)	Russia	1998–2013	Regression analysis	Supported the EKC hypothesis
(Egbetokun *et al* 2020)	Nigeria	1970–2017	ARDL	Supported the EKC hypothesis
(Sarkodie and Ozturk 2020)	Kenya	1971–2013	ARDL and Utest estimation	Confirmed the validity of the EKC hypothesis
(Hussein and Warsame 2023)	Somalia	1989–2020	ARDL	Confirmed the validity of the EKC hypothesis
Hundie and Daksa (2019)	Ethiopia	1979–2014	ARDL	Confirmed the validity of the EKC hypothesis
(Özokcu and Özdemir 2017b)	26 high-income OECD countries and 52 emerging countries	1980–2010	Panel regression analysis	Not supported the validity of the EKC hypothesis
(Al-Mulali and Weng-Wai *et al* 2015)	93-panel countries	1980–2008	Panel fixed effect and GMM	Not supported the validity of EKC hypothesis in lower-income countries
(Zambrano-Monserrate *et al* 2018)	Peru	1980–2011	ARDL	Not supported the validity of the EKC hypothesis
(Al-Mulali and Saboori *et al* 2015)	Vietnam	1981–2011	ARDL bounds testing and vector error correction model (VECM) Granger causality	Not supported the validity of EKC hypothesis
(Ahmed and Long 2012)	Pakistan	1971–2008	ARDL	Validated in the long run but not in the short run
(Baek 2015)	Nuclear generating countries	1980–2009	Pedroni and Kao cointegration, FMOLS, dynamic OLS (DOLS)	Not supported the validity of EKC hypothesis
(Yilanci and Korkut Pata 2020)	China	1965–2016	ARDL	Not supported the EKC hypothesis

(Kamran 2018, Tareen et al 2018, Gielen et al 2019, Warsame et al 2022). Numerous studies have investigated the influence of renewable and non-renewable energy sources on both economic growth and environmental pollution. The majority of these studies have identified that renewable energy improves environmental quality as well as economic growth (Apergis and Payne 2010, Dong et al 2018, Sarkodie and Adams 2018). Nonetheless, the findings regarding renewable energy's potential to reduce environmental pollution and promote sustainable development are inconclusive (Sarkodie and Adams 2018). Certain studies have indicated that there is no distinguishable impact of clean and fossil fuel energy production and consumption on GHG emissions (Farhani and Shahbaz 2014, Bilgili et al 2016, Mert and Bölük 2016). Moreover, it was observed that renewable energy exerts a positive influence on the environment, especially when it surpasses a minimum threshold level. Any adverse effects of clean energy on environmental quality are primarily attributed to technological limitations, storage quality, and inadequate transmission systems (Heal 2009). Hence, the recent surge in clean energy generation appears to be predominantly driven by government initiatives because of the relatively lower ecological footprint of clean energy production compared to fossil fuel sources, as it consumes fewer resources such as land, steel, and other materials. Although renewable energy has lifecycle emissions, they remain significantly lower than those of existing fossil-fuel-based power generation (Ansari et al 2021). Mitigating the negative environmental impact of renewable energy consumption requires technological advancements and efficient transmission systems (Hussein et al 2023). Therefore, it is of utmost importance for governments to assume a decisive role in driving forward the promotion of renewable energy, underscoring its genuine dedication to curbing environmental degradation.

The Intergovernmental Authority on Development (IGAD) is a trade bloc established in 1996. This block encompasses eight members, namely Uganda, Ethiopia, Somalia, Eritrea, Sudan, Kenya, and Djibouti. Kenya and Djibouti are categorized as lower-middle-income countries, whereas the rest of the members are ranked as low-income nations (IGAD 2023). In recent decades, the IGAD nations have witnessed notable economic growth and transformational changes (Atilaw Woldetensaye et al 2022). These positive shifts, however, have been coupled with burgeoning environmental pressures (Ssekibaala et al 2022). Oil dominated the IGAD's energy landscape in 2019, contributing 48% of the region's total energy output, with hydropower coming in second with 27% and other renewables coming in third with 16%. Carbon is emitted through diverse channels, but the three foremost contributors to GHG emissions are carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH4) emissions. Taking a historical glance, IGAD's carbon production was 4 million tons in 1990. Over the subsequent 29 years, emissions underwent a gradual ascent, culminating in a noteworthy 16 million tons by 2019. Consequently, this results in a temperature rise. Despite this increase, it's crucial to note that IGAD's carbon emissions in 2019 constituted only 4% of the total emissions across the African continent (IGAD 2023). Moreover, substantial population growth has emerged as a pivotal factor contributing to challenges such as food insecurity and environmental degradation (Molotoks et al 2021). Over the period from 1990 to 2019, IGAD's collective population, initially recorded at 124.7 million, more than doubled, reaching an impressive 281.7 million. The population growth in IGAD countries exhibited a sustained yearly growth rate above 2.6% during the specified time (IGAD 2023). The aforementioned factors have contributed to climate change-related challenges, including, but not limited to, elevated temperatures, droughts, floods, fluctuating rainfall patterns, and food insecurity. These issues, in turn, pose obstacles to economic growth (Warsame and Daror 2023). Therefore, understanding the relationships between these variables becomes imperative to conducting this study at the opportune moment. The goal of this study is to comprehensively grasp the complexities and subsequently propose viable policies to address and alleviate these multifaceted problems.

In the regional context, a multitude of comprehensive studies have explored the relationship between renewable energy, globalization, population, and economic growth concerning environmental pollution. However, these investigations frequently focused on specific nations such as Ethiopia (Hundie and Daksa 2019, Usama et al 2020, Hundie 2021), Somalia (Warsame and Sarkodie 2022, Hussein and Warsame 2023, Warsame et al 2023), Kenya (Sarkodie and Ozturk 2020, Chandra Voumik et al 2023), and Sudan (Eldowma et al 2023), which have commonly utilized CO_2 emissions and deforestation as metrics for gauging environmental quality. Nevertheless, carbon dioxide emissions represent only one facet of environmental detriment. In recent years, the ecological footprint, initially conceptualized by Wackernagel & Rees (Mathis Wackernagel 1997), has garnered widespread recognition as a comprehensive indicator for gauging the extent of environmental harm. We chose to investigate the IGAD countries for this study due to their geographic proximity and shared challenges in areas such as development, peace, security, and environmental sustainability. By focusing on the IGAD region that is facing similar socio-economic and environmental pressures, we aim to conduct a more targeted analysis of critical issues. The investigation of ecological footprint within this regional context provides an opportunity for a detailed examination of shared concerns and potential collaborative solutions. Additionally, the diversity of the IGAD countries allows for a comprehensive understanding of environmental dynamics, facilitating the identification of best practices and policy interventions that can be tailored to the specific needs of the region. Therefore, this study is distinctive in scholarly research due to its multifaceted contributions to the field. To the

Table 2. Data sources and descriptions.

Variable	Code	Measurement	Source
Ecological footprint	EFP	Footprint per capita	Global Footprint Network
Renewable Energy	RE	Percent of total energy consumption	World Bank
Real GDP	RGDP	Constant based on 2010	SESRIC
Globalization	GLO	Overall globalization	Kauf Swiss Institute
Population Density	POPD	Population density (People per sq. km of land area)	Worldbank

best of our knowledge, it represents the first empirical investigation of its kind, encompassing IGAD countries. Secondly, we select the ecological footprint as our primary environmental metric due to its potential to serve as a more effective measure of environmental degradation. Thirdly, the evaluation of causality was performed using the (Dumitrescu and Hurlin 2012) test, which is suitable for heterogeneous panel data compared to the traditional Granger causality examination.

The subsequent sections of the paper are structured in the following manner: section 2 elucidates the data collection process and the methodology adopted. Section 3 presents and scrutinizes the empirical findings derived from the analysis. Finally, section 4 closes the paper by discussing the policy suggestions that arise from the study's results.

2. Data and methods

2.1. Data

Climate change poses severe risks to IGAD member countries. It affects livelihoods, health, and economic productivity. Moreover, the region is experiencing massive deforestation and ecological footprints. In this regard, this undertaking assesses the role of renewable energy, globalization, and economic growth on the ecological footprint of a sample of IGAD member nations. The study also verifies the existence of the EKC hypothesis by including squared economic growth. Panel data from four member IGAD countries is utilized. The availability of the data determines the selection of the sampled nations. The data explanation is presented in table 2. Further, trends of the sampled variables are presented in figure 1.

Table 3 discloses the statistical descriptions of the sampled variables in IGAD countries. It also underscores the mean values of ecological footprint (0.14), globalization (3.6), renewable energy (4.49), economic growth (22.9), and population density (4). Economic growth and population density are more volatile than other parameters due to the higher standard deviation values they have. Besides, table 3 also provides the correlation of the interested parameters. It is observed that ecological footprint has a positive correlation with renewable energy and population density and a negative association with globalization and economic growth. Both economic growth and population are positively related to globalization, but renewable energy is adversely correlated with globalization. On the contrary, economic growth and population density have a negative association with renewable energy. Finally, there is a positive correlation between population density and economic growth.

2.2. Methods

2.2.1. Cross-sectional dependence test

Using panel data comes with its pros and cons. Even though panel data may suffer from heterogeneity and cross-sectional dependence (CSD) issues, the application of panel data may address the complex issues of its behavior. Moreover, panel models also consider more degrees of freedom and large samples compared to single-country studies. Before analyzing the data, we examine the CSD of the sampled variables among the observed countries. The Pesaran CD test, postulated by Pesaran (Pesaran 2004), is utilized. The null hypothesis is tested, which states there is cross-sectional independence among the interested variables, against the alternative hypothesis that the variables are cross-sectional dependent. Furthermore, to examine the impact of renewable energy, globalization, economic growth, and the square of growth on the ecological footprint in IGAD countries, we employ second-generation unit root tests. Specifically, the cross-sectional augmented Dickey-Fuller (CADF) unit root test and the cross-sectionally augmented Im, Pesaran, and Shin unit root test (CIPS). These tests control cross-sectional dependence among the parameters and produce robust results in the presence of cross-sectional dependence.

2.2.2. Panel cointegration methods

After verifying that none of the interested parameters are integrated at the second order I (2), we investigate the long-run cointegration between the regressand and regressors using Kao (Kao 1999), Pedroni (Pedroni 1999, 2004), and Johansen and Fisher cointegration methods (Maddala and Wu 1999). The null

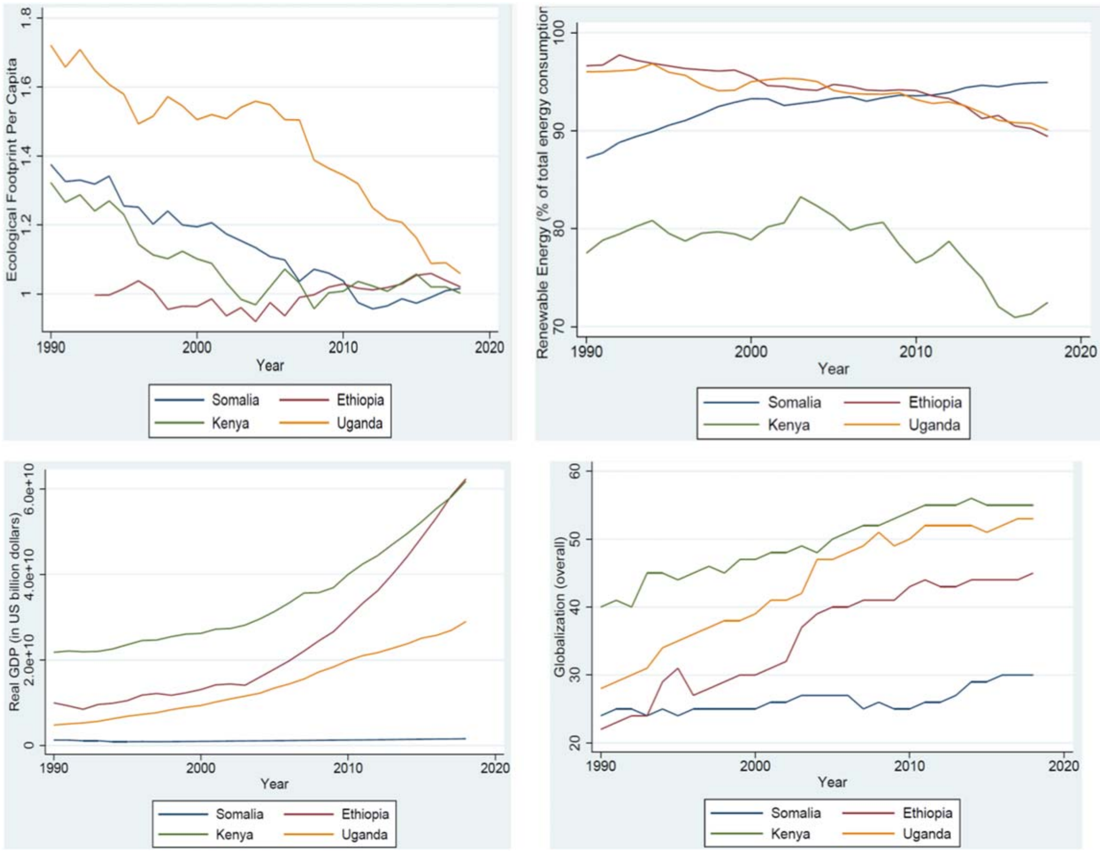

Figure 1. Trends of the sampled variables in IGAD countries.

Table 3. Descriptive statistics and correlation.

Variable	Mean		Std. dev.	Min	Max
lnEFP	.1424		.1686	−.084	.5432
lnGLO	3.614		.2892	3.091	4.025
lnRE	4.494		.084	4.262	4.582
lnRGDP	22.998		1.368	20.578	24.856
lnPOPD	4.007		.8255	2.327	5.33
Correlation					
	lnEFP	lnGLO	lnRE	lnRGDP	lnPOPD
lnEFP	1.0000				
lnGLO	−0.068	1.0000			
lnRE	0.225	−0.558	1.0000		
lnRGDP	−0.198	0.891	−0.483	1.0000	
lnPOPD	0.198	0.774	−0.058	0.804	1.0000

hypothesis is formulated as there is no long-run cointegration between the series, against the alternative hypothesis that the series are cointegrated in the long-run.

2.2.3. Heterogeneous panel cointegration methods

To determine the short- and long-run effects of renewable energy, globalization, economic growth, and squared economic growth, we employ heterogeneous panel cointegration methods of mean group (MG) and pooled mean group (PMG) developed by Pesaran (Pesaran *et al* 1999, Pesaran 2004). The key distinction between the two methods is that PMG assumes the long-run coefficient elasticities of the variables are the same across the sampled countries, whereas MG assumes that the slope and constant are different in individual nations. Hence, to find out a consistent method (PMG and MG), we use the Hausman test (1978) to determine the null hypothesis of homogeneity constraint in the long-run coefficient. However, the PMG could estimate variables regardless of the integration order unless they are not integrated at the second difference I (2).

Table 4. Cross-sectional dependence test.

Variable	CD-test	p-value	corr	abs(corr)
lnEFP	2.80	0.005	0.202	0.574
lnGLO	10.60	0.000	0.826	0.826
lnRE	0.90	0.369	0.076	0.768
lnRGDP	11.67	0.000	0.911	0.911
lnPOPD	10.88	0.000	0.851	0.851

To examine the long- and short-run effects of renewable energy, globalization, economic growth, and the square of economic growth on ecological footprint, the following panel autoregressive distributed lag (ARDL) model is specified, following the previous empirical studies of Yilanci and Korkut Pata (2020) and Ansari *et al* (2021):

$$\begin{aligned}\Delta lnEFP_{it} = {} & \alpha_0 + \beta_1 lnEFP_{it-1} + \beta_2 lnRE_{it-1} + \beta_3 lnGLO_{it-1} + \beta_4 lnRGDP_{it-1} \\ & + \beta_5 lnRGDP2_{it-1} + \beta_5 lnPOPD_{it-1} + \sum_{i=1}^{m} \theta_1 \Delta lnEFP_{it-k} + \sum_{i=1}^{n} \theta_2 \Delta lnRE_{it-k} \\ & + \sum_{i=1}^{n} \theta_3 \Delta lnGLO_{it-k} + \sum_{i=1}^{n} \theta_4 \Delta lnRGDP_{it-k} + \sum_{i=1}^{n} \theta_5 \Delta lnRGDP2_{it-k} \\ & + \sum_{i=1}^{n} \theta_5 \Delta lnPOPD_{it-k} + \mu_i + \varepsilon_t \end{aligned} \tag{1}$$

α_0 and β_{1-6} are the intercept and coefficients of the long-run parameters, respectively. θ_{1-6} represents the elasticities of the short run parameters, 'm' and 'n' are the best lag lengths of the regressand and regressors, respectively. Δ and ε_t are the first difference operator and the error term respectively, whereas μ_i is used to capture country-specific effects.

2.2.4. Dumitrescu-hurlin panel causality tests

One of the shortfalls of heterogeneous panel cointegration methods is that they cannot estimate the Granger causality among the sampled parameters. Hence, to examine the causality among the sampled variables, we employ the Dumitrescu-Hurlin causality test postulated by Dumitrescu and Hurlin (Dumitrescu and Hurlin 2012). This method has the superiority of providing advanced causality where a homogeneous non-causality hypothesis is examined. The null hypothesis of Granger causality is that the variables do not cause each other, whereas the alternative hypothesis is that the parameters cause each other (Dumitrescu and Hurlin 2012).

$$y_{it} = \alpha_i + \sum_{n=1}^{b} \theta_i^{(k)} y_{i,t-k} + \sum_{n=1}^{b} \beta_i^{(k)} x_{i,t-k} + \varepsilon_{it} \tag{2}$$

Where α_i is the intercept, and $\theta_i^{(k)}$ is the autoregressive parameter. $\beta_i^{(k)}$ shows the slope variables that are heterogeneous across countries, and b is the best lag length and is assumed the same across the countries.

3. Empirical results and discussion

3.1. Summary statistics

As a first step in the analysis of the data, we test the presence of cross-sectional dependence (CSD) among the interested parameters in different panels using Pesaran (Pesaran 2004). The preliminary analysis of the panel data for CSD is vital for choosing the appropriate unit root test to avoid biased and spurious results. The null hypothesis of the CSD is that the panel data are dependent across the countries, against the alternative hypothesis that the data are independent across the cross-sectional units. The results of the CSD, presented in table 4, indicated that the interested parameters are related across the countries and, hence, could not be used with the first-generation unit root test.

Since the interested parameters are cross-sectional dependence, we employ the second generation unit root test of CADF and CIPS. These tests are good at examining unit-root tests of parameters with cross-sectional dependence. The results of the unit roots disclosed in table 5 indicated that all sampled variables are integrated at the first difference I (1) except globalization and population density, which are stationary at both levels in the CIPS test. Therefore, the interested parameters are integrated in mixed orders, which is appropriate for the heterogeneous panel methods.

To find out if there is long-term cointegration between the dependent variable and the explanatory variables, we use the cointegration methods of (Kao 1999), Pedroni (Pedroni 1999, 2004), and Johansen and Fisher

Table 5. Second generation panel unit root test.

	CADF		CIPS	
	Without trend	With trend	Without trend	With trend
lnEFP	1.404	1.276	−1.074	−2.053
Δ lnEFP	−3.234***	−2.197**	−4.356***	−5.441***
lnGLO	−1.687	−2.64	−2.443**	−3.438***
Δ lnGLO	−3.300***	−3.372**	−5.889***	−6.145***
lnRE	−1.433	−2.324	−1.952	−2.442*
Δ lnRE	−2.647**	−3.323	−4.191***	−4.407***
lnRGDP	−1.765	−2.088	−1.814	−1.964
Δ lnRGDP	−3.666***	−4.020***	−3.894***	−4.162***
lnPOPD	−1.703	−1.981	−4.284***	−4.983***
Δ lnPOPD	−3.395***	−4.386***	−2.773***	−2.797*

Note: *** and ** indicate significance levels at 1% and 5%, respectively.

Table 6. Cointegration tests.

Pedroni residual cointegration test				
Within-dimension				
Statistic	Prob.	Statistic	Weighted Prob.	
Panel v-Statistic	0.634035	0.2630	0.594685	0.2760
Panel rho-Statistic	2.003581	0.9774	1.945571	0.9741
Panel PP-Statistic	−0.832720	0.2025	−0.861520	0.1945
Panel ADF-Statistic	−1.181552	0.1187	−1.201021	0.1149
Between-dimension				
	Statistic	Prob.		
Group rho-Statistic	2.310022	0.9896		
Group PP-Statistic	−2.181805	0.0146		
Group ADF-Statistic	−2.304065	0.0106		
		Kao Residual Cointegration Test		
	T-Statistic	Prob.		
ADF	−1.869549	0.0308		
Residual variance	0.000917			
HAC variance	0.000977			
		Johansen Fisher Panel Cointegration Test		
Hypothesized	Fisher Stat.*	Fisher Stat.*		
No. of CE(s)	(from trace test)	Prob.	(from max-Eigen test)	Prob.
None	182.3	0.0000	80.95	0.0000
At most 1	102.1	0.0000	56.41	0.0000
At most 2	55.58	0.0000	22.35	0.0043
At most 3	39.08	0.0000	18.81	0.0159
At most 4	29.11	0.0003	24.41	0.0020
At most 5	16.41	0.0369	16.41	0.0369

cointegration methods (Maddala and Wu 1999), as shown in table 6. The null hypothesis of no long-run cointegration is discarded by Kao, Johansen, and Fisher's cointegration methods. Moreover, two of the group test statistics of the Pedroni cointegration method also rejected the null hypothesis of no long-run cointegration among the variables. This implies that renewable energy, economic growth, squared growth, population density, and globalization are cointegrated into the ecological footprint in the long run.

Since the ecological footprint and the explanatory variables are linked over the long term, we assess the long-term coefficients of the interested predictors using heterogeneous panel methods of MG and PMG, as shown in table 7. The Hausman test underscores that PMG is more consistent and provides robust results compared to MG. The results of PMG underscore that all the coefficients are significant except for renewable energy. Clean energy improves environmental quality in IGAD countries, but it is inconsequential. A 1% increase in globalization leads to a decrease in the ecological footprint by about 0.31% in the long run. In the same vein, population density reduces the ecological footprint. A 1% increase in population density is associated with 0.43% reductions in ecological footprints in the long run. Economic growth and squared growth are significant

Table 7. Results of the PMG and MG.

	PMG		MG	
Variables	Coef.	t-statistics	Coef.	t-statistics
Long-run results				
lnRE	−0.061	0.922	0.560	0.535
lnGLO	−0.315**	0.016	0.729	0.196
lnRGDP	3.120**	0.036	−2.415	0.728
$lnRGDP^2$	−0.059**	0.048	0.053	0.712
lnPOPD	−0.439***	0.000	−1.179	0.007
Short-run results				
ECT_{-1}	−0.33**	0.045	−0.609***	0.000
ΔlnRE	−0.249	0.693	−0.438	0.565
ΔlnGLO	0.219	0.000	0.004	0.973
ΔlnRGDP	29.754	0.271	39.164	0.147
$\Delta lnRGDP^2$	−0.712	0.279	−0.898	0.159
ΔlnPOPD	1.017	0.111	2.806	0.230
Hausman χ^2	2.95	P-value	0.708	

Note: ***, **, * denote significance levels at 1%, 5% and 10%, respectively.

and have positive and negative effects on ecological footprints, respectively, in the long run; hence confirming the presence of the EKC hypothesis in IGAD countries. A 1% increase in economic growth is equivalent to a 3.12% increase in ecological footprint in the long run. Conversely, squared growth tends to improve environmental quality by reducing ecological footprints. A 1% increase in squared growth results in a 0.05% decrease in ecological footprint in the long run in IGAD countries. Hence, there is an inverted U-shaped relationship between economic growth and ecological footprint in the long run.

Further, the short-run coefficients are also disclosed in table 7. It reveals that most of the independent variables are insignificant in the short run. Globalization tends to impede environmental quality in IGAD countries in the short run by increasing their ecological footprint. A 1% increase in globalization leads to an increase of 0.22% in ecological footprint in the short run. Moreover, the ECT is significant and has a negative coefficient, which shows the convergence of the model. Renewable energy, economic growth, squared growth, globalization, and population density adjust 33% of the disequilibrium in ecological footprint annually in the long run.

3.2. Dumitrescu hurlin panel causality tests

Since the interested variables are cointegrated in the long run, we examine the Granger causality of the parameters, and its results are given in table 8. The causality results underscored bidirectional causality between population density and globalization, population density and economic growth, and population density and squared growth. Moreover, unidirectional causalities are detected from ecological footprint to population density, renewable energy, economic growth, and squared economic growth. Similarly, globalization causes economic growth and squared economic growth, but not the other way around. A unidirectional causality from renewable energy to population density, economic growth, and squared economic growth is observed. This could be explained by the fact that energy is an engine for economic growth and enhances the standard of living in society.

3.3. Robust analysis

We also use panel dynamic ordinary least squares (DOLS) to check the long-term results of panel cointegration methods (PMG and MG) to find reliable results. Its result is contained in table 9. It reveals that globalization, population density, renewable energy, and squared economic growth mitigate ecological footprints in the long run even though they are insignificant, whereas economic growth increases it. The coefficient results of DOLS are in line with the results of PMG in the long run.

3.4. Discussion of the result

The empirical findings of the study have established that economic growth inhibits environmental quality by about 3%; nevertheless, a square of growth improves the ecological footprint by 0.05% in the long run, hence verifying the presence of the EKC hypothesis in IGAD nations. Notably, environmental resources massively contribute to GDP, where the agriculture sector constitutes 70% of export earnings and creates 80% of employment opportunities in the region (IGAD 2023). Overexploitation of environmental resources increases economic productivity at the cost of increasing ecological footprints. This is in contrast to an empirical study by

Table 8. Dumitrescu Hurlin panel causality tests.

Null hypothesis:	W-stat.	Zbar-stat.	Prob.
lnGLO $\nRightarrow$ lnEFPC	2.369	0.131	0.896
lnEFPC $\nRightarrow$ lnGLO	3.192	0.802	0.423
lnPOPD $\nRightarrow$ lnEFPC	2.152	−0.047	0.963
lnEFPC $\nRightarrow$ lnPOPD	14.205	9.779	0.000
lnRE $\nRightarrow$ lnEFPC	1.381	−0.675	0.499
lnEFPC $\nRightarrow$ lnRE	7.281	4.135	4.E-05
lnRGDP $\nRightarrow$ lnEFPC	3.106	0.731	0.4647
lnEFPC $\nRightarrow$ lnRGDP	12.751	8.594	0.0000
lnRGDP^2 $\nRightarrow$ lnEFPC	3.126	0.748	0.454
lnEFPC $\nRightarrow$ lnRGDP^2	12.884	8.703	0.000
lnPOPD $\nRightarrow$ lnGLO	6.729	3.725	0.0002
lnGLO $\nRightarrow$ lnPOPD	291.751	238.099	0.0000
lnRE $\nRightarrow$ lnGLO	2.074	−0.104	0.9172
lnGLO $\nRightarrow$ lnRE	1.819	−0.313	0.7546
lnRGDP $\nRightarrow$ lnGLO	1.267	−0.767	0.4430
lnGLO $\nRightarrow$ lnRGDP	6.764	3.753	0.0002
lnRGDP^2 $\nRightarrow$ lnGLO	1.244	−0.787	0.431
lnGLO $\nRightarrow$ lnRGDP^2	6.712	3.711	0.0002
lnRE $\nRightarrow$ lnPOPD	9.892	6.325	3.E-10
lnPOPD $\nRightarrow$ lnRE	4.098	1.561	0.118
lnRGDP $\nRightarrow$ lnPOPD	66.102	52.547	0.000
lnPOPD $\nRightarrow$ lnRGDP	50.428	39.658	0.000
LRGDP^2 $\nRightarrow$ lnPOPD	62.554	49.629	0.000
lnPOPD $\nRightarrow$ lnRGDP^2	49.441	38.847	0.000
lnRGDP $\nRightarrow$ lnRE	4.163	1.614	0.106
lnRE $\nRightarrow$ lnRGDP	11.542	7.682	2.E-14
lnRGDP^2 $\nRightarrow$ lnRE	4.300	1.727	0.084
lnRE $\nRightarrow$ lnRGDP^2	11.663	7.782	7.E-15
lnRGDP^2 $\nRightarrow$ lnRGDP	1.545	−0.539	0.589
lnRGDP $\nRightarrow$ lnRGDP^2	1.568	−0.519	0.603

Table 9. Panel dynamic least squares (DOLS).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
lnGLO	−0.058	0.218	−0.266	0.792
lnPOPD	−0.487	0.235	−2.069	0.043
lnRE	−0.927	0.767	−1.208	0.232
lnRGDP	2.437	1.476	1.651	0.104
lnRGDP^2	−0.052	0.029	−1.744	0.087
	R-squared	0.97		
	Adjusted R-squared	0.95		

Sarkodie and Ozturk (2020) that found the existence of the EKC hypothesis in Kenya but contradicts the previous examination by Warsame *et al* (2022), who failed to establish the existence of the EKC hypothesis in Somalia. A plethora of studies verified the presence of the EKC hypothesis in various countries and regions, such as (Waluyo and Terawaki 2016) in Indonesia, (Ssali *et al* 2019) in a sample of six SSA countries.

Furthermore, it was observed that there exists a significant relationship between population density and the reduction of ecological footprint, with a long-term decrease of approximately 0.43%. The region is characterized by having more than 230 million populations with high growth rates. The average population density is estimated at 30 people per KM2 in the region. Nevertheless, there exists significant variability in population density across the member countries within the area, with Somalia exhibiting a density of 14.5 individuals per square kilometer, while Uganda tops this with a density of over 95 individuals per square kilometer (IGAD 2023). The reducing effect of population density on ecological footprints corroborates the previous results of Borck and Schrauth (2021), who found that population density reduces ozone concentrations in Germany. Similar results was produced by Yang *et al* (2021), that discovered an increase in population density enhances air quality in China. But this contradicts the study of Wafiq and Suryanto (2021) in Indonesia, who concluded that population density hampers the environmental quality index in Indonesia.

Likewise, it has been discovered that globalization has a substantial impact on reducing the ecological footprint in IGAD countries, resulting in an approximate long-term decrease of 0.31%. Consequently, this phenomenon contributes to the enhancement of environmental quality within these nations. Ample previous studies support our result. For instance, Rafindadi and Usman (2019) provided evidence indicating that globalization improves environmental quality in South Africa. A similar result has been observed by Akadiri *et al* (2019) in a sample of 15 panel countries. Zafar *et al* (2019) also concluded that globalization has a constructive role in enhancing environmental quality in OECD countries. On the other hand, others concluded that globalization has a detrimental effect on environmental quality via unsustainable economic development. For instance, Sabir and Gorus (2019) found that globalization tends to increase environmental degradation in South Asian countries.

Regarding the role of renewable energy in mitigating ecological footprints, it does not have any significant effect on ecological footprints in IGAD countries. The small share of renewable energy in the total energy mix in IGAD nations could be attributed to the inconsequential effect of clean energy on environmental quality in IGAD countries. A plethora of studies revealed the insignificant effect of renewable energy on environmental quality, such as those by Al-Mulali, Ozturk *et al* (2015) who revealed that renewable energy does not have any effect on pollution in a panel of 23 European countries.

4. Conclusion and policy implications

Environmental sustainability has become a topical in recent decades, fueling the debate on climate change mitigation and adaptation strategies. Several factors have been found to affect environmental quality in the literature. In this regard, this undertaking tries to verify the validity of the EKC hypothesis in a sample of IGAD countries. Moreover, the study also tries to quantify the impact of renewable energy and globalization on environmental quality. Contrary to previous attempts, this study uses ecological footprints as a measurement of environmental quality instead of CO_2 emissions, GHGs, and deforestation. The study applies a variety of econometric techniques including Pedroni, Kao, Johansen Fisher Panel Cointegration methods, panel heterogeneous methods, and Dumitrescu Hurlin Panel causality. Before the formal analysis, we test the presence of CSD among the interested parameters in different panels using the Pesaran test. The results of the CSD indicated that the interested parameters are related across the countries; hence, they could not be used with the first-generation unit root test. Because of cross-sectional dependence, we used the second-generation unit root test of the (CADF and the CIPS tests. Hence, the interested parameters are integrated into the mixed orders, which are appropriate for the heterogeneous panel methods. It was found that in the long term, renewable energy, globalization, economic growth, squared growth, and population density are all connected to the ecological footprint as shown by Kao, Pedroni, and Maddala and Wu cointegration methods.

Furthermore, the results of PMG revealed that clean energy enhances environmental quality in IGAD countries, but it is insignificant. In the same vein, population density reduces the ecological footprint. Economic growth and squared growth are significant and have positive and negative effects on ecological footprints, respectively, in the long run, hence confirming the validity of the EKC hypothesis in IGAD countries. In contrast, the causality results indicate bidirectional causality between population density and globalization, population density and economic growth, and population density and squared growth. Moreover, unidirectional causalities are detected from ecological footprint to population density, renewable energy, economic growth, and squared economic growth. Similarly, globalization causes economic growth and squared economic growth, but not the other way around. A unidirectional causality from renewable energy to population density, economic growth, and squared economic growth is observed.

In light of the empirical results, several policy implications are recommended. Since renewable energy has a negative coefficient but is insignificant, policymakers should increase the share of clean energy—geothermal, wind, biofuels, and solar energy—in the total energy mix. This will improve environmental quality without hampering sustainable economic growth. Moreover, it is observed that globalization significantly reduces the ecological footprint. As such, government policies and regulations that make it easy for IGAD member countries to integrate with the rest of the world in terms of trade, economics, and social issues are highly recommended. These will improve environmental quality by reducing the ecological footprint. Finally, economic growth significantly hampers environmental quality, but square growth boosts it. However, policymakers should install policies boosting growth along with cleaner energy production.

Despite the potential environmental benefits of ramping up the adoption of clean energy sources like geothermal, wind, biofuels, and solar energy, the feasibility of such a transition may be hampered by the lack of sufficient financial resources and infrastructure for renewable energy development and distribution in many IGAD nations. Additionally, reducing the ecological footprint through globalization requires addressing trade barriers, improving transportation networks, and bolstering technological capabilities, all of which may be hampered by existing infrastructural deficiencies and bureaucratic obstacles. Moreover, achieving a balance between economic growth and environmental preservation demands meticulous policy planning and execution to promote sustainable development while addressing pressing socio-economic needs. Policymakers must navigate these challenges by prioritizing investments in renewable energy infrastructure, enhancing trade facilitation, and enacting regulations that foster sustainable economic growth without worsening environmental degradation. Collaboration with international partners and tapping into external support may also be crucial for overcoming these barriers and ensuring the successful implementation of the proposed policy recommendations in the IGAD region.

Even though the study addresses a pressing issue of environmental sustainability, it is not immune from limitations. One of the limitations of the study is that it focused on socio-economic determinants of ecological footprints. Hence, we recommend future studies examine the role of institutional quality variables on ecological sustainability in IGAD countries using more updated data.

Declaration

Data availability

The datasets used and/or analysed during the current study are available at the following links:

https://kof.ethz.ch/en/data/kof-time-series-database.html

https://www.sesric.org/query.php

https://data.worldbank.org/country/somalia?view=chart

https://data.footprintnetwork.org/?_ga=2.114866626.455078021.1736608208-1803182371.1736608208#/

Compliance with ethical standards

Ethical approval

Not applicable.

Competing interests

The authors declare that they have no conflicts of interest.

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Authors' contributions

Abdimalik: Conceptualization, Methodology, Formal analysis, Writing e original draft. Hudayfe:Writing the introduction and literature.
Abdukadir: Reviewing &editing.

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