University of Reading

Government effectiveness, eco-efficiency and environmental sustainability in Africa

Article

Published Version

Creative Commons: Attribution-Noncommercial-No Derivative Works 4.0

Open Access

Dzudzor, M. A. ORCID: https://orcid.org/0009-0001-2150-1950, Oyawole, F. P. ORCID: https://orcid.org/0000-0001-5899-7120, Aminu, R. O. ORCID: https://orcid.org/0000-0003-4746-354X and Adusei Peasah, K. (2026) Government effectiveness, eco-efficiency and environmental sustainability in Africa. Scientific African, 32. e03406. ISSN 24682276 doi: 10.1016/j.sciaf.2026.e03406 Available at https://centaur.reading.ac.uk/130755/

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.

To link to this article DOI: http://dx.doi.org/10.1016/j.sciaf.2026.e03406

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the End User Agreement.

www.reading.ac.uk/centaur

University of Reading

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Scientific African 32 (2026) e03406

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Government effectiveness, eco-efficiency and environmental sustainability in Africa

Maxwell Adizor Dzudzor [a,*], Funminiyi Peter Oyawole [b,c], Raheem Olatunji Aminu [a,b], Kwadwo Adusei Peasah [a]

[a] School of Agriculture, Policy and Development, University of Reading, Earley Gate, Whiteknights, RG6 6UR Reading, United Kingdom
[b] Department of Agricultural Economics and Farm Management, Federal University of Agriculture Abeokuta, PMB 2240, Alabata Road, Abeokuta, Ogun State, Nigeria
[c] Department of Agricultural Economics and Agribusiness, University of Ghana, P.O. Box LG 25 Legon, Accra, Ghana

ARTICLE INFO

Editor: DR B Gyampoh

Keywords:
Eco-efficiency
Ecological footprint
EKC
Government effectiveness
Africa

ABSTRACT

The study examines the relationship between eco-efficiency, government effectiveness, and ecological footprint in Africa across low-income countries (LICs), lower-middle-income countries (LMICs), and upper-middle-income countries (UMICs) spanning 1992 to 2020. Using various standard pre-estimation tests to account for the dataset's structure, we used the Driscoll-Kraay Standard Error (DKSE) estimator and the Dumitrescu-Hurlin (DH) non-causality test for this study. The empirical findings reveal that eco-efficiency incentivises ecological degradation in LICs, whilst in LMICs it promotes ecological sustainability. The moderating effect of government effectiveness stimulates an increase in ecological footprint in LMICs, which possibly reflects weak institutional capacity that limits the translation of efficiency gains into environmental benefits, whilst in the LICs and UMICs categories, it spares ecological footprint. Additionally, the analysis revealed a two-way causation between eco-efficiency and ecological footprint across the LICs and LMICs, suggesting a feedback loop in which efficiency improvements both influence and respond to ecological pressure. In UMICs, a unidirectional causality from eco-efficiency to ecological footprint is observed, indicating that gains in efficiency directly impact environmental outcomes. Still, ecological pressure does not appear to drive further efficiency improvements. Thus, UMICs may benefit more from proactive policies that focus on enhancing eco-efficiency to reduce environmental degradation. Based on these findings, the study recommends the strengthening of public institutions across the Continent to design and implement tailored, eco-efficient environmental policies that not only reduce ecological footprints but also support long-term sustainability across African countries.

Introduction

In recent decades, the relationship between environmental degradation and economic growth has attracted significant attention, especially within the context of the Environmental Kuznets Curve (EKC) hypothesis [1,2]. Economic growth is often linked to increased natural resource extraction, leading to severe environmental outcomes such as deforestation, biodiversity loss, and land degradation.

* Corresponding author.
E-mail address: m.a.dzudzor@pgr.reading.ac.uk (M.A. Dzudzor).

https://doi.org/10.1016/j.sciaf.2026.e03406
Received 15 May 2025; Received in revised form 5 May 2026; Accepted 8 May 2026
Available online 10 May 2026
2468-2276/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

In particular, environmental degradation is frequently driven by inappropriate agricultural practices, including the absence of conservation measures, and heavy machinery use (AbdelRahman et al. 2018). These environmental pressures have prompted global efforts toward sustainable development, as reflected in the Sustainable Development Goals (SDGs), which aim to harmonise economic growth with environmental sustainability [3]. Environmental sustainability, in this context, refers to the responsible use and management of natural resources and ecosystems to meet present human needs without compromising their capacity to regenerate and support future generations [4,5].

This nexus between economic growth and environmental sustainability is particularly critical in Africa, where rapid economic expansion and population growth accelerate the demand for natural resources. Africa is the second-fastest-growing region in the world, behind Asia in terms of economic growth, and the fastest-growing continent by population, which is expected to double by 2050 [6]. Since 2007, Africa's ecological footprint has exceeded its biocapacity, indicating that the continent now consumes more resources than its ecosystems can regenerate [7]. Projections suggest that the continent's ecological footprint, as of 2015, may be doubled by 2040 [8], posing significant risks to economic stability and social well-being, given that many economies and livelihoods depend heavily on natural resources [9,10].

In response to these challenges, an increasing number of studies have examined factors influencing the ecological footprint in Africa, aiming to identify pathways toward environmentally sustainable development [8]. These studies have explored the influence of various factors, including urbanisation, foreign direct investment, globalisation, energy consumption, trade openness, and economic development, to validate the EKC hypothesis on the continent [8,11,12]. Despite these contributions, the roles of eco-efficiency and government effectiveness in shaping environmental outcomes remain underexplored in Africa. Building on this existing body of work, this study examines the influence of eco-efficiency and government effectiveness on the ecological footprint in Africa.

Eco-efficiency is defined as the ability to generate economic output while minimising environmental resource use and emissions, and operationalised in this study as the ratio of gross domestic product (GDP) to total domestic resource extraction [13,14]. While often associated with positive environmental outcomes, it can also negatively affect the ecological footprint. On the one hand, improving eco-efficiency is expected to generate economic value with fewer resources, thereby reducing resource use and environmental degradation. This occurs through the adoption of cleaner, "green" technologies and energy-efficient processes that minimise footprint [15]. However, gains in eco-efficiency can paradoxically increase the ecological footprint. This may occur when efficiency improvements reduce production costs, encouraging higher consumption and potentially increasing overall environmental impact [15].

Government effectiveness, an important dimension of institutional quality, is crucial in influencing environmental outcomes through the formulation and implementation of environmental policies. According to the World Bank [16], it refers to the quality of public services and the civil service, policy formulation and implementation, and the credibility of government decisions. In countries with weak governance and limited regulatory capacity, environmental regulations are often poorly designed and enforced, leading to greater environmental degradation. Conversely, effective governments can reduce ecological footprint by promoting sustainable practices across sectors and establishing and enforcing robust regulatory frameworks [17]. This study examines the joint effect of eco-efficiency and government effectiveness on ecological footprint, providing empirical evidence on the relationship between governance and resource efficiency in Africa.

This study makes three key contributions to the literature. First, it examines the interaction between government effectiveness and eco-efficiency, providing evidence on their combined impact on environmental outcomes in Africa. This focus is theoretically important because the dominant framework, the EKC hypothesis, primarily emphasises economic growth, with limited attention to the institutional conditions under which technological and production processes translate into environmental outcomes. Drawing on institutional theory, although eco-efficiency, through technological innovation and resource-use efficiency, is expected to reduce environmental degradation, its effectiveness depends on the quality of institutions that shape incentives, enforce regulations, and guide production behaviour [18–20]. Strong institutions, particularly effective governments, are essential for designing and implementing environmental policies and standards that ensure the adoption of cleaner technologies [21,22]. In this sense, government effectiveness provides the regulatory and policy environment that enables eco-efficiency gains to translate into improved environmental outcomes. Examining their interaction therefore offers a more comprehensive understanding of the channels through which economic activity affects environmental sustainability, particularly in Africa where institutional capacity and technological progress vary considerably.

Second, it contributes to the EKC debate in the literature regarding the hypothesised inverted-U relationship between environmental degradation and economic growth in Africa, where empirical evidence remains mixed. Unlike previous studies [8,12], this study utilises economic complexity instead of GDP per capita as a measure of economic development, as it more effectively reflects the structure and technological characteristics of an economy, which are more relevant to environmental outcomes [23]. Lastly, the study disaggregates the results into country income groups (LICs, LMICs, and UMICs), providing a better understanding of environmental outcomes across different stages of economic development. The paper is structured as follows: Section 2 reviews the relevant literature, and Section 3 outlines the methodology, detailing the data sources, variables, and econometric approach. Section 4 presents the empirical results and discusses the findings, and Section 5 concludes the paper.

Literature review

The channels of ecological degradation have been examined through various theoretical frameworks, including the EKC hypothesis, the pollution haven or halo hypothesis, and decoupling theory. Among these, the EKC hypothesis is the most widely used framework in related studies, and this research is grounded in this theoretical perspective. The EKC hypothesises that as economies develop, environmental degradation tends to increase but declines when income per capita grows to some threshold, creating an inverted "U" shaped relationship [8,12]. Despite gaining considerable attention, the EKC hypothesis remains debated in the literature due to inconsistent empirical evidence [24–26]. While some studies support the hypothesis [27,28], others find that degradation persists even at higher income levels [29,30]. This study contributes to the literature on this debate by utilising economic complexity rather than the typical GDP per capita used in previous African studies on the EKC [8,12], as it accounts for each country's economic structure and technological sophistication, both of which are directly linked to environmental outcomes [23].

The empirical divergence of evidence on the EKC hypothesis suggests that environmental outcomes depend not only on economic growth, but also on other contextual, country-specific factors [31]. One such factor is government effectiveness, a key measure of institutional quality, which determines how environmental policies are designed, implemented, and enforced, thereby influencing environmental outcomes. For instance, Wang et al. [17] demonstrated that government effectiveness significantly reduces ecological footprint within BRICS countries, highlighting how institutional quality can mitigate environmental degradation in emerging economies with relatively stronger governance structures. Conversely, Yang et al. [32] found that government effectiveness drives ecological footprint in ecological reserve countries, while no significant relationship was observed in ecological deficit countries. Khan et al. [33] also report mixed global findings, reflecting significant economic and institutional heterogeneity across countries that may influence the capacity of government effectiveness to impact ecological outcomes uniformly.

Eco-efficiency, a measure of a country's capacity to generate economic output while minimising environmental resource use, has also emerged as an important factor influencing ecological footprint in the literature. However, while empirical evidence suggests that improved eco-efficiency can mitigate ecological degradation through reduced resource use [34,35], its impact is not universally positive. For example, Chenavaz et al. [15] and Holm and Englund [36] find that eco-efficiency's impact on ecological footprint is counterintuitive, as improvements in eco-efficiency may trigger a rebound effect, in which efficiency gains lower production costs and inadvertently increase resource use. These mixed findings suggest that the effect of eco-efficiency on environmental outcomes may differ across countries, depending on existing environmental policy frameworks and institutional quality. Thus, this study explores this relationship by examining the joint effect of eco-efficiency and government effectiveness on ecological footprint in Africa.

Globalisation also affects environmental outcomes through its complex roles in economic integration, technology exchange, and resource use, as is evident in the mixed evidence on its impact in the literature. On the one hand, several studies [37–40] report that globalisation drives ecological degradation through increased resource overexploitation, higher carbon emissions from expanded trade and transportation, and greater waste generation, particularly in countries with weaker environmental regulations. On the other hand, other studies highlight its role in promoting the adoption of green technologies and environmentally sustainable inputs in production, thereby significantly reducing harmful gas emissions and solid and liquid waste [41–43].

Energy consumption represents another critical factor influencing ecological outcomes, particularly given its direct link to resource consumption and emissions. Different studies have shown that energy consumption, especially from conventional sources, is a major driver of ecological footprint through greenhouse gas emissions and air pollution [44–46]. However, the impact of energy

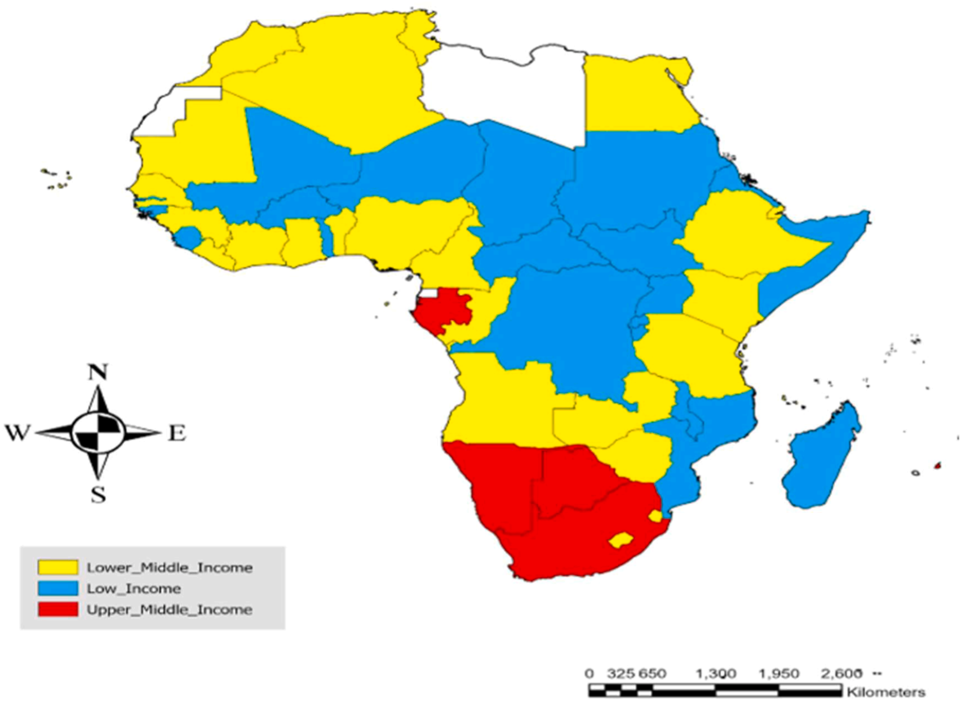

Fig. 1. Map of Africa showing the selected countries (Source: Authors).

consumption may not be generalisable to all countries, given the differences in their respective energy profiles. For example, increased energy consumption in countries that are heavily dependent on fossil fuels is expected to significantly increase ecological footprint, while countries with a greater proportion of clean energy in their energy profile may have a lower environmental impact [47]. Thus, this study disaggregates results by income group (LICs, LMICs, UMICs) to account for this heterogeneity in environmental outcomes across stages of economic development.

Overall, the above literature shows that ecological footprint is influenced by economic growth, and a range of factors including government effectiveness, eco-efficiency and globalisation. This study contributes to the literature by examining the joint effect of eco-efficiency and government effectiveness on ecological footprint, assessing the EKC hypothesis using economic complexity rather than GDP per capita and examining income-group heterogeneity to reveal how environmental drivers differ across development stages.

Materials and methods

Study area

This study was conducted in Africa due to the paucity of scholarly literature exploring the relationship between eco-efficiency, government effectiveness and ecological footprint within the continent. The continent comprises 56 countries [48], spanning various economic classifications, including low-income, lower-middle-income, upper-middle-income, and high-income countries. Africa's contribution to the global ecological footprint was just 3.8%, yet it experienced the most significant impact of the emission consequences [49]. Fig. 1 presents the map of Africa, indicating the countries selected for this study, and Table A of the appendix section also provides the list of these countries.

Data sources

In this study, a balanced panel dataset for 39 African countries spanning 1992 to 2020 was employed. The period is selected based on data availability, completeness, and consistency across variables and countries. Although some datasets extend beyond 2020, key indicators contain missing or inconsistent observations for many of the countries after this point, and extending the period would result in an unbalanced panel and potentially biased estimates.

The selected countries accounted for about 70% of the African countries, providing a representative coverage of the continent for robust empirical analysis. Table 1 outlines the descriptions, data sources, and codes for all variables included in our study.

Data processing

A preliminary data handling and manipulation exercise was conducted to ensure the suitability of the dataset for the analysis. For ease of interpretation, data on variables such as the economic complexity index (ECI) and government effectiveness (GEF) were transformed by adding +3.5 and +2.5 to their series, respectively, before taking their natural logarithm.

Theoretical underpinning and empirical model

The study draws on three complementary frameworks: institutional theory Mahmud, [20]; North, [50], which suggests environmental outcome is largely influenced by regulatory quality; the environmental kuznets curve (EKC) hypothesis Grossman & Krueger, [51], which posits a non-linear relationship between economic development and environmental degradation; and the eco-efficiency perspective Schaltegger & Sturm, [52]; Wang et al., [14] which focuses on decoupling economic output from resource use.

Accordingly, ecological footprint (EF) is modelled as a function of economic complexity (ECI), eco-efficiency (EFI), energy consumption (EU), globalisation index (GI) and government effectiveness (GEF):

Table 1
Data sources and measurement.

Variable	Description	Source	Code
Ecological footprint	Measures the demand human consumption places on the biosphere (global hectares).	Global footprint network	EF
Eco-efficiency	An index of gross domestic product (constant 2015 USD) over total domestic extraction from the environment (tonnes).	Authors' computation based on data from the World Bank database and the UN Environment Program database, respectively.	EFI
Economic complexity index	A metric of an economy's productive structure. It captures the inputs, technologies and innovations available to an economy to produce and trade competitively.	The Atlas of Economic Complexity	ECI
Energy consumption	Total energy consumption (terawatt-hours per year)	Our world of data	EU
Globalisation index	A composite index of countries' globalisation across three indices: social, economic and political.	KOF Swiss Economic Institute database	GI
Government effectiveness index	The quality of public services and policy formulation, and the degree of government commitment to such policies.	World Governance Indicators	GEF

$$EF = f(EFI, ECI, EU,\ GI,\ GEF) \tag{1}$$

Consistent with the view that institutional capacity conditions the effectiveness of resource efficiency [22], the model includes an interaction term between eco-efficiency and government effectiveness. A quadratic term of economic complexity is also incorporated to test the EKC hypothesis.

To account for heterogeneity, the model is estimated across disaggregated income groups (LICs, LMICs, and UMICs). This is motivated by the fact that the drivers of ecological degradation and the capacity of institutions to mitigate them may vary across developmental stages. Aggregated estimation may therefore cloud important group-specific dynamics.

The empirical model is specified as:

$$lnEF_{it} = \alpha_i + \beta_1 \cdot lnEFI_{it} + \beta_2 \cdot lnECI_{it} + \beta_3 \cdot lnECI_{it}^2 + \beta_4 \cdot lnEU_{it} + \beta_5 \cdot lnGI_{it} + \beta_6 \cdot lnGEF_{it} + \ \beta_7 (lnEFI_{it} \cdot lnGEF_{it}) + u_{it} \tag{2}$$

Where *ln* is the natural logarithm, *i* indexes the country, *t* represents the time, α, and β_{1-7} are the estimated parameters; u_{it} is the error term. The log-linear specification allows coefficients to be interpreted as elasticities, while the interaction term captures the conditional effect of eco-efficiency on government effectiveness.

Analytical strategy

The implementation of the analytical strategy began by subjecting the variables to diagnostic tests, including checks for cross-sectional dependence, slope homogeneity, and stationarity. Subsequently, the coefficients were estimated using the Driscoll-Kraay Standard Error Estimator (DKSE), and the analysis concluded with the Dumitrescu-Hurlin causality test.

Cross-sectional dependence (CD test)

A cross-sectional dependency test was conducted due to the regional interconnections among African economies, where a shock in one country can spread to others via the contagion effect [53]. Evidence also shows cross-sectional dependence in African economic data [54]. This test guides the choice of stationarity tests (first or second-generation) and estimation techniques. Using the Pesaran [55] CD method, the test is specified as follows:

$$\boldsymbol{CD} = \sqrt{\frac{2\boldsymbol{T}}{\boldsymbol{N}(\boldsymbol{N}-1)}}\left(\sum_{\boldsymbol{i}=1}^{\boldsymbol{N}-1}\sum_{\boldsymbol{j}=\boldsymbol{i}+1}^{\boldsymbol{N}}\boldsymbol{\rho_{ij}}\right) \Rightarrow \boldsymbol{N}(0,1) \tag{3}$$

Where ρ_{ij} is the cross-sectional correlation coefficient derived from the residuals; N is the number of countries, and T denotes years of observation. Furthermore, the Breusch-Pagan LM [56] was used to check the presence of panel effects on the dataset. The test is specified as.

$$LM_{BP} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^2 \tag{4}$$

In the situation whereby $N \to \infty$, Pesaran [55] suggested a scaled version of the Breusch-Pagan LM test as follows

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}\left(T\widehat{\rho}_{ij}^2 - 1\right) \tag{5}$$

Slope homogeneity test

After testing for cross-sectional dependency, the slope homogeneity test was conducted to determine if slope coefficients are homogeneous or heterogeneous. The null hypothesis is $H_o:\ \beta_1 = \beta$ for i while the alternative is stated as $H_1:\ \beta_1\ \neq \beta$ for all $i \neq j$. The Pesaran and Yamagata [57] slope homogeneity test was applied using Eqs. (5), 6 and 7, respectively.

$$\widetilde{S} = \sum_{i=1}^{N}(\widetilde{\beta}_i - \widetilde{\beta}_{WFE})'\frac{x'_i M_\tau x_i}{\widetilde{\sigma}_i^2}(\widehat{\beta}_i - \widetilde{\beta}_{WFE}) \tag{6}$$

Where $\widehat{\beta}_i$ equals the pooled OLS estimator, $\widetilde{\beta}_{WFE}$ represents the fixed effect pooled estimator, M_τ is the identity matrix and $\widetilde{\sigma}_i^2$ equals the estimator of σ_i^2.

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S} - k}{\sqrt{2k}}\right) \tag{5.a}$$

Δ is the delta tilde, while $\widetilde{\Delta}_{adj}$ stands for the adjusted delta tilde.

$$\widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}S - E(\widetilde{z}_{it})}{\sqrt{var(\widetilde{z}_{it})}}\right) \tag{7}$$

Where $E(\widetilde{z}_{it}) = K$ and the variance $var(\widetilde{z}_{it}) = 2k(T - k - 1)/T + 1$

Panel unit root

The stationarity of the study variables was checked using the cross-sectionally augmented Dickey-Fuller (CADF) test proposed by Pesaran [58]. The CADF is a panel unit root test that accounts for cross-sectional dependence in the data. It consists of the standard Dickey-Fuller regression, augmented with cross-sectional means of lagged levels and the first difference series i_{th} in the panel [58]. Consistent with existing studies, the CADF is specified as:

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t} + \delta_i y_{t-1} + \sum_{j=0}^{k} \delta_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{k} \Delta y_{i,t-j} + \varepsilon_{it} \tag{8}$$

Where $y_{t-1} = \frac{1}{N}\sum_{i=1}^{N} \Delta y_{i,t-1}; \Delta y_t = \frac{1}{N}\sum_{i=1}^{N} \Delta y_{it};$ α_i is constant; k is the lag specification; $t_i(N, T)$.

The empirical model: driscoll kraay standard error estimator (DKSEE)

Given the presence of cross-sectional dependency and slope heterogeneity in the dataset, the Driscoll-Kraay Standard Error (DKSE) estimator was utilised following Hafeez et al. [59] and Javeed et al. [60] to avoid biased estimates. The DKSE estimator is used in panel data regression to address potential violations of the assumptions underlying standard errors, such as heteroscedasticity and autocorrelation. It is ideal for data with temporal and cross-sectional dependence, delivering robust, consistent standard errors even when residuals are correlated across time and individuals [61,62].

Causality test

The analysis concludes with a causality test between the dependent and independent variables of interest, using the Dumitrescu & Hurlin [63] non-causality test. The method addresses heterogeneity and cross-sectional dependency via block bootstrapping to compute critical values and p-values [53]. The test is described in Eqs. (11) and 12 as:

$$x_{i,t} = \varphi_{1i} + \sum_{k=1}^{K} \varphi_{1i}^{(k)} x_{i,t-k} + \sum_{k=1}^{K} \psi_{1i}^{(k)} y_{i,t-k} + \varepsilon_{1i,t} \tag{11}$$

$$y_{i,t} = \varphi_{2i} + \sum_{k=1}^{K} \varphi_{2i}^{(k)} y_{i,t-k} + \sum_{k=1}^{K} \psi_{2i}^{(k)} y_{i,t-k} + \varepsilon_{2i,t} \tag{12}$$

The stationary dependent and independent variables are denoted by x *and* y, while φ_{1i} and φ_{2i} are country-specific effects. K is the lag length, chosen based on Akaike's information criteria (AIC) for each specific case. $(\varphi_{1i}^{(k)}\ and\ \varphi_{2i}^{(k)})$ and $(\psi_{1i}^{(k)}\ and\ \psi_{2i}^{(k)})$ represent the auto-regressive parameters and regression coefficients, respectively.

Results

The results from the study are presented in this section. The analysis begins with a CD test of dependency to establish the existence of cross-sectional interrelationships within the countries and to determine the type of panel unit root test to adopt, followed by a slope homogeneity test to assess whether the slope coefficients are homogeneous or heterogeneous. The panel unit root test is then implemented to confirm whether its statistical properties are consistent. These preliminary tests guided the choice of estimator to ensure the robustness and validity of the findings. Given the presence of cross-sectional dependency and slope homogeneity in the panel data structure, the study proceeded with the Driscoll-Kraay Standard Error (DKSE) to address potential violations of assumptions underlying standard errors, such as heteroscedasticity and autocorrelation. Finally, the Dumitrescu & Hurlin (DH) causality test is used to assess directional relationships among the study's key variables.

Results from cross-sectional dependency test

The results of the cross-sectional dependency (CSD) tests across the three income categories are presented in Table 2 employing Breusch-Pagan LM, Pesaran CD, and Pesaran scaled LM tests. Strong dependence is observed across all three income categories, given that the null hypothesis of no CSD is rejected in all three tests. These results suggest that a shock in a country in the same income

Table 2
Results of cross-sectional dependency test.

	LIC		LMIC		UMIC	
	Stat	**Prob**	**Stat**	**Prob**	**Stat**	**Prob**
Pesaran CD	10.279	0.000	3.313	0.000	3.015	0.013
Pesaran scaled LM	45.670	0.000	57.217	0.000	3.202	0.001
Breusch-Pagan LM	827.509	0.000	1305.358	0.000	10.843	0.003

category is likely to be transmitted to other countries within the same category and highlight the need for second-generation panel unit root testing.

Results from the slope homogeneity test

The results from the Pesaran and Yamagata slope homogeneity test are reported in Table 3. The null hypothesis of slope homogeneity is rejected at 1% significance level in both model 1 (the baseline model, without governance interaction) and model 2 (with governance interaction) and across the income categories. This indicates that the relationships between the explanatory variables and the ecological footprint differ across the countries, reflecting variations in governance effectiveness, eco-efficiency and economic complexity.

Panel unit root test result

To confirm the stationarity of the selected study variables, the cross-sectionally augmented Dickey-Fuller (CADF) test is applied across the three income groups. The results from Table 4 reveal that the variables are mixed ordered, i.e., some are stationary at level, I (0), while others become stationary after first differencing, I(1), across the income groups. Thus, the null hypothesis of a panel unit root is rejected at both levels and in first differences for the corresponding variables.

Results of driscoll-kraay estimator

The results of the estimation using the DKSE estimator are reported in Table 5. Model 1 presents the baseline model without eco-efficiency interacting with government effectiveness, while Model 2 includes this interaction. The models show satisfactory explanatory power across the income categories, as indicated by the adjusted R-squared values.

Table 5 indicates a positive effect of economic complexity on ecological footprint (significant at 10%) in LMICs. At the same time, the squared term is statistically significant and negative, supporting an EKC relationship with a turning point at 1.721, beyond which further increases in complexity reduce environmental impact. However, this pattern is absent in LICs and UMICs, where the expected statistical relationship does not hold. This suggests the relationship between economic complexity and environmental quality varies by development stage. Specifically, LMICs may be in a transitional phase of economic production, in which growing complexity enables cleaner production and improved institutional responses.

In contrast, UMICs may have moved beyond the EKC turning point, altering the nature of the relationship. This aligns with Destek and Sarkodie [64], who identified the EKC in newly industrialised countries, and Apergis and Ozturk [65], who found similar evidence in 14 Asian LMICs. However, it contradicts the findings of Tachega et al. [66], who reported EKC in LIC and UMIC African countries for GDP and carbon emissions. The difference between this study's EKC results and those of prior research, like Tachega et al. [66], likely arises from the use of the economic complexity index instead of GDP per capita. Unlike income-based measures, the economic complexity index captures structural and technological dimensions of the economy, which possibly detect the EKC transition differently from income-based indicators.

Eco-efficiency shows mixed effects across income groups. In LICs, it is linked with increases in ecological footprint by 0.36%, suggesting an efficiency rebound effect, where efficiency gains lead to increased resource use [36]. In LMICs, eco-efficiency is associated with a reduction in footprint by 0.13%, indicating a positive sustainability impact. This finding is consistent with Zhang and Ke [35] and Appiah et al. [34], who reported a similar negative relationship between eco-efficiency and ecological footprint in China and Sub-Saharan Africa, respectively. However, in UMICs, the effect is statistically insignificant, possibly due to a saturation effect, where earlier gains from eco-efficiency may have already been realised, and further improvements no longer translate into significant environmental benefits without deeper structural changes. The positive relationship between eco-efficiency and ecological footprint in LICs highlights that sustainable consumption policies in Africa's LICs may be weak. In contrast, the negative relationship observed in LMICs suggests relatively stronger policy frameworks that are better aligned with sustainability goals through improved production efficiency.

Similarly, government effectiveness has heterogeneous effects across the income categories. In LICs and LMICs, government effectiveness increases ecological footprint, suggesting that governance structures prioritise economic growth and development over environmental sustainability considerations. Consequently, these priorities heighten resource consumption and environmental degradation, making governance improvements ineffective in curbing environmental impacts. In contrast, government effectiveness

Table 3
Results from Pesaran Yamagata slope homogeneity test.

	LIC		LMIC		UMIC	
	$\widetilde{D}$	$\widetilde{D}_{adj}$	$\widetilde{D}$	$\widetilde{D}_{adj}$	$\widetilde{D}$	$\widetilde{D}_{adj}$
Model 1	10.903***	12.813***	14.144***	16.621***	4.527***	5.320***
Model 2	10.224***	12.813***	12.923***	15.561***	4.367***	5.258***

Note: ***, ** and * denotes 1%, 5% and 10% significance levels. The null hypothesis tested was that the slope was homogenous. Model 1 is the baseline model without governance interaction, whilst model 2 contains governance interaction.

Table 4
Results of cross-sectional ADF test.

	LIC		LMIC		UMIC	
Variable	Level	First diff.	Level	First diff.	Level	First diff.
LN_EF	−2.671***	−4.090***	−2.789***	−4.673***	−2.075	−3.788***
LN_EFI	−1.633	−3.823***	−2.176**	−3.656***	−1.647	−4.204***
LN_ECI	−2.581***	−4.372***	−2.614***	−2.552***	−1.222	−4.428***
LN_ECI2	−2.564***	−4.446***	−2.552***	−4.686***	−1.277	−4.358***
LN_EU	−1.990	−3.533***	−2.013	−3.761***	−0.943	−3.592***
LN_GI	−2.492***	−3.659***	−2.695***	−4.498***	−3.054***	−2.909**
LN_GEF	−1.943	−3.020***	−1.625	−3.089***	−2.909**	−2.933**
LN_EFILN_GEF	−1.943	−3.053***	−1.606	−2.865***	−2.518*	−2.977**

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

Table 5
Results of Driscoll-Kray standard error estimation.

	LIC		LMIC		UMIC	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
LN_EFI	0.359***	1.011**	−0.128**	−0.154**	−0.095	0.594
	[0.098]	[0.426]	[0.054]	[0.057]	[0.164]	[0.369]
LN_ECI	−4.260	−2.865	0.686*	0.585	0.609	0.262
	[2.624]	[2.194]	[0.372]	[0.416]	[1.160]	[1.056]
LN_ECI2	2.859*	2.091	−0.632**	−0.602**	−0.420	−0.127
	[1.513]	[1.310]	[0.241]	[0.270]	[0.623]	[0.563]
LN_EU	1.229***	1.144***	0.843***	0.844***	0.910***	0.880***
	[0.039]	[0.065]	[0.041]	[0.043]	[0.033]	[0.023]
LN_GI	−4.337***	−4.071***	−0.637***	−0.700***	0.338	0.462***
	[0.452]	[0.297]	[0.149]	[0.163]	[0.212]	[0.167]
LN_GEF	1.121***	8.793**	0.121*	−0.037	−0.439***	3.610**
	[0.161]	[4.088]	[0.067]	[0.047]	[0.101]	[1.453]
LN_EFILN_GEF		−1.513*		0.045**		−0.664***
		[0.799]		[0.021]		[0.240]
Constant	28.987***	24.346***	16.604***	16.994***	11.969***	7.409***
	[2.480]	[2.017]	[0.525]	[0.639]	[0.535]	[1.820]
EKC Holds	No	-	Yes	-	No	-
Turning point	N/A	-	1.721	-	N/A	-
Observations	464.000	464.000	580.000	580.000	87.000	87.000
R-squared	0.485	0.508	0.819	0.820	0.995	0.996
Number of groups	16.000	16.000	20.000	20.000	3.000	3.000

Standard errors in parentheses.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

reduces ecological footprint in UMICs, highlighting the role of strong institutions and better policy enforcement capacity, especially at the higher levels of economic development. This result corroborates prior evidence from Wang et al. [17] for BRICS countries and from Salman et al. [67] for Asian economies. Interestingly, the results show that the interaction between eco-efficiency and government effectiveness significantly reduces ecological footprint in LICs and UMICs by 1.513% and 0.664%, respectively, suggesting that these factors can reinforce each other to promote environmental sustainability. These results indicate the complementary roles of resource-use efficiency and effective government institutions in achieving better environmental outcomes. The interaction's positive effect in LMICs (0.045%), although small, possibly reflects weak institutional capacity that limits the translation of efficiency gains into environmental benefits.

Energy consumption significantly increases ecological footprint across all income groups at 1% significance level. A 1% rise in energy use boosts ecological footprint by 1.229% in LICs, 0.843% in LMICs, and 0.910% in UMICs, indicating that higher energy use for economic activities worsens environmental quality. This stems from Africa's dependence on non-renewable energy, limited by high costs and financing challenges for renewables. These results are consistent with findings by Destek and Sarkodie [64], Charfeddine and Mrabet [68] and Zafar et al. [69], who reported similar trends in Middle East and North African (MENA) countries, global industrialising economies, and the USA, respectively.

Globalisation index is unexpectedly associated with a reduction in ecological footprint of 4.337% in LICs and 0.637% in LMICs per 1% increase. This contradicts the pollution haven hypothesis, which suggests that improvement in globalisation relocates environmental degradation to regions with lax regulations. The observed association may stem from factors such as improved access to cleaner technologies, knowledge transfer, or stricter environmental regulations accompanying global integration.

Causality test results

Table 6 presents the results from the DH non-causality test. The results reveal a one-way causation from economic complexity to ecological footprint in LICs, and bi-directional causality in LMICs and UMICs. Thus, policy shocks to productive structures impact ecological footprint in LICs, while in LMICs and UMICs, changes in production affect ecological footprint and vice versa. Energy consumption Granger-causes ecological footprint in LICs and UMICs, with bi-directional causality in LMICs. The bi-directional causality found in the LMIC suggests that energy consumption determines ecological outcomes, and, conversely, ecological degradation constrains energy consumption. The LIC result contrasts with that of Ansari and Khan [70], who found that ecological footprint and direct energy use in lower-income Asian countries.

Globalisation and ecological footprint exhibit bi-directional causality across all income categories at 1% significance level, a finding consistent with Karimli et al. [71], which found similar results between social globalisation and ecological footprint in 35 European countries. Similarly, a bi-directional causality exists between ecological footprint and government effectiveness in LMICs, while in LICs and UMICs, causality runs one way from ecological footprint to governance. These results contrast with Zhu et al. [72], who found that government effectiveness drives ecological footprint in China. Lastly, eco-efficiency and ecological footprint show bi-directional causality in LICs and LMICs, but unidirectionally cause ecological footprint in UMICs.

Conclusions, recommendations, and study limitations

Conclusion

Africa's ecological footprint, though lower than that of other continents, is growing due to increasing industrialisation and socioeconomic activity, highlighting the need for sustainable consumption and production. This study examined the role of eco-efficiency, government effectiveness and related factors in shaping ecological footprint across 39 African countries (1992–2020). The results confirm an EKC relationship between economic complexity and ecological footprint in LMICs. Government effectiveness raises ecological footprint in LICs and LMICs but reduces it in UMICs, where stronger institutions support sustainability. Eco-efficiency has mixed impacts: it increases ecological footprint in LICs, reduces it in LMICs, and is insignificant in UMICs. The combined effect of eco-efficiency and governance reduces ecological footprint in LICs and UMICs but increases it in LMICs, highlighting governance quality as a key factor in shaping environmental outcomes. These findings are consistent with institutional theory, which emphasises that environmental outcomes depend not only on economic growth, resource-use efficiency, and technological improvements, but also on the quality of institutions that determine the regulatory and policy environment. In particular, the results show that government effectiveness conditions the environmental impact of eco-efficiency, although this effect varies across countries at different levels of development. Causality test results revealed that economic complexity drives ecological footprint in LICs, while the relationship is bi-directional in LMICs and UMICs. Eco-efficiency and ecological footprint are bi-directionally linked in LICs and LMICs, while in UMICs, eco-efficiency drives ecological footprint. Government effectiveness and ecological footprint are bi-directionally linked in LICs and UMICs, but one-way in LMICs.

Policy recommendations

Based on the study's findings, improving eco-efficiency alone may not lower ecological footprints, especially in LICs, where it can worsen degradation due to the rebound effect. To address this, LICs should pair eco-efficiency with strict environmental policies such as emission caps and pollution taxes to regulate resource-intensive sectors like the industrial and agricultural sectors. In LMICs, where eco-efficiency reduces ecological footprint, governments should support green innovation through targeted grants for cleaner technologies such as filtration and purification systems to reduce emissions, and investment in machinery that uses alternative fuel, e.g., biofuels. For UMICs, where eco-efficiency has no significant effect, policy focus should shift to broader sustainability strategies. For instance, given their relatively advanced industrial and infrastructural capacity, many of Africa's UMICs are well placed to adopt circular economy approaches, such as green innovation and industrial symbiosis (a collaborative relationship in which different

Table 6
Results of Dumitrescu & Hurlin causality test.

	LIC		LMIC		UMIC	
Null hypothesis	Z_bar	Direction of Causality	Z_bar	Direction of Causality	Z_bar	Direction of Causality
LN_EF ≠> LN_ECI	0.363	EF ⇐ ECI	4.944***	EF ⇔ECI	9.411***	EF ⇔ ECI
LN_ECI ≠> LN_EF	4.466***		3.637***		6.053***	
LN_EF ≠> LN_EU	1.619	EF ⇐ EU	6.941***	EF ⇔EU	−0.559	EF ⇐ EU
LN_ EU ≠> LN_EF	7.476***		13.040***		3.716***	
LN_EF ≠> LN_GI	12.427***	EF ⇔ GI	6.187***	EF ⇔ GI	15.638***	EF ⇔ GI
LN_ GI ≠>LN_EF	10.105***		2.785***		8.268***	
LN_EF ≠> LN_EFI	9.887***	EF ⇔ EFI	4.383***	EF ⇔ EFI	1.318	EF ⇐ EFI
LN_EFI ≠>LN_EF	7.001***		4.929***		5.890***	
LN_EF≠> LN_GEF	11.280***	EF ⇔ GEF	6.090***	EF ⇒ GEF	2.628***	EF ⇔ GEF
LN_ GEF≠>LN_EF	8.935***		1.325		3.309***	

industries or companies share resources and wastes), to improve resource efficiency and reduce their ecological footprint.

Improving government effectiveness is also critical, particularly in LMICs, where the gains from eco-efficiency are undermined by weak governance. This study recommends strengthening institutional capacity through establishing and enforcing robust regulatory frameworks to reverse this trend and promote sustainable practices across sectors. Furthermore, governance models from UMICs could serve as valuable references for LICs and LMICs to mitigate the direct environmental impact of weak government effectiveness.

Finally, to address the consistently observed adverse effect of energy consumption on ecological footprint across all income groups, policymakers should increase investment in renewable energy to reduce dependence on fossil fuels and increase the availability of green energy across the African continent.

Study limitations

Despite the study's empirical contribution to ecological sustainability in Africa, the research has some limitations. First, it excludes 17 African countries due to data unavailability, which may limit the generalisability of the findings, as the excluded countries could differ systematically from those included in the study. Future studies should aim to include these excluded countries as relevant data become available to provide a more comprehensive regional assessment. Second, while the study controls for key economic, institutional, and environmental variables, it does not explicitly account for social or cultural variables such as societal environmental values, which could also potentially influence environmental outcomes. Future research could explore incorporating these variables as appropriate cross-country data become available.

Lastly, the study relied on natural resource extraction per unit of GDP to measure ecological efficiency, which is considered a mono-directional measure, as it may understate ecological efficiency gains from technological improvements. Future studies could address this limitation by adopting broader efficiency indicators, such as total factor productivity.

Credit author statement

Maxwell Adizor Dzudzor: conceptualization, data handling, formal analysis, writing of the original manuscript and approved the final manuscript. Funminiyi Peter Oyawole: formal analysis, writing of the original manuscript and approved the final manuscript. Raheem Olatunji Aminu: data handling, formal analysis, writing of the original manuscript and approved the final manuscript. Kwadwo Adusei Peasah: formal analysis, writing of the original manuscript and approved the final manuscript.

Funding

This research work did not receive funding or financial support in the preparation of the document.

Data availability

The dataset used in the study is available on Mendeley at:
https://data.mendeley.com/datasets/9f747v659j/2

Declaration of competing interest

The authors declare no competing financial or non-financial interests that could influence this research work.

Appendix

Table A

Table A
Country classifications by income level.

S/N	LIC	S/N	LMIC	S/N	UMIC
1	Burundi	17	Angola	37	Gabon
2	Burkina Faso	18	Benin	38	Mauritius
3	Central African Rep.	19	Côte d'Ivoire	39	South Africa
4	DR. Congo	20	Cameroon		
5	Gambia	21	Rep. of Congo		
6	Guinea-Bissau	22	Comoros		
7	Madagascar	23	Cabo Verde		
8	Mali	24	Algeria		
9	Mozambique	25	Egypt		
10	Malawi	26	Ghana		
11	Niger	27	Guinea		
12	Rwanda	28	Kenya		
13	Sudan	29	Morocco		

(*continued on next page*)

Table A (*continued*)

S/N	LIC	S/N	LMIC	S/N	UMIC
14	Sierra Leone	30	Mauritania		
15	Togo	31	Nigeria		
16	Uganda	32	Senegal		
		33	Tunisia		
		34	Tanzania		
		35	Zambia		
		36	Zimbabwe		

Source: World Bank Group [16].

References

[1] A.O. Acheampong, E.E.O. Opoku, Environmental degradation and economic growth: Investigating linkages and potential pathways, Energy Econ. 123 (2023) 106734, https://doi.org/10.1016/j.eneco.2023.106734.

[2] B.V. Osuntuyi, H.H. Lean, Environmental degradation, economic growth, and energy consumption: the role of education, Sustain. Develop. 31 (2) (2023) 1166–1177, https://doi.org/10.1002/sd.2480.

[3] United Nations, The-sustainable-Development-Goals-Report-2023. https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf, 2023.

[4] V. Kaswan, M. Choudhary, P. Kumar, S. Kaswan, P. Bajya, Green production strategies, in: P. Ferranti, E. Berry, A. Jock (Eds.), Encyclopedia of Food Security and Sustainability, 2019, pp. 492–500, https://doi.org/10.1016/B978-0-08-100596-5.22292-0.

[5] M.A. Said, F.U. Hassan, M.S. Islam, M.E. Bin Toriman, A. Rehim, M.A. Bashir, H.M. Ali Raza, R. Nawaz, Environmental sustainability, in: S. Idris (Ed.), Global Challenges for the Environment and Climate Change, IGI Global Scientific Publishing, 2024, pp. 1–15, https://doi.org/10.4018/979-8-3693-2845-3.ch001.

[6] African Development Bank, Africa's macroeconomic performance and outlook. https://www.afdb.org/en/documents/africas-macroeconomic-performance-and-outlook-january-2024, 2024.

[7] J. Kouton, S.T. Tuo, E.W. Guilsou, Thresholds to sustainability: globalisation's impact on the institutional quality-ecological footprint nexus in Africa, Sci. Total Environ. 954 (2024) 176205, https://doi.org/10.1016/j.scitotenv.2024.176205.

[8] D.K. Espoir, R. Sunge, T. Nchofoung, A.A. Alola, Analysing the drivers of ecological footprint in Africa with machine learning algorithm, Environ. Impact. Assess. Rev. 104 (2024) 107332, https://doi.org/10.1016/j.eiar.2023.107332.

[9] S.M. Herrmann, M. Brandt, K. Rasmussen, R. Fensholt, Accelerating land cover change in West Africa over four decades as population pressure increased, Commun. Earth Environ. 1 (1) (2020) 53, https://doi.org/10.1038/s43247-020-00053-y.

[10] World Bank, Poverty reduction in Africa. https://openknowledge.worldbank.org/bitstream/handle/10986/32354/9781464812323.pdf, 2019.

[11] S.T. Marquart-Pyatt, Environmental sustainability: the ecological footprint in West Africa, Human Ecol. Rev. 22 (1) (2015), https://doi.org/10.22459/HER.22.01.2015.05.

[12] D.O. Okelele, R. Lokina, Effect of trade openness on ecological footprint in Sub-Saharan Africa, Afr. J. Econ. Rev. 10 (1) (2022).

[13] P. Sadorsky, Eco-efficiency for the G18: trends and future outlook, Sustainability 13 (20) (2021) 11196, https://doi.org/10.3390/su132011196.

[14] C.-N. Wang, H.-P. Hsu, Y.-H. Wang, T.-T. Nguyen, Eco-efficiency assessment for some European countries using slacks-based measure data envelopment analysis, Appl. Sci. 10 (5) (2020) 1760, https://doi.org/10.3390/app10051760.

[15] R.Y. Chenavaz, S. Dimitrov, F. Figge, When does eco-efficiency rebound or backfire? An analytical model, Eur. J. Oper. Res. 290 (2) (2021) 687–700, https://doi.org/10.1016/j.ejor.2020.08.039.

[16] World Bank, The Worldwide Governance Indicators: Revised Methodology For Measuring Governance Using Perception Data, World Bank Methodology Paper, 2025. https://www.worldbank.org/content/dam/sites/govindicators/doc/The%20Worldwide%20Governance%20Indicators%202025%20Methodology%20Revision.pdf.

[17] E. Wang, H. Padhan, S.K. Pruseth, J. Ma, Government efficiency, green technology, and ecological footprint: strategic framework for natural resource management efficiency targets, Res. Policy 91 (2024) 91, https://doi.org/10.1016/j.resourpol.2024.104826.

[18] G.B. Amegavi, Z. Langnel, A. Ahenkan, T. Buabeng, The dynamic relationship between economic globalisation, institutional quality, and ecological footprint: evidence from Ghana, J. Int. Trade Econ. Dev. 31 (6) (2022) 876–893, https://doi.org/10.1080/09638199.2022.2033303.

[19] M. Mahmoodi, N. Dahmardeh, Environmental kuznets curve hypothesis with considering ecological footprint and governance quality: evidence from emerging countries, Front. Environ. Sci. 10 (2022) 849676, https://doi.org/10.3389/fenvs.2022.849676.

[20] R. Mahmud, Understanding institutional theory in public policy, Dyn. Public Administr. 34 (2) (2017) 135, https://doi.org/10.5958/0976-0733.2017.00011.6.

[21] M. Bhattacharya, S.A. Churchill, S.R. Paramati, The dynamic impact of renewable energy and institutions on economic output and CO2 emissions across regions, Renew. Energy 111 (2017) 157–167, https://doi.org/10.1016/j.renene.2017.03.102.

[22] S.A. Asongu, N.M. Odhiambo, How enhancing information and communication technology has affected inequality in Africa for sustainable development: an empirical investigation, Sustain. Develop. 27 (4) (2019) 647–656, https://doi.org/10.1002/sd.1929.

[23] C.A. Hidalgo, R. Hausmann, The building blocks of economic complexity, Proc. Nat. Acad. Sci. 106 (26) (2009) 10570–10575, https://doi.org/10.1073/pnas.0900943106.

[24] O. Neagu, M.I. Neagu, The environmental Kuznets Curve revisited: economic complexity and ecological footprint in the most complex economies of the world. *Studia Universitatis Vasile Goldis Arad*, Econ. Series 32 (1) (2022) 78–99, https://doi.org/10.2478/sues-2022-0005.

[25] A.A. Purcel, New insights into the environmental Kuznets curve hypothesis in developing and transition economies: a literature survey, Environ. Econ. Policy Stud. 22 (4) (2020) 585–631, https://doi.org/10.1007/s10018-020-00272-9.

[26] N. Schneider, Sustainable development or environmental Kuznets curve: some unresolved controversies, Int. J. Environ. Stud. 80 (3) (2023) 531–534, https://doi.org/10.1080/00207233.2022.2078109.

[27] U. Shahzad, Z. Fareed, F. Shahzad, K. Shahzad, Investigating the nexus between economic complexity, energy consumption and ecological footprint for the United States: new insights from quantile methods, J. Clean. Prod. 279 (2021) 279, https://doi.org/10.1016/j.jclepro.2020.123806.

[28] R. Ulucak, F. Bilgili, A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries, J. Clean. Prod. 188 (2018) 144–157.

[29] L. Charfeddine, The impact of energy consumption and economic development on ecological footprint and CO2 emissions: evidence from a Markov Switching Equilibrium Correction model, Energy Econ. 65 (2017) 355–374, https://doi.org/10.1016/j.eneco.2017.05.009.

[30] M.A. Destek, R. Ulucak, E. Dogan, Analysing the environmental Kuznets curve for the EU countries: the role of ecological footprint, Environ. Sci. Pollut. Res. 25 (29) (2018) 29387–29396, https://doi.org/10.1007/s11356-018-2911-4.

[31] S.K. Mandal, D. Chakravarty, Is environmental Kuznets curve a universal phenomenon?: - an econometric analysis of the existing studies, J. Develo. Areas 50 (6) (2016) 261–276, https://doi.org/10.1353/jda.2016.0133.

[32] L. Yang, S.B. Danwana, F.L.Y. Issahaku, Achieving environmental sustainability in Africa: the role of renewable energy consumption, natural resources, and government effectiveness—evidence from symmetric and asymmetric ARDL models, Int. J. Environ. Res. Public Health 19 (13) (2022) 19, https://doi.org/10.3390/ijerph19138038.
[33] H. Khan, L. Weili, I. Khan, L. Oanh, Recent advances in energy usage and environmental degradation: does quality institutions matter? A worldwide evidence, Energy Reports 7 (2021) 1091–1103, https://doi.org/10.1016/j.egyr.2021.01.085.
[34] M. Appiah, S.T. Onifade, B.A. Gyamfi, Pathways to sustainability in Sub-Sahara Africa: are institutional quality levels subservient in achieving green GDP growth? J. Knowl. Econ. 16 (2024) 2366–2390, https://doi.org/10.1007/s13132-024-01774-7.
[35] H. Zhang, H. Ke, Understanding the heterogeneous impact of innovation efficiency on urban ecological footprint in China, Int. J. Environ. Res. Public Health 19 (10) (2022) 6054, https://doi.org/10.3390/ijerph19106054.
[36] S.O. Holm, G. Englund, Increased ecoefficiency and gross rebound effect: evidence from USA and six European countries 1960-2002, Ecol. Econ. 68 (3) (2009) 879–887, https://doi.org/10.1016/j.ecolecon.2008.07.006.
[37] Anser, M.K., Usman, M., Godil, D.I., Shabbir, M.S., Sharif, A., Tabash, M.I., Lopez, L.B., & Lydiabares, L.B.L. (2021). *Does globalisation affect the green economy and environment? The relationship between energy consumption, carbon dioxide emissions, and economic growth.* https://doi.org/10.1007/s11356-021-14243-4/Published.
[38] T. Daszkiewicz, Food production in the context of global developmental challenges, Agriculture (Switzerland) 12 (6) (2022) 832, https://doi.org/10.3390/agriculture12060832.
[39] H. Kopackova, A. Zelena, The effects of globalisation on application of environmental management system (EMS), in: SHS Web of Conferences 92, 2021 02030, https://doi.org/10.1051/shsconf/20219202030.
[40] T.T.H. Nguyen, T.A. Le, T. Le-Dinh, T.H.A. Pham, G.Q. Phan, T.M. Vuu, H.M. Bui, Nexus of Globalization and Environmental Quality: investigating heterogeneous effects through quantile regression analysis, Polish J. Environ. Stud. 33 (1) (2024) 767–779, https://doi.org/10.15244/pjoes/172042.
[41] D. Balsalobre-Lorente, M. Shahbaz, M. Murshed, F.M. Nuta, Environmental impact of globalisation: the case of central and Eastern European emerging economies, J. Environ. Manage. 341 (2023) 341, https://doi.org/10.1016/j.jenvman.2023.118018.
[42] J. Li, F. Yahya, M. Waqas, Exploring the nexus of globalisation and natural resource scarcity in driving green technology innovation: insights from advanced panel data techniques, Nat. Resour. Forum. 49 (2025) 1965–1995, https://doi.org/10.1111/1477-8947.12463.
[43] L. Zhang, M. Xu, H. Chen, Y. Li, S. Chen, Globalisation, Green economy and environmental challenges: state of the art review for Practical implications, Front. Environ. Sci. 10 (2022), https://doi.org/10.3389/fenvs.2022.870271.
[44] M.T. Kartal, The role of consumption of energy, fossil sources, nuclear energy, and renewable energy on environmental degradation in top-five carbon producing countries, Renew. Energy 184 (2022) 871–880, https://doi.org/10.1016/j.renene.2021.12.022.
[45] S.A. Sarkodie, V. Strezov, Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries, Sci. Total Environ. 646 (2019) 862–871, https://doi.org/10.1016/j.scitotenv.2018.07.365.
[46] M.W. Zafar, S.A.H. Zaidi, N.R. Khan, F.M. Mirza, F. Hou, S.A.A Kirmani, The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: the case of the United States, Res. Policy 63 (2019) 63, https://doi.org/10.1016/j.resourpol.2019.101428.
[47] J Kouton, D. Kamara, K.G.M. Kouame, Modelling the effects of energy diversification on ecological footprint: evidence from Côte d'Ivoire, Environ. Sci. Pollut. Res. 29 (21) (2022) 31761–31780, https://doi.org/10.1007/s11356-021-17603-2.
[48] M. Mostefaoui, P. Ciais, M.J. McGrath, P. Peylin, P.K. Patra, Y. Ernst, Greenhouse gas emissions and their trends over the last 3 decades across Africa, Earth Syst. Sci. Data 16 (1) (2024) 245–275, https://doi.org/10.5194/essd-16-245-2024.
[49] A.S. von Czechowski, CDP Africa Report: benchmarking progress towards climate safe cities, states, and regions, March, https://cdn.cdp.net/cdp-production/cms/reports/documents/000/005/023/original/CDP_Africa_Report_2020.pdf?1583855467, 2020.
[50] D.C. North, Institutions, Institutional Change and Economic Performance, Cambridge University Press, 1990.
[51] Grossman, G.M., & Krueger, A.B. (1991). *Environmental impacts of a North American free trade agreement* (Number 3914).
[52] Schaltegger, S., & Sturm, A. (1990). *Ökologieinduzierte entscheidungsprobleme des managements: ansatzpunkte zur ausgestaltung von instrumenten* (Number WWZ Discussion Paper No. 8914).
[53] J.T. Dada, C.O. Olaniyi, F.M. Ajide, A. Adeiza, M. Arnaut, Informal economy and ecological footprint: the case of Africa, Environ. Sci. Pollut. Res. 29 (49) (2022) 74756–74771, https://doi.org/10.1007/s11356-022-20919-2.
[54] C.E.W. Yameogo, J.A. Omojolaibi, R.O.S. Dauda, Economic globalisation, institutions and environmental quality in Sub-Saharan Africa, Res. Globaliz. 3 (2021) 100035, https://doi.org/10.1016/j.resglo.2020.100035. December 2020.
[55] M.H. Pesaran, General diagnostic tests for cross section dependence in panels, Economics 1240 (1) (2004) 1.
[56] T.S. Breusch, A.R. Pagan, The lagrange multiplier test and its applications to model specification in econometrics, Rev. Econ. Stud. 47 (1) (1980) 239, https://doi.org/10.2307/2297111.
[57] M. Hashem Pesaran, T. Yamagata, Testing slope homogeneity in large panels, J. Econom. 142 (1) (2008) 50–93, https://doi.org/10.1016/j.jeconom.2007.05.010.
[58] M.H. Pesaran, A simple panel unit root test in the presence of cross-section dependence, J. Appl. Econom. 22 (2007) 265–312, https://doi.org/10.1002/jae.951.
[59] M. Hafeez, C. Yuan, K. Shahzad, B. Aziz, K. Iqbal, S. Raza, An empirical evaluation of financial development-carbon footprint nexus in one Belt and Road region, Environ. Sci. Pollut. Res. 26 (24) (2019) 25026–25036, https://doi.org/10.1007/s11356-019-05757-z.
[60] S. Javeed, H.M.A. Siddique, F. Javed, Ecological footprint, globalisation, and economic growth: evidence from Asia, Environ. Sci. Pollut. Res. 30 (31) (2023) 77006–77021, https://doi.org/10.1007/s11356-023-27754-z.
[61] D. Hoechle, Robust standard errors for panel regressions with cross-sectional dependence, Stata J. 7 (3) (2007) 281–312, https://doi.org/10.1177/1536867x0700700301.
[62] T.J. Vogelsang, Heteroskedasticity, autocorrelation, and spatial correlation robust inference in linear panel models with fixed-effects, J. Econom. 166 (2) (2012) 303–319, https://doi.org/10.1016/j.jeconom.2011.10.001.
[63] E.I. Dumitrescu, C. Hurlin, Testing for Granger non-causality in heterogeneous panels, Econ. Model. 29 (4) (2012) 1450–1460, https://doi.org/10.1016/j.econmod.2012.02.014.
[64] M.A. Destek, S.A. Sarkodie, Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development, Sci. Total Environ. 650 (2019) 2483–2489, https://doi.org/10.1016/j.scitotenv.2018.10.017.
[65] N. Apergis, I. Ozturk, Testing environmental Kuznets curve hypothesis in Asian countries, Ecol. Indic. 52 (2015) 16–22, https://doi.org/10.1016/j.ecolind.2014.11.026.
[66] M.A. Tachega, X. Yao, Y. Liu, D. Ahmed, W. Ackaah, M. Gabir, J. Gyimah, Income heterogeneity and the environmental kuznets curve turning points: evidence from Africa, Sustainability (Switzerland) 13 (10) (2021) 13, https://doi.org/10.3390/su13105634.
[67] M. Salman, X. Long, L. Dauda, C.N. Mensah, The impact of institutional quality on economic growth and carbon emissions: evidence from Indonesia, South Korea and Thailand, J. Clean. Prod. (2019) 241, https://doi.org/10.1016/j.jclepro.2019.118331.
[68] L. Charfeddine, Z. Mrabet, The impact of economic development and social-political factors on ecological footprint: a panel data analysis for 15 MENA countries, in: Renewable and Sustainable Energy Reviews, 76, Elsevier Ltd, 2017, pp. 138–154, https://doi.org/10.1016/j.rser.2017.03.031.
[69] M.W. Zafar, S.A.H. Zaidi, N.R. Khan, F.M. Mirza, F. Hou, S.A.A. Kirmani, The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: the case of the United States, Res. Pol. (2019) 63, https://doi.org/10.1016/j.resourpol.2019.101428.

[70] M.A. Ansari, N.A. Khan, Decomposing the trade-environment nexus for high income, upper and lower middle income countries: what do the composition, scale, and technique effect indicate? Ecol. Indic. 121 (2021) 107122 https://doi.org/10.1016/j.ecolind.2020.107122.
[71] T. Karimli, N. Mirzaliyev, H. Guliyev, The globalization and ecological footprint in European countries: correlation or causation? Res. Globaliz. 8 (2024) 100208 https://doi.org/10.1016/j.resglo.2024.100208.
[72] Z.-G. Zhu, Y. Zhang, B. Obuobi, The impact of forest rents on ecological footprints in China: the moderating role of government effectiveness, Forests. 16 (3) (2025) 415, https://doi.org/10.3390/f16030415.