economies

Article

Evaluating Environmental Sustainability in Africa: The Role of Environmental Taxes, Productive Capacities, and Urbanization Dynamics

Adel Ben Youssef [1,*] and Mounir Dahmani [2]

[1] Groupe de Recherche en Droit, Economie, Gestion (GREDEG), Centre National de la Recherche Scientifique (CNRS), Côte d'Azur University, 06000 Nice, France
[2] Department of Economics, Higher Institute of Business Administration, University of Gafsa, Gafsa 2112, Tunisia; mounir.dahmani@isaeg.u-gafsa.tn
* Correspondence: adel.ben-youssef@univ-cotedazur.fr

Abstract: This study examines the complex relation among environmental taxes, productive capacities, urbanization, and their collective effects on environmental quality in Africa, drawing on two decades of data from twenty African countries. It situates the study within the broader discourse on sustainable development and economic growth, emphasizing the Environmental Kuznets Curve (EKC) framework to examine the relationship between economic development, characterized by urban expansion and increased productive capacities, and the adoption of environmental taxes amidst the continent's diverse economic and environmental environments. Using advanced econometric techniques, including the Cross-Section Augmented Autoregressive Distributed Lag (CS-ARDL) model and the Dynamic Common Correlated Effects Mean Group (DCCEMG) estimator, the study addresses data challenges such as cross-sectional dependence and slope heterogeneity. The results provide important insights into the dynamics of environmental quality in relation to economic and urban growth and the role of environmental taxation. The study proposes tailored policy strategies aimed at strengthening sustainable development initiatives in line with international agreements such as the Paris Agreement and the Sustainable Development Goals. These strategies advocate for a nuanced application of environmental taxes and the promotion of productive capacities to enhance environmental sustainability across the African continent.

Keywords: environmental taxes; productive capacities; urbanization; environmental quality; CS-ARDL; DCCEMG; AMG; Africa

JEL Classification: Q56; Q53; Q58; O44; R11; H23

check for updates

Citation: Ben Youssef, Adel, and Mounir Dahmani. 2024. Evaluating Environmental Sustainability in Africa: The Role of Environmental Taxes, Productive Capacities, and Urbanization Dynamics. *Economies* 12: 80. https://doi.org/10.3390/economies12040080

Academic Editor: Angeliki N. Menegaki

Received: 18 February 2024
Revised: 19 March 2024
Accepted: 26 March 2024
Published: 29 March 2024

1. Introduction

The quest for sustainable development in Africa is marked by a compelling paradox: the continent's minimal contribution to global greenhouse gas emissions contrasts sharply with its significant vulnerability to the impacts of climate change. This stark contrast underscores the urgent need for African countries to adopt development models that combine economic growth with environmental sustainability. This challenge is multidimensional, requiring the promotion of economic and technological progress while addressing the impacts of climate change, all within the framework of global sustainability benchmarks such as the Paris Agreement and the Sustainable Development Goals (SDGs). At this critical crossroads where aspirations for development, environmental integrity, and social equity meet, our study seeks to shed light on the intricate linkages between economic development, environmental sustainability, and social progress in the African context.

The paper identifies environmental taxes, productive capacities, and urbanization as key areas of investigation. Environmental taxes, based on the polluter pays principle

(Eurostat 2013; OECD 2019), are posited as influential mechanisms for promoting sustainable practices by imposing financial penalties on environmentally harmful activities. However, the discourse on their effectiveness is divided. Some studies emphasize their potential to mitigate environmental degradation (Tan et al. 2022; Köppl and Schratzenstaller 2023), while others highlight the socio-economic challenges they can create (Al-Rawi et al. 2023; Ullah et al. 2023). This divergence reinforces the need for environmental fiscal policies that are nuanced and tailored to the African context. At the same time, improving productive capacities is emerging as a critical strategy for sustainable growth, going beyond mere technological and infrastructural advances to include human capital development (UNCTAD 2021). However, the empirical literature presents a complex and varied picture of the relationship between productive capacities and environmental sustainability (Demissew Beyene and Kotosz 2020; Xin et al. 2023), underscoring the need for integrated and holistic development strategies.

Urbanization in Africa presents a dual narrative of progress and vulnerability. While urban expansion signals economic development, it also magnifies environmental challenges. The transformation of urban areas into centers of economic activity significantly affects environmental quality, primarily through changing pollution dynamics and resource consumption patterns (Ben Youssef et al. 2021; Balsalobre-Lorente et al. 2023; Khan et al. 2023; Abdulqadir 2024). Moreover, the search for affordable energy in rapidly urbanizing contexts in Africa is closely linked to rising carbon emissions, which are particularly pronounced in sub-Saharan Africa (Awad et al. 2023; Wang et al. 2023). These developments bring to the forefront the complex interactions between urbanization, renewable energy adoption, and environmental protection, requiring a comprehensive understanding of the environmental impacts of urban growth to inform sustainable development strategies.

Using the EKC hypothesis as a conceptual framework (Grossman and Krueger 1991; Dinda 2004; Stern 2004), this study examines the complex dynamics between environmental taxes, productive capacities, and urbanization within African countries. The EKC hypothesis suggests a nuanced relationship between economic growth and environmental health, positing an initial increase in environmental degradation that eventually subsides as income levels rise. This framework is central to analyzing the sustainable development trajectories of African countries. This research evaluates how African countries navigate the EKC through different stages of economic growth and assesses the collective impact of environmental taxes, productive capacities, and urbanization on environmental quality. By employing advanced econometric techniques to address issues of cross-sectional dependence, structural breaks, and slope heterogeneity (Pesaran 2006; Baltagi 2015), the study aims to achieve a comprehensive and nuanced understanding of the data while addressing the complexities inherent in panel data analysis.

This study contributes to the discourse on sustainable development in Africa by providing empirically grounded analysis that can inform policy formulation and stakeholder engagement for sustainable growth. By integrating economic and environmental dynamics within a robust analytical framework, our research seeks to guide African countries towards achieving the SDGs in line with global environmental standards.

The paper is organized sequentially, first providing a literature review that sets the theoretical and empirical stage, followed by a detailed description of the research methodology using advanced econometric approaches. An analysis of the data precedes a discussion section that situates the findings within the broader narrative of sustainable development. The study concludes with policy recommendations aimed at promoting sustainable development across the continent, thus affirming its contribution to the global sustainability agenda.

2. Background and Literature Review

2.1. Measuring Environmental Quality

Advancing sustainable development requires a nuanced understanding of environmental quality that integrates ecosystem health with socio-economic impacts. This integration of human initiatives and nature underscores the breadth of environmental quality, which goes beyond mere environmental metrics to include socio-economic impacts on human progress. Yolles (2018) and Purvis et al. (2019) delve into this deep connection between ecosystems and human well-being, shedding light on the multifaceted nature of environmental challenges. In addition, work by Shobande et al. (2024) on the marriage of information technology infrastructure with renewable energy heralds an important step in this cross-disciplinary dialogue, charting a path toward climate adaptability. Research by Caglar et al. (2024) and Wang et al. (2024) on the symbiotic relationship between environmental taxes, renewable energy initiatives, and the indispensable role of economic ingenuity in driving environmental progress underscores the critical need for sustainable policy frameworks tailored to African contexts.

Caglar et al.'s (2023) exploration of the interplay between natural resource use and environmental sustainability through the innovative lens of the load-capacity curve hypothesis offers new perspectives on managing natural resources for improved environmental health. This study enriches the broader discussion of strategic environmental management. Ali et al. (2024) and Luo et al. (2023) bring to light the substantial gains from green products and low-carbon technologies, which are further enhanced by environmental regulations that promote green innovation, highlighting the need for sound green market structures and comprehensive policy frameworks. In addition, Afshan and Yaqoob's (2023) analysis of green innovation and taxation, positioned within the load-capacity curve theory, underscores the strategic importance of green policies in the field of environmental governance. Huang et al. (2023), Karlilar et al. (2023), and Li et al. (2023) continue this discussion by analyzing how environmental laws, digitalization, and green innovation affect business and environmental sustainability and by arguing in favor of an integrated policy approach. The findings of Anttila and Jussila (2022), Chukkali et al. (2022), and Struwig (2022) on the link between sustainability and societal well-being, coupled with Afshari et al.'s (2022) analysis of social sustainability indicators in the energy sector, call for a holistic strategy. This strategy, which combines technological advances, renewable energy, and unified policies, is paramount to addressing the complexities of environmental sustainability in Africa and promoting sustainable practices across the continent.

2.2. Environmental Taxes and Environmental Quality

Africa's policy toolkit for enhancing environmental quality is starting to include environmental taxes as a key component. As defined by the OECD (2019), these fiscal measures target activities with a significant environmental footprint and embody the polluter pays principle by aiming to internalize the costs associated with environmental damage (Eurostat 2013). This range of taxes extends from pollution taxes, such as carbon taxes, aimed at reducing greenhouse gas emissions (Dahmani 2023; Köppl and Schratzenstaller 2023), to resource taxes that discourage the overuse of natural resources in line with circular economy principles (Tan et al. 2022), and includes taxes on specific products and services, such as single-use plastics, to promote sustainable consumption habits (Runst and Höhle 2022).

The tax rate, the availability of substitutes for the goods subject to the tax, and the distinct institutional and economic features of each region are among the variables that determine whether environmental taxes are successful in accomplishing their objectives (He et al. 2023; Youssef et al. 2023). Despite their potential, the application of these taxes faces challenges, in particular their regressive nature, which disproportionately affects low-income households (Al-Rawi et al. 2023; Ullah et al. 2023; Ben Youssef and Dahmani 2024), necessitating equitable measures such as subsidies or tax credits to ensure social equity. In addition, the phenomenon of carbon leakage, where stringent environmental taxes may induce industries to relocate to regions with less stringent regulations (Ahmed et al. 2022), underscores the importance of international cooperation in the area of environmental taxation.

The double dividend hypothesis proposed by Pearce (1991) introduces a more nuanced perspective, suggesting that environmental taxes can provide the dual benefits of environmental protection and employment growth. However, empirical research presents a mixed picture, indicating variability in the effectiveness of the hypothesis across the African continent, with different impacts on environmental degradation and employment (Mpofu 2022; Zhang et al. 2022; Degirmenci and Aydin 2023).

Furthermore, environmental taxes are instrumental in facilitating the transition to a greener economy by providing incentives for both businesses and consumers to adopt cleaner technologies and sustainable practices. This shift could catalyze innovation in green technology sectors and drive sustainable economic progress. However, the influence of these taxes shows significant variation across different economic landscapes, highlighting the nuanced nature of their impact (Abel et al. 2023; Farooq et al. 2023). Policy considerations, as highlighted by Tchapchet Tchouto et al. (2024), point to the potential negative impacts of green tax regimes on the industrialization process in African contexts, advocating for a balanced and cautious approach to the implementation of environmental tax policies. Comparative analyses further call for the tailoring of environmental tax policies to the different conditions prevailing in African countries (Ambareen 2023; Nemavhidi and Jegede 2023).

The success of environmental taxes in encouraging sustainable practices across a range of industries has been further illuminated by recent research. These studies highlight the strategic importance of environmental taxes in facilitating carbon sequestration, encouraging the adoption of renewable energy, promoting digital inclusion, and attracting foreign investment. Such fiscal strategies are closely aligned with the SDGs, particularly SDG 7 (clean energy) and SDG 13 (climate action), underscoring their role in advancing Africa towards these global goals (Bala and Khatoon 2024; Iyke-Ofoedu et al. 2024; Ullah et al. 2024; Yiadom et al. 2024). This body of research advocates for policy frameworks that judiciously balance environmental, economic, and social considerations, and positions environmental taxes as critical tools in unraveling the intricate nexus between economic activity, urban development, and environmental quality. When applied strategically, these taxes can help steer Africa toward a sustainable future where environmental protection, economic growth, and social welfare are in harmony.

2.3. Productive Capacities, Urbanization and Environmental Quality

Sustainable development in Africa is a complex interweaving of productive capacities, urbanization, and environmental quality. The United Nations Conference on Trade and Development (UNCTAD 2021) identifies the synergy of human and natural resources, together with advances in energy, transport, and information and communication technologies (ICTs), as critical pillars for sustainable economic growth that is in harmony with the planet's ecological balance.

The central role of human capital is underscored by Adjei et al. (2023) and Jahanger et al. (2023), who note that improved education and skills can lead to greater environmental awareness and the adoption of sustainable behaviors. However, this increased knowledge can also lead to consumption patterns that strain natural resources, presenting a nuanced challenge in aligning educational progress with environmental sustainability. The importance of natural capital in ensuring sustainable economic growth is highlighted by Brandt et al. (2017) and Oluc et al. (2023), with the latter study illustrating the environmental impact of structural changes in middle-income countries. They argue for a delicate balance between economic expansion and the preservation of environmental quality, highlighting the trade-offs inherent in structural transformation efforts.

The role of renewable energy in the transition of the energy sector is critical, as shown by Ahmad and Zhang (2020), Dahmani et al. (2021b), and Murshed et al. (2022), who emphasize the need to mitigate the environmental impacts of traditional energy sources. The evolution of the transportation sector towards sustainability is elaborated by Hasan et al. (2019), Li et al. (2021), and Alotaibi et al. (2022), pointing to the importance of sustainable mobility solutions in minimizing the environmental footprint of urban development.

The adoption of ICTs poses environmental challenges that require a balanced approach to their deployment and disposal (Chatti 2021; Dahmani et al. 2021a, 2023; Awad 2022;

Awad and Saadaoui Mallek 2023; Lin et al. 2023). This discussion is further enriched by Abba Yadou et al. (2024), who examine the nexus between remittances and ecological footprints in Africa, considering the mitigating role of ICTs. Their findings show that, while ICTs can exacerbate environmental degradation through increased energy demand, they also offer opportunities to reduce the environmental impact of remittances by facilitating more sustainable consumption patterns.

Effective governance and institutional strength are essential for steering economic activity toward environmental sustainability, with research by Awad (2022), Du et al. (2022), Hadj et al. (2023), and Sahoo et al. (2023) highlighting the role of policy and regulation in promoting sustainable practices. The involvement of the private sector in environmental quality, as discussed by Aldieri et al. (2020) and Demiral and Demiral (2023), illustrates both the opportunities and challenges of integrating sustainability into business operations.

The significant impact of urbanization on environmental quality requires sustainable urban planning and infrastructure development to mitigate pollution, waste generation, and resource depletion (Li et al. 2021). Khan et al. (2023) and Balsalobre-Lorente et al. (2023) examine the environmental impacts of urbanization in sub-Saharan Africa and the potential for ICTs to enhance urban environmental sustainability, respectively. Awad et al. (2023) highlight the positive role of sustainable infrastructure in improving urban ecological footprints, in line with the *SDGs*, which focus on sustainable cities and communities (SDG 11) and responsible consumption and production (SDG 12).

Adams and Kaffo Fotio's (2024) findings on economic integration and environmental quality in Africa, Nkemgha et al.'s (2024) exploration of the environmental impacts of industrialization mitigated by policy stringency, and Uche and Ngepah's (2024) examination of the influence of green technology and energy transition on South Africa's load factor collectively underscore the multifaceted relationship between economic activities, policy interventions, and environmental sustainability. These nuanced perspectives underscore the need for integrated strategies that deftly navigate the complex terrain of economic development, environmental conservation, and social equity to chart a sustainable course for the future of Africa.

2.4. Sustainable Development Goals, the Environmental Kuznets Curve and Their Trade-Offs

The complex relationship between the SDGs and the EKC provides a compelling lens through which to examine the necessary equilibrium between economic progress, environmental conservation, and social equity in Africa. Central to this discussion is the EKC hypothesis, which posits an inverted U-shaped curve to describe the relationship between economic growth and environmental degradation. This hypothesis is critically analyzed by Wu et al. (2024), who interrogate the "sustainability trilemma" and challenge the conventional wisdom that economic prosperity, environmental integrity, and social equity can be achieved simultaneously.

At the nexus of this debate is the strategic development of productive capacities, with an emphasis on sustainability. Such progressive developments imply a potential shift in the traditional trajectory of the EKC by promising to provide environmental benefits at the outset of economic development. The work of Bouraima et al. (2024) and Akromah et al. (2024), which showcase the adoption of solar energy and mycelial composite technologies, is a testament to the alignment of economic endeavors with environmental sustainability. These initiatives advocate for a holistic approach to development that does not compromise environmental protection, as reflected in the SDGs, which focus on promoting sustainable urban environments (SDG 11) and encouraging mindful consumption and production (SDG 12).

Within this inclusive framework, environmental taxes are emerging as critical tools for advancing sustainability. By incentivizing the transition to cleaner technologies and practices, these fiscal measures directly support the goals of SDG 7 (affordable and clean energy) and SDG 13 (climate action). Moreover, the innovative exploration of Eurobonds for climate action by Amankwa et al. (2024) illustrates the seamless integration of financial mechanisms with environmental goals, thereby promoting decent work and economic growth (SDG 8).

The discourse also highlights the significant environmental footprint of urbanization, underscoring the urgent need for sustainable urban planning and infrastructure. As urban areas expand, so do the challenges of pollution, waste management, and resource scarcity. The findings of Khan et al. (2023) and Balsalobre-Lorente et al. (2023) highlight the critical need for urban development strategies that not only address these environmental issues, but also strengthen community resilience, inclusiveness, and sustainability, in line with SDG 11. In addition, the link between remittances and ecological footprints, explored by Abba Yadou et al. (2024), highlights the critical role of ICTs in mitigating the environmental impacts of economic activities, thus providing viable pathways to poverty reduction (SDG 1) through greener practices.

By weaving together these diverse strands of research, the narrative underscores the importance of recognizing and managing the trade-offs between economic growth, environmental protection, and social equity. It advocates the adoption of technological innovations, the application of sustainable financial models, and the implementation of environmentally conscious urban planning as key strategies for steering Africa toward a sustainable future. By embedding these strategies within the fabric of the SDGs, this comprehensive approach aims to seamlessly integrate economic development with environmental stewardship and social inclusivity, providing a nuanced blueprint for Africa's journey toward sustainable development.

3. Data and Methodology

3.1. Data Sources and Variables

This study examines the interaction between environmental taxation, productive capacities, and environmental quality, focusing on twenty African countries from 2000 to 2021. The selection of countries—Botswana, Burkina Faso, Cabo Verde, Cameroon, Côte d'Ivoire, Egypt, Eswatini, Ghana, Kenya, Madagascar, Mali, Morocco, Niger, Uganda, the Democratic Republic of the Congo, Rwanda, Senegal, South Africa, Togo, and Tunisia—reflects the dual criteria of data availability for key variables and the determination of the time period based on this data availability. Key variables examined include per capita greenhouse gas emissions (GHG_PC), per capita gross domestic product (GDP_PC), and GDP_PC squared to evaluate the EKC hypothesis, as well as environmental tax revenue (ERTR), the Productive Capacities Index (PCI), and population density (PDENS). Data sources include the Organization for Economic Cooperation and Development (OECD 2023) and the United Nations Conference on Trade and Development (UNCTAD 2023).

Table 1 highlights key indicators and shows that per capita GHG emissions average 3621 metric tons of CO_2 equivalent, ranging from 0.755 to 16.642 metric tons. This variance reflects the different levels of industrial development and commitment to environmental policy among the selected countries. GDP per capita, averaging USD 4,665,318, reveals the economic heterogeneity within the group, with values ranging from USD 587.06 to USD 14,828.29. This economic disparity underscores the importance of wealth and investment capacity in shaping the effectiveness of environmental policies. Environmental tax revenues, with an average of 1.125% of GDP and a range of 0.787, illustrate the varying intensity and application of environmental fiscal policies across the continent. The PCI, with an average of 32.075 and a range of 13.346 to 53.888, highlights the differences in technological progress and infrastructure. In addition, population density, with an average of 82,448 persons per km^2 and a range of 2.21 to 511.08 persons per km^2, underscores the challenges of urbanization and resource management, particularly in densely populated areas. This underscores the need for urban planning and mobility policies to reduce greenhouse gas emissions.

Table 1. Variable definitions and descriptive statistics.

Variable	GHG	GDP	ERTR	PCI	PDENS
Definition	Greenhouse gas emissions per capita (tons of carbon dioxide equivalent)	Gross domestic product per capita (constant 2015 USD)	Environmentally related tax revenue (% of the GDP)	Productive capacities index	Population density (people per sq. km of land area)
Source	OECD	OECD	OECD	UNCTAD	OECD
Obs.	440	440	440	440	440
Mean	3.621	4665.318	1.125	32.075	82.448
Std. dev.	2.858	3803.491	0.787	10.702	81.708
Min	0.755	587.060	0.040	13.346	2.210
Max	16.642	14,828.290	4.140	53.888	511.080

The compilation of these data provides a solid basis for analyzing the complex relationships between economic growth, environmental fiscal policies, and environmental quality in the African context. It highlights the critical need for policies that are tailored to the unique conditions and challenges of each country. This targeted approach is essential for promoting effective environmental governance and sustainable development across the continent and provides stakeholders and policymakers with a detailed roadmap for harmonizing economic, environmental, and social objectives in a sustainable and coherent manner.

3.2. Methodological Framework and Analysis

3.2.1. Model Specification and Theoretical Background

Our methodological approach is grounded in environmental economics and draws on the EKC theory, which posits a nuanced relationship between economic development and environmental degradation. Originally introduced by Kuznets (1955) and further developed by Grossman and Krueger (1991), the EKC hypothesis suggests that the environmental impact of an economy follows a non-linear trajectory as it develops. In the early stages of economic growth, environmental degradation increases due to resource-intensive industrial activities and minimal environmental regulation. As a nation progresses economically, higher income levels facilitate the adoption of green technologies and stronger environmental policies, leading to a reduction in pollution (Panayotou 1993; Andreoni and Levinson 2001; Dinda 2004; Stern 2004).

To capture these dynamics, our model integrates GDP per capita and its square to capture the characteristic inverted U-shaped curve of the EKC. We also include environmental tax revenues, the productive capacities index (PCI), and population density as additional variables to examine their direct impact on per capita greenhouse gas (GHG) emissions. The equation formulating the model is as follows:

$$GHG_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 ERTR_{it} + \beta_4 PCI_{it} + \beta_5 PDENS_{it} + \varepsilon_{it} \quad (1)$$

This equation reflects the per capita greenhouse gas emissions (GHG_{it}) for the country i at the time t, where GDP_{it} and GDP_{it}^2 are the economic output and its square, and $ERTR_{it}$ is the environmental tax revenue, PCI_{it} is the productive capacities index, $PDENS_{it}$ is population density, β_0 to β_5 are the coefficients to be estimated, and ε_{it} is the error term.

To facilitate empirical analysis, we linearize the model using natural logarithms, which allows the coefficients to be interpreted as elasticities. This linearized form, shown below, provides insight into how percentage changes in the independent variables influence percentage changes in GHG emissions:

$$\begin{aligned} \ln(GHG_{it}) = \beta_0 + \beta_1 \ln(GDP_{it}) + \beta_2 \ln\left(GDP_{it}^2\right) + \beta_3 \ln(ERTR_{it}) \\ +\beta_4 \ln(PCI_{it}) + \beta_5 \ln(PDENS_{it}) + \varepsilon_{it} \end{aligned} \quad (2)$$

This specification allows for a detailed examination of the potential EKC in the African context and the impact of environmental policies and productive capacities on environmental quality. The inclusion of environmental taxes reflects an examination of their effectiveness in reducing emissions, while the PCI provides insight into how a country's productive capacities might affect its environmental footprint. The model seeks to contribute to the empirical understanding of how sustainable development strategies, in line with the Paris Agreement and the United Nations 2030 Agenda for Sustainable Development, can be effectively implemented in different African economies.

3.2.2. Selection and Justification of Econometric Models

The choice of panel data models is central to our analysis, which examines the economic and environmental dynamics of twenty African countries over a twenty-two-year period. Given the structure of our data, with time periods (T) outnumbering units (N), the use of panel cointegration techniques emerges as a methodologically sound choice, adept at navigating the complexities of the extensive time series data inherent in our study.

Within the spectrum of econometric models suitable for panel data analysis, we have a number of options, each designed to shed light on different aspects of our research questions. Static models, including fixed effects (FE) and random effects (RE), are particularly effective in dealing with unobserved heterogeneity, allowing the unique characteristics of each country to be considered. Conversely, when our focus shifts to the dynamic interplay of variables over time, models such as Vector Autoregression (VAR) and Vector Error Correction Model (VECM) become indispensable for their ability to elucidate the temporal dependencies and paths to equilibrium within the data.

To further enhance our econometric toolkit, the Generalized Method of Moments (GMM) stands out for its ability to deal with potential specification errors or endogeneity through its innovative use of data moments for parameter estimation. In the context of cointegrated series, both Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) offer refined estimates of long-run relationships, while the Canonical Cointegration Regression (CCR) model provides adjustments for endogeneity and serial correlation, ensuring robust long-run analysis.

For analysis that requires a nuanced understanding of both group-level homogeneities and individual-specific dynamics, the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effect (DFE) estimators offer versatile approaches. These methods are adept at balancing the need for individual specificity with overarching trends across the dataset. In addition, the Driscoll and Kraay model's resistance to cross-sectional dependence and its ability to provide consistent standard error estimates make it a valuable addition to ensure analytical robustness.

However, the Autoregressive Distributed Lag (ARDL) model, as formulated by Pesaran et al. (2001), is chosen primarily for its ability to accommodate variables of mixed integration orders, thus facilitating a comprehensive examination of both the short-run dynamics and the long-run relationships among the variables under study. The applicability of this model to our relatively small sample size and its compatibility with the PMG, MG, and DFE methodologies underscore its utility in providing a nuanced examination of the economic and environmental interfaces within our dataset. Through the judicious application of these econometric models, our study seeks to uncover the intricate relationships between environmental taxes, productive capacities, and environmental quality in the context of African economies, paving the way for informed policy interventions and sustainable development strategies. The ARDL model, which is central to the analysis of the interactions in our study, is described as follows:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \beta_{ij} Y_{it-j} + \sum_{k=1}^{q} \gamma_{ik} X_{kit} + \epsilon_{it} \quad (3)$$

In this equation, Y_{it} is the dependent variable for each country i at time t, α_i is the individual-specific intercept, and β_{ij} and γ_{ik} are the coefficients on the lagged dependent variable and the explanatory variable X_{kit}, respectively. Here, p and q denote the number of lags for Y_{it} and each X_{kit}, encapsulating the depth of historical influence on current observations, while ϵ_{it} embodies the error term.

Extending the conceptual foundation laid out in Equation (2), our customized ARDL model refines and specifies the variables directly relevant to our investigative lens, as delineated within our theoretical framework. The refined model equation is thus expressed as follows:

$$\begin{aligned} \ln(GHG_{it}) = \alpha_i + \beta_1 \ln(GDP_{it}) + \beta_2 \ln\left(GDP_{it}^2\right) + \beta_3 \ln(ERTR_{it}) + \beta_4 \ln(PCI_{it}) \\ +\beta_5 \ln(PDENS_{it}) + \sum_{j=1}^{p} \phi_{ij} \ln\left(GHG_{it-j}\right) + \sum_{k=1}^{q} \theta_{ik} X_{kit} + \epsilon_{it} \end{aligned} \tag{4}$$

In Equation (4), the intercept α_i captures the country-specific constants that affect per capita GHG emissions. The coefficients, β_1 through β_5, quantify the impact of our economic and demographic variables, and are log-transformed to stabilize the variance and improve model interpretability. Specifically, β_2 is tasked with capturing the quadratic relationship indicative of the EKC hypothesis. The inclusion of lagged terms, ϕ_{ij} and θ_{ik}, is crucial for incorporating the influence of past emissions and ancillary variables on current environmental outcomes, thereby embedding the temporal dynamics integral to our analysis. The error term, ϵ_{it}, adheres to the assumption of a normal distribution and accounts for the unexplained variability in emissions across countries and time periods.

Recognizing the substantial utility of the ARDL model in our analysis, as described in Equation (3), leads us to consider its limitations in the context of first-generation econometric techniques. Originally groundbreaking, the conventional panel ARDL framework assumes cross-sectional independence across units, an assumption that may not hold in the face of global economic dynamics and common external shocks that may affect multiple countries simultaneously. This oversight risks introducing bias by neglecting cross-sectional dependencies, which are increasingly recognized as crucial for robust econometric analysis.

To overcome these obstacles, second-generation econometric models offer refined methodologies that account for cross-sectional dependencies. Coakley et al. (2006) critically assess the ability of Pesaran et al.'s (1999) MG estimator to account for cross-sectional interdependencies, prompting the emergence of methodologies capable of effectively modeling these interrelationships. Pesaran (2006) introduces an augmented ARDL framework that incorporates a cross-sectional mean of observable variables to adequately represent unit correlations.

This methodological enhancement, refined by Chudik and Pesaran (2015) and Everaert and De Groote (2016), introduces the Common Correlated Effects (CCE) approach, based on the assumption that integrating cross-sectional means into model estimations provides a consistent approximation of common factors. This advance allows for two different adaptations of the panel-adjusted ARDL model: the Cross-Section Augmented Distributed Lag (CS-DL) for longitudinal analyses and the Cross-Section Augmented Autoregressive Distributed Lag (CS-ARDL) model for comprehensive short- and long-term studies. Our analysis gravitates toward the CS-ARDL model, as proposed by Chudik et al. (2016), for its nuanced ability to incorporate an optimal lag structure while ensuring robust estimates amidst cross-sectional dependencies.

Consequently, the CS-ARDL model selected for our empirical investigation enhances the traditional ARDL model by incorporating cross-sectional averages of all variables, thereby accounting for common factors that collectively affect the panel. The augmented model is expressed as follows:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \beta_{ij}\left(Y_{it-j} - \overline{Y}_{t-j}\right) + \sum_{k=1}^{q} \gamma_{ik}\left(X_{kit} - \overline{X}_{kt}\right) + \delta D_t + \mu_i + \epsilon_{it} \tag{5}$$

Here, $\overline{Y}_{t-j}$ and $\overline{X}_{kt}$ denote the cross-sectional averages of the dependent and independent variables, respectively, for each lag j and k, thereby mitigating the influence of common trends across the panel. The coefficient δ associated with the time fixed effects D_t and the term μ_i denoting the individual fixed effects encapsulate the unique characteristics of each country, while ϵ_{it} describes the error term specific to the time observations for each unit. This methodological progression underscores our commitment to addressing the multifaceted dynamics of environmental sustainability in the African context by accounting for both the individual peculiarities of the countries studied and the overarching trends that affect them collectively.

To further refine our econometric analysis, the incorporation of the Dynamic Common Correlated Effects Mean Group Estimator (DCCEMG) and Augmented Mean Group (AMG) models offers advanced perspectives on dealing with unobserved common factors in panel data. The DCCEMG model, introduced by Chudik and Pesaran (2015), embodies a sophisticated approach by assimilating lags of cross-sectional means. This inclusion allows for a comprehensive treatment of cross-sectional dependencies and slope heterogeneity, and accounts for potential structural breaks within the dataset. The model is written as follows:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \phi_{ij} Y_{it-j} + \sum_{k=1}^{q} \theta_{ik} X_{kit} + \sum_{j=1}^{p} \lambda_j \overline{Y}_{t-j} + \sum_{k=1}^{q} \gamma_k \overline{X}_{kt} + \mu_i + \epsilon_{it} \tag{6}$$

In this model, α_i represents the individual fixed effect identifying unique attributes of each unit, while ϕ_{ij} and θ_{ik} correspond to the coefficients on the lags of the dependent and explanatory variables, respectively. The terms λ_j and γ_k adjust for lagged cross-sectional averages, effectively controlling for the influence of unobserved common factors. μ_i denotes the individual-specific fixed effects, and ϵ_{it} is the idiosyncratic error term.

In parallel, the Augmented Mean Group (AMG) model conceptualized by Eberhardt and Teal (2010) introduces a common dynamic effect ψ_t. This effect quantifies the overarching impact of unobserved common factors on the entire panel, thereby enriching the analysis with the ability to account for the dynamic interplay of global economic trends and structural changes. The AMG model is written as follows:

$$Y_{it} = \alpha_i + \sum_{j=1}^{p} \beta_{ij} Y_{it-j} + \sum_{k=1}^{q} \gamma_{ik} X_{kit} + \psi_t \overline{C}_t + \epsilon_{it} \tag{7}$$

where α_i is the individual fixed effect, β_{ij} and γ_{ik} are the coefficients on the lags of the dependent and explanatory variables, ψ_t is the common dynamic effect that captures the average influence of unobserved factors, and $\overline{C}_t$ is the cross-sectional average used to model the common effects. We leave ϵ_{it} as the idiosyncratic error term.

Adapting the methodologies embodied in the CS-ARDL, DCCEMG, and AMG models to our empirical analysis allows for a nuanced understanding of the interplay between environmental taxes, productive capacities, and environmental quality across twenty African countries. These adapted models, which are precisely tailored to the variables of our study, provide a multifaceted approach to accounting for the cross-sectional dependencies and heterogeneities inherent in our panel data.

The CS-ARDL model refines the traditional ARDL approach by incorporating cross-sectional averages of all variables, thereby controlling for unobserved common factors that potentially affect all countries in the panel. This adjustment is expressed as follows:

$$\begin{aligned} \ln(GHG_{it}) = {} & \alpha_i + \sum_{j=1}^{p} \beta_{ij} \Big(\ln(GHG_{it-j}) - \overline{\ln(GHG_{t-j})} \Big) + \sum_{k=1}^{q} \gamma_{ik} \big(X_{kit} - \overline{X_{kt}} \big) \\ & + \delta D_t + \mu_i + \epsilon_{it} \end{aligned} \tag{8}$$

where $\ln(GHG_{it})$ is the natural log of per capita GHG emissions for country i at time t, α_i captures individual fixed effects, β_{ij} and γ_{ik} are coefficients of the lagged dependent and explanatory variables, respectively, adjusted for cross-sectional averages, and ϵ_{it} is the error term.

The DCCEMG model further controls for cross-sectional dependencies and slope heterogeneity by including lags of cross-sectional averages. Its formulation is as follows:

$$\ln(GHG_{it}) = \alpha_i + \sum_{j=1}^{p} \phi_{ij} \ln(GHG_{it-j}) + \sum_{k=1}^{q} \theta_{ik} X_{kit} + \sum_{j=1}^{p} \lambda_j \overline{\ln(GHG_{t-j})} + \sum_{k=1}^{q} \gamma_k \overline{X}_{kt} + \mu_i + \epsilon_{it} \tag{9}$$

Here, ϕ_{ij} and θ_{ik} are coefficients for the lags of the dependent and explanatory variables, respectively, λ_j and γ_k account for the lagged cross-sectional average effects, and μ_i is the individual fixed effect.

The AMG model introduces a common dynamic effect, ψ_t, which reflects the average impact of unobserved common factors on all units in the panel:

$$\ln(GHG_{it}) = \alpha_i + \sum_{j=1}^{p} \beta_{ij} \ln(GHG_{it-j}) + \sum_{k=1}^{q} \gamma_{ik} X_{kit} + \psi_t C_t + \epsilon_{it} \tag{10}$$

where C_t represents the contemporaneous effect of common factors, providing a unique perspective on the interconnectedness of economies and structural variation within panel data.

Incorporating these advanced econometric models into our analysis enhances our ability to navigate the complex dynamics at play, ensuring a robust examination of the effects of environmental policies and productive capacities on environmental quality. Through these advanced econometric strategies, our study delves into the multifaceted relationships between economic development, environmental protection, and sustainability goals in the African context. This comprehensive approach, detailed through equations and variable descriptions, strengthens the empirical foundation of our research and provides insights into policy formulation and the pursuit of sustainable development across the continent.

3.3. Estimation Techniques and Preliminary Tests

3.3.1. Cross-Sectional Dependence Tests

In line with panel data analysis, O'Connell (1998), Pesaran (2004), Baltagi (2015), and Pesaran and Xie (2021) have highlighted the prevalence of cross-sectional dependence (CSD). This phenomenon is characterized by correlated residuals across different units in a panel and can be caused by common economic shocks, shared unobserved characteristics, regional and macroeconomic interdependencies, or unobserved externalities. Detecting and correcting for CSD is crucial, as its omission can lead to errors in unit root tests and thus to inaccurate conclusions about economic dynamics.

To detect the presence of CSD in our panel of African data, we use Pesaran's (2015, 2021) CD test and Fan et al.'s (2015) CD_{w+} test. These tools are fundamental for detecting the complexity of interactions between the economies under study, and for ensuring that subsequent econometric techniques are well suited to the data structure.

The formula for the CD test of Pesaran (2015, 2021) is as follows:

$$\text{CD} = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \rho_{ij}$$

where T is the number of time observations, N is the number of units in the panel, and ρ_{ij} is the correlation of the regression residuals between units i and j.

The Fan et al. (2015) CD_{w+} test is formulated as follows:

$$CD_{w+} = \sqrt{\frac{2}{TN(N-1)}} \sum_{t=1}^{T} \sum_{i=2}^{N} \sum_{j=1}^{i-1} (w_i \hat{\varepsilon}_{i,t} w_j \hat{\varepsilon}_{j,t}) + \sum_{i=2}^{N} \sum_{j=1}^{i-1} |\hat{\rho}_{ij}| 1 \left(|\hat{\rho}_{ij}| > 2\sqrt{\frac{\ln(N)}{T}} \right)$$

where $\hat{\rho}_{ij}$ denotes the cross-sectional correlation estimator, w_i and w_j the individual-specific covariance weights, and $\hat{\varepsilon}_{i,t}$ and $\hat{\varepsilon}_{j,t}$ the vectors of idiosyncratic error terms.

Running these tests ensures that the data structure is correctly understood, which is essential before proceeding to more advanced econometric analyses such as unit root tests and cointegration studies.

The results of the cross-sectional dependence tests, CD and CD_{w+}, shown in Table 2, indicate a high probability of economic shocks affecting one economy in the entire panel. This result refutes the hypothesis of cross-sectional independence in the residuals of all the variables studied, with a significance level of 1% for most variables, except for the variable LnERTR, which is significant only at the 10% level in the CD test. This trend suggests the importance of including cross-sectional correlation in any econometric analysis of panel data to ensure the accuracy and reliability of the estimates. Consequently, the application of second-generation unit root tests is recommended for the treatment of these panel data.

Table 2. Cross-sectional dependence analysis results.

Variables	CD	CDw+
GHG emissions per capita (LnGHG)	16.00 ***	467.53 ***
GDP per capita (LnGDP)	47.41 ***	710.54 ***
Squared GDP per capita (LnGDP2)	47.44 ***	711.60 ***
Environmentally related tax revenue (LnERTR)	1.91 *	339.78 ***
Productive Capacities Index (LnPCI)	56.36 ***	774.59 ***
Population density (LnPDENS)	33.71 ***	819.24 ***

Notes: The CD statistic is normally distributed under the null hypothesis of weak cross-section dependence. *** and * indicate the statistical significance level at 1% and 10%, respectively.

3.3.2. Slope Homogeneity Tests

After verifying the presence of CSD in our data panel, it is essential to continue our analysis by testing for slope homogeneity. This step is essential to determining whether the coefficients of the econometric models are consistent across the different units of our panel, which includes 20 African countries with different economic characteristics. Slope heterogeneity can significantly affect the reliability of estimation methods and econometric results, especially when using techniques that assume identical coefficients for all countries.

To address this issue, the slope homogeneity test developed by Pesaran and Yamagata (2008) is used. This test assesses whether the slope coefficients are significantly different within the panel, which could indicate that each country has its own dynamics and responses to the independent variables. The delta $\widetilde{\Delta}$ and adjusted delta $\widetilde{\Delta}_{adj}$ statistics from this test are used to test the null hypothesis of slope homogeneity against the alternative hypothesis of heterogeneity. The equations for these tests are as follows:

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

$$\widetilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\widetilde{S}-k}{\sqrt{\frac{2k(T-k-1)}{T+1}}}\right)$$

where N is the number of cross-sectional units, T is the time dimension, and k is the number of independent variables. The $\widetilde{S}$ statistic is derived from the modified Swamy (1970) test, which assesses the homogeneity of slope coefficients across panel units. Bersvendsen and Ditzen (2021) highlight the robust performance of this test, especially in scenarios where the time dimension T is larger than the number of cross-sectional units N. This aspect is important because it enhances the usefulness of the test in panels with longer time series. In addition, the ability of this test to account for residual CSD significantly strengthens the validity and reliability of the slope homogeneity estimates.

Table 3 presents the results of the slope homogeneity test by Pesaran and Yamagata (2008). The values of the $\widetilde{\Delta}$ and $\widetilde{\Delta}_{adj}$ statistics indicate strong heterogeneity in the model. The results of our analysis lead us to reject the null hypothesis of slope homogeneity in favor of the alternative hypothesis of slope heterogeneity at the 1% significance level. This conclusion suggests that there is significant heterogeneity among the sampled African countries with respect to the variables analyzed. Consequently, it is necessary to apply heterogeneous panel techniques that allow for parameter variation between countries to account for this heterogeneity.

Table 3. Slope homogeneity test (Pesaran and Yamagata 2008).

Slope Homogeneity Tests	Δ Statistic	*p*-Value
$\widetilde{\Delta}$ test	13.934	0.000
$\widetilde{\Delta}_{adj}$ test	16.340	0.000

Notes: The null hypothesis for the slope heterogeneity test is that slope coefficients are homogenous.

3.3.3. Second-Generation Panel Unit Root Tests

The third stage of our econometric analysis addresses the issue of non-stationarity in our panel data. The confirmed existence of CSD within our panel of African countries necessitates the use of second-generation unit root tests. These advanced methods are essential because neglecting CSD could potentially bias conclusions about the properties of the time series under study. Therefore, we opt for specific tests that provide a refined analysis that is consistent with the specificities of our panel and that, unlike first-generation tests, are able to account for CSD.

To test for stationarity while accounting for CSD, we apply the Cross-sectionally Augmented Dickey–Fuller (CADF) test and the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test introduced by Pesaran (2007). These tests are specifically designed to address the challenges posed by the presence of cross-sectional dependencies and heterogeneity among the units in our panel, thus providing a robust and reliable analysis of data non-stationarity. The results of these tests will determine whether the variables in our study are integrated in the order of one, I(1), and consequently whether it is appropriate to proceed to cointegration analyses.

The mathematical formulation of the CADF test is as follows:

$$\Delta Z_{it} = \phi_i + \varsigma_i Z_{i,t-1} + \sigma_i \overline{Z}_{t-1} + \sum_{j=0}^{p} \sigma_{ij} \Delta \overline{Z}_{t-1} + \sum_{j=1}^{p} \lambda_{ij} \Delta Z_{i,t-1} + \varepsilon_{it}$$

In this equation, Δ represents the differencing operator, $\overline{Z}_{t-1}$ and $\Delta\overline{Z}_{t-1}$ denote the cross-sectional averages of lagged levels and first differences, respectively, and ε is the error term.

The CIPS statistics are then computed based on the individual CADF statistics for each panel unit. This is formulated as follows:

$$CIPS = \frac{1}{N} \sum_{i=1}^{n} CADF_i$$

where T is the number of cross-sections and N is the sample size in terms of periods.

The results of the CIPS and CADF tests, presented in Table 4, indicate that all the variables in the study are stationary and integrated in the order of one, I(1), after the first difference. This result leads us to examine the cointegration of the study variables using the Westerlund (2007) test.

Table 4. Results of panel unit root tests.

Variables	Level		First-Difference		Ordre
	Without Trend	With Trend	Without Trend	With Trend	
Cross-Sectionally Augmented IPS (CIPS)					
LnGHG	−2.370 **	−3.236 ***	−4.424 ***	−4.496 ***	I(1)
LnGDP	−2.307 **	−2.042	−3.901 ***	−4.278 ***	I(1)
LnGDP2	−2.271 **	−2.048	−3.899 ***	−4.265 ***	I(1)
LnERTR	−1.917	−2.932 ***	−4.629 ***	−4.700 ***	I(0)
LnPCI	−2.192 *	−2.548	−4.464 ***	−4.662 ***	I(1)
LnPDENS	−2.043	−2.332	−3.780 ***	−4.100 ***	I(1)
Cross-Sectionally Augmented Dicky–Fuller (CADF)					
LnGHG	−1.831	−2.720 **	−3.738 ***	−3.965 ***	I(1)
LnGDP	−1.905	−1.861	−3.812 ***	−4.176 ***	I(1)
LnGDP2	−1.984	−1.905	−2.703 ***	−2.872 ***	I(1)
LnERTR	−1.826	−2.838 ***	−4.708 ***	−4.723 ***	I(0)
LnPCI	−2.047 *	−2.430	−4.464 ***	−4.520 ***	I(1)
LnPDENS	−2.186 *	−2.538	−4.293 ***	−4.290 ***	I(1)

Notes: The panel unit root test was performed under the null hypothesis that the variables are non-stationary and homogeneous. ***, ** and * indicate the level of statistical significance at 1%, 5%, and 10%, respectively.

Table 5 presents the results of the sequential test used to identify potential structural breaks in the time series, following the method developed by Ditzen et al. (2021). This method is particularly useful for detecting unexpected breaks or regime shifts, which are crucial for in-depth analysis of the data in the presence of CSD.

Table 5. Sequential test for multiple breaks at unknown breakpoints.

	Bai and Perron Critical Values			
	Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
F(1 ∣ 0)	4.19	6.09	4.66	4.03
F(2 ∣ 1)	3.86	6.59	5.24	4.64
F(3 ∣ 2)	3.78	6.92	5.61	4.99
F(4 ∣ 3)	2.71	7.33	5.87	5.23
F(5 ∣ 4)	1.54	7.49	6.05	5.45

The test statistics for each model, from F(1 ∣ 0) to F(5 ∣ 4), are consistently below Bai and Perron's critical values for significance levels of 1%, 5%, and 10%, according to the values obtained in the sequential test. These results indicate that we cannot reject the null hypothesis that there are no structural breaks in our data. In other words, there is no statistical evidence of mean changes or regime shifts in the analyzed series. This suggests that the time series of our panel exhibits a certain stability over time, without major breaks that could affect the analysis of non-stationarity or long-run economic relationships. The absence of structural breaks allows us to continue using our econometric models without having to adjust for specific break points, thus simplifying the analysis and increasing the reliability of the results obtained.

3.3.4. Cointegration Test

In the fourth step of our econometric analysis, we apply the panel cointegration test of Westerlund (2007). This test is particularly suitable for our panel of data because it accounts for both slope heterogeneity and CSD, which are common problems in the analysis of complex and interdependent panel data.

The specification of the Westerlund (2007) test is as follows:

$$\Delta y_{it} = \delta_i' d_t + \alpha_i \left(y_{it-1} - \beta_i' x_{it-1} \right) + \sum_{j=1}^{p_i} \alpha_{ij} \delta y_{it-j} + \sum_{j=0}^{p_i} \gamma_{ij} \Delta x_{it-j} + e_{it}$$

This equation allows the assessment of cointegration, accounting for the first differences between the dependent and independent variables, where e_{it} represents the error term. The test generates two types of statistics: group mean statistics (G_τ and G_α) and panel statistics (P_τ and P_α), which are used to test for cointegration across different cross-sectional units or the entire panel.

These statistics are expressed for large samples as follows:

$$G_\tau = \frac{1}{N} \sum_{i=1}^{N} \frac{\hat{\alpha}_i}{SE(\hat{\alpha}_i)} \text{ and } P_\tau = \frac{\hat{\alpha}}{SE(\hat{\alpha})}$$

For small samples:

$$G_\alpha = \frac{1}{N} \sum_{i=1}^{N} \frac{T\hat{\alpha}_i}{\hat{\alpha}_i(1)} \text{ and } P_\alpha = T\hat{\alpha}$$

These tests are essential to confirm the existence of long-run relationships between the studied variables, even in the presence of individual non-stationarity. In the case of cointegration, we proceed with the analysis of short- and long-term relationships using second-generation models that consider the specificities of the time series in the face of common shocks and possible structural changes present in our sample of African countries.

Table 6 presents the results of the cointegration tests by Westerlund (2007). These results clearly indicate the existence of at least one cointegration equation in our model. The statistically significant values of the four test statistics (G_τ, G_α, P_τ, and P_α) at the 1% threshold reject the null hypothesis of no cointegration relationship among the variables. These results suggest a long-run relationship between GHG emissions and factors such as economic growth, environmental tax revenues, the productive capacities index, and population density in the African countries in our panel. This confirmation allows us to proceed with the analysis of long-run elasticities using the CS-ARDL, AMG, and DCCEMG models.

Table 6. The results from the Westerlund (2007) cointegration analysis.

Statistic	Value	Z-Value	*p*-Value
G_τ	−3.852	−9.358	0.000
G_α	−11.735	−2.810	0.003
P_τ	−17.561	−8.905	0.000
P_α	−12.524	−5.845	0.000

Notes: The G_τ and G_α statistics assess cointegration for each individual cross-section, while the P_τ and P_α statistics evaluate panel cointegration when the null hypothesis of no cointegration is assumed.

4. Results and Discussion

4.1. Analysis of Long-Run and Short-Run Relationships: CS-ARDL Model

The CS-ARDL model used in our analysis elucidates the complex dynamics between economic growth, environmental policies, and GHG emissions within the African continent, as shown in Table 7. The model's error correction term (ECT), with a coefficient of −0.666, illustrates the rapid ability of these economies to recalibrate toward equilibrium after perturbations, indicating a high degree of adaptability in the face of economic and environmental change. Moreover, a CD statistic of 0.94 suggests minimal cross-sectional dependence, reinforcing the appropriateness of the model for our analysis.

Table 7. CS-ARDL panel data estimation results.

	Coefficient	Std. Err.	Z-Statistics	*p*-Value
		Short-run results		
ECT (−1)	−0.666	0.077	−8.63	0.000
LnGDP	0.868	0.194	−6.85	0.000
LnGDP2	−0.047	0.022	−4.46	0.000
LnERTR	−0.016	0.028	−1.52	0.129
LnPCI	−0.135	0.079	−2.01	0.045
LnPDENS	0.224	0.192	−2.60	0.009
		Long-run results		
LnGDP	0.645	0.145	9.13	0.000
LnGDP2	−0.037	0.015	−6.51	0.000
LnERTR	−0.041	0.027	−1.80	0.071
LnPCI	−0.246	0.144	−2.06	0.039
LnPDENS	0.301	0.268	2.72	0.007
CD Statistic	0.94			0.347

Notes: The CD statistic test is standard normally distributed under the null of hypothesis of weak cross-sectional dependence.

Examining the relationship between GDP per capita (LnGDP and its square, LnGDP2) and GHG emissions, we find support for the EKC hypothesis. Specifically, the short-run and long-run coefficients of LnGDP (0.868 and 0.645, respectively) juxtaposed with those of LnGDP2 (−0.047 and −0.037, respectively) show an initial increase followed by a subsequent decrease in GHG emissions relative to economic growth. This pattern suggests that while early stages of economic development may increase emissions, crossing a certain income threshold encourages the adoption of cleaner technologies, thereby reducing emissions.

Environmental tax revenues (LnERTR) reveal nuanced effects. In the short run, their impact is statistically insignificant (*p*-value = 0.129), but in the long run, there is a marginal but negative coefficient of −0.041 at the 10% significance level. This is consistent with Pearce's double dividend hypothesis, suggesting that environmental taxes can generate revenue for further economic development initiatives beyond emissions mitigation.

In the African context, where the SDGs are increasingly guiding policy priorities, the long-term impact of environmental taxes points to potential progress towards these goals. Tax revenues, if strategically reinvested in sectors critical to sustainable development (e.g., green infrastructure, education, health), could support environmental sustainability (SDG 13) alongside inclusive and sustainable economic growth (SDG 8).

The initial ineffectiveness of environmental taxes is due to the adjustment challenges within African economies. Consistent with the findings of Dogan et al. (2022) and Guo et al. (2022), entrenched consumption habits and development barriers may hinder rapid policy adaptation. Nevertheless, the gradual influence of environmental taxes over time is likely to spur sustainable investment and innovation in line with SDG goals. There is an urgent need to address barriers to the implementation of environmental taxes in Africa, particularly concerns related to equity and social justice (Al-Rawi et al. 2023) and the risk of carbon leakage (Ahmed et al. 2022). Overcoming these hurdles is critical to progress toward key SDGs, particularly those focused on poverty reduction (SDG 1) and sustainable consumption and production patterns (SDG 12).

Despite their initially muted impact, environmental taxes hold significant long-term promise for steering African countries toward a sustainable economic path. Viewed through the lens of the double dividend hypothesis and the SDGs, they offer a powerful mechanism for reconciling environmental protection with socioeconomic progress, provided they overcome initial hurdles and promote sustainable consumption and production practices.

Examining the productive capacities index (LnPCI) across African countries reveals significant findings, with negative coefficients observed in both the short term (−0.135) and long term (−0.246). This suggests that improving overall productive capacities can contribute to reducing GHG emissions. While our analysis did not disaggregate the impact of individual components within the index, an implicit association suggests that advances in areas such as human capital, natural capital, energy, transportation, ICT, the private sector, institutions, and structural change have the potential to significantly improve environmental quality and sustainability.

Regarding human capital, the findings of Adjei et al. (2023) and Jahanger et al. (2023) highlight that the promotion of skills, education, and health could indirectly foster better natural resource management and increase environmental awareness, thereby nudging societal behaviors toward more sustainable practices. At the same time, nuanced natural resource management, highlighted by Brandt et al. (2017) and Oluc et al. (2023), is proving to be crucial in reducing environmental impacts and promoting sustainability. In the energy domain, a key facet of the index, the focus on efficiency, underscored by Ahmad and Zhang (2020) and Murshed et al. (2022), plays a critical role in guiding sustainable economic development and presumably mitigating environmental harms. In addition, in the transportation sector, efforts towards energy efficiency and the adoption of less polluting technologies, as described by Hasan et al. (2019) and Alotaibi et al. (2022), are in line with the trends identified in our findings. ICTs also contribute to this ecosystem of productive capacities in a dualistic manner, increasing process efficiency and promoting smarter resource management. Despite their potential to escalate energy consumption, ICTs also drive the transition to a greener service economy, a development articulated by Chatti (2021), Awad (2022), and Awad and Saadaoui Mallek (2023).

The effectiveness of institutional frameworks and the commitment of the private sector to sustainable practices are seen as essential. Robust institutional structures are essential for the adoption of effective environmental policies, while a conscientious private sector is crucial for integrating environmental considerations into its operational and investment decisions. Although the direct impacts of the PCI's subcomponents have not been assessed individually, it's plausible to infer that comprehensive improvements in these dimensions could significantly reduce GHG emissions in the African context. Such improvements represent strategic alignment with the Sustainable Development Goals (SDGs) and embody a holistic method for synchronizing economic expansion, enriched quality of life, and environmental protection.

Examination of the impact of population density (LnPDENS) on environmental quality, represented by GHG emissions, reveals a nuanced relationship. Positive coefficients observed in both the short term (0.224) and long term (0.301) suggest that higher population density is correlated with increased GHG emissions, challenging the notion of a simple relationship between population density and environmental quality. This finding is consistent with Zarco-Periñán et al. (2021), who found an association between higher population density and increased CO_2 emissions, particularly in urban areas. Similarly, Dimnwobi et al. (2021) highlighted the significant role of population growth and density in exacerbating environmental degradation across Africa.

The relevance of these findings is further confirmed by research by Haouas et al. (2023) in the Middle East and North Africa region, which also showed that demographic factors contribute positively to CO_2 emissions. Luqman et al. (2023) added depth to this discussion by directly linking urbanization to an increase in CO_2 emissions, noting that the rapid escalation of emissions in developing urban areas reflects a global trend in which urbanization is a primary driver of increased emissions. In contrast, Kostakis et al. (2023) presented evidence suggesting that higher population density in certain contexts could lead to reductions in CO_2 emissions, contrary to the general trend observed in our analysis. This discrepancy underscores the complex dynamics unique to the African continent and highlights the intricate relationship between population density and environmental impact. This complexity calls for careful consideration of the multiple factors at play, including urban planning, technology adoption, and policy frameworks, in addressing the environmental challenges associated with increasing population density.

4.2. Results Robustness: DCCEMG and AMG Estimators

The robustness checks using the DCCEMG and AMG estimators of the long-run relationships between economic growth, environmental policies, and GHG emissions across African countries confirm the initial findings from the CS-ARDL model analysis. Table 8, supported by the CD statistic from the DCCEMG model indicating low cross-sectional dependence, strengthens the reliability of our results.

Table 8. DCCEMG and AMG panel data long-run estimation results.

	DCCEMG		AMG	
Variables	**Coefficients**	**Standard Error**	**Coefficients**	**Standard Error**
LnGDP	0.916 ***	0.220	0.774 ***	0.214
LnGDP2	−0.037 ***	0.023	−0.018 ***	0.015
LnERTR	−0.051 **	0.030	−0.067 *	0.032
LnPCI	−0.195 **	0.184	−0.152 **	0.065
LnPDENS	0.260 ***	0.196	0.216 ***	0.180
CD Statistic	1.05 (0.293)			

Notes: The CD statistic test is standard normally distributed under the null hypothesis of weak cross-sectional dependence. The value in parentheses for the CD statistic is the *p*-value. ***, **, and * indicate the statistical significance level at 1%, 5%, and 10%, respectively.

The observed coefficients for LnGDP and LnGDP2 in both the DCCEMG (0.916 and −0.037) and AMG (0.774 and −0.018) models support the EKC hypothesis, showing an inverted U-shaped relationship between economic growth and GHG emissions. The effects of LnERTR, with coefficients of −0.051 in DCCEMG and −0.067 in AMG, indicate a negative impact of environmental taxes on emissions, which is more pronounced in the AMG model results. This indicates the importance of designing environmental fiscal policies that are effectively tailored to the specific needs and contexts of African countries to ensure emission reductions.

The analysis also reveals positive coefficients for population density (LnPDENS) of 0.260 in DCCEMG and 0.216 in AMG, highlighting the role of urbanization in increasing GHG emissions. This underscores the critical need for effective urban management and planning to address emissions challenges in the growing cities of African countries.

These findings from the DCCEMG and AMG estimates highlight the complex relationships between economic development, environmental policies, urbanization, and GHG emissions. They highlight the need for integrated strategies, in line with the Sustainable Development Goals (SDGs), to effectively manage GHG emissions while promoting sustainable development in African countries.

4.3. Policy Implications and Strategic Recommendations

Achieving sustainable development across the African continent requires a comprehensive understanding of its diverse economic environments, environmental challenges, and social structures. It is therefore essential that strategic recommendations are carefully tailored to ensure that economic progress is in harmony with environmental protection and social inclusion.

For industrial heavyweights such as South Africa and Egypt, with significant greenhouse gas emissions, an urgent shift to green manufacturing and increased use of renewable energy is critical. The foundation of this shift lies in the strategic implementation of green taxes to incentivize industries to transition to sustainable production practices.

In countries experiencing rapid urbanization, including Kenya and Nigeria, the importance of sustainable urban planning cannot be overstated. Strategies must prioritize the development of green public transportation systems, the creation of urban green spaces, and the advancement of waste management practices. These steps are critical to reducing the ecological impact of urban growth and ensuring the sustainability of environmental health.

Agriculture-based economies, particularly Ghana and Côte d'Ivoire, stand to benefit immensely from the promotion of sustainable agricultural practices. The adoption of climate-smart agricultural techniques and measures to prevent deforestation will help achieve both environmental sustainability and agricultural productivity.

Rwanda's progress in digital transformation provides a unique opportunity to leverage technology to promote environmental sustainability. The use of ICTs to optimize energy management and promote smart agriculture demonstrates the potential of digital innovation to contribute to environmental protection.

Central to these strategic recommendations for all African countries is the development and application of environmental fiscal policies, with a particular focus on fine-tuning carbon taxes. These policies must be carefully designed to minimize the burden on low-income households, while ensuring that the revenues generated are reinvested in projects that promote sustainable development. Furthermore, investments in clean technologies in various sectors, including industry and transport, are essential for a smooth transition to a low-carbon economy.

Building productive capacities through education, research, and innovation is another critical component of this approach. By cultivating a workforce capable of leading and supporting green and digital transformations, African countries can lay the foundation for a future that balances economic growth with environmental protection.

Addressing the challenges of rapid urbanization requires a focus on sustainable infrastructure development. Regional and international cooperation is also essential to share knowledge, align environmental policies, and secure financial support for sustainable development and climate change initiatives.

Integrating the SDGs into national policy frameworks is a critical step to ensure that economic, social, and environmental goals are pursued simultaneously. This approach aims to create policy synergies that address the needs of vulnerable populations while promoting sustainable economic opportunities.

By adopting a holistic and integrated strategy that encompasses environmental, economic, and digital transformations, African countries can navigate towards a future where development is economically viable, socially inclusive, and environmentally sustainable. This adaptive strategy, tailored to the unique challenges and opportunities of different African countries, underscores the continent's potential to achieve significant milestones in sustainable development and sets a precedent for balanced and inclusive growth in the face of global environmental challenges.

5. Concluding Remarks and Strategic Outlook

5.1. Conclusions

This research explores the complex relationships between environmental fiscal policies, the enhancement of productive capacities, and their impact on environmental quality in the African context. The analysis shows that environmental taxes, particularly carbon taxes, are effective in reducing greenhouse gas emissions, although their success depends on careful implementation and adaptation to the unique circumstances of different African countries. This underscores the need for policies that are both environmentally beneficial and supportive of economic growth.

The paper also highlights that improving productive capacities through innovation and technology plays an important role in improving environmental quality. This points to the importance of integrating sustainability into development strategies to ensure that economic growth does not come at the expense of environmental degradation.

Urbanization is identified as an important factor, with results showing that areas with high population density tend to have higher levels of GHG emissions. This suggests the need to implement urban planning and transport policies that promote sustainability and minimize the environmental impact of urban growth.

The research highlights the complex challenges that African countries face in achieving sustainable development. It calls for integrated approaches that consider the economic, social, and environmental impacts of policies. It also identifies the critical role of collaboration between governments, the private sector, international organizations, and civil society in moving towards more sustainable and resilient economies.

5.2. Limitations and Future Recommendations

While providing valuable insights, this study has certain limitations due to its reliance on secondary data, which may limit the depth of temporal and spatial analysis and affect the generalizability of the findings across Africa's diverse landscape. The use of the aggregated productive capacities index (PCI) may mask the differential impact of its components on environmental sustainability.

Future research should aim to disaggregate the PCI to understand the specific impacts of its components on environmental quality. Longitudinal studies with detailed, country-specific data could improve our understanding of how economic-environmental dynamics evolve over time. Examining the role of institutional and socioeconomic factors in the effectiveness of environmental fiscal policies could provide deeper insights into how to optimize policies for different African contexts.

Expanding the scope of the model to include variables related to technological innovation, green investment, and societal behavior could provide a more comprehensive view of sustainable development pathways. Continuing this research will not only address the identified gaps but will also contribute to the discourse on sustainable development and provide practical insights for policy development and implementation across Africa.

Author Contributions: Conceptualization, A.B.Y. and M.D.; methodology, A.B.Y. and M.D.; formal analysis, A.B.Y. and M.D.; writing—original draft preparation, A.B.Y. and M.D.; writing—review and editing, A.B.Y. and M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study's data is publicly available. Sources include the OECD's Green Growth Indicators, accessible at https://stats.oecd.org/Index.aspx?DataSetCode=GREEN_GROWTH (accessed on 27 November 2023), and UNCTAD's Productive Capacities Index (PCI), available at https://unctadstat.unctad.org/datacentre/dataviewer/US.PCI (accessed on 27 November 2023).

Conflicts of Interest: The authors declare no conflicts of interest.

References

Abba Yadou, Barnabe, Philemon Bonaventure Ntang, and Louise Angèle Baida. 2024. Remittances-Ecological Footprint Nexus in Africa: Do ICTs Matter? *Journal of Cleaner Production* 434: 139866. [CrossRef]

Abdulqadir, Idris Abdullahi. 2024. Urbanization, Renewable Energy, and Carbon Dioxide Emissions: A Pathway to Achieving Sustainable Development Goals (SDGs) in Sub-Saharan Africa. *International Journal of Energy Sector Management* 18: 248–70. [CrossRef]

Abel, Sanderson, Julius Mukarati, Leward Jeke, and Pierre Le Roux. 2023. Carbon Tax and Environmental Quality in South Africa. *International Journal of Energy Economics and Policy* 13: 484–88. [CrossRef]

Adams, Samuel, and Hervé Kaffo Fotio. 2024. Economic Integration and Environmental Quality: Accounting for the Roles of Financial Development, Industrialization, Urbanization and Renewable Energy. *Journal of Environmental Planning and Management* 67: 688–713. [CrossRef]

Adjei, Mavis, Huaming Song, Emmanuel Nketiah, Bright Obuobi, and Gibbson Adu-Gyamfi. 2023. Sustainable Development of West African Economies to Achieve Environmental Quality. *Environmental Science and Pollution Research* 30: 15253–66. [CrossRef] [PubMed]

Afshan, Sahar, and Tanzeela Yaqoob. 2023. Unravelling the Efficacy of Green Innovation and Taxation in Promoting Environmental Quality: A Dual-Model Assessment of Testing the LCC Theory in Emerging Economies. *Journal of Cleaner Production* 416: 137850. [CrossRef]

Afshari, Hamid, Sahid Agnihotri, Cory Searcy, and Mohamad Y. Jaber. 2022. Social Sustainability Indicators: A Comprehensive Review with Application in the Energy Sector. *Sustainable Production and Consumption* 31: 263–86. [CrossRef]

Ahmad, Tanveer, and Dongdong Zhang. 2020. A Critical Review of Comparative Global Historical Energy Consumption and Future Demand: The Story Told so Far. *Energy Reports* 6: 1973–91. [CrossRef]

Ahmed, Nihal, Adnan Ahmed Sheikh, Zeeshan Hamid, Piotr Senkus, Ricardo Cosio Borda, Aneta Wysokińska-Senkus, and Waldemar Glabiszewski. 2022. Exploring the causal relationship among green taxes, energy intensity, and energy consumption in Nordic countries: Dumitrescu and Hurlin causality approach. *Energies* 15: 5199. [CrossRef]

Akromah, Stefania, Neha Chandarana, and Stephen J. Eichhorn. 2024. Mycelium Composites for Sustainable Development in Developing Countries: The Case for Africa. *Advanced Sustainable Systems* 8: 2300305. [CrossRef]

Aldieri, Luigi, Teemu Makkonen, and Concetto Paolo Vinci. 2020. Environmental Knowledge Spillovers and Productivity: A Patent Analysis for Large International Firms in the Energy, Water and Land Resources Fields. *Resources Policy* 69: 101877. [CrossRef]

Ali, Ernest Baba, Samira Shayanmehr, Riza Radmehr, Richard Bayitse, and Ebenezer Agbozo. 2024. Investigating environmental quality among G20 nations: The impacts of environmental goods and low-carbon technologies in mitigating environmental degradation. *Geoscience Frontiers* 15: 101695. [CrossRef]

Alotaibi, Saleh, Mohammed Quddus, Craig Morton, and Marianna Imprialou. 2022. Transport Investment, Railway Accessibility and Their Dynamic Impacts on Regional Economic Growth. *Research in Transportation Business & Management* 43: 100702.

Al-Rawi, Yasser A., Yusri Yusup, Essa Ahmed, Ali F. Ali, and Sofri Bin Yahya. 2023. An examination of environmental taxes from the Islamic and Shariah perspectives. *Journal of Environmental Studies and Sciences* 13: 141–55. [CrossRef]

Amankwa, Richard Fosu, Eric B. Yiadom, Evans Acheampong, and John K. M. Mawutor. 2024. Climate Change Mitigation with Eurobonds: An Environmental Kuznets Curve Analysis. *Cogent Economics & Finance* 12: 2312782.

Ambareen, Beebeejaun. 2023. A critical analysis of environmental taxes in Mauritius; A comparative study with South Africa. *Development Southern Africa* 40: 1038–52. [CrossRef]

Andreoni, James, and Arik Levinson. 2001. The Simple Analytics of the Environmental Kuznets Curve. *Journal of Public Economics* 80: 269–86. [CrossRef]

Anttila, Juhani, and Kari Jussila. 2022. Sustainability as an Aspect of Societal Quality. *Environmental Sciences Proceedings* 15: 70.

Awad, Atif. 2022. Is there any impact from ICT on environmental quality in Africa? Evidence from second-generation panel techniques. *Environmental Challenges* 7: 100520. [CrossRef]

Awad, Atif, and Ray Saadaoui Mallek. 2023. Globalisation's impact on the environment's quality: Does the proliferation of information and communication technologies services matter? An empirical exploration. *Environmental Development* 45: 100806. [CrossRef]

Awad, Atif, Ray Saadaoui Mallek, Ilhan Ozturk, and Yousif Abdelbagi Abdalla. 2023. Infrastructure Development's role in environmental degradation in sub-Saharan Africa: Impacts and transmission channels. *Journal of Cleaner Production* 414: 137622. [CrossRef]

Bala, Hussaini, and Ghousia Khatoon. 2024. Effect of Green Taxation on Renewable Energy Technologies: An Analysis of Commonwealth and Non-Commonwealth Countries in Sub-Saharan Africa. *Environmental Science and Pollution Research* 31: 11933–49. [CrossRef]

Balsalobre-Lorente, Daniel, Jaffar Abbas, Chang He, Ladislav Pilař, and Syed Ale Raza Shah. 2023. Tourism, urbanization and natural resources rents matter for environmental sustainability: The leading role of AI and ICT on sustainable development goals in the digital era. *Resources Policy* 82: 103445. [CrossRef]

Baltagi, Badi H., ed. 2015. *The Oxford Handbook of Panel Data*. Oxford: Oxford University Press.

Ben Youssef, Adel, and Mounir Dahmani. 2024. Assessing the impact of digitalization, tax revenues, and energy resource capacity on environmental quality: Fresh evidence from CS-ARDL in the EKC framework. *Sustainability* 16: 474. [CrossRef]

Ben Youssef, Adel, Séverine Borderon-Carrez, and Mounir Dahmani. 2021. Territories' adaptation to climate change and the effects of pandemics. In *Survival Solutions for the Economy, Biodiversity, Climate and Health*. Edited by Sukriti Anand and Miriam Kennet. Reading: The Green Economics Institute.

Bersvendsen, Tore, and Jan Ditzen. 2021. Testing for Slope Heterogeneity in Stata. *The Stata Journal: Promoting Communications on Statistics and Stata* 21: 51–80. [CrossRef]

Bouraima, Mouhamed Bayane, Badi Ibrahim, Yanjun Qiu, Lawan Jibril Muhammad, and Marko Radovanović. 2024. Assessment of Solar Energy Technologies in Meeting the 2030 Agenda and Sustainable Development Goals Under an Interval-Valued Fermatean Fuzzy Environment. *Journal of Operations Intelligence* 2: 114–28. [CrossRef]

Brandt, Nicola, Paul Schreyer, and Vera Zipperer. 2017. Productivity Measurement with Natural Capital. *Review of Income and Wealth* 63: S7–S21. [CrossRef]

Caglar, Abdullah Emre, Muhammet Daştan, and Soumen Rej. 2024. A New Look at China's Environmental Quality: How Does Environmental Sustainability Respond to the Asymmetrical Behavior of the Competitive Industrial Sector? *International Journal of Sustainable Development & World Ecology* 31: 16–28.

Caglar, Abdullah Emre, Salih Bortecine Avci, Muhammet Daştan, and Mehmet Akif Destek. 2023. Investigation of the Effect of Natural Resource Dependence on Environmental Sustainability under the Novel Load Capacity Curve Hypothesis. *International Journal of Sustainable Development & World Ecology* 1–16. [CrossRef]

Chatti, Walid. 2021. Moving towards Environmental Sustainability: Information and Communication Technology (ICT), Freight Transport, and CO_2 Emissions. *Heliyon* 7: e08190. [CrossRef]

Chudik, Alexander, and M. Hashem Pesaran. 2015. Common Correlated Effects Estimation of Heterogeneous Dynamic Panel Data Models with Weakly Exogenous Regressors. *Journal of Econometrics* 188: 393–420. [CrossRef]

Chudik, Alexander, Kamiar Mohaddes, M. Hashem Pesaran, and Mehdi Raissi. 2016. Long-Run Effects in Large Heterogeneous Panel Data Models with Cross-Sectionally Correlated Errors. *Essays in Honor of Aman Ullah* 85–135.

Chukkali, Surekha, Kritika Rastogi, Amritkant Mishra, Sonakshi Nayar, and Tanisha Gupta. 2022. Impact of Urban Environmental Quality, Residential Satisfaction, and Personality on Quality of Life Among Residents of Delhi/NCR. *ECS Transactions* 107: 19875–87. [CrossRef]

Coakley, Jerry, Ana-María Fuertes, and Ron Smith. 2006. Unobserved Heterogeneity in Panel Time Series Models. *Computational Statistics & Data Analysis* 50: 2361–80.

Dahmani, Mounir. 2023. Environmental quality and sustainability: Exploring the role of environmental taxes, environment-related technologies, and R&D expenditure. *Environmental Economics and Policy Studies*. [CrossRef]

Dahmani, Mounir, Mohamed Mabrouki, and Adel Ben Youssef. 2021a. *The ICT, Financial Development, Energy Consumption and Economic Growth Nexus in MENA Countries: Panel CS-ARDL Evidence (No. 2021-46)*. Nice: Groupe de REcherche en Droit, Economie, Gestion (GREDEG CNRS), Université Côte d'Azur.

Dahmani, Mounir, Mohamed Mabrouki, and Adel Ben Youssef. 2023. The ICT, financial development, energy consumption and economic growth nexus in MENA countries: Dynamic panel CS-ARDL evidence. *Applied Economics* 55: 1114–28. [CrossRef]

Dahmani, Mounir, Mohamed Mabrouki, and Ludovic Ragni. 2021b. Decoupling Analysis of Greenhouse Gas Emissions from Economic Growth: A Case Study of Tunisia. *Energies* 14: 7550. [CrossRef]

Degirmenci, Tunahan, and Mehmet Aydin. 2023. The effects of environmental taxes on environmental pollution and unemployment: A panel co-integration analysis on the validity of double dividend hypothesis for selected African countries. *International Journal of Finance & Economics* 28: 2231–38.

Demiral, Mehmet, and Özge Demiral. 2023. Socio-Economic Productive Capacities and Energy Efficiency: Global Evidence by Income Level and Resource Dependence. *Environmental Science and Pollution Research* 30: 42766–90. [CrossRef] [PubMed]

Demissew Beyene, Sisay, and Balázs Kotosz. 2020. Testing the environmental Kuznets curve hypothesis: An empirical study for East African countries. *International Journal of Environmental Studies* 77: 636–54. [CrossRef]

Dimnwobi, Stephen Kelechi, Chukwunonso Ekesiobi, Chekwube V. Madichie, and Simplice A. Asongu. 2021. Population Dynamics and Environmental Quality in Africa. *Science of The Total Environment* 797: 149172. [CrossRef]

Dinda, Soumyananda. 2004. Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics* 49: 431–55. [CrossRef]

Ditzen, Jan, Yiannis Karavias, and Joakim Westerlund. 2021. Testing and Estimating Structural Breaks in Time Series and Panel Data in Stata. *arXiv* arXiv:2110.14550.

Dogan, Eyup, Sabina Hodžić, and Tanja Fatur Šikić. 2022. A Way Forward in Reducing Carbon Emissions in Environmentally Friendly Countries: The Role of Green Growth and Environmental Taxes. *Economic Research-Ekonomska Istraživanja* 35: 5879–94. [CrossRef]

Du, Qiang, Na Wu, Fengyi Zhang, Yuting Lei, and Asif Saeed. 2022. Impact of Financial Inclusion and Human Capital on Environmental Quality: Evidence from Emerging Economies. *Environmental Science and Pollution Research* 29: 33033–45. [CrossRef]

Eberhardt, Markus, and Francis Teal. 2010. *Productivity Analysis in Global Manufacturing Production*. Economics Series Working Papers (515). Oxford: University of Oxford, Department of Economics.

Eurostat. 2013. *Environmental Taxes—A Statistical Guide*, 2013th ed. Luxembourg: Publications Office of the European Union.

Everaert, Gerdie, and Tom De Groote. 2016. Common Correlated Effects Estimation of Dynamic Panels with Cross-Sectional Dependence. *Econometric Reviews* 35: 428–63. [CrossRef]

Fan, Jianqing, Yuan Liao, and Jiawei Yao. 2015. Power Enhancement in High-Dimensional Cross-Sectional Tests. *Econometrica* 83: 1497–541. [CrossRef]

Farooq, Umar, Bilal Haider Subhani, Muhammad Nouman Shafiq, and Seemab Gillani. 2023. Assessing the environmental impacts of environmental tax rate and corporate statutory tax rate: Empirical evidence from industry-intensive economies. *Energy Reports* 9: 6241–50. [CrossRef]

Grossman, Gene M., and Alan B. Krueger. 1991. *Environmental Impacts of a North American Free Trade Agreement*. NBER Working Papers, no. 3914. Cambridge: National Bureau of Economic Research, Inc.

Guo, Bingnan, Yu Wang, Haiyan Zhou, and Feng Hu. 2022. Can Environmental Tax Reform Promote Carbon Abatement of Resource-Based Cities? Evidence from a Quasi-Natural Experiment in China. *Environmental Science and Pollution Research* 30: 117037–49. [CrossRef] [PubMed]

Hadj, Tarek Bel, Adel Ghodbane, Ezzedine Ben Mohamed, and Abdullah Abdulmohsen Alfalih. 2023. Renewable Energy for Achieving Environmental Sustainability: Institutional Quality and Information and Communication Technologies as Moderating Factors. *Environmental Science and Pollution Research* 30: 75799–816. [CrossRef]

Haouas, Ilham, Muhammad Haseeb, Muhammad Azam, and Zia Ur Rehman. 2023. Do Demographic Factors Affect the Environment? Empirical Evidence from the Middle East and North African Countries. *Environmental Science and Pollution Research* 30: 77077–95. [CrossRef]

Hasan, Md Arif, David J. Frame, Ralph Chapman, and Kelli M. Archie. 2019. Emissions from the Road Transport Sector of New Zealand: Key Drivers and Challenges. *Environmental Science and Pollution Research* 26: 23937–57. [CrossRef] [PubMed]

He, Pinglin, Shuhao Zhang, Lei Wang, and Jing Ning. 2023. Will Environmental Taxes Help to Mitigate Climate Change? A Comparative Study Based on OECD Countries. *Economic Analysis and Policy* 78: 1440–64. [CrossRef]

Huang, Xiaoqi, Wei Liu, Zhan Zhang, Xinyu Zou, and Pujuan Li. 2023. Quantity or quality: Environmental legislation and corporate green innovations. *Ecological Economics* 204: 107684. [CrossRef]

Iyke-Ofoedu, Maureen Ifeoma, Samuel Manyo Takon, David O. Ugwunta, Hillary Chijindu Ezeaku, Ebele Sabina Nsofor, and Obiamaka P. Egbo. 2024. Impact of CO_2 Emissions Embodied in the Agricultural Sector on Carbon Sequestration in South Africa: The Role of Environmental Taxes and Technological Innovation. *Journal of Cleaner Production* 444: 141210. [CrossRef]

Jahanger, Atif, Mohammad Razib Hossain, Muhammad Usman, and Joshua Chukwuma Onwe. 2023. Recent Scenario and Nexus between Natural Resource Dependence, Energy Use and Pollution Cycles in BRICS Region: Does the Mediating Role of Human Capital Exist? *Resources Policy* 81: 103382. [CrossRef]

Karlilar, Selin, Mehmet Balcilar, and Firat Emir. 2023. Environmental Sustainability in the OECD: The Power of Digitalization, Green Innovation, Renewable Energy and Financial Development. *Telecommunications Policy* 47: 102568. [CrossRef]

Khan, Syed Abdul Rehman, Hafiz Muhammad Zia-Ul-Haq, Pablo Ponce, and Laeeq Janjua. 2023. Re-investigating the impact of non-renewable and renewable energy on environmental quality: A roadmap towards sustainable development. *Resources Policy* 81: 103411. [CrossRef]

Kostakis, Ioannis, Stavros Armaos, Konstadinos Abeliotis, and Eleni Theodoropoulou. 2023. The investigation of EKC within CO_2 emissions framework: Empirical evidence from selected cross-correlated countries. *Sustainability Analytics and Modeling* 3: 100015. [CrossRef]

Köppl, Angela, and Margit Schratzenstaller. 2023. Carbon Taxation: A Review of the Empirical Literature. *Journal of Economic Surveys* 37: 1353–88. [CrossRef]

Kuznets, Simon. 1955. Economic growth and income inequality. *American Economic Review* 45: 1–28.

Li, Liang, Gang Li, Ilhan Ozturk, and Sana Ullah. 2023. Green Innovation and Environmental Sustainability: Do Clean Energy Investment and Education Matter? *Energy & Environment* 34: 2705–20.

Li, Xiaolong, Sidra Sohail, Muhammad Tariq Majeed, and Waheed Ahmad. 2021. Green Logistics, Economic Growth, and Environmental Quality: Evidence from One Belt and Road Initiative Economies. *Environmental Science and Pollution Research* 28: 30664–74. [CrossRef] [PubMed]

Lin, Shu, Asif Razzaq, and Kefu Yi. 2023. Heterogenous Influence of Productive Capacities Pillars and Natural Resources on Ecological Sustainability in Developing Belt and Road Host Countries. *Resources Policy* 85: 103776. [CrossRef]

Luo, Gengyan, Jitao Guo, Fangyi Yang, and Chuyi Wang. 2023. Environmental Regulation, Green Innovation and High-Quality Development of Enterprise: Evidence from China. *Journal of Cleaner Production* 418: 138112. [CrossRef]

Luqman, Muhammad, Peter J. Rayner, and Kevin R. Gurney. 2023. On the Impact of Urbanisation on CO_2 Emissions. *NPJ Urban Sustainability* 3: 6. [CrossRef]

Mpofu, Favourate Y. 2022. Green Taxes in Africa: Opportunities and Challenges for Environmental Protection, Sustainability, and the Attainment of Sustainable Development Goals. *Sustainability* 14: 10239. [CrossRef]

Murshed, Muntasir, Samiha Khan, and A.K.M. Atiqur Rahman. 2022. Roadmap for Achieving Energy Sustainability in Sub-Saharan Africa: The Mediating Role of Energy Use Efficiency. *Energy Reports* 8: 4535–52. [CrossRef]

Nemavhidi, Muano, and Ademola Oluborode Jegede. 2023. Carbon tax as a climate intervention in South Africa: A potential aid or hindrance to human rights? *Environmental Law Review* 25: 11–27. [CrossRef]

Nkemgha, Guivis Zeufack, Symphorien Engone Mve, Tekam Oumbé Honoré, and Alim Belek. 2024. Linking Industrialization and Environmental Quality in Sub-Saharan Africa: Does the Environmental Policy Stringency Matter? *International Economic Journal* 38: 166–84. [CrossRef]

O'Connell, Paul G. J. 1998. The overvaluation of purchasing power parity. *Journal of International Economics* 44: 1–19. [CrossRef]

OECD. 2019. *Environmentally Related Tax Revenue Accounts: OECD Methodological Guidelines in line with the SEEA*. Paris: OECD.

Oluc, Ihsan, Mehdi Ben Jebli, Muhlis Can, Ihsan Guzel, and Jan Brusselaers. 2023. The Productive Capacity and Environment: Evidence from OECD Countries. *Environmental Science and Pollution Research* 30: 3453–66. [CrossRef] [PubMed]

Organization for Economic Co-operation and Development [OECD]. 2023. OECD.Stat: Green Growth Indicators. Available online: https://stats.oecd.org/Index.aspx?DataSetCode=GREEN_GROWTH (accessed on 22 November 2023).

Panayotou, Theodore. 1993. *Empirical Tests and Policy Analysis of Environmental Degradation at Different Stages of Economic Development*. IDEAS Working Paper Series from RePEc; Geneva: International Labour Organization.

Pearce, David. 1991. The Role of Carbon Taxes in Adjusting to Global Warming. *The Economic Journal* 101: 938–48. [CrossRef]

Pesaran, M. Hashem. 2004. General diagnostic tests for cross section dependence in panels. IZA Discussion Paper No. 1240 and CESifo Working Paper No. 1229. *Economics* 1240: 1.

Pesaran, M. Hashem. 2006. Estimation and Inference in Large Heterogeneous Panels with a Multifactor Error Structure. *Econometrica* 74: 967–1012. [CrossRef]

Pesaran, M. Hashem. 2007. A Simple Panel Unit Root Test in the Presence of Cross-Section Dependence. *Journal of Applied Econometrics* 22: 265–312. [CrossRef]

Pesaran, M. Hashem. 2015. Testing Weak Cross-Sectional Dependence in Large Panels. *Econometric Reviews* 34: 1089–117. [CrossRef]

Pesaran, M. Hashem. 2021. General diagnostic tests for cross-sectional dependence in panels. *Empirical Economics* 60: 13–50. [CrossRef]

Pesaran, M. Hashem, and Takashi Yamagata. 2008. Testing slope homogeneity in large panels. *Journal of Econometrics* 142: 50–93. [CrossRef]

Pesaran, M. Hashem, and Yimeng Xie. 2021. A Bias-Corrected CD Test for Error Cross-Sectional Dependence in Panel Data Models with Latent Factors. Cambridge Working Papers in Economics 2158. *arXiv* arXiv:2109.00408.

Pesaran, M. Hashem, Yongcheol Shin, and Richard J. Smith. 2001. Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics* 16: 289–326. [CrossRef]

Pesaran, M. Hashem, Yongcheol Shin, and Ron P. Smith. 1999. Pooled Mean Group Estimation of Dynamic Heterogeneous Panels. *Journal of the American Statistical Association* 94: 621–34. [CrossRef]

Purvis, Ben, Yong Mao, and Darren Robinson. 2019. Three pillars of sustainability: In search of conceptual origins. *Sustainability Science* 14: 681–95. [CrossRef]

Runst, Petrik, and David Höhle. 2022. The German Eco Tax and Its Impact on CO_2 Emissions. *Energy Policy* 160: 112655. [CrossRef]

Sahoo, Malayaranjan, Narayan Sethi, and Miguel Angel Esquivias Padilla. 2023. Unpacking the Dynamics of Information and Communication Technology, Control of Corruption and Sustainability in Green Development in Developing Economies: New Evidence. *Renewable Energy* 216: 119088. [CrossRef]

Shobande, Olatunji A., Lawrence Ogbeifun, and Aviral Kumar Tiwari. 2024. Unlocking information technology infrastructure for promoting climate resilience and environmental quality. *Technological Forecasting and Social Change* 198: 122949. [CrossRef]

Stern, David I. 2004. The Rise and Fall of the Environmental Kuznets Curve. *World Development* 32: 1419–39. [CrossRef]

Struwig, Jarè. 2022. Environmental Protection, Satisfaction with. In *Encyclopedia of Quality of Life and Well-Being Research*. Cham: Springer International Publishing, pp. 1–6.

Swamy, Paravastu A. V. B. 1970. Efficient Inference in a Random Coefficient Regression Model. *Econometrica* 38: 311. [CrossRef]

Tan, Zhe, Yufeng Wu, Yifan Gu, Tingting Liu, Wei Wang, and Xiaomin Liu. 2022. An Overview on Implementation of Environmental Tax and Related Economic Instruments in Typical Countries. *Journal of Cleaner Production* 330: 129688. [CrossRef]

Tchapchet Tchouto, Jules-Eric, Loudi Njoya, Tii Nchofoung, and Isaac Ketu. 2024. Investigating the effects of environmental tax regulations on industrialization in African countries. *Environment, Development and Sustainability* 26: 2153–82. [CrossRef]

Uche, Emmanuel, and Nicholas Ngepah. 2024. How Green-Technology, Energy-Transition and Resource Rents Influence Load Capacity Factor in South Africa. *International Journal of Sustainable Energy* 43. [CrossRef]

Ullah, Sami, Ben Niu, and Muhammad Saeed Meo. 2024. Digital inclusion and environmental taxes: A dynamic duo for energy transition in green economies. *Applied Energy* 361: 122911. [CrossRef]

Ullah, Sami, Rundong Luo, Tomiwa Sunday Adebayo, and Mustafa Tevfik Kartal. 2023. Dynamics between environmental taxes and ecological sustainability: Evidence from top-seven green economies by novel quantile approaches. *Sustainable Development* 31: 825–39. [CrossRef]

UNCTAD. 2021. *Productive Capacities Index: Methodological Approach and Results*. Geneva: United Nations Conference on Trade and Development.

United Nations Conference on Trade and Development [UNCTAD]. 2023. UNCTADSTAT-Data Center: UNCTAD's Productive Capacities Index (PCI). Available online: https://unctadstat.unctad.org/datacentre/dataviewer/US.PCI (accessed on 22 November 2023).

Wang, Anqi, Abdul Rauf, Ilhan Ozturk, Junhao Wu, Xiaolei Zhao, and Huimin Du. 2024. The key to sustainability: In-depth investigation of environmental quality in G20 countries through the lens of renewable energy, economic complexity and geopolitical risk resilience. *Journal of Environmental Management* 352: 120045. [CrossRef] [PubMed]

Wang, Jingyi, Chenglin Jiang, Mingquan Li, Shuai Zhang, and Xuebiao Zhang. 2023. Renewable energy, agriculture, and carbon dioxide emissions nexus: Implications for sustainable development in sub-Saharan African countries. *Sustainable Environment Research* 33: 31. [CrossRef]

Westerlund, Joakim. 2007. Testing for Error Correction in Panel Data. *Oxford Bulletin of Economics and Statistics* 69: 709–48. [CrossRef]

Wu, Tong, Juan C. Rocha, Kevin Berry, Tomas Chaigneau, Maike Hamann, Emilie Lindkvist, Jiangxiao Qiu, Caroline Schill, Alon Shepon, Anne-Sophie Crépin, and et al. 2024. Triple Bottom Line or Trilemma? Global Tradeoffs Between Prosperity, Inequality, and the Environment. *World Development* 178: 106595. [CrossRef]

Xin, Yongrong, Tahseen Ajaz, Mohsin Shahzad, and Jia Luo. 2023. How productive capacities influence trade-adjusted resources consumption in China: Testing resource-based EKC. *Resources Policy* 81: 103329. [CrossRef]

Yiadom, Eric B., Lord Mensah, Godfred A. Bokpin, and John K. M. Mawutor. 2024. Carbon Tax Adoption and Foreign Direct Investment: Evidence from Africa. *Cogent Economics & Finance* 12: 2312783.

Yolles, Maurice. 2018. Sustainability development: Part 2—Exploring the dimensions of sustainability development. *International Journal of Markets and Business Systems* 3: 257. [CrossRef]

Youssef, Adel Ben, Mounir Dahmani, and Mohamed Mabrouki. 2023. The impact of environmentally related taxes and productive capacities on climate change: Insights from european economic area countries. *Environmental Science and Pollution Research* 30: 99900–12. [CrossRef]

Zarco-Periñán, Pedro J., Irene M. Zarco-Soto, and Fco Javier Zarco-Soto. 2021. Influence of Population Density on CO_2 Emissions Eliminating the Influence of Climate. *Atmosphere* 12: 1193. [CrossRef]

Zhang, Yanyan, Irfan Khan, and Muhammad Wasif Zafar. 2022. Assessing environmental quality through natural resources, energy resources, and tax revenues. *Environmental Science and Pollution Research* 29: 89029–44. [CrossRef] [PubMed]