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Heterogeneous and dynamic impacts of growth, urbanization, deforestation, and energy intensity on environmental degradation in Africa using the MM-Quantile regression method

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Abstract. *This study investigates how economic growth, urbanization, energy use, trade openness, and forest area affect pollution in Africa from 1990 to 2022. Using the moment-quantile approach for panel data, we capture heterogeneous effects across the conditional distribution of CO2 emissions. Economic growth raises emissions at all quantiles, with stronger effects at higher pollution levels. Trade openness is beneficial at lower quantiles, while energy intensity worsens environmental quality everywhere. Forest resources mitigate emissions, especially in high-pollution countries, whereas urbanization mainly affects intermediate pollution levels. The findings support smart urban planning, energy transition, and forest management to curb emissions without hindering development.*

Keywords: dioxide emissions, growth, heterogeneous effects, Africa, MM quantile.

JEL Classification: Q53, O55, C23, Q56.

1. Introduction

In recent decades, Africa has experienced continued economic growth, rapid urbanisation and expanded trade along with an increasing consumption of energy (Kazemzadeh et al., 2023). The favorable aspect of this phenomenon is an impetus for economic change and development opportunities, which however comes with many environmental fallout including climate change due to greenhouse gas emission, deforestation, water and food security issues, as well as urban sprawl management (Pawar, 2023).

Despite contributions from Africa to global CO_2 emissions being less than the contribution of developed countries (Pata et al., 2021), the continent remains one of the most vulnerable regions due to its geographical location, high dependence on climate-sensitive sectors and limited capacity for adaptation (Abidoye & Odusola 2015; Ntarmah et al., 2021). These vulnerabilities are then compounded by a growing frequency and severity in climate-related hazards that directly obstruct national development (Dodman, 2009).

The linkage of Africa to the world economy depends upon and/or reifies its accelerated industrialization, rapid urbanization and enhanced trade but it is challenged by series of structural problems like unemployment, poverty, inflation (Muftau et al., 2014). These processes are not only shaping the continent's economy and society, but they are also causing increasing pressure on biodiversity and the environment. This pressure can be seen in increasing depletion of energy and timber resources, increased release of carbon dioxide to the atmosphere and, overall reduced environmental quality. This seems to be a paradox of development vs. based environmental sustainability (Azam et al., 2022; Congregado et al., 2016; Muftau et al., 2014).

As the environment becomes polluted, scientists and governments should prioritize sustainability. The UN's Sustainable Development targets, specifically SDG 13 on climate action and sustainable ecosystem management, and the Paris Agreement's climate targets make Africa more resilient to climate change and push African countries to consider their development. Countries must balance economic, social, and environmental growth to guarantee a sustainable long-term trajectory (Kazemzadeh et al., 2022; Muftau, 2014). Several studies have linked environmental degradation to energy consumption, global trade, natural resource dependence, deforestation, and demographic needs. These assessments stress the need for dynamic models to better explain complex economic growth-pollution linkages in Africa.

The literature on distributional heterogeneity is limited. Most studies assume homogeneous impacts, although pollution affects growth, urbanization, trade, energy consumption, and forest resources. This work fills this gap by using quantile regression via moments to capture the distinct effect of these factors on African carbon dioxide emissions. This study improves understanding of the varied dynamic effects of economic growth, trade openness, urbanization, energy consumption, and forest resources on CO_2 emissions across quantiles. Policymakers can use the empirical results to construct environmental and development policies that balance economic growth with environmental sustainability.

In fact, this research aims to address the following question: To what degree do economic growth, trade openness, urbanization, energy use, and forest resource influence CO_2 emissions in Africa, with differences depending on pollution levels?

Research hypotheses: This research assumes that Africa's economic and demographic development is putting increasing pressure on the environment, the intensity of which varies according to national contexts and pollution levels.

Limitations of the research: This study is confined to 25 African countries (N=25) over the period 1990–2022 (T=33 years), with a specific focus on the theoretical framework of the STIRPAT model.

Research methodology: The study combines a descriptive analysis of the theoretical framework with an econometric approach applied to a panel of 25 African countries over the period 1990–2022. Advanced dynamic panel techniques were used to take into account the specific heterogeneity of each country. The moment-based quantile regression (MM-QR) was used to understand the conditional distribution of the effects of dioxide emissions in both low-emission and high-emission nations. Finally, this approach is resilient to non-normality models and cross-sectional dependence, which reinforces the relevance of the results for public policy.

Study content: The article is structured in four sections. The next section provides a concise overview of previous research. The section 3 describes the model and the data. The section 4 presents and analyzes the empirical outcomes. The final section closes by addressing the primary implications of the study.

2. Literature review

Recent researches have extensively examined the impacts of economic growth, trade liberalization, urbanization, and natural resource management on the quality of the environment. These factors are key determinants in the analysis of pollutant emissions, particularly in developing countries. However, empirical results remain mixed, due to differences in socio-economic contexts, methodologies used and regional specificities. A critical review of existing work thus highlights the main contributions and limitations concerning the interactions between development, trade integration, urban dynamics and ecosystem preservation, while emphasising the specific challenges facing the African continent.

The amount of work regarding the connection between economic growth and environmental degradation is largely organized around the environmental Kuznets curve hypothesis, which suggests an inverted U-shaped correlation between income and pollution (Kuznets, 1995; Grossman & Krueger, 1991). In the early stages of development, Economic growth initially increases emissions (size effect), then a composition effect and, at higher income levels, a technical effect associated to cleaner inventions reduce pollution. As GDP grows, countries gain financial, institutional, and technological capacity to invest in sustainable infrastructure, promote energy efficiency, and enforce stronger environmental regulations, reducing emissions and ecological degradation.

However, the empirical evidence remains mixed and varies across countries and periods. Several studies confirm the environmental Kuznets curve (EKC) hypothesis in Africa and elsewhere (Abidoye & Odusola, 2015; Ali et al., 2017; Baidoo, 2023; Ertugrul et al., 2016; Hacıimamoğlu & Cengiz, 2024; Neagu & Neagu, 2022; Özkan et al., 2023; Satrio et al., 2025; Shahbaz et al., 2013; Tachega et al., 2021; Wani et al., 2025; York et al., 2003), highlighting disparities according to income levels, regional specificities and economic structures. Indeed, economic activity tends to be correlated with significant energy consumption, infrastructure expansion and intensified industrial production, thereby placing greater pressure on natural resources (York et al., 2003; Satrio et al., 2025; Abdi et al., 2025; Ahmad et al., 2019). Some research shows that while high-income countries can achieve a decoupling of GDP and environmental degradation through technological advances and green policies, middle- and low-income countries generally see their environmental pollution increase with economic progress due to limited access to sustainable technologies (Satrio et al., 2025).

Furthermore, the literature has mixed findings in relation to trade liberalisation and pollution. Al-Mulali & Ozturk (2015); Ertugrul et al. (2016); Sultana et al. (2023) report that international trade brings about additional ecological pressure by promoting the exploitation of fossil resources and economic growth. Conversely, Ali et al. (2017) and Shahbaz et al. (2013) have an article on the reduction of the CO_2 emissions because of liberalization of trade. Other reports suggest a two-way association (Abdi et al., 2025; Wani et al., 2025), with Sharma et al. (2022) argue that the effects are determined by the composition of imports. A distributed organization structure can contribute to promote such eco-footprint, whereas an integrated one may help assimilate it. Lastly, Ghazali & Ali (2019) as well as Salahuddin et al. (2019) draw a very limited role of trade liberalisation in polluting the environment. Overall, these results draw attention to the ambivalence of trade for environmental sustainability which is conditioned by economic and structural contexts.

Urbanization is an issue in literature with inconsistent consequences. On the contrary, urban growth aggr scratch) is perceived as a home to due to its purpose of concentration/ aggregation human activities taking place within it., contributing in no ̈small part in wear and tear on fossil fuel use that adds more nuisance to climate stress (Grimm et al., 2008; Al-Mulali & Ozturk, 2015, Mignamissi & Djeufack, 2022). In other words urban population growth leads to demand for energy, water and land which goes beyond the available local or regional biocapacity (York et al.,2003). It leads to enormous amounts of waste and pollution produced primarily by heightened consumption in cities that are being driven by rising incomes, infrastructure needs, transportation (Satrio et al., 2025; Zhang et al., 2022). Alternatively, studies indicate that in certain contexts, dense urban areas can enhance energy efficiency and reduce carbon footprints when equipped with sustainable infrastructure, which promotes economies of scale and resource-efficient designs. Furthermore, the research conducted by Martínez-Zarzoso & Maruotti (2011) found an inverted U-shaped link between urbanization and pollution. At low levels of urbanization, urbanization leads to an increase in emissions, reflecting a greater environmental impact in less developed regions.

A review of the literature highlights a close link between energy consumption and pollution, particularly in emerging nations where fossil fuel use increases ecological vulnerability. Several studies confirm that energy consumption directly stimulates pollution. Ertugrul et al. (2016) show that increased energy consumption leads to environmental degradation without generating sustainable economic growth, suggesting that reducing energy intensity could be an effective way to limit emissions. Similarly, Shahbaz et al. (2013), Acaravci and Ozturk (2010), Azam et al. (2022), Apergis &Payne (2010) and Ozcan (2013) identified high energy intensity as a core carbon emission determinant. Other research emphasizes the incredible generator effect of a fossil fuel dominated power structure. Al-Mulali & Ozturk (2015) and Apergis & Payne (2010) prove that in emerging countries, the reliance on fossil fuels causes a high increase of CO_2 emissions, so they defend diversification towards clean renewable energies. Kazemzadeh et al. (2023) indicated that energy intensity policies have opposite impacts on pollution according to the context (the countries and intensity levels). This leads the authors to argue that replacing fossil fuels with clean energy increases ecological quality.

Furthermore, results suggest that technological innovation can play a role in reducing environmental degradation by stretching energy. Energy efficiency increases, spread of new energy vehicles, and the introduction of more energyefficient industrial processes would also decompose decrease in CO_2 intensity and emission from correspondent source but less than that (Mushtaq et al., 2024; Wang et al., 2025).

Finally, the literature shows how forest cover is related to environmental deterioration. In the following paragraphs, we will see many pieces of research and study that argue that deforestation has great influence on the air pollution and ecosystem degradation. Arshad et al. (2020) and Andrée et al. (2019) demonstrate that forest loss, and land use in terms of production contribute to pollution and the loss of biodiversity. In addition, the rapid urbanization contributes to deforestation and pressure on natural ecosystems as it supersedes forest in favour of infrastructures and housing (Ahmad et al., 2019).

3. Materials and methods

Research Population and Sample: This quantitative study uses panel data to measure variable changes over time and across countries. The analysis covers 1990–2022, including 25 African nations. It analyzes how economic growth, urbanization, energy use, and forests resources affect dioxide emissions. The countries included in the sample are: Benin, Botswana, Burkina Faso, Cameroon, Democratic Republic of Congo, Egypt, Eswatini, Ethiopia, Gabon, Kenya, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, South Africa, Tanzania, Togo, Uganda, Zambia and Zimbabwe. These nations were determined by the availability and quality of data during the review period. Econometric estimates were performed using STATA 17 software.

Variables and sources: The various variables used in this study are compiled in Table 1, and with the corresponding sources. The dependent variable is the total volume of carbon dioxide emissions, measured in megatonnes of CO_2 equivalent.

The independent variables are:

- GDP per capita (in current dollars), used as a proxy for the level of economic development;
- Trade openness (TRADE), measured as a percentage of GDP, is used as an indicator of the degree of globalization;
- Urban population growth (in annual %), representing the dynamics of urbanization;
- Energy consumption (in kilograms of oil equivalent per capita), used as a proxy for energy intensity;
- Forest cover (as a percentage of total land area), to take into account the availability of natural resources and their role in environmental regulation.

Table 1. *Description of all variables*

Variable	Designation	Source
CO_2 emissions (CO_2)	Total carbon dioxide emissions	World Development Indicators (www.databank.worldbank.org)
GDP per capita (GDPpc)	Gross Domestic Product per capita (constant US$)	
Trade Openness (TRADE)	(Exports + Imports) as a percentage of GDP	
Urban population growth (URB)	Urban population growth (annual %)	
Energy intensity (ENERGY use)	Energy use per unit of GDP	
Forest area (FOREST)	Forest area (% of land area)	

Study model: The panel model utilized in this research is articulated in equation (1). This specification indicates that the impact of the explanatory variables (Z) varies across the conditional quantiles of the dependent variable (Y).

$$Y_{it} = \alpha_i + X'_{it}\beta + (\delta + Z'_{it}\gamma)U_{it}\ldots \quad (1)$$

Where:

Y_{it} is the dependent variable CO_2,

α_i : the fixed effects specific to each country i,

X_{it} : vector of explanatory variables $(GDPpp, TRADE, URB, ENERGYuse, FOREST)$

β_i : average coefficients associated with X_{it},

Z_{it} : vector of explanatory variables that allows heterogeneity to be introduced into the quantiles,

δ, γ : parameters that modulate how the quantiles are influenced,

U_{it} : random term (i.i.d)

Equation (1) will be estimated using the moment-based quantile regression (MM-QR) developed by Machado & Santos Silva (2019), which allows for the heterogeneity of the conditional distribution of CO_2 emissions. Unlike traditional least squares approaches, this method offers a more robust analysis by capturing the differentiated effects of environmental determinants across the entire distribution, not just on the mean, while correcting for bias issues related to heteroscedasticity and unobserved individual effects (Machado & Santos Silva, 2019). Equation (1) can be written as follows, given that the effect of the explanatory variable is not constant but depends on the position of the conditional distribution of Y.

$$Q_\tau(Y_{it}|X_{it}) = \alpha_i(\tau) + X'_{it}\beta + Z'_{it}\gamma q(\tau)\ldots \quad (2)$$

Where:
$Q_\tau(Y_{it}|X_{it})$: is the τ^{th}quantile of the dioxide emissions for country i and t conditional on the covariates,
$\alpha_i(\tau) = \alpha_i + \delta q(\tau)$: fixed effects vary according to the quantile,
$q(\tau)$: function that depends on the quantile (in our case 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90).

Data description and Correlation matrix:

This study draws on a balanced panel of annual data covering 25 African countries over the period 1990–2022. All variables were transformed into logarithmic values to simplify coefficient interpretation in terms of CO_2 elasticity and reduce heteroscedasticity.

The descriptive statistics of the variables for 25 African nations over 33 years are shown in Table 2 (N = 25; T = 33). CO_2 emissions have a mean of 2.51 with a standard deviation of 1.56, ranging from 0.32 to 6.88. The dispersion is mainly inter-country (1.53), much more pronounced than the intra-country temporal variation (0.45). GDP per capita (GDPpc) averages 7.67 with an overall standard deviation of 1.08, ranging from 5.26 to 10.05; the differences are due more to variation between countries (0.98) than over time (0.49). Trade openness (TRADE) averages 4.47, with a variability of 0.52, mainly explained by differences between countries (0.45). The urban population (URB) has an average of 1.90 and a standard deviation of 0.58, ranging from -1.89 to 4.13; inter-country disparities (0.47) dominate over intra-country disparities (0.34). Finally, energy intensity (ENERGYuse) has an average of 6.88 with a standard deviation of 0.68, with greater variability between countries (0.62) than over time (0.30). The share of forests (FOREST) shows relatively moderate variability: overall values range from 0.0439 to 5.217, with an average of 3.73 and a standard deviation of 1.18. The variation between countries (standard deviation = 1.20) remains more pronounced than that observed within countries over time (standard deviation = 0.07), indicating that the differences are explained more by national specificities than by temporal fluctuations.

Table 2. *Descriptive Statistics*

Variable		Mean	Std. Dev.	Min	Max	Observations
CO_2	overall	2.516	1.569	0.321	6.883	N = 825
	between		1.531	0.739	6.683	n = 25
	within		0.457	1.121	3.747	T = 33
GDP pc	overall	7.677	1.080	5.261	10.056	N = 825
	between		0.980	6.289	9.410	n = 25
	within		0.493	6.375	9.074	T = 33
TRADE	overall	4.475	0.524	2.270	5.860	N = 825
	between		0.451	3.839	5.317	n = 25
	within		0.280	2.906	5.440	T = 33
URB	overall	1.901	0.580	-1.898	4.136	N = 825
	between		0.474	0.319	2.460	n = 25
	within		0.347	-1.938	4.096	T = 33
ENERGY~use	overall	6.886	0.687	0	8.685	N = 825
	between		0.628	5.696	8.431	n = 25
	within		0.306	-0.059	7.732	T = 33
FOREST	overall	3.736	1.177	.0439	5.217	N = 825
	between		1.197	.0543	5.212	n = 25
	within		.0650	3.488	4.038	T = 33

Source: Author.

Correlation matrix and multicollinearity test:

Table 3 presents the results of the correlation matrix and the estimates of the variance inflation factor (VIF). CO_2 emissions are positively and significantly correlated with GDP per capita (0.416) and energy consumption (0.360). Conversely, they are negatively correlated with trade openness (-0.093), urbanization (-0.141) and forest cover (-0.265). Furthermore, the correlations observed between the independent variables remain well below the critical threshold of 0.8, ruling out any risk of severe multicollinearity. The VIF values corroborate this finding: they vary between 1.143 and 2.19, with an average of 1.60, well below the threshold of 10. These results thus confirm the statistical validity and relevance of the econometric model used.

Table 3. *Pairwise correlations and VIF estimation*

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) CO_2	1.000					
(2) GDPpc	0.416* (0.000)	1.000				
(3) TRADE	-0.093* (0.008)	0.537* (0.000)	1.000			
(4) URB	-0.141* (0.000)	-0.413* (0.000)	-0.323* (0.000)	1.000		
(5) Energyuse	0.360* (0.000)	0.653* (0.000)	0.393* (0.000)	-0.363* (0.000)	1.000	
(6) Forest	-0.265* (0.000)	0.014 (0.695)	0.261* (0.000)	0.097* (0.005)	0.093* (0.007)	1.000
VIF	-	2.19	1.584	1.281	1.81	1.143
1/VIF	-	.457	.631	.781	.553	.875

* $p<0.1$

Source: Author.

4. Empirical results

Prior to estimating the MM-QR model, it is crucial to verify several prerequisites, namely: the normality test of the distribution, the presence of slope heterogeneity, the presence of Pesaran's cross-sectional dependence, and the presence of the unit root.

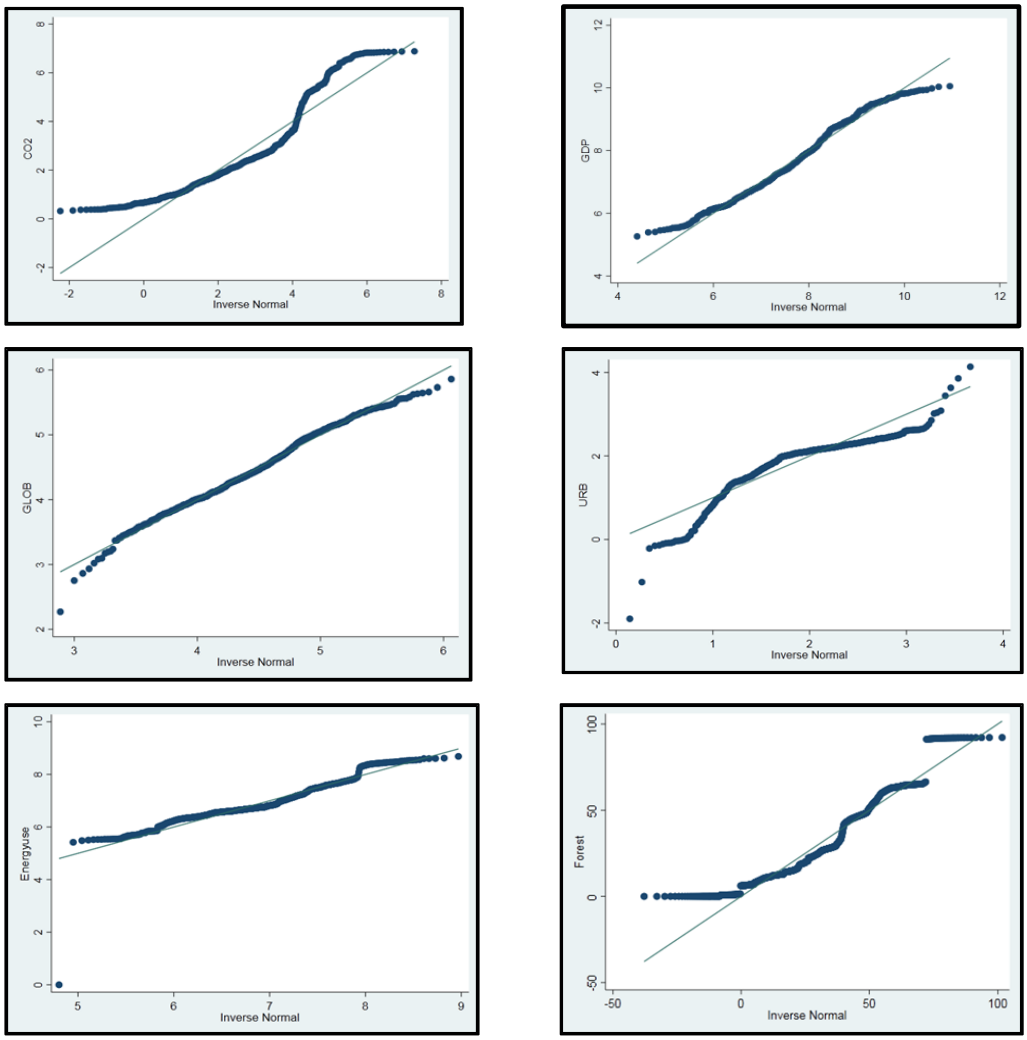
Normality test: Table 4 shows the Shapiro–Wilk and Kolmogorov–Smirnov normality tests for distribution normality. The results of both tests indicate that all variables in the model reject the null hypothesis of normality at the 1% threshold. These results support the quantile approach, which better captures heterogeneous impacts along the conditional distribution of variables.

Table 4. *Normal distribution test*

Variables	Shapiro–Wilk Test		Kolmogorov–Smirnov Test		Observations
	z	Prob>z	D	P-value	
CO_2	14.125	0.000	0.3992	0.000	825
GDPpc	12.013	0.000	0.8090	0.000	825
TRADE	9.413	0.000	0.1256	0.000	825
URB	12.170	0.000	0.9415	0.000	825
ENERGY use	12.373	0.000	0.2131	0.000	825
FOREST	8.874	0.000	0.1312	0.000	825

Source: Author.

Figure 1. *The normal Q-Q plot of all variables*



Source: Author, generated using STATA.

Furthermore, Figure 1 illustrates the distribution of data using Q-Q plots to test the normality of variables. When the points coincide with the reference line, the distribution can be considered normal. Conversely, any marked deviation from this line reveals a deviation from normality. As shown in Figure 1, all variables show significant deviations, confirming their non-normal distribution. This finding justifies the use of robust econometric methods, such as quantile regression.

Breusch Pagan and Hausman tests: In order to test for the existence of specific, fixed or random effects, Table 5 presents the Breusch-Pagan and Hausman LM optimal model selection tests. The results show that the Breusch-Pagan LM test is highly significant ($p < 0.01$), confirming the presence of individual effects, which makes the pooled OLS

regression model inappropriate (Pooled OLS). Furthermore, the Hausman test rejects the null hypothesis of the validity of random effects in favour of fixed effects ($p < 0.01$). The findings suggest the fixed effects model is best for our dataset.

Table 5. *Model selection tests*

Breusch-Pagan (LM test)		Hausman Test	
chibar2(01)	Prob	chibar2(05)	Prob
8876.15	0.0000	113.8	0.0000

Source: Author.

Homogeneity test: Table 6 presents the results of the Pesaran and Yamagata (2008) homogeneity test for slopes. The results indicate that the p-value of the Delta test is less than 0.05, which means that the hypothesis of homogeneous slopes is rejected, indicating significant heterogeneity.

Table 6. *Pesaran & Yamagata test for slope homogeneity*

Pesaran & Yamagata test	Statistique value	P-value
Delta	32.485	0.000
adj	36.616	0.000

Source: Author.

Pesaran CD test: Cross-sectional dependence of errors was tested using the Pesaran CD test. As the p-values shown in Table 7 are all below 5%, the hypothesis of cross-sectional independence is rejected, revealing a significant dependence between units.

Table 7. *Pesaran CD test analysis*

Variable	CD-test	p-value	corr	abs(corr)
CO_2	60.660	0.000	0.613	0.729
GDPpc	84.850	0.000	0.856	0.856
TRADE	16.610	0.000	0.168	0.370
URB	8.780	0.000	0.089	0.336
Energy~e	18.730	0.000	0.190	0.535
Forest	58.330	0.000	0.589	0.877

Source: Author.

Panel Unitroot test: In light of the presence of cross-sectional error dependence, second-generation unit root tests, such as CADF and CIPS Pesaran (2007), are applied. The findings in Table 8 indicate that all series display integration of order 1 (I(1)).

Table 8. *CADF and CIPS Unitroot test*

Variables	PESCADF		CIPS		Observations
	At level	Δ	At level	Δ	
CO2	1.887 (0.970)	-4.016*** (0.000)	-2.132	-5.254	I(1)
GDPpc	-0.306 (0.380)	-2.612** (0.005)	-2.743	-5.042	I(1)
TRADE	-1.224 (0.110)	-5.809*** (0.000)	-2.272	-5.520	I(1)
URB	-0.442 (0.329)	-6.256*** (0.000)	-2.515	-4.509	I(1)
ENERGY use	-1.069 (0.142)	-4.727*** (0.000)	-2.206	-5.168	I(1)
FOREST	1.184 (0.882)	-4.514*** (0.000)	-1.807	-4.971	I(1)

*** p<0.01, ** p<0.05, * p<0.1

Source: Author.

Cointegration Test: The long-term cointegration relationship between the model variables is examined in Pedroni and Westerlund's cointegration tests in Table 9. The findings of the Pedroni test reveal that the Modified Phillips–Perron t statistic is significant ($p<0.01$), suggesting the existence of a cointegration relationship, although the other statistics are less conclusive. Similarly, the Westerlund test shows that two statistics are significant (, supporting the hypothesis of possible cointegration between CO_2 and its determinants. These findings may indicate a long-term relationship. We then proceed to evaluate the dynamics between CO_2 emissions and the independent variables (GDPpc, TRADE, URB, ENERGYuse, FOREST) using the moment quantile approach (MM-QR).

Table 9. *Cointegration test results*

Cointegration Test		Value	Robust P-value
Pedroni Test	Modified Phillips–Perron t	3.1030**	0.0010
	Phillips–Perron t	-0.9148	0.1802
	Augmented Dickey–Fuller t	-3592	0.3597
Westerlund test	G_T	-1.788**	0.050
	G_a	-3.500	0.160
	P_T	-10.523***	0.000
	P_a	-4.051*	0.010

*** p<0.01, ** p<0.05, * p<0.1
Source: Author.

Given the presence of heterogeneity in slopes, cross-sectional dependence of errors, unit roots and non-normality of the model variables, as well as the potential existence of long-term cointegration, estimation of the model using the quantile moment method is the most appropriate way to estimate the dynamic relationship between the dependent variable 'carbon dioxide emissions' and the independent variables 'GDPpc, TRADE, URB, ENERGYuse, FOREST'. This approach takes into account the heterogeneity of the impact of the determinants on the entire conditional distribution of CO_2 and provides robust estimates in the face of endogeneity and cross-sectional dependence issues.

Estimation by the Method of Moments quantile regression (MM-QR):

Table 10 displays the results of the model estimates derived from the MM-QR approach, considering the 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th quantiles. Figure 2 provides a visual representation of the effects of the independent variables on the dependent variable, complementing the results shown in Table 10.

This table indicates a positive and significant relationship between GDP per capita and CO_2 emissions across all quantiles. The coefficients increase gradually from 0.380 at the 30^{th} quantile to 0.402 at the 90^{th} quantile, reflecting an intensification of the effects of economic growth associated with elevated emission levels. These results indicate that economic growth contributes to increased CO_2 emissions in all contexts, but that its effect is more pronounced in countries or situations characterised by high emissions. In other words, the more a country is on a highly polluting trajectory, the more growth amplifies environmental degradation.

These findings demonstrate that economic expansion drives CO_2 emissions in Africa. The rise in coefficients along the quantiles aligns with the findings of York et al. (2003) and Satrio et al. (2025), demontrating that economic activity intensifies environmental pressures through increased energy consumption and industrial expansion, especially in contexts where access to clean technologies remains limited.

Furthermore trade openness, the findings indicate that trade openness has a positive and considerable impact on carbon dioxide emissions, so affirming that international commerce exacerbates ecological pressure (Al-Mulali & Ozturk, 2015; Ertugrul et al., 2016; Sultana et al., 2023). However, the intensity of this effect gradually decreases along the conditional distribution, from 0.209 at the 30th quantile to 0.113 at the 90th quantile. This finding indicates that trade openness induces more pollution in low-polluted countries; however, the effect of trade openness becomes less significant in high polluting economies. These results indicate that in low-emitting countries, trade openness has a relatively higher effect on emission growth while in highemitting environments its impact gradually stagnates. This is due to the heterogeneities of moving forward in order to strengthen polluting activities and in order to adopt pollution abatement technologies that can be obtained through an increasing trade (Abdi et al., 2025; Bakri et al., 2025 Sharma, et al., 2022; Wani, et al., 2025). The outcome agrees with that of Bakri et al. (2025); Frankel & Rose (2005) and Özkan et al. (2023) which found that trade liberalization is an avenue for the spread of cleaner technologies and environmentally friendly techniques. Furthermore, economies that are highly integrated into international trade tend to reorient their productive structure towards less carbon-intensive sectors, taking advantage of their comparative advantages in more environmentally efficient activities.

Urbanization has a significant adverse effect only in the intermediate quantiles (30^{th} q and 60^{th} q), with coefficients ranging from -0.091 to -0.047. These findings suggest that in situations of average pollution, urbanization can promote more efficient organization (better energy management, modern infrastructure). These findings correspondent with the research of Dodman (2009) and Glaeser & Kahn (2010), which highlights the potential of cities to reduce their carbon footprint when technological innovations and investments in sustainable infrastructure accompany urbanization.

However, the effect becomes insignificant at the extremes of the distribution. At low emission levels, this can be explained by the fact that urbanization remains insufficient to induce real energy efficiency gains, as highlighted by Martínez-Zarzoso & Maruotti (2011), who associate initial urban growth with increased resource consumption and environmental pressures (Ahmad et al., 2019). At high emission levels, the absence of a protective effect could be interpreted as a sign that urban capacity to offset pollution has reached the saturation point: above a certain threshold, urban density and expansion contribute more to increasing pressures (waste production, energy demand, motorised transport), thereby limiting the effect of pollution mitigation. This dynamic is consistent with the idea that urbanization alone is not enough to reverse the pollution trend in high-emission countries, supporting the hypothesis of a non-linear relationship put forward by Martínez-Zarzoso & Maruotti (2011).

Table 10 indicates that energy intensity displays a positive, stable, and significant effect across all quantiles, with coefficients between 0.254 and 0.257. This consistency reflects the central role of energy consumption in emissions dynamics, confirming that regardless of the intensity of emissions, energy use remains a major driver of pollution. In other words, the countries studied remain heavily dependent on fossil fuels, which limits the possibility of decoupling economic growth and environmental sustainability.

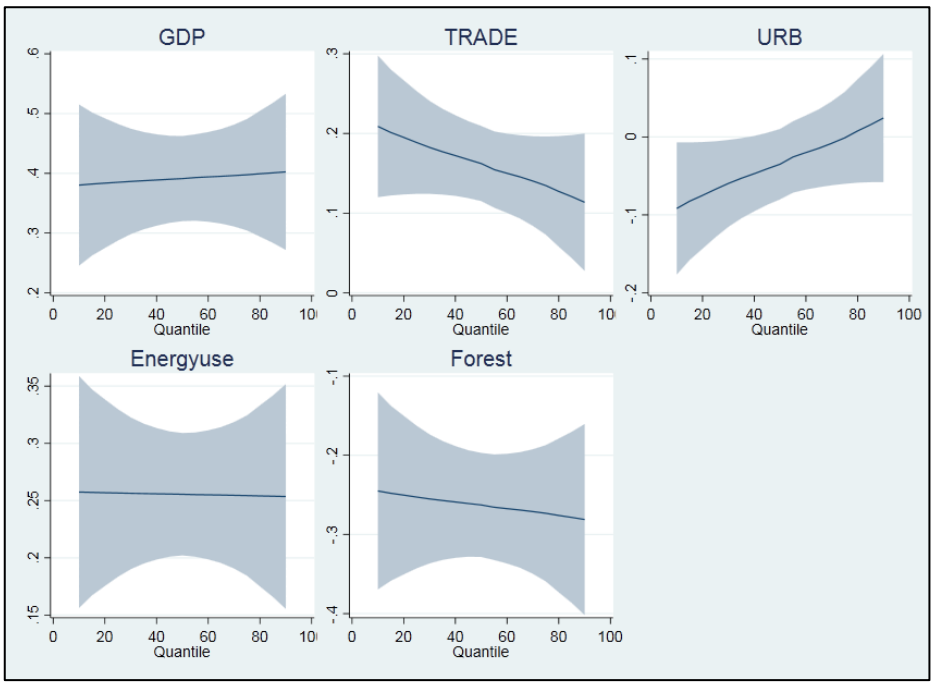
Table 10. *Estimation results from the MM-QR/ XTQREG approach*

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Location	Scale	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
GDPpc	0391*** (0.077)	0.007 (0.025)	0.380*** (0.068)	0.383*** (0.055)	0.386*** (0.045)	0.388*** (0.039)	0.391*** (0.036)	0.394*** (0.038)	0.396*** (0.043)	0.399*** (0.053)	0.402*** (0.066)
GLOB	0.161*** (0.044)	-0.030 (0.021)	0.209*** (0.045)	0.195*** (0.036)	0.182*** (0.029)	0.172*** (0.025)	0.162*** (0.024)	0.150*** (0.025)	0.140*** (0.28)	0.127*** (0.035)	0.113** (0.044)
URB	-0.033 (0.046)	0.036 (0.022)	-0.091** (0.043)	-0.074** (0.034)	-0.059** (0.028)	-0.047* (0.024)	-0.034 (0.023)	-0.019 (0.024)	-0.008 (0.027)	0.007 (0.033)	0.024 (0.041)
Eng-use	0.255** (0.087)	-0.001 (0.015)	0.257*** (0.051)	0.256*** (0.041)	0.256*** (0.033)	0.255*** (0.029)	0.255*** (0.027)	0.255*** (0.028)	0.254*** (0.032)	0.254*** (0.040)	0.253** (0.050)
Forest	-0.263*** (0.092)	-0.011 (0.024)	- 0.245*** (0.063)	- 0.250*** (0.051)	- 0.255*** (0.041)	- 0.258*** (0.035)	- 0.262*** (0.033)	- 0.267*** (0.035)	- 0.271*** (0.040)	- 0.275*** (0.049)	- 0.281*** (0.061)
Constant	0.003*** (0.0005)	0.425*** (0.0002)	/	/	/	/	/	/	/	/	/

Std. err statistics in parentheses
* p < 0.05, ** p < 0.01, *** p < 0.001
Source: Author.

These results are consistent with the literature that identifies energy consumption as one of the main determinants of ecological degradation (Ertugrul et al., 2016; Apergis & Payne, 2010; Acaravci & Ozturk, 2010; Ozcan, 2013; Shahbaz et al., 2013; Azam et al., 2022). As pointed out by Al-Mulali & Ozturk (2015) and Kazemzadeh et al. (2023), the predominance of fossil fuels in the energy mix of developing countries explains the strong correlation between energy intensity and emissions. In this context, the absence of significant variation in coefficients between quantiles suggests that structural dependency on fossil fuels affects the environment despite changing emission levels.

Figure 2. *Heterogeneous effects of independent variables across quantiles*



Source: Author, generated using stata.

Causality analysis

Given the heterogeneity of slopes and the cross-sectional dependence of errors, the Dumitrescu-Hurlin (2012) causality test is the most appropriate for detecting short-term Granger causality between CO_2 and the various independent variables.

Table 11. *Dumitrescu-Hurlin causality test results*

Direction	W-bar	Z-bar stat	p-value	Observations
GDPpc → CO_2	1.9983	3.5295	0.0004	GDPpc does Granger-cause CO_2 for at least one panel var (Country).
TRADE → CO_2	1.6497	2.2972	0.0216	TRADE does Granger-cause CO_2 for at least one panel var (Country).
URB → CO_2	2.3243	4.6821	0.0000	URB does Granger-cause CO_2 for at least one panel var (Country).
Energyuse → CO_2	2.0204	3.6077	0.0003	Energy use does Granger-cause CO_2 for at least one panel var (Country).
Forest → CO_2	4.2087	11.3445	0.0000	Forest does Granger-cause CO_2 for at least one panel var (Country).

Source: Author.

Table 11 presents the results of the Dumitrescu-Hurlin causality test, demonstrating that all causal relationships between the independent variables and carbon dioxide emissions are significant at the 5% threshold, particularly economic growth, trade, urbanization, energy use, and forest resources, thus confirming the role of economic and structural dynamics in increasing environmental pressure. The results obtained are consistent with several conclusions in the literature, noting that economic growth, trade openness, and urban concentration fuel energy demand and consumption, with subsequent increases in emissions.

Robustness check

To validate the robustness of the estimates generated by the MM-QR model, two complementary techniques were applied: fixed effects estimation (FE model) and Jackknife bias correction (JK correction).

Table 12. *MM-QR results with JK correction and clustered standard errors (for the median)*

VARIABLES	(1) FE model	(2) JK correction model
GDPpc	0.391*** (0.0297)	0.371*** (0.052)
TRADE	0.162*** (0.0225)	0.170*** (0.033)
URB	-0.0339 (0.0219)	-0.031 (0.031)
Energyuse	0.256*** (0.0239)	0.264*** (0.039)
Forest	-0.263*** (0.0287)	-0.287*** (0.048)
Constant	0.00307 (0.0210)	/ /
R-squared	0.638	/

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Source: Author.

The findings in Table 12 indicate that the coefficients maintain consistent signs and levels of significance across both alternative definitions. Specifically, GDP per capita, international trade, and energy consumption exhibit a positive and significant effect on CO_2 emissions, while forest cover continues to play a negative and protective role. Urbanization remains insignificant, confirming its limited impact.

The similarity of the coefficients between the reference model and the corrected versions (e.g. the effect of GDP varies from 0.391 to 0.371 and that of forests from –0.263 to –0.287) attests to the stability and reliability of the estimates. The JK correction also reduces biases associated with small sample sizes and dynamic specifications, while the fixed-effects model incorporates for unobservable country-specific heterogeneity. These consistent results reinforce the empirical validity of the main conclusions and suggest that the relationships identified are not sensitive to estimation biases or model choice.

5. Conclusion

This study examines the heterogeneous dynamic impact of economic growth, trade openness, urbanization, energy intensification and forests resource on various levels of environmental degradation in 25 African countries over the period from 1990 to 2022. This relationship was estimated with the moment based quantile regressions (MM-QR), that takes into account the distribution non-normalities of variables, country heterogeneity and cross-sectional error dependence (Machado & Santos Silva, 2019). Fixed effects modeling and Jackknife bias correction (JK correction) were used to reduce the likelihood of spurious results. The findings supported the efficiency of MM-QR estimator and thus empirical relevance of our conclusions.

The empirical results suggest that economic growth has detrimental effects on the environment, at all levels of emissions. It is especially impactful in high-emission situations. By contrast, the overall effects of trade openness on pollution are positive, however such effect is mitigated in polluted economies, now individuating a possible evidence about the cleaner technologies' diffusion.

Urbanization is a two-sided issue. While it reduces emissions at the middle quantiles, its effect is limited to low and high emission levels. Energy consumption is another climate-vulnerable variable, but its effect on environmental quality is consistent across all quantiles, implying that African countries do not use renewable energy to the same extent as their counterparts elsewhere. The contribution of forest resources is even more important in reducing environmental pressure in polluted regions and higher quantiles, highlighting its strategic role in addressing climate change.

The adoption of targeted programs is essential for African countries to avoid environmental decline. First, governments must imperatively increase the energy efficiency of their economies by reducing their dependence on fossil fuels and encouraging innovation in industrial pollution reduction. Green trade openness could increase through international cooperation, trade treaties, and technology transfer for cleaner processes. These measures could promote pro-environmental behaviors and reduce energy conservation and

sustainability. Third, urban form and population growth must be controlled. To prevent premature urban pollution in low-emission countries, we must ensure planned urbanization and early action on the energy transition. In high-emission countries, environmental fees and property taxes will be necessary to compensate for the saturation of urbanization benefits by energy. Finally, environmental policy must be country-specific and not an indissoluble link between growth, environmental sustainability, poverty reduction, regional conservation, and unemployment.

This research has some limitations, mainly related to data availability. Future research could rely on longer observation periods and include a larger number of countries and variables, particularly institutional ones, to refine the results. Such research could also examine environmental convergence between countries with similar trajectories, thus allowing for a better understanding of these processes.

References

Abdi, A., Siyad, S., Okash, M., and Mohamed, O. (2025). Approaches to ecological sustainability in sub-Saharan Africa: Evaluating the role of globalization, renewable energy, economic growth, and population density, *Research in Globalization*, 10, 100273. <https://doi.org/10.1016/j.resglo.2025.100273>

Abidoye, B., and Odusola, A. (2015). Climate change and economic growth in Africa: An econometric analysis, *Journal of African Economies*, 24, 1–25. <https://doi.org/10.1093/jae/eju033>

Acaravci, A., and Ozturk, I. (2010). On the relationship between energy consumption, CO_2 emissions and economic growth in Europe, *Energy*, 35(12), 5412–5420.

Ahmad, M., Zhao, Z.-Y., and Li, H. (2019). Revealing stylized empirical interactions among construction sector, urbanization, energy consumption, economic growth and CO_2 emissions in China, *Science of the Total Environment*, 657, 1085–1098. <https://doi.org/10.1016/j.scitotenv.2018.12.112>

Ali, W., Abdullah, A., and Azam, M. (2017). Re-visiting the environmental Kuznets curve hypothesis for Malaysia: Fresh evidence from ARDL bounds testing approach, *Renewable and Sustainable Energy Reviews*, 77, 990–1000. <https://doi.org/10.1016/j.rser.2016.11.236>

Al-Mulali, U., and Ozturk, I. (2015). The effect of energy consumption, urbanization, trade openness, industrial output, and political stability on environmental degradation in the MENA region, *Energy*, 84, 382–389. <https://doi.org/10.1016/j.energy.2015.03.004>

Andrée, B.P.J., Chamorro, A., Spencer, P., Koomen, E., and Dogo, H. (2019). Revisiting the relation between economic growth and the environment: A global assessment of deforestation, pollution and carbon emission, *Renewable and Sustainable Energy Reviews*, 114, 109221. <https://doi.org/10.1016/j.rser.2019.06.028>

Apergis, N., and Payne, J.E. (2010). The emissions, energy consumption, and growth nexus: Evidence from CIS countries, *Energy Policy*, 38(1), 650–655.

Arshad, Z., Robaina, M., Shahbaz, M., and Botelho, A. (2020). The effects of deforestation and urbanization on sustainable growth in Asian countries, *Environmental Science and Pollution Research*, 27 < https://doi.org/10.1007/s11356-019-07507-7>

Azam, M., Uddin, I., Khan, S., and Tariq, M. (2022). Are globalization, urbanization, and energy consumption causing carbon emissions in the SAARC region? Evidence from CS-ARDL approach, *Environmental Science and Pollution Research*, 29(58), 87746–87763. <https://doi.org/10.1007/s11356-022-21835-1>

Baidoo, D. (2023). Does the validity of the environmental Kuznets curve depend on the level of human development in Africa? *American Journal of Environment Studies*, 6, 64–91. <https://doi.org/10.47672/ajes.1646>

Bakri, M.A., Chia, Y.E., and Chia, R. (2025). Trade openness and carbon emissions using threshold approach: Evidence from Asian countries, *Carbon Research*, 4. <https://doi.org/10.1007/s44246-025-00211-x>

Congregado, E., Feria-Gallardo, J., Golpe, A.A., and Iglesias, J. (2016). The environmental Kuznets curve and CO_2 emissions in the USA, *Environmental Science and Pollution Research*, 23(18), 18407–18420. <https://doi.org/10.1007/s11356-016-6982-9>

Dodman, D. (2009). Blaming cities for climate change: An analysis of urban greenhouse gas emissions inventories, *Environment and Urbanization*, 21, 185–201. <https://doi.org/10.1177/0956247809103016>

Ebrahimi Salari, T., Roumiani, A., and Kazemzadeh, E. (2021). 'Globalization, renewable energy consumption, and agricultural production impacts on ecological footprint', *Environmental Science and Pollution Research*, 28, 1–15. <https://doi.org/10.1007/s11356-021-14204-x>

Ertugrul, H., Cetin, M., Seker, F., and Dogan, E. (2016). The impact of trade openness on global CO_2 emissions, *Ecological Indicators*, 67, 543–555. <https://doi.org/10.1016/j.ecolind.2016.03.027>

Frankel, J., and Rose, A. (2005). Is trade good or bad for the environment? Sorting out the causality, *The Review of Economics and Statistics*, 87(1), 85–91.

Ghazali, A., and Ali, G. (2019). Key contributors of CO_2 emissions in newly industrialized countries: A DCCE approach, *Energy Reports*, 5, 242–252. <https://doi.org/10.1016/j.egyr.2019.02.006>

Glaeser, E.L., and Kahn, M.E. (2010). The greenness of cities: CO_2 emissions and urban development, *Journal of Urban Economics*, 67(3), 404–418. <https://doi.org/10.1016/j.jue.2009.11.006>

Grimm, N. et al. (2008). Global change and the ecology of cities, *Science*, 319, 756–760. <https://doi.org/10.1126/science.1150195>

Grossman, G., and Krueger, A. (1991). *Environmental impacts of a North American free trade agreement*. NBER Working Paper w3914. <https://doi.org/10.3386/w3914>

Hacıimamoğlu, T., and Cengiz, V. (2024). Natural resource rents and renewable energy as solutions for environmental degradation, *Sustainability*, 16, 1–20. <https://doi.org/10.3390/su16072736>

Kazemzadeh, E. et al. (2022). Economic complexity, export quality and ecological footprint, *Sustainability*, 14(18), 11153. <https://doi.org/10.3390/su141811153>

Kazemzadeh, E. et al. (2023). Effects of energy consumption structure on ecological footprint, *Environmental Science and Pollution Research*, 30(19), 55884–55904. <https://doi.org/10.1007/s11356-023-26118-x>

Kuznets, S. (1955). Economic growth and income inequality, *American Economic Review*, 45(1).

Machado, J.A.F., and Santos Silva, J.M.C. (2019). Quantiles via moments, *Journal of Econometrics*, 213(1), 145–173. <https://doi.org/10.1016/j.jeconom.2019.04.009>

Martínez-Zarzoso, I., and Maruotti, A. (2011). Impact of urbanization on CO_2 emissions: Evidence from developing countries, *Ecological Economics*, 70(7), 1344–1353.

Mignamissi, D., and Djeufack, A. (2022). Urbanization and CO_2 emissions intensity in Africa, *Journal of Environmental Planning and Management*, 65(9), 1660–1684.

Muftau, O., Iyoboyi, M., and Ademola, A.S. (2014). CO_2 emissions and economic growth in West Africa, *Economics*, 2014, 1–17. <https://doi.org/10.5923/j.economics.20140401.01>

Mushtaq, Z., Wei, W., and Li, Z. (2024). Technological innovations and energy structure in China's coal consumption, *Environmental Science and Pollution Research*, 31. <https://doi.org/10.1007/s11356-023-31785-x>

Neagu, O., and Neagu, M. (2022). Environmental Kuznets curve and economic complexity, *Studia Universitatis Vasile Goldis – Economics Series*, 32, 78–99. <https://doi.org/10.2478/sues-2022-0005>

Ntarmah, A.H., Kong, Y., and Manu, E.K. (2021). Credit supply, growth and environment in SSA, *Environmental Science and Pollution Research*, 28(5), 5786–5808. <https://doi.org/10.1007/s11356-020-10875-0>

Ozcan, B. (2013). Carbon emissions, energy consumption and economic growth in Middle East countries, *Energy Policy*, 62(C), pp. 1138–1147.

Özkan, O. et al. (2023). EKC, pollution haven and halo hypotheses in China, *Environmental Science and Pollution Research*, 30, pp. 68163–68176. <https://doi.org/10.1007/s11356-023-26671-5>

Pata, U.K., Aydin, M., and Haouas, I. (2021). Natural resource abundance, human development and ecological footprint, *Resources Policy*, 70, 101923. <https://doi.org/10.1016/j.resourpol.2020.101923>

Pawar, M. (2023). Environmental and social safeguards in urban planning, *International Journal of Science and Research*, 12, 829. <https://doi.org/10.21275/SR23908185219>

Salahuddin, M. et al. (2019). Urbanization, globalization and CO_2 emissions in SSA, *Environmental Science and Pollution Research*, 26(3), 2699–2709. <https://doi.org/10.1007/s11356-018-3790-4>

Satrio, A., Fattah, S., and Fitrianti, R. (2025). Balancing growth and ecology: Evidence from Indonesia, 3200–3212. <https://doi.org/10.2991/978-94-6463-758-8_267>

Shahbaz, M., Tiwari, A.K., and Nasir, M. (2013). Financial development, growth, coal consumption and CO_2 in South Africa, *Energy Policy*, 61, 1452–1459. <https://doi.org/10.1016/j.enpol.2013.07.006>

Sharma, R. et al. (2022). Diversified imports and ecological footprint in BRICS, *Environment Development and Sustainability*, 24. <https://doi.org/10.1007/s10668-022-02177-x>

Sultana, T. et al. (2023). Globalization and carbon emissions in Next-11 countries, *Energy Reports*, 10. <https://doi.org/10.1016/j.egyr.2023.06.020>

Tachega, M.A. et al. (2021). Income heterogeneity and EKC turning points in Africa, *Sustainability*, 13(10), 1–22.

Wang, L., Wu, T.W., and Ren, F.-R. (2025). Spatial differences in carbon-emission reduction of new-energy vehicles in China, *Energies*, 18, 635. <https://doi.org/10.3390/en18030635>

Wani, M.J.G. et al. (2025). Emissions-growth nexus in leading economies, *Journal of Applied Economics*, 28(1), 2554712. <https://doi.org/10.1080/15140326.2025.2554712>

York, R., Rosa, E., and Dietz, T. (2003). Footprints on the Earth: The environmental consequences of modernity, *American Sociological Review*, 68. <https://doi.org/10.2307/1519769>

Zhang, R., Li, P., and Xu, L. (2022). Ecological security in Shaanxi Province, *Ecological Indicators*, 144, 109483. <https://doi.org/10.1016/j.ecolind.2022.109483>