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Reflections on COP27: How do technological innovations and economic freedom affect environmental quality in Africa?

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ABSTRACT

Studies in literature argue that technological innovation is a crucial component that could provide an enduring solution to the effects of climate change. However, we argue in this study that technology-driven climate solutions may not be sustainable in the absence of robust economic freedom, particularly in Africa where there are manifestly weak governance indices. Hence, we investigate the interaction effects of technological innovation and economic freedom on environmental quality in Africa. By doing this, we deviate from prior studies that have considered only non-interactive regressions and offer a net effect approach which allows us to simultaneously introduce economic freedom as a modulating policy variable. We utilize panel data from the Fraser Institute and the World Bank Database for the period 2000 to 2018 for 31 African nations. Using an array of econometric techniques, our initial findings disclose a significant unconditional negative impact of technological innovation and economic freedom on the proxies of environmental quality. When both variables are interacted, the net effect suggests further negative impact. We account for potential endogeneity, and our results, yet remain consistent. We then evaluate the effect across regions and income classes. Our findings suggest that technological innovation improves environmental quality in low-middle and upper-middle income African nations, whereas the opposite is observed in low-income and Western nations. Our findings offer comprehensive and policy-relevant information to African stakeholders and international organizations, on the suitable strategies to managing environmental degradation.

1. Introduction

Countries in Africa are renowned for their abundant mineral (natural) resources, which are ostensibly their primary source of income. These resources, which include oil, coal, natural gas, petroleum, and other by-products, are classified as fossil fuels, and have recently sparked global concern due to their negative effects on the environment, such as climate change. The impact of climate change can be compared to the contagious nature of the last global financial crisis, which began in one region and progressively spread to others. Consequently, African countries may not be able to avoid the contagion, even though their contribution to global warming is negligible compared to that of developed nations. According to the United Nations, Africa contributes approximately 3 % of the world's carbon emissions; however, due to its extreme vulnerability, it bears the brunt of the climate catastrophe.

Research indicates that, on average, Africa is warming more rapidly than other continents (Aluko et al., 2022). Africa is, in fact, the epicenter of the escalating effects of climate change, which include insufficient precipitation, desertification, poverty, health problems, conflicts, and forced migration. Avom et al. (2020) provide evidence indicating that approximately 2 million people are displaced annually due to unprecedented climate change-induced inundation in Western Africa. In the Horn of Africa, a precarious famine caused by drought has forced people to migrate; massive wildfires are also ravaging the North of Africa, and a massive wave of cyclones is destroying Southern Africa; all of these are the result of climate change. As the world is already experiencing the

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negative effects of climate change, a growing number of studies in the academic literature have investigated crucial factors that can improve environmental quality to provide policy recommendations that would prevent the most grievous effects of climate change.

A line of inquiry identifies the importance of technological innovations. In the context of climate change, technological innovation refers to the use of modern, clean, renewable, and secure processes to produce energy that is less damaging to the environment (Sohag et al., 2021). Existing research within this field of study suggests that adequate investments in technological innovations, through the advancement of research and development, can substantially reduce or eliminate GHG emissions from the atmosphere. Proponents of technological innovation assert that it fosters energy independence and reduces ecological pollution, promotes eco-friendly economic and productive activities, and safeguards the most vulnerable members of society (Obobisa et al., 2022). All of these reduce environmental stress, enhance its quality, and constitute a viable strategy for overcoming climate-related obstacles. Although technological innovation is rapidly evolving and has become a crucial tool for addressing the climate crisis, it is not without its limitations. Studies argue that it may result in employment losses in the traditional fossil fuel sector and may be hampered by cultural and socioeconomic obstacles (Khattak et al., 2020; Dogan et al., 2021). Besides, the cost of producing (or acquiring) energy-efficient technologies can be substantial and prohibitive, especially for developing countries.

We argue, from a novel perspective, that economic freedom should be considered when assessing the impact of technological innovations on environmental quality. Economic freedom refers to the ease with which economic agents – households, businesses, and government entities – make their personal and investment decisions without institutional interference. Indicators of a nation's economic freedom include freedom from corruption, fiscal freedom, and trade freedom (Fraser Institute Economic Freedom Basics, 2022). Therefore, economic freedom depends on regulations and institutions that ensure free trade, the prosperity of economic agents, and the protection of property rights. Literature hypothesizes that the economic freedom structures of a country can influence the quality of its environment through a variety of mechanisms. For instance, in the context of trade liberalization and openness, governments can entice investments in climate-friendly technologies by enhancing the ease of doing business, particularly for firms willing to develop sustainable energy solutions (Dogan et al., 2020; Mahmood et al., 2022; Paramati et al., 2022). This, in turn, increases competition in the production of large-scale green products, reduces the price of clean and secure energy over time, and ultimately improves environmental quality. In addition, governments can enhance environmental safety in the context of market-based modulations by implementing economic policies that encourage the use of clean energies. These policies may include imposing high environmental levies on businesses whose operations significantly contribute to climate calamity.

Interestingly, despite the abundance of literature documenting the relationship between technological innovation and environmental quality, no study has investigated how economic freedom moderates the relationship. We complement the extant body of knowledge by exploring how economic freedom can modulate the effect of technological innovation on environmental quality. This is imperative, particularly in Africa, where governance mechanisms are manifestly deficient. Economic freedom, as discussed earlier, has been documented to be critical in fostering sustainable clean energy solutions that would ultimately abate carbon emission levels. Moreover, our selection of Africa is predicated on its low level of socio-economic, infrastructural, and technological development, which covertly impedes the region's use of renewable energies such as solar and wind despite its immense natural endowments. Importantly, this study comes at a crucial time when the entire world is converging on the African continent - COP 27 - to discuss pragmatic solutions to climate crises. Hence, in our empirical analysis, we interact technological innovation with economic freedom to ascertain the overall net effect on environmental quality. By doing this, we deviate from prior studies that have considered only non-interactive regressions. The net effect approach, which allows us to simultaneously introduce economic freedom as a modulating variable, offers more comprehensive information that is policy-relevant to macroeconomic outcomes (Tchamyou and Asongu, 2017; Tchamyou, 2019).

For the purposes of our research, we utilize panel data from the Fraser Institute and World Bank Database, spanning the years 2000 to 2018, for 31 African nations. Our empirical research reveals the following results. Our panel regression results corroborate that technological innovation reduces environmental degradations (proxied by ecological footprint) in Africa. This negative effect, supported by a battery of additional tests, demonstrates that an increase in innovative technology improves environmental quality. In addition, we demonstrate that the coefficient of economic freedom is substantially negative, reducing environmental damage. To further validate our baseline results, we employ CO_2 emission per capita as a new dependent variable, divide countries by income and regional classifications, and control for potential endogeneity using quantile regression and Bayesian estimations. Our results corroborate evidence that the combined effect of economic freedom and technological innovation has a negative impact on environmental quality in low-income countries, albeit in the Western region; however, it improves environmental quality in low-middle and upper-middle income countries.

Considering the unprecedented and escalating impact of climate change on the planet, our research adds to the current literature in various ways. First, we corroborate existing body of knowledge by demonstrating empirically how technological innovation reduces environmental damage, thereby extending previous works in climate literature (Gu et al., 2019; Dinda, 2018). Second, we provide novel evidence of how the indices of economic freedom influence the quality of the environment in African nations. This contribution provides valuable information to key stakeholders in Africa, especially policymakers involved in the design and implementation of fiscal and economic policies for the continent's environmental safety. Finally, we examine the validity of the population haven hypothesis by concentrating on how foreign investments can improve the climate system's efficiency. This contribution is essential for investors and businesses to comprehend how their corporate activities can mitigate climate change.

The remainder of the paper is organized as follows. The next section (Section 2) describes relevant studies in literature. The third section presents our data and methodology. In Section 4, we present the empirical findings and policy implications of our study, and Section 5 concludes the paper.

2. Literature review

2.1. Theoretical underpinning

The Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) and Environment Kuznetz Curves (EKC) frameworks are two widely used models for conceptualizing the relationship between the environment, technology, affluence, energy, population, and other variables. The STIRPAT model explains the interplay between the economy's three most important pillars—technology, prosperity, and population—and the natural world. Dietz and Rosa (1994) were the first to apply STIRPAT to analyze the relationship between the environment, population, wealth, and technology by converting Ehrlich and Holdren's (1971) IPAT model into a stochastic model. The transformation enabled a contextualization of environmental changes that occurred over time and across units because of population growth, technological advancement, and economic expansion. Following the seminal study by Dietz and Rosa (1994), subsequent studies have used alternative variables to conceptualize technological development, economic prosperity, and population size. Renewable energy (Dong et al., 2018), energy efficiency (Bargaoui et al., 2014), and the intensity of industrial activity (Dinda, 2018) are some of the proxies that have been used for technological innovations. Similarly, urbanization (Poumanyvong and Kaneko, 2010), population size (Dong et al., 2018), and total urban population (Liddle, 2013) are all ways in which population is conceptualized. The expansion of the economy is often used as a surrogate for affluence.

Several studies have utilized the Environmental Kuznets Curve (EKC) to illustrate the relationship between technological innovation and environmental quality. The inverted EKC curve depicts a U-shaped relationship indicating that in the early stages of development, increased technological innovation and economic freedom improve environmental quality. However, once a certain threshold is reached, environmental degradation tends to aggravate rather than improve (Grossman and Krueger, 1991; Stern, 2004). Although the curve is primarily used for growth and environment research, a few studies have used it to study the environment and other socioeconomic conditions such as energy, information and communication technology, democracy, tourism, and institutions (Apergis and Ozturk, 2015; Asongu, 2020a).

Meanwhile, it is well-known that companies from industrialized nations often tend to locate their factories in developing nations due to the latter's vast resources, lax environmental regulations, and inexpensive labor (Aluko et al., 2022). While these provide opportunities for developing countries to attract FDI, the result is that such investments pollute and degrade the host country's environment. Consequently, a multitude of empirical studies have investigated the significance of the population haven hypothesis (PHH) in the context of environmental degradation. Most studies in literature have substituted PHH with FDI, and the results have been inconsistent. Al-mulali (2012), for instance, identified FDI net inflows as a significant cause of CO_2 emission in 12 Middle Eastern countries. Their findings demonstrate the need for strict environmental regulations to restrict the arbitrary influx of pollution-intensive investments. Gill (2018) and Singhania and Saini (2021) provide additional evidence of the pollution haven hypothesis in developing countries by demonstrating that FDI is substantially positively correlated with environmental degradation in sampled countries. Their findings suggest that developing nations have become potential pollution havens for industrialized nations' businesses. Using a multivariate framework, Al-Mulali and Tang (2013) investigated the validity of the pollution refuge hypothesis in GCC countries, and their findings indicate that CO_2 emission is negatively correlated with foreign direct investment over the long term. In other words, the increase in FDI in these countries has minimal environmental impact. In sum, it is crystal obvious that the above theories are indispensable for analyzing environmental quality. Consequently, we evaluate the effect of these variables while controlling for other variables that may affect environmental degradation. Importantly, we divide these factors into mitigation and adaptation strategies, which are discussed further below.

2.2. Empirical literature & testable hypotheses

2.2.1. Technological innovation and the environment

Studies such as Awad (2022) and Villanthenkodath and Mahalik (2022) demonstrate that technological innovation has three effects on the environment. One is the direct effect of the introduction and use of ICT tools, which is accompanied by an increase in energy consumption and refuse production, thus contributing to environmental degradation. A second way is through the substitution effect, in which the increased use of ICT tools results in a more efficient processing method that reduces waste generation and results in less environmental degradation. For example, technological progress that enables the provision of e-services as opposed to on-site/physical service. The third method is the cost/return effect, which reverses the benefits of an improved environment's quality. This occurs when decreased prices of products resulting from a more efficient production method leads to an increase in demand. This can also occur, for instance, when increased energy efficiency results in lower energy prices, allowing people to consume more and thereby increasing demand.

Villanthenkodath and Mahalik (2022) discovered that mobile phone utilization as a proxy for ICT in South Africa increased the level of environmental degradation, whereas internet use contributed to an improvement in environmental quality, as measured by the level of CO_2 emissions. On the one hand, it was believed that the use of mobile phones powered by lithium batteries was the primary cause of environmental degradation, as the batteries generate pollutants by emitting toxic substances into the atmosphere during disposal. Internet use, on the other hand, improved environmental quality because companies relied more on e-services such as e-mail, online marketing, e-banking, etc., thereby reducing the demand for paper-based communication, which would require large-scale paper production by industries and contribute to environmental pollution (Bhujabal and Sethi, 2020; Chu et al., 2023). In a study of 12 African countries, Wen et al. (2022) discovered that technological innovation, as measured by patent application resident, had a negative and statistically significant effect on environmental degradation, as proxied by CO_2 emission. Similar to the findings of other studies (such as Park and Kim, 2014; Amri, 2018; Wang et al., 2022), they argued that newer technological processes introduced innovations that made energy production more efficient and environmentally friendly. For a panel of 47 Sub-Saharan African (SSA) countries, Awad (2022) discovered that development in ICT did not correlate with an improvement in environmental quality. This result was attributable to the presence of energy poverty, which restricted the use of ICT tools in the investigated nations. In an earlier study, Asongu (2018) had concluded that the effect of ICT on the environment in 44 SSA countries depends on the proxy measure used for the environment. The authors discovered that higher internet and mobile phone penetration reduced per capita CO_2 emissions but increased CO_2 emissions from liquid fuel use. They put their claim to the test using two surrogate measures of environmental degradation: the ecological footprint in global hectares per person and carbon dioxide emissions per person. Based on the foregoing, we propose the following hypothesis:

Hypothesis 1. Technological innovation can mitigate environmental degradation.

2.2.2. Economic freedom and the environment

The level of economic freedom in a country is frequently linked with its social and economic objectives, such as environmental quality, level of development, income level, etc. This is because economic freedom is viewed as a catalyst that can promote a nation's growth and development through the introduction and implementation of policies that encourage the efficient and effective use of resources in a competitive environment (Wood and Herzog, 2014; Dogan et al., 2022). Carlsson and Lundström (2001) argued that the effect of economic freedom on the environment may be transmitted via channels such as institutional quality, market efficiency, and macroeconomic policy stability. For instance, it is anticipated that there will be less environmental pollution if appropriate laws are enacted and enforced to curb the activities of polluters. Stable macroeconomic policies also stimulate economic expansion, investment, and consumption. However, the increase in production due to increased demand may result in increased environmental pollution, necessitating the implementation of appropriate measures, such as regulatory policies and laws, to control pollution. In addition, competitive markets are anticipated to produce novel and more efficient methods of production and service delivery, which will ultimately result in lower prices. This is possible through the transmission of technology from developed to developing nations (Gallagher and Thacker, 2008; Tchamyou and Asongu, 2017). This can also substantially aid developing nations in adapting to the challenges posed by climate-related catastrophes.

Moreover, Asongu (2018) argue that the three main components of effective environmental protection are contained within the economic freedom metric: accountability, openness, and information flow. The increased demand for goods and services caused by higher income levels in the G-20 countries was shown to degrade environmental quality by Alola et al. (2022), using a set of economic freedom variables that included trade openness, regulation, legal framework, sound money, and property right. On the other hand, Awad (2022) demonstrated that better political institutions brought about by good governance led to higher environmental standards, as informed citizens are better able to exercise their political rights and enjoy the benefits of a free press which monitor the use of their nation's natural resources. Ali et al. (2019) are just one of many studies to discover similar results. Nonetheless, when ICT is broken down into mobile phones and internet penetration, Asongu (2020b) found that institutional quality, as represented by regulation quality, affected the environment differently depending on the proxy used for the environment. Internet penetration was found to raise CO_2 emissions from liquid fuel consumption whereas mobile phone use decreased these emissions. This indicates that there are rules in place that limit the use of mobile phones, whereas the opposite is true for internet access. Considering the preceding information, we test the following hypotheses:

Hypothesis 2. The quality of economic freedom indices can improve the quality of the environment.

Additionally, we hypothesize that the interaction of technological innovation and economic freedom (indirect effect) would lead to less environmental degradation. Therefore, we propose that:

Hypothesis 3. The interaction of technological innovation and economic freedom enhances environmental quality.

3. Methodology

3.1. Data and variables' measurement

This study investigates the interplay between technological innovation and economic freedom on environmental quality using data for 31 African countries between 2000 and 2018. The list of selected African nations, based on the availability of data, is shown in the Appendix. To attain this study's objectives, we follow extant theoretical and empirical literature. Two surrogates are used to measure environmental degradation: ecological footprint (EFP) and carbon dioxide emission (CO_2). Technological innovation is measured by constructing an index using principal component analysis (PCA) based on the natural log of scientific and technical journal articles published, patent application for residents and non-residents, research and development expenditure, investment in ICT, and trademark application for residents and non-residents. We use market freedom and the extent of institutional freedom to proxy economic freedom.

The selection of our control variables is guided by the available literature. According to the STIRPAT and pollution haven hypotheses, economic growth (LGDP), inflation rate (CPI), population growth (PG), consumption of renewable energy (REC), foreign direct investment (FDI), and internet penetration (Internet) are significant drivers of environmental degradation. Moreover, Dada et al. (2022) and Ajide et al. (2023) provide empirical evidence that economic growth exacerbates environmental degradation in Africa (see also Zafar et al., 2019; Ibrahiem and Hanafy, 2020). On the other hand, empirical disagreements exist regarding the effect of internet penetration on environmental degradation. For example, Avom et al. (2020) demonstrate that the internet only affects environmental quality through energy consumption. Amri (2018) demonstrate that there is no correlation between the two variables while Adedoyin et al. (2020) demonstrate that the internet negatively affects environmental quality. Further empirical evidence shows that population growth exacerbates environmental stress (Dada et al., 2022) while renewable energy also alleviates ecological stresses (Bekun et al., 2021; Adedoyin et al., 2020). Concerning inflation, Ahmed et al. (2020) state that a high level of inflation reduces investment and economic growth, thereby decreasing activities that may harm the environment. In contemplating the influence of technological innovation and economic freedom, we therefore control the effect of these variables. Table A in the Appendix illustrates the variables' sources and measurements.

3.2. Empirical model and estimation strategies

We commence our empirical estimation with the following pooled OLS regression:

$$ENV_{it} = \alpha_o + \beta_1 INOV_{it} + \beta_2 EF_{it} + \beta_3{}' X_{it} + \varepsilon_{it} \tag{1}$$

where ENV_{it} represents environmental degradation as captured by the two proxies, $INOV$ is the technological innovation index, EF represents economic freedom. X_{it} is the vector of control variables, as stated above. α_0 is the intercept, β_1 is the slope of the equation, X_{it} represents the predictors and ε_{it} is the error term.

To account for the moderating role of economic freedom in the above equation, we re-write the equation to capture the interaction effects as shown below.

$$ENV_{it} = \alpha 0 + \beta_1 INOV_{it} + \beta_2 EF_{it} + \beta_3 EF \times INOV_{it} + \gamma' X_{it} + \varepsilon_{it} \tag{2}$$

In Eq. (2), $EF \times INOV$ is the interaction variable while X_{it} is the vector of control variables. ε_{it} is the error term, t and i are the time and country identity respectively. Moreover, given the nature of our data, we employ a generalized linear model (GLM) regression to estimate the models to avoid endogeneity issues and potential non-normal distribution issues. The GLM models use the Poisson, gamma, and binomial distributions (Nelder and Wedderburn, 1972) and specify a link function between the response variable and a vector of predictor variables. The model is specified as:

$$g(Y_{it}) = \alpha_o + \sum_{j=1}^{p} \beta_i x_{it} + \varepsilon_{it} \tag{3}$$

As a form of robustness, we employ a battery of econometric analyses to validate the baseline results. First, we employ Machado and Silva's (2019) innovative Method of Moments-Quantile Regression (MM-QR). This estimation method considers the distribution and heterogeneity of the effects of independent variables on the explained variable. The method is efficient for addressing fixed effect structure and panel quantile regression. It offers conditional distribution estimates for the 10th, 25th, 50th, 75th, and 90th percentiles of dependent variables. The scale and location variants of the estimates permit us to evaluate the significance of variables of interest based on variances and the mean of the estimated parameters. Eq. (2) above can be reformulated as the conditional quantile:

$$Q_{ENV_{it}}(\tau_j / X_{it}) = (\sigma_i + \gamma_{iq}(\tau)) + X' \beta(\tau_i) + \varnothing_i(\tau_j) + U_t(\tau_j), \tau_j \epsilon (0, 1) \tag{4}$$

$Q_{ENV_{it}}(\tau_j / X_{it})$ is the quantile of the ENV conditioned on X_{it}, implying that ENV variable is conditioned on the location of independent variables, X_{it}. The corresponding fixed effect of quantile τ for individual cross-sectional units is defined by the scalar coefficient $\sigma_i + \gamma_{iq}(\tau)$. $\varnothing_i$ and U_t are unobserved country identity and time identity for fixed effect. The quantile estimates are dependent on the scale and location coefficients (Rehman et al., 2021). The sensitivity of environmental degradation to technological innovation depends on the magnitude and sign of the coefficient as well as the efficacy of a nation's institutional system as measured by the economic freedom index.

To avoid some pitfalls that may affect the reliability of our estimations, particularly considering the use of interactive regressions in our estimation technique, it is imperative to note that interpretation of interactive regressions would be based on net effects (Brambor et al.,

2006) and conditional marginal impact (Tchamyou and Asongu, 2017; Tchamyou, 2019; Asongu, 2020a). For the net effect to be computed, the coefficient of both the conditional and unconditional (interaction) effects must be significant (Asongu, 2020b). The net effect is calculated as:

$$([\text{coefficient of conditional effect*mean value of interaction variable}] + \text{coefficient of unconditional effect}) \tag{5}$$

In addition, Bayesian regression is employed to validate the consistency of the MM-QR results. One of the advantages of Bayesian technique is that it effectively manages sample bias, heteroscedasticity, and endogeneity problems.

$$y = X\Lambda + \epsilon, where\ \epsilon \sim N\left(0, \tau^{-1} I_{NT}\right) \tag{6}$$

y represents a panel of $N \times T$. X is the matrix of the explanatory variables of the size $NT \times (K + N)$. The vector Λ is of length $K + N$. We estimate the parameters using the Gibbs sampler Markov Chain Monte Carol (MCMC) sampling method where the simulation sample is drawn from the comparable posterior model. A total of 12,500 iterations were run per model and 2500 burn-in iterations were discarded. The results of the diagnostic tests show that convergence is achieved.

3.3. Summary statistics, correlation matrix and variance inflation factor (VIF)

Table 1 depicts descriptive statistics for each variable, whereas Tables 2 and 3 illustrate the pairwise correlation and VIF between variables. The table shows that on average, ecological footprint per capita is 1.447 with a maximum value of 3.918 per capita. Furthermore, the value of carbon dioxide emission is relatively lower than EFP but has a maximum value of 8.572 per capita. Similar to prior studies (Aluko et al., 2021), we find that these figures are considerably less than the EFP and CO_2 emissions of industrialized nations. The technological innovation index proxy has a standard deviation that falls between the maximum and minimum values. The same holds true for the economic freedom proxy (EF proxy). In addition to examining descriptive statistics, a summary of the extent of pairwise correlation and VIF is analyzed. Both estimates indicate that the variables are moderately correlated with one another.

4. Discussion of results and findings

Here, we present the findings that demonstrate the impact of technological innovation and economic freedom on environmental degradation in Africa. Indicators of environmental degradation include ecological footprint and carbon emission. The results of OLS estimates for our baseline model are presented in Table 4. The first and second columns report the direct effect of the variables under consideration, while the third and fourth columns illustrate the interaction effect of technological innovations and economic freedom. At the 1 % and 5 % significance levels, the estimated coefficients of technological innovations that reduce environmental degradation are displayed across the columns. Invariably, our results reveal that technological innovation functions as a mechanism for reducing the negative environmental impact of economic activities. Environmentally favorable innovation decreases pollution and protects the ecosystem. Consequently, investments in eco-friendly technological innovation would go a long way towards mitigating Africa's environmental problems. Our findings confirm the mitigation strategy and previous findings that innovation decreases carbon emission (Gu et al., 2019; Yu and Du, 2019).

However, the coefficients of economic freedom are significant and positive at the 1 % and 5 % levels across all dimensions. In this regard, we argue that the conventional wisdom regarding economic freedom holds that it promotes fundamental institutions that ensure free markets and trade. In a free market economy, it is anticipated that restrictions on entry will be loosened, and economic activities will continue to expand; this expansion, especially in the absence of stringent environmental regulations, will ultimately contribute to an uncontrolled increase in environmental degradation. This corroborates the finding of Alola et al. (2022) as well as the findings of Ali et al. (2019) and Awad (2022), which assert that there will be less environmental pollution if appropriate laws are enacted and implemented to control the activities of pollutants.

The interaction effect coefficients (technological innovation and economic freedom) are negative and significantly associated with environmental degradation across all parameters at the 5 % significance level. When the net effect of the interaction term is considered, it also reveals negative values of −2.2665 and −3.7818. This suggests that the interactive variables would have a combined significant long-term marginal reduction on environmental degradation in Africa.[1] Policy-wise, this further connotes that a combination of a high level of economic liberalization and sufficient eco-friendly innovation would benefit the environment. This is consistent with the inverted EKC curve, which describes a U-shaped relationship indicating that in the early stages of development, increased technological innovation and economic freedom improve environmental quality. According to Jaffe et al. (2003), the prospect of new technology is a key determinant of sustainable environmental achievement in Africa; therefore, hypothesis three is accepted.

Regarding the control variables, the economic growth coefficient is positive and statistically significant, supporting the EKC hypothesis and the existing literature (Dada et al., 2022). Our findings corroborate that economic expansion pollutes the environment via production activities in manufacturing industries and marketing services involving the transportation of goods and services to final consumers. Moreover, FDI is positively associated with environmental degradation. FDI is a significant contributor to environmental degradation, consistent with the STIRPAT and pollution haven hypotheses. Inflation rate also has a negative impact on the ecological footprint and suggests that a high inflation rate reduces economic activity and, consequently, reduces environmental degradation.

Across the columns, population coefficients are positive and

Table 1
Summary statistics.

Variables	Mean	Standard deviation	Min	Max
Ecological footprint (efp)	1.45	0.63	0.66	3.82
Carbon emission (co2)	1.05	1.59	0.03	8.57
Innovation (inn)	0.18	0.43	0.00	3.00
Economic freedom (ef)	54.27	8.13	21.40	72.00
FDI	3.77	5.17	−10.72	39.81
Inflation (inf)	12.29	45.54	−3.50	557.20
Population (pop)	2.47	0.73	0.23	4.63
Renewable (ren)	63.50	28.96	0.06	98.34
Internet (int)	10.15	13.79	0.01	64.80
GDP	3.05	0.42	2.14	4.03

Note: GDP per capita is in log form. FDI is scaled by GDP.

[1] The net effect shown in columns 4 and 5 of Table 4 are −2.2665 and −3.7818, respectively. Please see the notes under Table 4 for their calculations. To calculate the net effect, the coefficients of both the primary and interaction variable must be significant.

Table 2
Correlation matrix.

Variables	efp	co2	inn	ef	fdi	cpi	pop	ren	int	GDP
Efp	1.00									
co2	0.80*	1.00								
inn	−0.05	−0.05**	1.00							
ef	0.45*	0.26*	0.04***	1.00						
Fdi	0.13*	0.10*	0.03	−0.10*	1.00					
inf	−0.10*	−0.06	−0.06	−0.34*	0.03	1.00				
pop	−0.43*	−0.47*	−0.11*	−0.06	0.13*	−0.06	1.00			
Ren	−0.51*	−0.58*	−0.02	−0.18*	0.12*	0.08	0.46*	1.00		
Int	0.44*	0.46*	0.25*	0.23*	−0.09*	−0.08*	−0.32*	−0.41*	1.00	
GDP	0.76*	0.77*	0.02	0.34*	−0.05	−0.09*	−0.32*	−0.43*	0.57*	1.00

Note: *, **, and *** stand for level of significance at 10%, 5% and 1%, respectively.

Table 3
Variance inflation factor test.

	VIF	1/VIF	R-square
Internet	2.48	0.40	0.62
GDP	2.35	0.42	0.58
Population	1.87	0.54	0.61
Renewable	1.77	0.56	0.82
Economic freedom	1.30	0.77	0.66
Inflation	1.18	0.85	0.71
Innovation	1.13	0.89	0.59
FDI	1.08	0.93	0.62
Mean VIF	1.56		

statistically significant, indicating that population growth accelerates environmental degradation (see also Dada et al., 2022). The coefficient of internet penetration is negative for ecological footprint, indicating that ICT reduces environmental damage by increasing production system efficiency through e-commerce, e-banking, and e-services rather than physical visits and carbon dioxide emissions from physical transportation (Bhujabal and Sethi, 2020). Moreover, the renewable energy consumption coefficient is negative and significant. This is consistent with expectations as renewable energy is expected to reduce environmental degradation and promote the preservation of ecological resources.

Due to the limitations of OLS regression, we then undertake an additional test on our baseline model using GLM regression. This method is deemed preferable because it eliminates endogeneity and non-normal distribution issues (Nelder and Wedderburn, 1972). Intriguingly, the results in Table 5 are comparable to the OLS estimates in Table 4, reaffirming that economic freedom and technological innovation have substantial effects on environmental degradation in Africa. Therefore, for both regressions, it is evident that technological innovation is a viable means of mitigating the problem caused by a free-market economy and reducing environmental degradation.

Table 4
OLS regression result.

Variables	Without interaction term		With interaction term	
	Ecological footprint	Carbon emission	Ecological footprint	Carbon emission
	(1)	(2)	(3)	(4)
Innovation (INV)	−0.1715***	−0.4494***	−1.0510**	−1.6707**
	(0.0336)	(0.0883)	(0.4216)	(0.8033)
Econ. freedom (EF)	0.0225***	0.0097**	0.0247***	0.0135***
	(0.0024)	(0.0044)	(0.0026)	(0.0048)
INV * EF	–	–	−0.0224***	−0.0389**
	–	–	(0.0079)	(0.0155)
GDP	1.8535***	5.5751***	1.8583***	5.5835***
	(0.1881)	(0.5495)	(0.1875)	(0.5482)
FDI	0.3502**	0.5500**	0.4410*	0.7120***
	(0.024)	(0.0047)	(0.0022)	(0.0048)
Inflation	−0.0006**	0.0007	−0.0007***	0.0008
	(0.0002)	(0.0007)	(0.0002)	(0.0007)
Population	0.2801***	0.4512***	0.3152***	0.5121***
	(0.0533)	(0.0951)	(0.0557)	(0.0978)
Renewable	−0.0841***	−0.3756***	−0.0687***	−0.3489***
	(0.0194)	(0.0371)	(0.0198)	(0.0384)
Internet	0.2723	0.7143	−0.3931*	0.9238
	(0.2022)	(0.6302)	(0.2031)	(0.6501)
Constant	−1.2838***	−4.1740***	−1.4141***	−4.3999***
	(0.2890)	(0.7105)	(0.2959)	(0.7348)
Net effect	na	na	−2.2665	−3.7818
Countries	31	31	31	31
Year effect	Yes	Yes	Yes	Yes
Country effect	Yes	Yes	Yes	Yes
Observations	589	589	589	589
Fisher	56.52***	94.40***	54.64***	85.62***
R-squared	0.573	0.587	0.579	0.590

Note: *, **, *** for level of significance at 10 %, 5 % and 1 % respectively. Robust standard errors are in parenthesis. The net effect of −2.2655 is calculated as ([−0.0224 * 54.27] + −1.0510), where −0.0224 is the conditional coefficient of the interaction between the primary variable (innovation) and modulating policy variable (economic freedom). 54.27 is the mean value of the modulating policy variable - economic freedom and is constant in the equation.
−1.0510 is the unconditional coefficient value of the primary variable – innovation. To calculate the net effect, the coefficients of both the primary and interaction variable must be significant.

Table 5
GLM results.

Variables	Without interaction term		With interaction term	
	Ecological footprint	Carbon emission	Ecological footprint	Carbon emission
	(1)	(2)	(1)	(2)
Innovation (INV)	−0.1715***	−0.4494***	−1.0510**	−1.6707**
	(0.0334)	(0.0876)	(0.4180)	(0.7964)
Economic freedom (EF)	0.0225***	0.0097**	0.0247***	0.0135***
	(0.0024)	(0.0044)	(0.0026)	(0.0048)
INV * EF	–	–	−0.0224***	−0.0389**
	–	–	(0.0079)	(0.0153)
GDP	1.8535***	5.5751***	1.8583***	5.5835***
	(0.1867)	(0.5453)	(0.1859)	(0.5435)
FDI	0.1892*	0.2219*	0.1021*	0.1230**
	(0.1130)	(0.4017)	(0.2002)	(0.2081)
Inflation	−0.0006**	0.0007	−0.0007***	0.0008
	(0.0002)	(0.0007)	(0.0002)	(0.0007)
Population	0.2801***	0.4512***	0.3152***	0.5121***
	(0.0529)	(0.0944)	(0.0552)	(0.0969)
Renewable	−0.0841***	−0.3756***	−0.0687***	−0.3489***
	(0.0193)	(0.0368)	(0.0196)	(0.0380)
Internet	0.2723	0.7143	−0.3931*	0.9238
	(0.2006)	(0.6253)	(0.2013)	(0.6446)
Constant	−1.2838***	−4.1740***	−1.4141***	−4.3999***
	(0.2868)	(0.7050)	(0.2934)	(0.7286)
Net effect	Na	Na	−2.2665	−3.7818
Year effect	Yes	Yes	Yes	Yes
Country effect	Yes	Yes	Yes	Yes
Countries	31	31	31	31
Observations	589	589	589	589

Note: *, **, *** for level of significance at 10 %, 5 % and 1 % respectively. Robust standard errors are in parenthesis.

4.1. Robustness checks

Using MM-Quantile regression at various conditional distributions of the dependent variable, such as 0.10, 0.25, 0.50, 0.75, and 0.90, we examine our baseline results in Tables 4 and 5 (Brambor et al., 2006; Machado and Silva, 2019). The MM-QR results are presented in Tables 6 and 7, and the graph is shown in Fig. 1. Quantile regression results (at the conditional median) indicate that the interaction effect of technological innovation and economic freedom reduces ecological footprint at the 0.10, 0.25, and 0.50 quantiles and carbon emission at the 0.10, 0.50, & 0.75 quantiles. The coefficients of the joint effect of economic freedom and technological innovation reduce environmental degradation, particularly carbon emissions, as shown in Fig. 1.

The estimated coefficients of the control variables are comparable to those derived from Tables 4 and 5. As anticipated, the coefficients of GDP, FDI, and population have positive and significant effects, whereas the coefficients of inflation, renewable energy, and the internet have negative and significant relationships with environmental degradation. These results are consistent with the hypotheses of STIRPAT and pollution havens. In addition, to demonstrate the marginal impact of interaction between technological innovation and economic freedom, we use Eq. (5) to determine the net effect. The net effect across different quantiles shows negative values, thus suggesting that technological innovation when combined with strong indices economic freedom can

Table 6
MM Quantile regression with interaction term (Dependent variable: Ecological footprint).

Variables	Location	Scale	Q (10)	Q (25)	Q (50)	Q (75)	Q (90)
Innovation (INV)	−1.0510**	−0.4204	−1.5942***	−1.4416***	−1.1850***	0.7035	0.2596
	(0.4177)	(0.3100)	(0.2125)	(0.2226)	(0.3363)	(0.6522)	(0.9714)
Economic freedom (EF)	0.0247***	0.0050**	0.0182***	0.0200***	0.0231***	0.0288***	0.0340***
	(0.0026)	(0.0019)	(0.0015)	(0.0015)	(0.0021)	(0.0041)	(0.0060)
INV * EF	−0.0224***	0.0060	−0.0302***	−0.0280***	−0.0244***	−0.0175	−0.0111
	(0.0079)	(0.0058)	(0.0040)	(0.0042)	(0.0063)	(0.0122)	(0.0182)
GDP	1.8583***	0.4732***	1.2468***	1.4185***	1.7074***	2.2496***	2.7494***
	(0.1857)	(0.1227)	(0.1396)	(0.1385)	(0.1650)	(0.2749)	(0.3849)
FDI	0.1311*	0.3391*	0.2133*	0.2018*	0.3622*	0.3201*	0.3111*
	(0.1219)	(0.1262)	(0.1321)	(0.1222)	(0.2328)	(0.1233)	(0.3331)
Inflation	−0.0007***	−0.0002	−0.0009***	−0.0008***	−0.0007***	0.0005	0.0003
	(0.0002)	(0.0002)	(0.0002)	(0.0001)	(0.0002)	(0.0004)	(0.0006)
Population	0.3152***	0.0078	0.3253***	0.3225***	0.3177***	0.3088***	0.3005***
	(0.0552)	(0.0378)	(0.0435)	(0.0416)	(0.0481)	(0.0793)	(0.1153)
Renewable	−0.0687***	−0.0121	−0.0531***	−0.0575***	−0.0649***	−0.0787***	−0.0914***
	(0.0196)	(0.0114)	(0.0184)	(0.0175)	(0.0182)	(0.0253)	(0.0352)
Internet	−0.3931*	−0.2731**	−0.7460***	−0.6469***	−0.4802***	0.1673	−0.1212
	(0.2012)	(0.1201)	(0.1453)	(0.1475)	(0.1775)	(0.2810)	(0.3970)
Constant	−1.4141***	−0.4531**	−0.8286***	−0.9931***	−1.2697***	−1.7887***	−2.2672***
	(0.2932)	(0.2059)	(0.2047)	(0.2015)	(0.2517)	(0.4430)	(0.6362)
Net effect	−2.2667	Na	−3.2331	−2.9612	−2.5092	Na	Na
Observations	589	589	589	589	589	589	589

Note: *, **, *** for level of significance at 10 %, 5 % and 1 % respectively. Robust standard errors are in parenthesis.

Table 7
MM Quantile regression with interaction term (Dependent variable: Carbon emission).

	Location	Scale	Q(10)	Q(25)	Q(50)	Q(75)	Q(90)
Innovation (INV)	−1.6707**	−0.2858	−1.3445***	−1.4272***	−1.5659***	−1.7866	2.3397
	(0.7958)	(0.8603)	(0.5103)	(0.4130)	(0.5493)	(1.1150)	(2.7396)
Economic freedom (EF)	0.0135***	0.0099**	0.0022	0.0050**	0.0099***	0.0175**	0.0368**
	(0.0048)	(0.0050)	(0.0030)	(0.0024)	(0.0033)	(0.0070)	(0.0173)
INV * EF	−0.0389**	−0.0095	−0.0281***	−0.0309***	−0.0354***	−0.0427**	−0.0610
	(0.0153)	(0.0164)	(0.0096)	(0.0078)	(0.0106)	(0.0215)	(0.0527)
GDP	5.5835***	2.4785***	2.7547***	3.4722***	4.6750***	6.5892***	11.3859***
	(0.5430)	(0.4589)	(0.2756)	(0.2432)	(0.3931)	(0.8370)	(1.9144)
FDI	0.3201**	0.2190*	0.2916*	0.9238	0.3596***	−0.2309**	0.2491*
	(0.3019)	(0.2556)	(0.2031)	(0.0501)	(0.0628)	(0.1026)	(0.0380)
Inflation	0.0008	0.0010	−0.0003	−0.0000	0.0005	0.0013	0.0032
	(0.0007)	(0.0009)	(0.0004)	(0.0002)	(0.0004)	(0.0011)	(0.0027)
Population	0.5121***	0.1195	0.3757***	0.4103***	0.4683***	0.5606***	0.7918***
	(0.0968)	(0.0889)	(0.0705)	(0.0634)	(0.0747)	(0.1278)	(0.2947)
Renewable	−0.3489***	−0.0137	−0.3333***	−0.3373***	−0.3439***	−0.3545***	−0.3809***
	(0.0380)	(0.0310)	(0.0265)	(0.0255)	(0.0305)	(0.0480)	(0.1047)
Internet	0.9238	−0.0286	−0.9565***	−0.9482***	−0.9343*	0.9122	0.8567
	(0.6440)	(0.5022)	(0.2984)	(0.3307)	(0.4883)	(0.8299)	(1.7734)
Constant	−4.3999***	−2.8556***	−1.1406***	−1.9673***	−3.3531***	−5.5586***	−11.0852***
	(0.7280)	(0.6614)	(0.3872)	(0.3324)	(0.5188)	(1.1262)	(2.6195)
Net effect	−3.7818	Na	−2.8695	−3.1041	−3.4871	Na	Na
Observations	589	589	589	589	589	589	589

Note: *, **, *** for level of significance at 10 %, 5 % and 1 % respectively. Robust standard errors are in parenthesis.

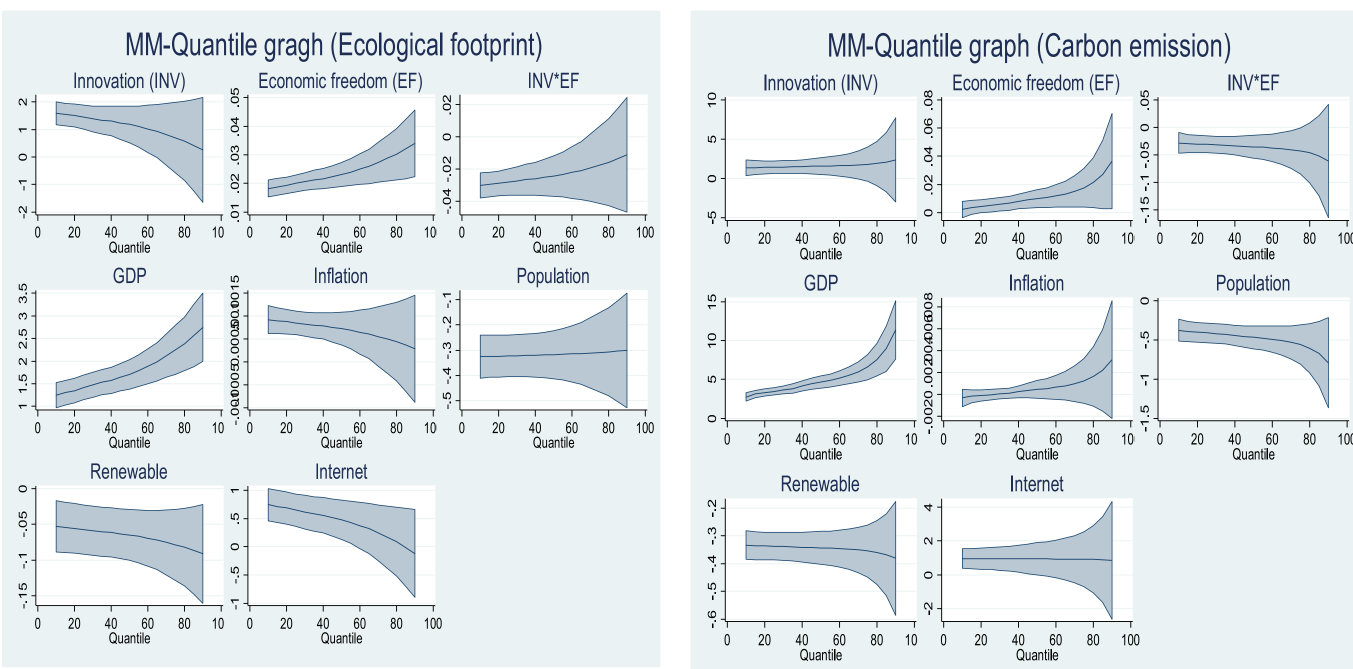

Fig. 1. MM-quantile graph (source: own chart).

reduce environmental damage in Africa. Our results materially do not differ with the OLS and GLM results shown earlier in Tables 4 and 5.

Furthermore, to account for the disparity in sample characteristics, we subdivide the nations by region and income level according to the World Bank classification. We employ a Bayesian model that effectively addresses sample bias, heteroscedasticity, and endogeneity problems. Consequently, Table 8 presents the results of an examination of the effect of economic freedom and technological innovation on environmental degradation according to the income level of the units. The interaction effect of economic freedom and technological innovation becomes more pronounced as the income level of the units rises. The direct effect of technological innovation reduces environmental degradation, whereas the direct effect of economic freedom increases environmental degradation as income rises. Meanwhile, the joint effect exacerbates environmental degradation in low-income countries but mitigates it in low-middle and upper-middle income nations. We argue that this is due to institutional differences and industrialization levels (see also Albitar et al., 2023). Overall, we witness response diversity between groups. A plausible explanation for this is that low-middle and upper-middle income countries are better outfitted than their counterparts with policies that can combat any environmental adversity resulting from free-market ideology and absorb benefits accruing from technological innovation.

Intriguingly, the subregional results presented in Table 9 bolster the preceding discussion. Most of the low-income countries in Table 8 are from the Western region; consequently, the results for the low-income countries align with those of the Western region. Similarly, countries in the Eastern, Central, and Northern regions are classified as low-

Table 8
Bayesian panel regression results using income classification of countries.

Variable	Ecological footprint				Carbon emission			
	All countries	Low-income countries	Low-middle countries	Upper-income countries	All countries	Low-income countries	Low-middle countries	Upper-income countries
INV	−1.119	−1.329	−1.170	−31.156	−2.675	−0.327	−1.247	−32.899
	(0.071)	(0.051)	(0.044)	(0.264)	(0.200)	(0.011)	(0.066)	(2.569)
EF	0.025	0.024	0.013	0.070	0.019	−0.001	−0.016	−0.251
	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.0002)	(0.008)
INV * EF	−0.024	0.028	−0.022	−0.462	−0.058	0.007	−0.019	−0.474
	(0.001)	(0.001)	(0.001)	(0.004)	(0.004)	(0.000)	(0.001)	(0.037)
GDP	1.829	1.827	0.267	3.761	5.085	0.425	1.454	10.955
	(0.028)	(0.017)	(0.007)	(0.123)	(0.057)	(0.007)	(0.035)	(0.565)
FDI	0.241	0.355	0.401	0.331	0.412	0.234	0.541	0.256
	(0.122)	(0.018)	(0.104)	(0.202)	(0.210)	(0.113)	(0.062)	(0.144)
Inflation	0.001	0.001	0.0004	−0.007	0.001	−0.0001	−0.0001	−0.078
	(0.000)	(0.0001)	(0.0004)	(0.003)	(0.000)	(0.0001)	(0.0004)	(0.008)
Population	0.308	0.336	0.187	0.910	0.749	0.063	0.318	0.091
	(0.003)	(0.005)	(0.004)	(0.049)	(0.006)	(0.004)	(0.005)	(0.189)
Renewable	−0.074	−0.072	−0.126	−0.769	−0.296	−0.043	−0.451	−3.112
	(0.002)	(0.002)	(0.001)	(0.027)	(0.005)	(0.004)	(0.002)	(0.082)
Internet	−0.424	−0.395	0.901	−0.401	−1.164	−0.552	0.911	−0.629
	(0.029)	(0.018)	(0.014)	(0.040)	(0.072)	(0.013)	(0.026)	(0.137)
Constant	−1.408	−1.325	0.861	−4.418	−3.839	0.022	1.958	16.477
	(0.029)	(0.034)	(0.012)	(0.107)	(0.089)	(0.011)	(0.051)	(1.206)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Iterations	12,500	12,500	12,500	12,500	12,500	12,500	12,500	12,500
Burn-in	2500	2500	2500	2500	2500	2500	2500	2500
Sample size	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Average acceptance rate	61 %	69 %	73 %	67 %	77 %	71 %	63 %	69 %
No of countries	31	13	14	4	31	13	14	4

Note: Monte-Carlos standard errors are in parenthesis.

Table 9
Bayesian panel regression results using regional classification of countries.

Variable	Ecological footprint					Carbon emission				
	Western Africa	Southern Africa	Eastern Africa	Central Africa	Northern Africa	Western Africa	Southern Africa	Eastern Africa	Central Africa	Northern Africa
INV	−0.660	−3.106	−1.398	−1.393	−2.098	−0.222	−7.015	−0.620	−8.149	−1.678
	(0.040)	(0.578)	(0.207)	(0.213)	(0.029)	(0.022)	(2.659)	(0.061)	(0.641)	(0.406)
EF	0.002	0.037	0.008	0.034	−0.003	−0.007	−0.122	−0.008	0.003	−0.012
	(0.0004)	(0.002)	(0.0004)	(0.001)	(0.001)	(0.0001)	(0.005)	(0.0001)	(0.001)	(0.003)
INV * EF	0.010	0.623	−0.021	−0.035	−0.031	0.003	0.427	−0.011	−0.137	−0.022
	(0.001)	(2.047)	(0.004)	(0.003)	(0.001)	(0.0004)	(1.996)	(0.001)	(0.009)	(0.007)
GDP	0.064	−0.061	0.916	1.197	1.446	1.009	−14.960	0.454	7.859	1.261
	(0.026)	(0.091)	(0.074)	(0.080)	(0.079)	(0.014)	(0.272)	(0.006)	(0.071)	(0.121)
FDI	0.311	0.519	0.341	0.129	0.332	0.210	0.442	0.164	0.136	0.175
	(0.011)	(0.123)	(0.024)	(0.110)	(0.150)	(0.100)	(0.029)	(0.024)	(0.042)	(0.189)
Inflation	0.004	0.0005	0.0004	0.001	0.013	0.004	−0.081	0.0002	0.002	0.031
	(0.0002)	(0.001)	(0.00002)	(0.0004)	(0.0005)	(0.0001)	(0.004)	(0.0001)	(0.0001)	(0.001)
Population	0.065	0.095	0.192	0.711	0.102	0.107	6.106	0.345	1.580	0.075
	(0.016)	(0.027)	(0.006)	(0.072)	(0.012)	(0.007)	(0.086)	(0.004)	(0.037)	(0.021)
Renewable	0.085	−1.179	0.080*	−0.462	−0.054	−0.235	−7.752	0.268	1.381	−0.291
	(0.004)	(0.012)	(0.029)	(0.024)	(0.002)	(0.005)	(0.036)	(0.006)	(0.028)	(0.004)
Internet	0.180	−0.563	−0.027	0.800	0.080	0.319	−1.210	1.133	−0.814	−0.102
	(0.039)	(0.019)	(0.099)	(0.053)	(0.032)	(0.026)	(0.077)	(0.026)	(0.101)	(0.056)
Constant	0.820	4.193	−0.522	1.003	0.130	0.656	52.952	−0.745	−12.175	1.650
	(0.030)	(0.215)	(0.195)	(0.117)	(0.084)	(0.007)	(0.397)	(0.033)	(0.204)	(0.135)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Iterations	12,500	12,500	12,500	12,500	12,500	12,500	12,500	12,500	12,500	12,500
Burn-in	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Sample size	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Average acceptance rate	67 %	64 %	76 %	69 %	66 %	83 %	79 %	68 %	73 %	79 %
No of countries	12	3	6	6	4	12	3	6	6	4

Note: Monte-Carlos standard errors are in parenthesis.

middle income countries, which provides additional support for Table 8's findings. It is striking that the Southern region's result differs from what is reported in Table 8. In this case, the joint effect exacerbates environmental degradation in the Southern region, even though these countries are classified as upper-middle income. A plausible explanation is that their institutions were unable to slow the rate at which innovation

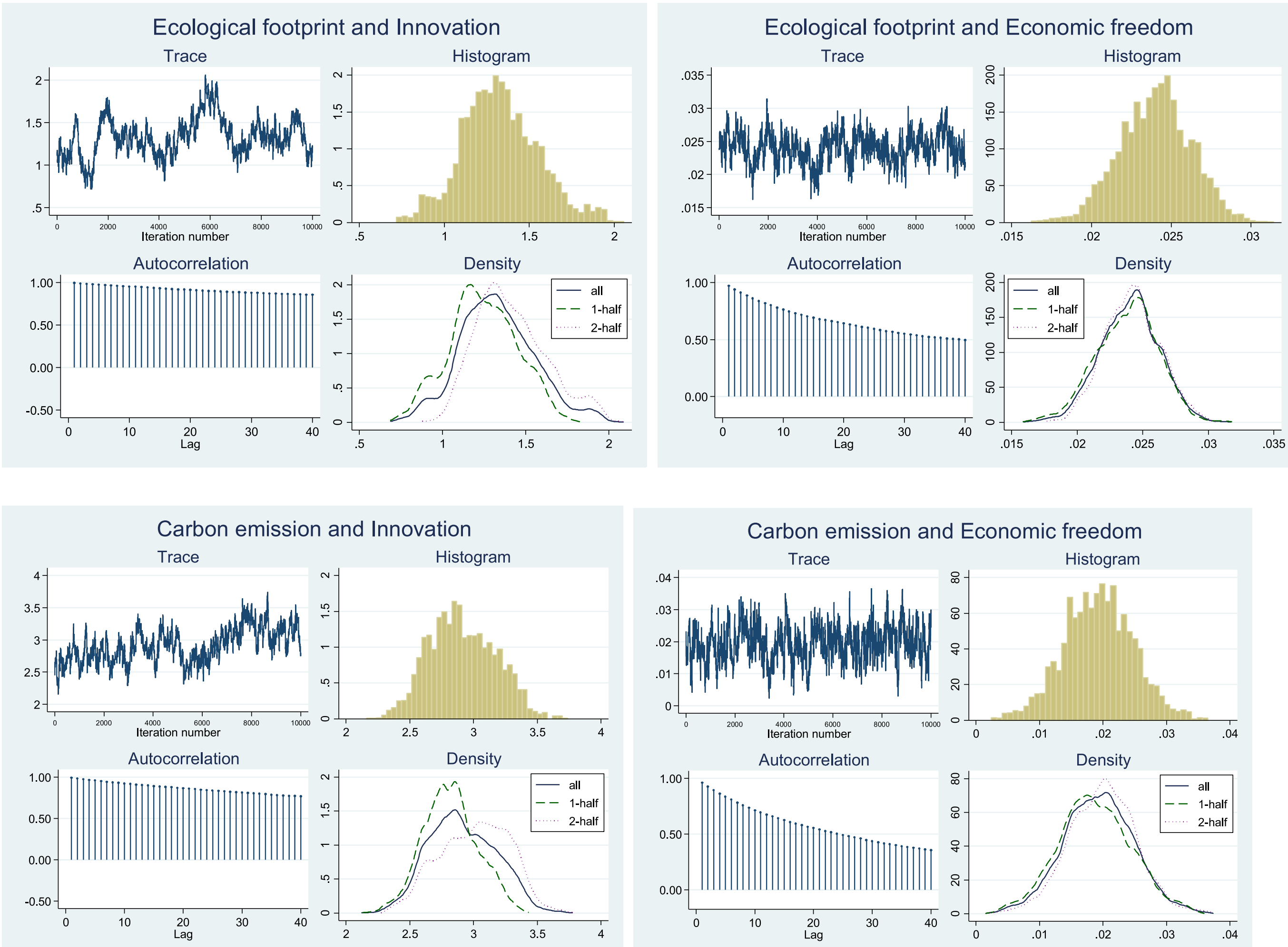

Fig. 2. Bayesian graph (source: own chart).

spreads through industrialization, which has a negative impact on the environment. Lastly, the results of the control variables are comparable across various subregions and income levels in Africa. These results are consistent with expectations. Our diagnostic results (Fig. 2) indicate that convergence is achieved with a sample size of 10,000, which was derived from a total of 12,500 iterations per model after 2500 burn-in iterations were eliminated.

5. Conclusion, policy implications and direction for future research

Changes in the earth's climate have been exacerbated by the cumulative effect of human-caused increases in carbon emissions throughout time. The global effects of the climate crisis are immense and far-reaching. Despite making relatively small contributions, African countries bear a disproportionate share of the consequences of the climate disaster because of their extreme vulnerability. This has prompted significant environmental protection concerns on both the national and international levels. A plethora of studies in academic literature have examined the contributing (or mitigating) factors to climate disaster from a variety of perspectives. A portion of the literature suggests the application of technological innovation; however, we argue in this study that technology-driven propositions may not provide sustainable climate solutions in the absence of robust economic freedom. Therefore, we investigate the interaction effects of technological innovation and economic freedom on environmental quality in Africa.

Using an array of econometric techniques, our findings demonstrate a substantial negative impact of technological innovation and economic freedom proxies on the dependent variables (ecological footprint and CO_2 emission). In addition, our results show that the net effect of both proxies when interacted would help to improve environmental quality in Africa. We also evaluate the effect across regions and income classes. Our findings indicate that technological innovation reduces degradation in low-middle and upper-middle income African nations, whereas the opposite is observed in low-income and Western nations.

Our findings provide vital information to relevant stakeholders in Africa, especially policymakers, regarding the need to improve economic freedom indices in the region. At the last climate conference (COP 27) in Egypt, compensation for climate-related losses and damages, or climate reparation, was on the agenda. The issues raised by the conference are (1) who will pay the reparation, (2) to whom, and (3) how far back it should be paid. In this study, from the perspectives of adaptation and mitigation strategies, we present two essential solutions to this smoldering conflict. We propose that climate reparations, an adaptation solution, should be paid by highly industrialized nations to climate-threatened poor countries, particularly those in Africa, which seems reasonable for a region that suffers the most from climate change despite having contributed the least to its cause. Climate reparations can be used by impoverished nations to invest in technological infrastructure to mitigate climate crisis-related suffering. However, we are aware that, like foreign aid, reparations may be mismanaged by recipient nations and fail to achieve their intended purpose. In addition, it may provide justification for industrialized nations to increase their carbon emissions at the expense of vulnerable developing nations.

Although reparations will assist developing nations in adapting to the effects of climate change, they will not mitigate future climate crises. As a result, we propose mitigating strategy as the most sustainable solution for saving the planet. This would require wealthy nations to provide climate-friendly technological innovations to developing nations for free or at a reduced cost. In addition to climate compensation, this will demonstrate the developed world's willingness to mitigate the plights of vulnerable nations. To take advantage of both adaptation and mitigation solutions, we urge African governments to increase their respective economic freedom indices. This will attract substantial investments in climate solutions fueled by technology. We contend that sustained investments in cutting-edge technology can rid the continent of carbon emissions and protect it from future climate catastrophes.

Despite the extensive findings uncovered by our study, we believe it has some inherent limitations, and, to that end, we propose some avenues for future research. Our study investigates the interplay between technological innovation and economic freedom in Africa's environmental quality. Future research can investigate the impact of these interactions on other world regions. Focusing on other continents would demonstrate the veracity and consistency of our findings in a new context. Also, in our analysis, we employed ecological footprint and carbon emission to proxy environmental quality as well as some variables from the Heritage Foundation database to measure economic freedom. Future research may use other proxies such as nitrogen oxide, greenhouse gas emissions and economic freedom metrics from sources such as the Fraser Institute to provide additional support for our findings. Lastly, our study is focused on the African continent and its regions, future studies can replicate our empirical strategy to offer country-specific evidence.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix A

Table A

Sources of data and measurement of variables.

Variables and acronym	Measurement	Sources
Dependent variables		
Ecological footprint	Ecological footprint per capita global hectares	Global Footprint Network
Carbon emission	Carbon dioxide per capita	WDI
Independent & control variables		
Innovation	Technology innovation index	WDI
GDP	GDP per capita (current US$)	WDI
FDI	Foreign direct investment	WDI
Inflation	Inflation, consumer prices (annual %)	WDI
Population	Population growth (annual %)	WDI
Renewable	Renewable energy consumption (% of total final energy consumption)	WDI
Internet	Individuals using the Internet (% of population)	WDI
Economic freedom	Economic freedom index	Heritage Foundation

Variables and acronym	Measurement	Sources
Dependent variables		
Ecological footprint	Ecological footprint per capita global hectares	Global Footprint Network Ecological Footprint - Global Footprint Network
Carbon emission	Carbon dioxide per capita	WDI World Development Indicators | DataBank (worldbank.org)
Independent & control variables		
Innovation	Technology innovation index	WDI World Development Indicators | DataBank (worldbank.org)
GDP	GDP per capita (current US$)	WDI World Development Indicators | DataBank (worldbank.org)
FDI	Foreign direct investment	WDI World Development Indicators | DataBank (worldbank.org)
Inflation	Inflation, consumer prices (annual %)	WDI World Development Indicators | DataBank (worldbank.org)
Population	Population growth (annual %)	WDI World Development Indicators | DataBank (worldbank.org)
Renewable	Renewable energy consumption (% of total final energy consumption)	WDI World Development Indicators | DataBank (worldbank.org)
Internet	Individuals using the Internet (% of population)	WDI World Development Indicators | DataBank (worldbank.org)
Economic freedom	Economic freedom index	Heritage Foundation Index of Economic Freedom: Promoting Economic Opportunity and Prosperity by Country (heritage.org)

Note: WDI denotes World Development Indicators.

Table B1
Income-classification of countries.

1	2	3
Low-income countries	Low-middle countries	Upper-income countries
Democratic Republic of Congo	Angola	Botswana
Gambia	Burkina Faso	Gabon
Guinea	Cameroon	Namibia
Guinea-Bissau	Congo Republic	South Africa
Madagascar	Cote d'Ivoire	
Mali	Ghana	
Malawi	Kenya	
Mozambique	Nigeria	
Niger	Senegal	
Sierra Leone	Zimbabwe	
Togo	Egypt	
Uganda	Algeria	
Zambia	Morocco	
	Tunisia	

Source. World Bank Data: CLASS.xlsx (live.com).

Table B2
Regional classification of countries.

Regions in Africa				
1	2	3	4	5
Western	Eastern	Southern	Central	Northern
Burkina Faso	Kenya	Botswana	Angola	Algeria
Cote d'Ivoire	Madagascar	Namibia	Cameroon	Egypt
Gambia	Malawi	South Africa	Congo Republic	Morocco
Ghana	Mozambique		Democratic Republic of Congo	Tunisia
Guinea	Uganda		Gabon	
Guinea-Bissau	Zambia			
Mali	Zimbabwe			
Niger				
Nigeria				
Senegal				
Sierra Leone				
Togo				

Source: United Nations Statistics: UNSD — Methodology.

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