Dynamic and Asymmetric Influence of Financial Credit, Economic Growth and Technological Innovation on the Ecological Footprint in Sub-Saharan Africa

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Abstract

We used a machine learning technique (Kernel Regularized Least Squares, KRLS) to investigate the dynamic and asymmetric influence of financial credit, economic growth and technological innovation (i.e. trade marks) on ecological footprints in 19 selected sub-Saharan African (SSA) countries from 2000 to 2022. The findings show that financial credit, economic growth and technological innovation have asymmetric/non-linear influence on the ecological footprint. A 1% increase in financial credit (domestic credits to the private sector) reduces the ecological footprint by 0.14%. In turn, financial credits decrease the ecological footprint in the 10th to 80th percentiles while increasing it in the 90th percentile. This suggests that financial credit reduces the ecological footprint and a larger increase in financial credit increases it. Economic growth reduces the ecological footprint by 0.003% at the 10th percentile and increases it at the 20th to 90th percentiles. This implies that an increase in economic growth initially reduces the ecological footprint, and a greater increase in economic growth increases the ecological footprint. The findings reveal that technological innovation reduces the ecological footprint in the 10th to 40th percentiles while increasing it in the 50th to 90th percentiles. This suggests that technological innovation initially reduces the ecological footprint, and a steady increase in technological innovation greatly increases the ecological footprint in SSA. The results are robust, supported by Bayesian estimates. To tackle the ecological footprint challenges in SSA, policy implications should introduce green technologies as a means to mitigate the impact of economic growth and financial credit on the ecological footprint in SSA, ultimately promoting climate change mitigation and achieving sustainable development goals by 2030.

Keywords: Ecological footprint; technological innovation; financial credit; economic growth
JEL Classification Codes: C01,C11,Q58,Q56

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1. Introduction

Macroeconomic factors such as financial development and economic growth can have a dynamic significant negative or positive influence on the ecological footprint on a global scale (Alqaralleh, 2024; Aslam et al., 2023; Omoke et al., 2020). The ecological footprint is a comprehensive indicator that measures the impact of human activities on ecosystems, encompassing forest, grazing land, cropland, and fishing grounds necessary for food and timber production for human consumption (Zhang et al., 2025). The ecological footprint is therefore key to sustainable development, encouraging people to reduce their use of resources and their waste emissions in order to promote environmental sustainability.

Analyzing macroeconomic factors such as financial credit (i.e. domestic credit to the private sector) and economic growth is crucial to understand their impact on the ecological footprint in the African context to achieve ecological sustainabibilty goals. For instance, economic growth, as measured by gross domestic product (GDP), often reflects increases in a country's production and consumption levels. Similarly, with higher economic growth and financial development, the demand for food, shelter, industrial products, and infrastructure increases, putting overall pressure on the environment (Alvarado et al., 2021; Nassani et al., 2021; Zambrano-monserrate et al., 2020). These growth trends can lead to increased resource extraction, energy consumption, and waste generation, directly impacting the ecological footprint – the measure of human demand on the earth's ecosystems.

Studies suggest that while economic growth can lead to improvements in living standards, if not managed sustainably, it can also lead to environmental degradation (Ritu and Kaur, 2024; Ali et al., 2021). For example, industrialization, which typically accompanies economic growth, can result in higher emissions of greenhouse gases and other pollutants (Raihan et al., 2022). On the other hand, studies suggest that financial expansion has proven to be harmful to the environment (Byaro et al., 2024b; Saqib et al., 2024; Ahmed et al., 2021; Dada et al., 2022; Khan et al., 2019; Kihombo et al., 2021). This implies that financial development initiatives might hinder resource conservation. However, as noted earlier, the ecological footprint of financial development can be either positive or negative at a specific point with underlying forces/determinants (Ahmed et al., 2021; Zeraibi et al., 2021).

It is well documented that the ecological footprint continues to increase worldwide, particularly in sub-Saharan Africa, due to the region's unique environmental challenges (Guliyev, 2024). This increase can be attributed to various factors such as population growth, which impacts resource consumption, unsustainable land use practices, deforestation, urbanization, industrialization (resulting in waste and emissions), economic activities, and the exploitation of natural resources (Dam et al., 2017; Nautiyal & Goel, 2021; Wackernagel and Kitzes, 2008). All these factors contribute to greater demands on the environment, leading to ecological imbalances and environmental degradation.

Conversely, technological innovation (i.e. brands/trademarks) is a driving force for economic growth (Byaro et al., 2024). It can also lead to an increase in the ecological footprint, particularly through the mechanisms of trademark protection and branding. For example, when companies innovate to create products that are less expensive due to branding, consumers may buy more. This can increase demand and lead to greater resource extraction, energy consumption, and waste generation, resulting in an increase in the ecological footprint. Moreover, technological innovations (e.g. brands/trademarks), when linked with sustainability, can enhance a brand's reputation and incentivize companies to embrace more environmentally friendly practices (See Kihombo et al., 2021). Companies may invest in green technologies not only for compliance purposes but also as a marketing strategy to appeal to environmentally conscious consumers. Overall, policymakers perceive technological innovation as a crucial tool for environmental sustainability goals. This study employs trademarks as a proxy for technology indicators.

Therefore, our study aims to analyze the asymmetric/non-linear effect of economic growth, financial credit (i.e. domestic credits to the private sector), and technological innovation on the ecological footprint in SSA from 2000 to 2022 while considering non-renewable energy in the regression model. Understanding the nonlinear relationship between financial credit, technological innovation, and economic growth on the environmental footprint in sub-Saharan Africa (SSA) can assist policymakers in crafting policies that foster sustainable economic practices while minimizing environmental impact. Thus, reducing the ecological footprint through financial credit, technological innovation, and economic growth is a crucial step for policymakers in sub-Saharan Africa to advance sustainable development goals (SDG), conserve natural resources, and strive towards a more environmentally sustainable future.

Our study focuses on sub-Saharan Africa (SSA) because the continent is prone to environmental problems (Byaro, et al., 2023; Byaro et al., 2022). Sub-Saharan Africa is a region abundant in natural resources and experiencing high population growth, which can significantly impact the ecological footprint due to the substantial demands on resources. The percentage share of domestic credit to the private sector in SSA's GDP was 27% in 2022, notably lower than the European Union's 85.2% and East Asia and the Pacific's 173.1% (World Development Indicators, 2023). Regarding ecological footprints, South Africa, with an average of 3.5, and Botswana, with an average of 2.9, stand out as the largest contributors to the ecological footprint (average per capita consumption) in SSA. The median ecological footprint (consumption per capita in global hectares) in 19 selected countries in SSA from 2000 to 2022 is 1.2, indicating a potential overexploitation of natural resources like forests, freshwater systems, and biodiversity, leading to habitat loss, land degradation, and heightened vulnerability to the impacts of climate change. In addition, there is a lack of studies in Africa exploring the asymmetric relationship between macroeconomic variables, technological innovation and ecological footprints.

Our novel contribution in this study is the use of machine learning techniques known as Kernel Regularized Least Squares (KRLS), to examine the asymmetric effect of economic growth, financial credit, economic growth and technological innovation on the ecological footprint using updated data from 2000 to 2022. Using a Bayesian panel regression analysis as a robustness check also provides novelty to the existing studies compared to previous studies that used traditional mean regression such as ARDL-PMG and System-GMM. Both advantages of KRLS and Bayesian panel regression analysis are described in detail in the methodology section. Our main research question are: (1) Is there an asymmetrical relationship between economic growth, financial credit and ecological footprint in sub-Saharan Africa? (2) Does technological innovation lead to asymmetric impacts on the ecological footprint?

The remainder of this study is organized as follows: Section 2 presents a literature review, Section 3 describes the data and methodology, Section 4 reports the results, and Section 5 provides a discussion of findings while the last section concludes with policy implications.

2. Literature Review

2.1 Theoretical literature

The quality of the environment is highly influenced by economic growth (Jahanger et al., 2022; Byaro et al., 2024). From this perspective, the nexus between economic growth and the quality of the environment is well explained by the Environmental Kuznets Curve (EKC) framework (Grossman and Krueger, 1991). The Environmental Kuznets Curve describes the connection between economic growth and environmental degradation, suggesting that as an economy develops, environmental degradation initially increases, reaches a peak, and then decreases as income increases, following an inverted U-shaped curve (Aydin and Turan, 2020; Khan et al. 2021). In the early stages of economic development, countries experience rapid industrialization and urbanization, leading to increased resource depletion, energy consumption, and pollutant emissions. This phase is characterized by the use of outdated and polluting technologies as industries expand to meet growing demands, resulting in a sharp increase in environmental degradation. As the economy grows further, pollution levels peak, leading to heightened awareness of environmental issues and advocacy for sustainable practices and regulatory measures to reduce degradation. Beyond the peak, continued economic growth is often associated with improvements in environmental quality, including investments in cleaner technologies and renewable energy sources (Grossman & Krueger, 1991; Jahanger et al., 2022; Nathaniel et al., 2024). Investing in green technologies is crucial for reducing the ecological footprint and enhancing environmental quality (Kongbuamai et al., 2020; Bekun, 2024). However, technology can have both positive and negative impacts on the environment, either increasing energy efficiency or contributing to pollution (Zhou et al., 2021).

On the other hand, domestic credits to the private sector or financial credits refer to borrowed funds provided to individuals or businesses for investment in various projects. Financial credit can potentially contribute to environmental degradation by enabling many businesses and industries to expand their productive capacities, thereby fostering economic growth. Theoretically, financial development can have both positive and negative impacts on environmental quality. For instance, financial development can support environmental conservation through mechanisms such as green financing that mitigate environmental harm (Ozturk et al., 2023). Conversely, financial credit can also exacerbate environmental degradation (Saqib et al., 2024). Additionally, the ecological footprint serves as a metric for evaluating the environmental impact of all human activities, particularly in terms of resource consumption and waste generation.

2.2 Empirical Literature Review

Table 1 sheds light on the reviewed empirical literature concerning the impact of non-renewable energy use, technological innovations, economic growth, and financial development on the ecological footprint. Several studies have explored the relationship between economic growth (i.e., GDP), financial development, and the ecological footprint globally. For instance, Ali et al. (2021), Baloch et al. (2019), Kongbuamai et al. (2020), Nathaniel (2021), Omoke et al. (2020), and Ritu and Kaur (2024) have all found that economic growth leads to an increase in the ecological footprint.

On the other hand, the studies by Alqaralleh (2024), Liu et al. (2022), Liu et al. (2022), and Usman et al. (2020) reveal a negative relationship between economic growth and the ecological footprint. Nevertheless, other studies, including Destek and Sarkodie (2019), Destek and Sinha (2020), and Khan et al. (2019), have stated the U-shaped relationship between economic growth and the ecological footprint, while Shujah-ur-Rahman et al. (2019) have found an N-shaped relationship between economic progress and the ecological footprint.

Furthermore, when examining the relationship between financial development and the ecological footprint, the results show a mix of findings. Several studies have indicated a significant positive relationship between financial development and the ecological footprint (Ahmed et al., 2021; Dada et al., 2022; Khan et al., 2019; Kihombo et al., 2021; Liu et al., 2022; Zhang et al., 2022; Baloch et al., 2019; Shujah-ur-Rahman et al., 2019). This positive association is attributed to financial development accelerating investment in various economic activities, such as industrialization, leading to increased CO_2 emissions from fossil fuel consumption and consequently an increase in the ecological footprint (Zhang et al., 2022).

Likewise, several studies have shown that financial development contributes to the reduction of the ecological footprint (Aslam et al., 2023; Aydin and Turan, 2020; Feng et al., 2022; Nathaniel et al., 2024; Omoke et al., 2020; Ozturk et al., 2023). Additionally, Liu et al. (2022) reported that financial development increases the ecological footprint in developing countries while decreasing it in developed countries. This finding contrasts with the results of Jahanger et al. (2022), who found that the impact of financial development on the reduction of the ecological footprint is consistent across other developing countries except those in Africa, the caribbean, and Latin America.

Most studies also indicate that the consumption of non-renewable energy contributes to increasing the ecological footprint. For example, research conducted by Alola et al.,2019), Baloch et al., 2019), Belaïd and Zrelli, 2019), Destek and Sinha , 2020), Dogan et al., 2019), Kongbuamai et al., 2020), Liu et al., 2022), Omoke et al.,2020), and Shujah-ur-Rahman et al., 2019) has highlighted the significant role of non-renewable energy consumption in the escalation of the ecological footprint.

Overall, the empirical evidence from the reviewed literature shows mixed findings. Similarly, the scarcity of similar studies in sub-Saharan Africa is highlighted, calling for additional research in this area. Methodologically, based on the reviewed literature, the majority of studies have utilized regression models such as Autoregressive Distributive Lag Model (ARDL), Cross-sectional Augmented Autoregressive Distributed Lags Model (CS- ARDL), Panel Quantile Regression, Panel Pool Mean Group (PMG), Non-Linear Autoregressive Distributed Lag (NARDL), among other regression methods. Notably, none of the reviewed studies have employed Kernel Regularized Least Squares (KRLS) regression as a machine learning technique, which is a novel application in our study. KRLS has the capability to handle non-linear relationships among variables.

Table 1: Empirical literature review

S/N	Author(s)	Country(s)/Region	Duration	Method(s)	Key Findings
2.	Guliyev (2024)	European Countries	1992-202	Bayesian Model Averaging	The use of energy & financial development affects the ecological footprint
3.	Feng et al.(2022)	China	2011-2019	Benchmark Regression Analysis	Digital financial development reduces the ecological footprint
4.	Liu et al. (2022)	Pakistan	1980-2017	ARDL Bounds	The use of energy increase the ecological footprint.Economic growth reduces the ecological footprint.
5.	Aslam et al. (2023)	Middle and high-income countries	1990-2020	Panel Quantile Regression	The higher the financial development, the lower the ecological footprint.
6.	Zhang et al. (2022)	G-7 Countries	2000-2020	Continuously updated full modified (CUP-FM)	There is a positive impact of financial development on ecological footprint.
7.	Jahanger et al. (2022)	73 Developing Countries	1990-2016	Second-generation panel unit root	Financial development decreases the ecological footprint but not in Africa, Latin America and the Caribbean region.
8.	Alqaralleh (2024)	4 ASEAN Countries.	1972-2018	Asymmetric quantile regression.	Economic growth negatively affects the ecological footprint.
9.	Liu et al. (2022)	Developing and Developed Countries.	1990-2018	Cross-sectional Augmented Autoregressive Distributed Lags Model (CS- ARDL)	Economic growth reduces the ecological footprint.Financial development increases the ecological footprint in developing countries and lowers it in developed countries.
10.	Ali et al. (2021)	128 Countries	1995-2019	Panel Data Regression	Economic growth increases environmental footprints.
11.	Çakmak and Acar (2022)	Oil producing countries	1999-2017	Dynamic Panel Data Analysis	Economic growth has a positive impact on the ecological footprint.
12.		India	1997-2020		

S/N	Author(s)	Country(s)/Region	Duration	Method(s)	Key Findings
	Ritu and Kaur (2024)			Autoregressive Distributed Lag Model (ARDL)	Economic growth increaseecological footprint.
13.	Alola et al. (2019)	EuropenUnion	1997-2014	Panel Pool Mean Group, Autoregressive Distributive Lag (PMG-ARDL)	Non-renewable energy increases the ecological footprint
14.	Ozturk et al. (2023)	South Asia	1971-2018	Westerland Cointegration test	Financial development reduces the ecological footprint.Energyconsumption increases the ecological footprint.
15.	Nathaniel (2021)	Indonesia	1971-2014	ARDL	Economic growth and energy consumption increase the ecological footprint in the long run.
16.	Nathaniel et al. (2024)	Bangladesh	1975-2018	Dynamic ARDL simulation technique	Financial development reduces the ecological footprint.
17.	Baloch et al. (2019)	Belt and Road Countries (BRC)	1990-2016	Driscoll-Kraay Regression Model	Financial development, economic growth and energy use increase the ecological footprint.
18.	Shujah-ur-Rahman et al. (2019)	Sixteen central and eastern European countries.	1991-2014	DyanamicSeemigly Unrelated-co-Integration Regression (DSUR)	Financial development and energy consumption significantly contribute to ecological footprint.
19.	Kongbuamai et al. (2020)	Thailand	1974-2016	ARDL boundary test, VECM,Granger Causality.	Existence of a positive relationship between economic growth and energy consumption with ecological footprint.
20.	Khan et al. (2019)	Belt and Road Initiatives (BRI)	1990-2016	Common Correlated Effect Mean Group (CCEMG). Panel Heterogeneous Causality (PHC)	Existence of a positive relationship between economic growth, financial development and energy use on ecological footprint.
21.	Omoke et al. (2020)	Nigeria	1971-2014	Non-Linear Autoregressive Distributed Lag (NARDL)	Economic growth and energy consumption increase the ecological footprint. Financial development decreases ecological footprint.

S/N	Author(s)	Country(s)/Region	Duration	Method(s)	Key Findings
22.	Usman et al. (2020)	33 Upper-Middle-income countries from Africa, Asia, Europe and America.	1994-2017	Dumitrescu and Hurlin (D-H) non-causality test	There is a negative relationship between economic growth and ecological footprint in Africa and Europe.
23.	Aydin and Turan (2020)	BRICS countries	1996-2016	Environment Kuznet Curve (EKC) hypothesis testing	Financial development reduces the ecological footprint of India & South Africa
24.	Ahmed et al. (2021)	Japan	1971-2016	ARDL Method	Financial progress and energy consumption increase the ecological footprint.
25.	Belaïd & Zrelli (2019)	MediterraneanCountries	1980-2014	PMG, panel ARDL.	Non-renewable energy consumption and economic growth increase the ecological footprints.
26.	Dada et al. (2022)	Malaysia	1984-2017	Autoregressive Distributed Lag Bounds	Financial development increases the ecological footprint.
27.	Destek and Sarkodie (2019)	Eleven Industrialised Countries	1977-2013	Augmented Mean Group (AMG)	Existence of U-shaped relation between ecological footprint and economic growth.
28.	Destek and Sinha (2020)	Twenty four economic and development countries organisation.	1980-2014	Second generation panel data.	Non renewable energy consumption increases the ecological footprint.
29.	Dogan et al. (2019)	Indonesia, Nigeria, Mexico and Turkey	1971-2013	Autoregressive Distributed Lag (ARDL)	Non-renewable energy and financial development increase the ecological footprint.
30.	Khan et al. (2021)	Malaysia	1980-2019	Dynamic SimulatedARDL	Financial development and economic growth increases the ecological footprint.
31.	Kihombo et al. (2021)	West Asia and Middle East Coutries.	1990-2017	STIRPAT Framework	Financial development increases the ecological footprint. Technological innovation decreases ecological footprints

S/N	Author(s)	Country(s)/Region	Duration	Method(s)	Key Findings
32.	Pata et al. (2024)	BRICS countries	1992-2020	Cointegration test	Technological innovation (patents) have no impact on ecological footprints
33.	Zeraibi et al. (2021)	ASIAN	1985-2016	CS-ARDL	Technological innovation reduces ecological footprints
34.	Wang and Luo (2020)	30 Provinces in China	2006-2016	Panel threshold regression	Technology innovation positively increase environmental pollution
35.	Jebli and Hakimi (2022)	10 countres with high technology	2004-2019	Panel mean group-ARDL	Technological innovation decreases environmental degradation
36.	Wang and Guo (2022)	China	2000-2020	OLS and quantile regression	Technological innovation reduces environmental pollution
37.	Huo et al (2023)	China	1991-2017	ARDL	Environmental technologies increase environmental degradation

3. Data and Methodology

3.1 Data sources

Table 2 displays the annual data sources and unit of measurements sourced from World Bank Development Indicators, (2023). The ecological footprint data was obtained from the Global footprint network (2022). The time frame for the selected 19 countries covers the annual period from 2000 to 2022, constrained by data availability specifically technological innovation (i.e. trade mark application) and ecological footprint. Unbalanced panel data analysis was employed, and the selection of variables was supported by previous empirical studies such as Dam et al. (2024), Uche et al. (2023), Ullah et al. (2021), Kihombo et al. (2021), and Jahanger et al. (2022).

Table 2: Description of variables and data sources

Variables	Symbol	Unit of measure	Sources
Fossil fuels energy use	FOSSIL	% of total	WDI
GDP per capita	GDP	Gross Domestic Product (constant 2015 US$)	WDI
Financial development	CREDIT	Domestic credit to private, % of GDP	WDI
Ecological footprint	ECOL	Consumption per capita (gha)	Global footprint Network (2022)
Trade mark application	TECH	Applications count	WDI

Note: Ecological footprint serves as a proxy for environmental sustainability, while WDI refers to the World Development Indicators Database.

3.1 Model specification and estimation techniques

This study is based on the Environmental Kuznet Curve (EKC) theory developed by Grossman and Krueger (1991) and other previous empirical studies by Kihombo et al. (2021) and Jahanger et al. (2022). We examine the impact of financial credit, economic growth, and technological innovation on ecological footprint in 19 selected countries in sub-Saharan africa (SSA) from 2000 to 2022 using Kernel Regularized Least Squares (KRLS). We develop an ecological footprint function based on technological innovation (i.e. trademarks), financial credit (i.e. domestic credit to the private sector), and economic growth (GDP per capita) while taking non-renewable energy consumption (i.e. fossil fuels) as control variables as follows:

$$ECOL_{it} = f(\,TECH_{it}, GDP_{it}, GDP^2{}_{it}, CREDIT_{it},\ FOSSIL_t) \qquad (1)$$

Where ECOL= Ecological footprint, GDP= per capita income, TECH= technological innovation, CREDIT= domestic credit to the private sector, FOSSIL=non-renewable energy consumption,t = time period, i= number of countries. Eq. (1) can be converted into linear form by introducing natural logarithm to reduce heteroscedasticity as follows; -

$$InECOL_{it} = \alpha_0 + \beta_1 ln\, TECH_t + \beta_2 lnGDP_{it} + \beta_3 lnGDP^2{}_{it} + \beta_4 lnCREDIT_{it} + \beta_5 lnFOSSIL_{it} + \mu_{it} \quad (2)$$

Note that μ_{it}= idiosyncratic error term. The Kernel Regularized Least Squares (KRLS) can handle both linear and non-linear time-varying effects (Byaro and Rwezaula, 2025). It is based on the regularized least squares algorithm, which is a method for estimating the parameters of a linear regression model using kernel functions (Lin and Ullah, 2024). The KRLS model equation for a non-linear function is expressed in Eq. (3) as follows:

$$ECOL_{it} = \sum_{i=1}^{n} \alpha_i(t)\, k\big((x)_i, x(t)\big) \qquad (3)$$

Where: $ECOL_{it}$represent ecological footprint, n = number of vectors support,$\alpha_i(t)$= coefficients associated with each support vector (i.e. technological innovation, economic growth, financial credit, fossil fuels). $k\big((x)_i, x(t)\big)$= represent the kernel function that measures the relationship between the support vectors and the input at time t. The kernel function, as denoted in Eq. (3), plays a crucial role as it dictates how data points of explanatory variables are mapped into a higher-dimensional feature space, enabling the KRLS model to capture intricate nonlinear relationships within the data (see lin and Ullah, 2024).

For estimation purposes, KRLS overcomes the traditional linear regression model that assumes a linear relationship between dependent and explanatory variables. It achieves this by mapping explanatory variables into a higher-dimensional space, where the kernel function accurately estimates a linear relationship using antilogarithm, as opposed to traditional linear regression (See, Hainmueller and Hazlett, 2014). Another advantage of using KRLS is its ability to handle a large number of explanatory variables in a single model, unlike traditional regression models that struggle with many variables due to issues such as multicollinearity and overfitting (Byaro and Rwezaula, 2025). To mitigate multicollinearity and overfitting, KRLS incorporates regularization through lambda. An interesting aspect of KRLS, compared to other regression techniques, is its ability to provide marginal coefficient estimates at different percentiles, ensuring consistent and robust estimates without misspecification bias (Hainmueller and Hazlett, 2014). Furthermore, there is no requirement to test for unit roots of variables or cross-sectional dependence of the variables (Byaro et al., 2024; Warsame, 2023). Additionally, KRLS assumes no autocorrelation, and lambda regularization minimizes the effects of endogeneity in variables, thereby improving the accuracy of coefficient estimates (Byaro and Rwezaula, 2025).

4. Results

Table 3: Summary of descriptive statistics.

	Domestic credit(%)	Trademark applications (count)	Ecological footprint(Consumption per capita, gha)	GDP per capita (US $ constant, 2015)	Fossil fuels (% of total)
N	351	258	345	436	191
Mean	28.32	2445.06	1.59	2778.17	34.78
Median	16.50	1238	1.19	1265.79	19.69
Min	1.89	27.24	.55	255.1	0
Max	142.42	17921	4.54	17117	88.14

N.B: The descriptive statistics are in raw values

Table 4 indicates the pointwise results of KRLS for estimates of financial credit and economic growth on ecological footprints in sub-Saharan Afric (SSA) for selected 19 countries from 2000 to 2022. The findings show that a 1% increase in average domestic credit to the private sector is associated with an average reduction of ecological footprints by approximately 0.14%. However, at 10th to 80th quantiles, the magnitude of domestic credit to private sector in reducing ecological footprint decreases progressively. Notably, across the 90th quantiles, domestic credit to the private sector appear to increase ecological footprints. In other words, domestic credits to the private sector has a non-linear relationships with ecological footprints in SSA. Economic growth and its squares, and fossil fuels increase ecological footprints. Specifically, an increase in 1% of economic growth (i.e.GDP) and fossil fuels leads to an increase of ecological footprints by 0.11% and 0.08%, respectively. Looking into percentiles, the result demonstrate that technological innovation (i.e. trademarks) decreases ecological footprints across 10th to 40th quantiles. From 50th to 90th quantiles trademark as a proxy for technological innovation increases ecological footprints in SSA. This implies that trademark has a non-linear impact on ecological footprints. Trademarks as legal protections for brands can be associated with marketing strategies that encourage consumption patterns. If a branded product without sustainable practices may leads to higher consumption, and in turn could indirectly lead to a larger ecological footprint. As expected, fossil fuels consumption increases ecological footprints in all percentiles and its magnitude increases progressively from low quantiles to higher quantiles.

In the context of the environmental kuznet curve (EKC), both GDP and its square (GDP^2) are used mathematically to model this relationship. The inclusion of GDP^2 makes it possible to capture the non-linear aspect of the relationship, which is essential for depicting the tipping point at which environmental degradation begins to decrease while income continues to rise. Our result show that as a country's economy grows (measured by GDP), environmental quality (i.e. ecological footprints) initially deteriorates but eventually improves once a certain income level is reached. This is only applies to average marginal coefficients and across the 10th quantile. When GDP is positive, it means the economy is growing. This growth typically leads to an increase in industrial activity, consumption and resource extraction, which can lead to higher ecological footprints. The role of GDP^2 in the EKC helps to illustrate how an increase in economic output can lead to greater environmental impacts until a certain threshold is reached.

Table 4: Pointwise derivatives using (KRLS) estimates for ecological footprints

	Domestic credit	GDP	GDP²	Trademark applications	Fossil fuels
Marginal average	-.136*** (.020)	.105***(.009)	.006***(.001)	.018***(.004)	.075*** (.015)
Percentiles					
τ = 0.10	-.269	-.003	-.0003	-.040	.013
τ = 0.20	-.251	.044	.003	-.034	.018
τ = 0.30	-.227	.071	.005	-.018	.026
τ = 0.40	-.217	.094	.006	-.000	.056
τ = 0.50	-.161	.110	.007	.038	.094
τ = 0.60	-.112	.127	.007	.049	.111
τ = 0.70	-.035	.135	.008	.053	.124
τ = 0.80	-.001	.164	.010	.063	.140
τ = 0.90	.016	.181	.012	.073	.148
N= observations	67				
Looloss	.62				
Lambda	.15				
R^2	.98				

Note: GDP=Economic growth. All variables are expressed in logarithnm. Standard errors are shown in brackets ( ), while *** indicates 1% significance levels

Since KRLS processes nonlinear data in percentiles, we display three important diagnostic tests: R^2, "looloss", and the regularization parameter "lambda". 'Looloss' is a loss function in the context of machine learning that quantifies how well a model's predictions match the actual results. 'Lambda' is a regularization parameter that prevents overfitting and controls the tradeoff between model fitting and data. Lower values of 'looloss' and 'lambda' indicate better model performance. R^2 explains how well fossil fuels, technological innovation, domestic credit to the private sector, and economic growth explain variability in the ecological footprint within a regression model. With an R^2 of 0.98, the model demonstrates a good fit.

Figure 1 shows the pointwise marginal effects of domestic credit to the private sector, economic growth, fossil fuels, and technological innovation on the ecological footprint. The figure shows a smooth fitted curve representing the predicted relationship between the dependent and independent variables. The curve is displayed by applying kernels to fit data points without taking a specific functional form. To interpret the graph, it is important to understand how changes in the explanatory variables affect the dependent variable. For example, the curve shape in Figure 1 indicates existence of a nonlinear relationship. When the curve flattens and then rises steeply (see Figure 1a), this suggests that domestic credit to the private sector reduces the environmental footprint and a larger increase in domestic credit increases the environmental footprint. Likewise, an increase in economic growth initially reduces the ecological footprint, and a greater increase in economic growth increases the ecological footprint (see Figure 1b). An increase in fossil fuels increase the ecological footprint, and a further increase in fossil fuels increase the ecological footprint (see Figure 1c). An increase in trademark (i.e., technological innovation) reduces the ecological footprint, and a steady increase in technological innovation greatly increases the ecological footprint, then smoothes the ecological footprint and begins to increase the ecological footprint again (see Figure 1d). The discussion section provides a detailed explanation of these mechanisms in detail.

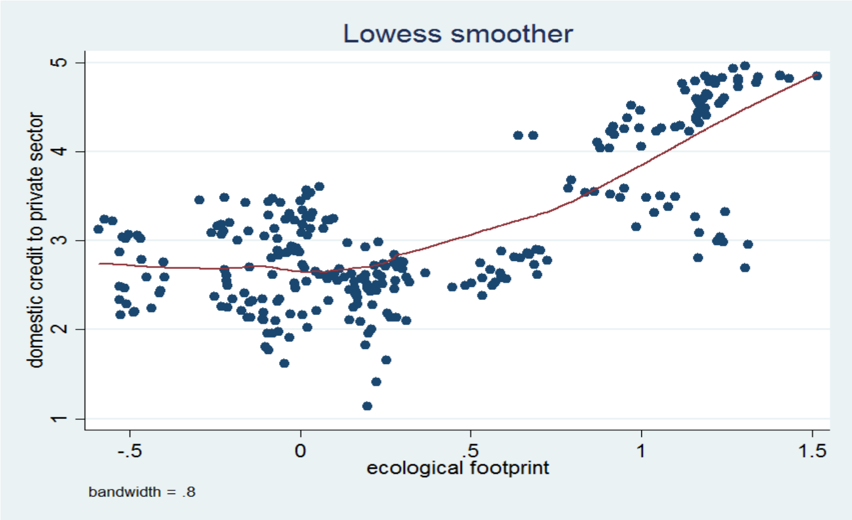

Figure 1a: Pointwise marginal effects of domestic credit

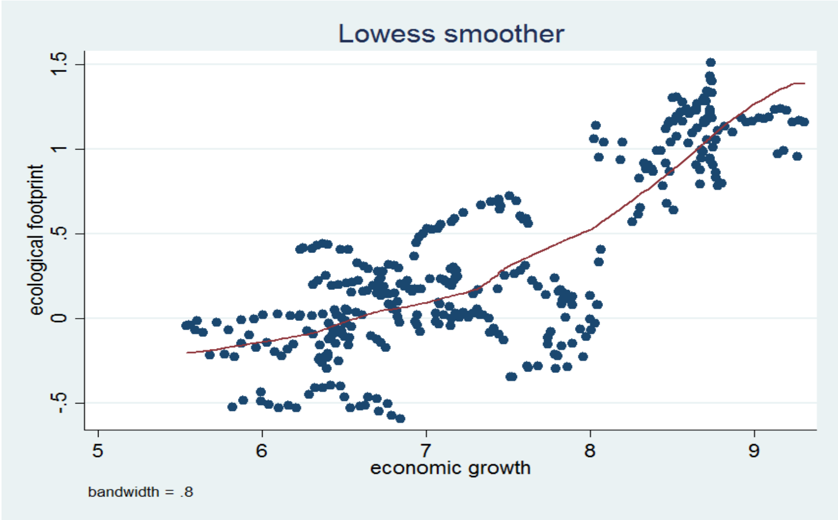

Figure 1b: Pointwise marginal effects of economic growth

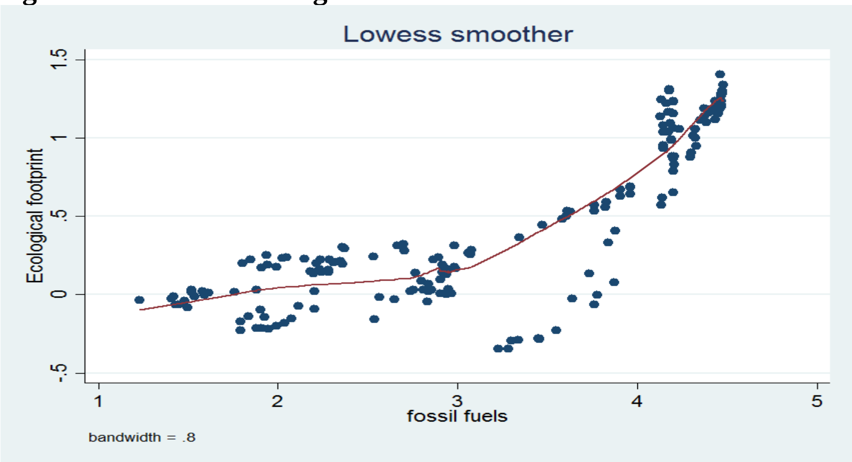

Figure 1c: Pointwise marginal effect of fossil fuels

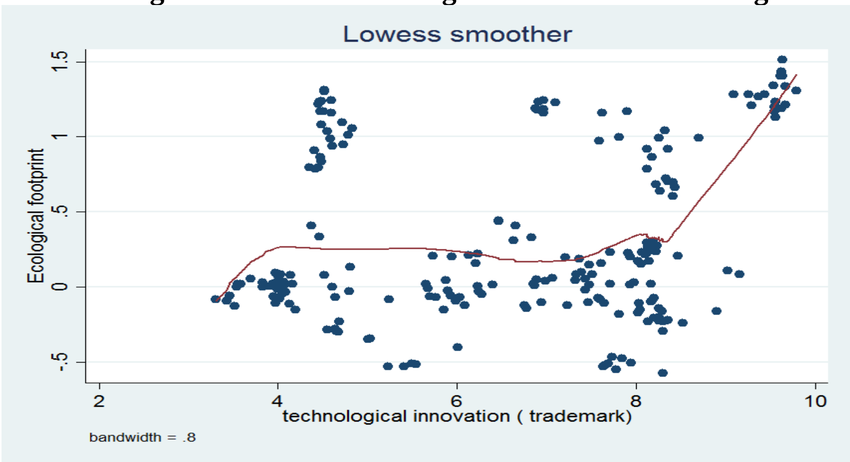

Figure 1d: Pointwise marginal effect of technological innovation

4.1 Sensitivity testing

We conducted a robustness test to validate the results, utilizing the Bayesian panel regression model. Table 5 presents Bayesian estimates for ecological footprints in 19 selected countries in SSA. The results indicate that the mean or median coefficients for economic growth (GDP) and its square (GDP^2) are positive and negative, respectively, aligning with the EKC hypothesis in SSA. Moreover, the mean or median coefficient of GDP is positive and falls within a 95% positive credible interval, suggesting that an increase in GDP raises the ecological footprint in the region with a 95% probability. Conversely, the mean or median coefficients of GDP^2 are negative and lie within both negative and positive 95% credible intervals, indicating uncertainty regarding GDP^2's impact on decreasing ecological footprints. Additionally, the mean or median coefficients for fossil fuels consumption (non-renewable consumption) and technological innovation (trademarks) are positive, signifying their contribution to increasing ecological footprints. However, these coefficients also fall within negative and positive 95% credible intervals, underscoring the uncertainty surrounding their effects on ecological footprints. The results further indicate that domestic credit to the private sector reduces ecological footprints in SSA, as the mean or median coefficients for this parameter fall within a negative 95% credible interval. Most findings from Bayesian estimations support the KRLS results outlined in Table 4.

Table 5: Bayesian posterior estimates for ecological footprintsin SSA.

Parameters	Mean	Std. dev.	MCSE	Median	95% credible intervals	
GDP	1.408	.924	.055	1.43	.451	3.129
GDP^2	-.082	.061	.004	-.083	-.195	.041
Fossilfuel	.182	.134	.007	.181	-.083	.445
Trademark applications	.023	.051	.005	.025	-.079	.120
Domestic credit	-.156	.051	.002	-.156	-.256	-.054
Constant	-5.48	3.25	.151	-5.52	-11.65	.99
var_U	.231	.243	.025	.157	.029	.862
sigma2	.005	.001	.000	.004	.003	.007

Note: Number of observations: 67, MCMC sample size was set to 10,000 with a burn-in period of 2,500, and a normal prior distribution was applied.

Figure 2 shows the diagnostic test for ecological footprint and domestic credit to the private sector. The trace diagrams show the clear mixing of the chains according to the Monte Carlo simulation (MCMC), which implies a convergence-stationarity equilibrium (Byaro et al., 2024a). The histogram shows a normal distribution of parameters, an autocorrelation that decreases towards zero and a normal kernel density showing that the domestic credit coefficients are within negative values, which means a reduction in the ecological footprint.

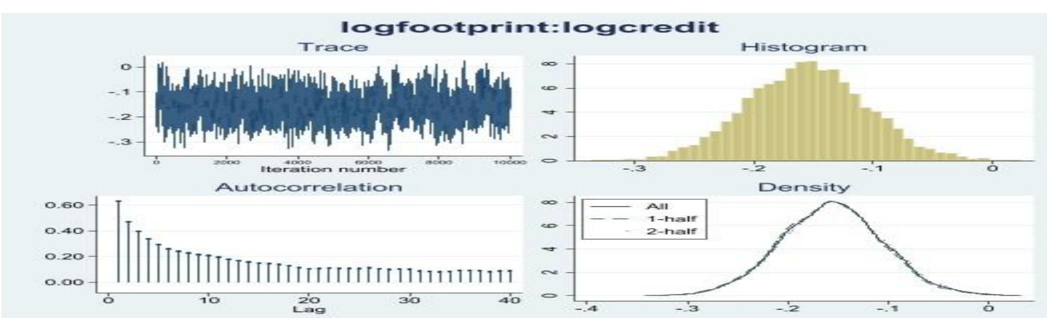

Figure 2: Diagnostic test for Bayesian estimates for domestic credit and ecological footprints

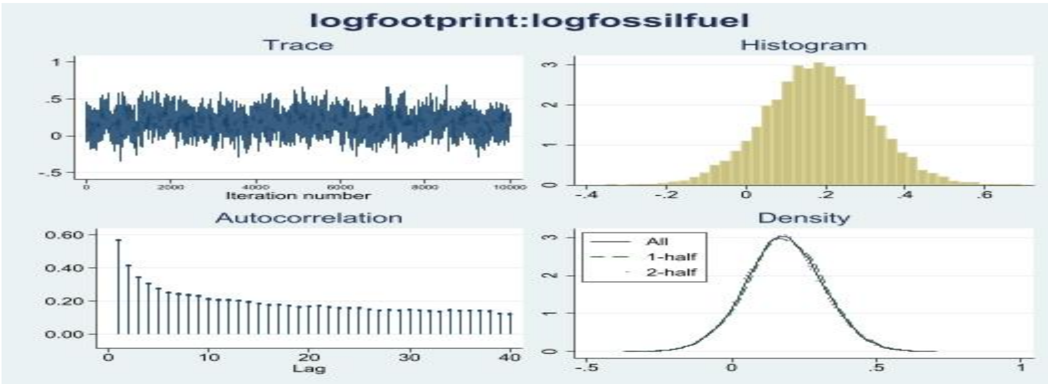

Figure 3: Diagnostic test for Bayesian estimates for fossil fuels and ecological footprints

Figure 3 also demonstrates the clear mixing of chains and presents normal distributions for both the histogram and kernel density. Fossil fuels exhibit predominantly positive values, with a minor portion displaying negative values. Autocorrelation diminishes with an increase in lags. While not explicitly detailed in this discussion, all other parameters exhibit similar patterns of convergence to stationarity, normal histogram, and kernel density, affirming the reliability of the findings for interpretation.

5. Discussion of results

We examined the heterogeneous effects of financial development, particularly domestic credit to the private sector, economic growth, and technological innovations (trademarks), while controlling for non-renewable energy use (i.e., fossil fuels) on ecological footprints in sub-Saharan African (SSA) countries from 2000 to 2022. We utilized KRLS regression in our estimates and conducted a robustness test using Bayesian panel regression.

The results of our study show that economic growth (GDP) increases the ecological footprint in SSA. An average increase in economic growth (measured by GDP per capita) leads to an increase in the ecological footprint, as observed in most KRLS quantiles (20th to 90th), as shown in Table 4. As SSA economies grow, there is often an increase in production and consumption in industries, which can lead to a larger ecological footprint (Ali et al., 2021; Guliyev, 2024; Jahanger et al., 2022). On the other hand, economic growth leads to rapid expansion of urbanization, accompanied by the construction of large-scale infrastructure and other development activities, which in turn leads to deforestation and general loss of biodiversity, all of which reduce the Earth's natural capacity to absorb greenhouse gas emissions (Baloch et al., 2019; Belaïd & Harbaoui, 2019; Khan et al., 2021). This, in turn, increases the ecological footprint of the urban population.

At the 10th quantile (Table 4), economic growth (GDP) appears to reduce the ecological footprint in SSA. The key mechanism influencing this is that as SSA economies grow, industries and companies invest in research and development (R&D), leveraging technological innovations. Some of these technologies used in the industry reduce energy consumption per unit of production, thereby lowering the environmental footprint associated with production processes. Our study results align with Usman et al. (2020) and Alqaralleh (2024) that economic growth can lead to a reduction in the ecological footprint.

Our findings indicate that fossil fuels have a notable impact on increasing the ecological footprint in SSA, representing a substantial portion of it. Fossil fuels, such as coal, oil, and natural gas, play a significant role in the ecological footprint due to their widespread use in energy production and various industrial processes (Fan et al., 2024; Ibrahiem and Hanafy, 2020; Alola et al., 2019; Guliyev, 2024; Kongbuamai et al., 2020; Liu et al., 2022; Omoke et al., 2020; Ozturk et al., 2023). The results also show that financial development (i.e. domestic credit to the private sector) reduces the ecological footprint in the 20th to 80th quantiles. However, at the 90th quantiles, the impact of financial credit (i.e. domestic credit to the private sector) on the ecological footprint is positive, meaning that financial credit increases the ecological footprint. Regardless, Bayesian panel regression confirms a negative impact of financial credit on the ecological footprint in SSA. The most important mechanism for financial lending to reduce the ecological footprint is to promote green investments. This includes renewable energy projects and sustainable agricultural practices. The use of cleaner and proper technologies, especially in industrial processes, reduces the ecological footprint (Aslam et al., 2023; Pham & Nguyen, 2024; Zhang et al., 2022). By providing funding to agriculture and industry sectors, it helps reduce dependence on fossil fuels and therefore reduces the ecological footprint. Our results agree with previous studies that financial development (i.e. domestic credit to the private sector) reduces the ecological footprint (Nathaniel et al., 2024; Pham & Nguyen, 2024; Ozturk et al.,2023; Aydin and Turan, 2020; Omoke et al., 2020).

As noted, domestic credit to the private sector increases the ecological footprint at the 90th percentile. The key mechanism that causes financial credit to increase the environmental footprint is that financial credit boosts economic growth by providing businesses and individuals with the capital they need to invest in infrastructure, production, and services (Fan et al., 2024). In many African countries, access to credit enables greater investment in sectors such as agriculture, manufacturing, and energy production. This economic expansion leads to greater consumption of resources. While financial credit can drive economic progress, it can also contribute to a larger environmental footprint due to the greater demand for resource extraction. Our results are consistent with previous studies suggesting that financial development increases the ecological footprint, including Fan et al. (2024), Dada et al. (2022), Ahmed et al. (2021), Dogan et al. (2019), and Baloch et al. (2019). Overall, our results suggest that the impact of financial credit (i.e., domestic credit to the private sector) on the ecological footprint in SSA exhibits an asymmetrical relationship.

Moreover, the results of our study reveal the asymmetric relationship between technological innovation (trademarks) and the ecological footprint. An average 1% increase in technological innovation increases the ecological footprint by 0.02%. However, technological innovations reduce the ecological footprint in the 10th to 40th percentiles, while they increase the ecological footprint in the 50th to 90th percentiles. This implies that technological innovation (i.e. brands/trademarks) is a driving force for economic growth (Byaro et al., 2024), leading to an increase in the ecological footprint, particularly through the mechanisms of trademark protection and branding. For instance, when firms or businesses innovate to create products that are cheaper due to branding, consumers may buy more. This can increase demand and lead to greater resource extraction, energy consumption, and waste generation, resulting in an increase in the ecological footprint. Studies supporting technological innovation increasing the ecological footprint include Wang and Luo (2020), Huo et al. (2023), and Adebayo and Kirikkaleli (2021).

Besides, our study shows that technological innovations (e.g. brands/trademarks) reduce the ecological footprint in the 10th to 40th percentiles. This means that technological innovation (trademarks), when associated with sustainability, can improve a brand's reputation and encourage companies/businesses to adopt more environmentally friendly practices (See Dam et al., 2024; Kihombo et al., 2021; Hao et al., 2020; Ali et al., 2020). Our results are consistent with Ullah et al. (2021) and Uche et al. (2023) who found the asymmetric relationship between technological innovation such as trademarks, environmental technology, and environmental degradation, respectively.

6. Conclusion and policy implications

This study aims to examine the asymmetric or symmetric impacts of economic growth, financial credit and technological innovation (i.e trademark) on ecological footprint in the selected 19 sub-Saharan African (SSA) taking into account the non-renewable energy use (i.e fossil fuels) for annual data spanning from 2000 to 2022. The key contribution of our study is the adoption of the KRLS a machine learning techniques. To ensure the robustiness of our study results, we used the Bayesian panel regression analysis. The findings of KRLS indicates the asymmetric or nonlinear impacts of economic growth, financial credit (domestic credit to private sector), technological innovation on ecological footprint in SSA. Moreover, Bayesian posterior estimates indicate that the mean or median for financial credit reduces ecological footprint, while the mean for technological innovation (trademarks), economic growth (GDP per capita) and fossil fuels have positive impact on ecological footprint. The results are robust and valid for estimation techniques. To address the challenges of the ecological footprint in SSA, policymakers should introduce cleaner technologies to mitigate the impact of economic growth and financial credit on the ecological footprint. This will help in promoting climate change mitigation and achieving sustainable development goals by 2030. Policymakers need to focus on strengthening technology and financial credit policies while implementing measures to reduce non-renewable energy consumption, such as fossil fuels. Additionally, stabilizing economic growth is crucial, and this can be achieved by promoting and adopting cleaner energy technologies to prevent further increases in the ecological footprint in SSA. Practical policy implications include the promotion of green technological innovation for the production of goods and services to reduce the ecological footprint, as well as encouraging eco-certification through the labeling of products and services that meet environmental standards, thus reducing the ecological footprint in SSA.

The main limitation of this study is the use of unbalanced panel data as some of the country variables are missing. This means that during the regression analysis, certain observations were discarded due to missing data. However, using statistical models that directly account for missing data can help mitigate problems associated with incomplete data. For example, the use of Bayesian methods allows parameter estimation without requiring complete data sets. In this way, we used the Bayesian method to conduct the sensitivity test. Overall, our study is not affected by the missing observations due to the unbalanced panel among the selected countries. Future studies should consider employing alternative methodologies that incorporate additional control variables and alternative proxies for environmental quality, such as the load capacity factor, to further explore the connections between economic growth, technological innovation, and financial indicators in developing nations.

Availability of data and materials
The data was extracted from publicly available databases, including the World Bank Development Indicators, 2023) and the Global footprint Network (2022).

References

Adebayo, T. S., & Kirikkaleli, D. (2021). Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. *Environment, Development and Sustainability*, *23*(11), 16057-16082.

Ahmed, Z., Zhang, B., & Cary, M. (2021). Linking economic globalization, economic growth, financial development, and ecological footprint: Evidence from symmetric and asymmetric ARDL. *Ecological Indicators*, *121*(September 2020), 107060. https://doi.org/10.1016/j.ecolind.2020.107060

Ali, Q., Yaseen, M. R., Anwar, S., Makhdum, M. S. A., & Khan, M. T. I. (2021). The impact of tourism, renewable energy, and economic growth on ecological footprint and natural resources: A panel data analysis. *Resources Policy*, *74*(September), 102365. https://doi.org/10.1016/j.resourpol.2021.102365

Ali, W., Rahman, I. U., Zahid, M., Khan, M. A., & Kumail, T. (2020). Do technology and structural changes favour environment in Malaysia: An ARDL-based evidence for environmental Kuznets curve. *Environment, Development and Sustainability*, *22*, 7927-7950.

Alola, A. A., Bekun, F. V., & Sarkodie, S. A. (2019). Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Science of the Total Environment*, *685*, 702–709. https://doi.org/10.1016/j.scitotenv.2019.05.139

Alqaralleh, H. (2024). On the factors influencing the ecological footprint: using an asymmetric quantile regression approach. *Management of Environmental Quality: An International Journal*, *35*(1), 220–247. https://doi.org/10.1108/MEQ-04-2023-0128

Alvarado, R., Ortiz, C., Jiménez, N., Ochoa-Jiménez, D., & Tillaguango, B. (2021). Ecological footprint, air quality and research and development: The role of agriculture and international trade. *Journal of Cleaner Production*, *288*, 125589. https://doi.org/10.1016/j.jclepro.2020.125589

Aslam, B., Zhang, G., Amjad, M. A., Guo, S., & Ji, M. (2023). Does the impact of financial development reinforce sustainability ecological footprint? Fresh evidence from middle and high-income economies. *Journal of Cleaner Production*, *429*(August), 139573. https://doi.org/10.1016/j.jclepro.2023.139573

Aydin, M., & Turan, Y. E. (2020). The influence of financial openness, trade openness, and energy intensity on ecological footprint: revisiting the environmental Kuznets curve hypothesis for BRICS countries. *Environmental Science and Pollution Research*, *27*(34), 43233–43245. https://doi.org/10.1007/s11356-020-10238-9

Baloch, M. A., Zhang, J., Iqbal, K., & Iqbal, Z. (2019). The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation. *Environmental Science and Pollution Research*, *26*(6), 6199–6208. https://doi.org/10.1007/s11356-018-3992-9

Belaïd, F., & Harbaoui, M. (2019). Renewable and non-renewable electricity consumption , environmental degradation and economic development : Evidence from Mediterranean countries. *Energy Policy*, *133*(August), 110929. https://doi.org/10.1016/j.enpol.2019.110929

Belaïd, F., & Zrelli, M. H. (2019). Renewable and non-renewable electricity consumption, environmental degradation and economic development: Evidence from Mediterranean countries. *Energy Policy*, *133*(May), 110929. https://doi.org/10.1016/j.enpol.2019.110929

Bekun, F. V. (2024). Race to carbon neutrality in South Africa: what role does environmental technological innovation play?. Applied Energy, 354, 122212.

Byaro, M., Mafwolo, G., & Mayaya, H. (2022). Keeping an eye on environmental quality in Tanzania as trade, industrialization, income, and urbanization continue to grow. Environmental Science and Pollution Research, 29(39), 59002-59012.

Byaro, M., Nkonoki, J., & Mafwolo, G. (2023). Exploring the nexus between natural resource depletion, renewable energy use, and environmental degradation in sub-Saharan Africa. Environmental Science and Pollution Research, 30(8), 19931-19945.

Byaro, M., Ngowi, N., & Rwezaula, A. (2024a). Do higher government spending, financial development, and trade reduce income inequality in low-income countries? A Bayesian perspective. Politics & Policy.

Byaro, M., & Rwezaula, A. (2024). How do technological innovation and urbanization drive economic growth in Tanzania and transform societies? Exploring the potential channels. Journal of Economy and Technology, 2, 235-246.

Byaro, M., Maguta, M. M., & Rwezaula, A. (2024b). Do domestic credits to the private sector contribute to zero carbon emissions in Africa? A quantile regression analysis. *Discover Sustainability*, *5*(1), 451.

Byaro, M., & Rwezaula, A. (2025). The health impacts of renewable energy consumption in sub-Saharan Africa: A machine learning perspective. *Energy Strategy Reviews*, *57*, 101621.

Çakmak, E. E., & Acar, S. (2022). The nexus between economic growth, renewable energy and ecological footprint: An empirical evidence from most oil-producing countries. *Journal of Cleaner Production*, *352*(March), 131548. https://doi.org/10.1016/j.jclepro.2022.131548

Dada, J. T., Adeiza, A., Ismail, N. A., & Arnaut, M. (2022). Financial development–ecological footprint nexus in Malaysia: the role of institutions. *Management of Environmental Quality: An International Journal*, *33*(4), 913–937. https://doi.org/10.1108/MEQ-10-2021-0251

Dam, M. M., Kaya, F., & Bekun, F. V. (2024). How does technological innovation affect the ecological footprint? Evidence from E-7 countries in the context of the SDGs. Journal of Cleaner Production, 443, 141020.

Dam, T. A., Pasche, M., &Werlich, N. (2017). *Trade patterns and the ecological footprint a theory-based empirical approach* (No. 2017-005). Jena Economic Research Papers.

Destek, M. A., & Sarkodie, S. A. (2019). Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development. *Science of the Total Environment*, *650*, 2483–2489. https://doi.org/10.1016/j.scitotenv.2018.10.017

Destek, M. A., & Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries. *Journal of Cleaner Production*, *242*, 118537. https://doi.org/10.1016/j.jclepro.2019.118537

Dogan, E., Taspinar, N., & Gokmenoglu, K. K. (2019). Determinants of ecological footprint in MINT countries. *Energy and Environment*, *30*(6), 1065–1086. https://doi.org/10.1177/0958305X19834279

Feng, S., Chong, Y., Yu, H., Ye, X., & Li, G. (2022). Digital financial development and ecological footprint: Evidence from green-biased technology innovation and environmental inclusion. *Journal of Cleaner Production*, *380*(P2), 135069. https://doi.org/10.1016/j.jclepro.2022.135069

Grossman, G. M., & Krueger, A. B. (1991). *Environmental Impacts of a North American Free Trade Agreement.* (3914). Natl. Bur. Econ. Res. https://doi.org/https://doi.org/10.3386/w3914

Guliyev, H. (2024). Determinants of ecological footprint in European countries: Fresh insight from Bayesian model averaging for panel data analysis. *Science of the Total Environment*, *912*(December 2023), 169455. https://doi.org/10.1016/j.scitotenv.2023.169455

Hainmueller, J. and Hazlett, C., 2014. Kernel regularized least squares: Reducing misspecification bias with a flexible and interpretable machine learning approach. *Political Analysis*, *22*(2), pp.143-168. https://doi.org/10.1093/pan/mpt019

Hao, Y., Wu, Y., Wu, H., & Ren, S. (2020). How do FDI and technical innovation affect environmental quality? Evidence from China. *Environmental Science and Pollution Research*, *27*, 7835-7850.

Huo, W., Zaman, B. U., Zulfiqar, M., Kocak, E., & Shehzad, K. (2023). How do environmental technologies affect environmental degradation? Analyzing the direct and indirect impact of financial innovations and economic globalization. *Environmental Technology & Innovation*, *29*, 102973.

Jahanger, A., Usman, M., Murshed, M., Mahmood, H., & Balsalobre-Lorente, D. (2022). The linkages between natural resources, human capital, globalization, economic growth, financial development, and ecological footprint: The moderating role of technological innovations. *Resources Policy*, *76*(January), 102569. https://doi.org/10.1016/j.resourpol.2022.102569

Jebli, M. B., & Hakimi, A. (2023). How do financial inclusion and renewable energy collaborate with environmental quality? Evidence for top ten countries in technological advancement. *Environmental Science and Pollution Research*, *30*(11), 31755-31767.

Khan, A., Chenggang, Y., Hussain, J., & Bano, S. (2019). Does energy consumption, financial development, and investment contribute to ecological footprints in BRI regions? *Environmental Science and Pollution Research*, *26*(36), 36952–36966. https://doi.org/10.1007/s11356-019-06772-w

Khan, M. K., Abbas, F., Godil, D. I., Sharif, A., Ahmed, Z., & Anser, M. K. (2021). Moving towards sustainability: how do natural resources, financial development, and economic growth interact with the ecological footprint in Malaysia? A dynamic ARDL approach. *Environmental Science and Pollution Research*, *28*(39), 55579–55591. https://doi.org/10.1007/s11356-021-14686-9

Kihombo, S., Ahmed, Z., Chen, S., Adebayo, T. S., & Kirikkaleli, D. (2021). Linking financial development, economic growth, and ecological footprint: what is the role of technological innovation? *Environmental Science and Pollution Research*, *28*(43), 61235–61245. https://doi.org/10.1007/s11356-021-14993-1

Kongbuamai, N., Zafar, M. W., Zaidi, S. A. H., & Liu, Y. (2020). Determinants of the ecological footprint in Thailand: the influences of tourism, trade openness, and population density. *Environmental Science and Pollution Research*, *27*(32), 40171–40186. https://doi.org/10.1007/s11356-020-09977-6

Lin, B. and Ullah, S., 2024. Modeling the impacts of changes in nuclear energy, natural gas, and coal in the environment through the novel DARDL approach. *Energy*, *287*, p.129572. https://doi.org/10.1016/j.energy.2023.129572

Liu, X., Razzaq, A., Shahzad, M., & Irfan, M. (2022). Technological changes, financial development and ecological consequences: A comparative study of developed and developing economies. *Technological Forecasting and Social Change*, *184*(December 2021), 122004. https://doi.org/10.1016/j.techfore.2022.122004

Liu, Y., Sadiq, F., Ali, W., & Kumail, T. (2022). Does tourism development, energy consumption, trade openness and economic growth matters for ecological footprint: Testing the Environmental Kuznets Curve and pollution haven hypothesis for Pakistan. *Energy*, *245*, 123208. https://doi.org/10.1016/j.energy.2022.123208

Nassani, A. A., Mohammed, A., & Zaman, K. (2021). Ecological footprints jeopardy for mineral resource extraction : Efficient use of energy , financial development and insurance services to conserve natural resources. *Resources Policy*, *74*(October 2020), 102271. https://doi.org/10.1016/j.resourpol.2021.102271

Nathaniel, S. P. (2021). Ecological footprint, energy use, trade, and urbanization linkage in Indonesia. *GeoJournal*, *86*(5), 2057–2070. https://doi.org/10.1007/s10708-020-10175-7

Nathaniel, S. P., Ahmed, Z., Shamansurova, Z., & Fakher, H. A. (2024). Linking clean energy consumption, globalization, and financial development to the ecological footprint in a developing country: Insights from the novel dynamic ARDL simulation techniques. *Heliyon*, *10*(5), e27095. https://doi.org/10.1016/j.heliyon.2024.e27095

Nautiyal, H., & Goel, V. (2021). Sustainability assessment: Metrics and methods. *Methods in Sustainability Science: Assessment, Prioritization, Improvement, Design and Optimization*, 27–46. https://doi.org/10.1016/B978-0-12-823987-2.00017-9

Omoke, P. C., Nwani, C., Effiong, E. L., Evbuomwan, O. O., & Emenekwe, C. C. (2020). The impact of financial development on carbon, non-carbon, and total ecological footprint in Nigeria: new evidence from asymmetric dynamic analysis. *Environmental Science and Pollution Research*, *27*(17), 21628–21646. https://doi.org/10.1007/s11356-020-08382-3

Ozturk, I., Farooq, S., Majeed, M. T., & Skare, M. (2023). An empirical investigation of financial development and ecological footprint in South Asia: Bridging the EKC and pollution haven hypotheses. *Geoscience Frontiers*, *xxxx*, 101588. https://doi.org/10.1016/j.gsf.2023.101588

Pata, U. K., Tiwari, A. K., & Erdogan, S. (2024). Technological innovation, globalization and ecological quality: A disaggregated ecological footprint approach for BRICS countries. Journal of Environmental Management, 370, 122518.

Pham, D. T. T., & Nguyen, H. T. (2024). Effects of trade openness on environmental quality: evidence from developing countries. *Journal of Applied Economics*, *27*(1). https://doi.org/10.1080/15140326.2024.2339610

Raihan, A., Muhtasim, D. A., Farhana, S., Pavel, M. I., Faruk, O., Rahman, M., & Mahmood, A. (2022). Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. *Energy and Climate Change*, *3*, 100080.

Ritu, R. K., & Kaur, A. (2024). Towards environmental sustainability: nexus of ecological footprint, human capital, economic growth and energy consumption in India. *Management of Environmental Quality: An International Journal*, *35*(1), 179–200. https://doi.org/10.1108/MEQ-06-2023-0172

Saqib, N., Usman, M., Ozturk, I., & Sharif, A. (2024). Harnessing the synergistic impacts of environmental innovations, financial development, green growth, and ecological footprint through the lens of SDGs policies for countries exhibiting high ecological footprints. Energy Policy, 184, 113863.

Shujah-ur-Rahman, Chen, S., Saud, S., Saleem, N., & Bari, M. W. (2019). Nexus between financial development, energy consumption, income level, and ecological footprint in CEE countries: do human capital and biocapacity matter? *Environmental Science and Pollution Research*, *26*(31), 31856–31872. https://doi.org/10.1007/s11356-019-06343-z

Uche, E., Das, N., Bera, P., & Cifuentes-Faura, J. (2023). Understanding the imperativeness of environmental-related technological innovations in the FDI–Environmental performance nexus. *Renewable energy*, *206*, 285-294.

Ullah, S., Ozturk, I., Majeed, M. T., & Ahmad, W. (2021). Do technological innovations have symmetric or asymmetric effects on environmental quality? Evidence from Pakistan. *Journal of cleaner production*, *316*, 128239.

Usman, M., Kousar, R., Yaseen, M. R., & Makhdum, M. S. A. (2020). An empirical nexus between economic growth, energy utilization, trade policy, and ecological footprint: a continent-wise comparison in upper-middle-income countries. *Environmental Science and Pollution Research*, *27*(31), 38995–39018. https://doi.org/10.1007/s11356-020-09772-3

Wackernagel, M., & Kitzes, J. (2008). Ecological Footprint. *Encyclopedia of Ecology, Five-Volume Set*, 1031–1037. https://doi.org/10.1016/B978-008045405-4.00620-0

Wang, X., & Luo, Y. (2020). Has technological innovation capability addressed environmental pollution from the dual perspective of FDI quantity and quality? Evidence from China. *Journal of cleaner production*, *258*, 120941.

Wang, C., & Guo, X. (2022). Spatio-temporal effect of provincial technological innovation on environmental pollution in China. *Frontiers in Public Health*, *10*, 1073920.

Warsame, A.A., 2023. Environmental pollution and life expectancy in Somalia: do renewable energy, urbanization, and economic growth matter?. *Environmental Science and Pollution Research*, *30*(51), pp.110528-110538.https://doi.org/10.1007/s11356-023-30114-6

World Bank Development Indicators. (2023). Washington, D.C.: The World Bank (producer and distributor). http://data.worldbank.org/data-catalog/world-development-indicators

Zambrano-monserrate, M. A., Alejandra, M., Orme, V., & Sanchez-loor, D. A. (2020). *Global Ecological Footprint and spatial dependence between countries*. *272*(July), 1–16. https://doi.org/10.1016/j.jenvman.2020.111069

Zeraibi, A., Balsalobre-lorente, D., Murshed, M., & Balsalobre-lorente, D. (2021). *The influences of renewable electricity generation , technological innovation , financial development , and economic growth on ecological footprints in ASEAN-5 countries*.

Zhang, C., Wang, Q., & Li, R. (2025). Revisiting the relationship between geopolitical risk and ecological footprint: A comprehensive analysis based on dual machine learning. *Journal of Environmental Management*, *374*, 124125.

Zhang, X., Song, X., Lu, J., & Liu, F. (2022). How financial development and digital trade affect ecological sustainability: The role of renewable energy using an advanced panel in G-7 Countries. *Renewable Energy*, *199*(May), 1005–1015. https://doi.org/10.1016/j.renene.2022.09.028

Zhou, Q., Shi, M., Huang, Q., & Shi, T. (2021). Do double-edged swords cut both ways? The role of technology innovation and resource consumption in environmental regulation and economic performance. *International Journal of Environmental Research and Public Health*, *18*(24), 13152.

Appendix A:Countries included in the analysis:

Angola, Botswana, Ethiopia, Ghana, the Gambia, Kenya, Malawi, Madagascar, Mauritius, Mozambique, Namibia, Nigeria, Rwanda, Sao Tome and principe, Seychelles, South Africa, Tanzania, Uganda, Zambia.