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Ecological footprint and income inequality in South Africa: a hidden dynamic?

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Abstract

Purpose – This study examines the complex relationship between income inequality and the ecological footprint in South Africa, emphasizing its implications for more inclusive environmental policies.

Design/methodology/approach – The result offers social, economic and environmental perspectives by employing both the autoregressive distributed lag model (ARDL) and the nonlinear autoregressive distributed lag (NARDL) models for data from 1980 to 2017.

Findings – The ARDL findings indicate that income inequality does not significantly influence the ecological footprint. However, while financial development negatively affects the ecological footprint, factors such as energy consumption, economic growth and trade openness positively influence it in both the short and long term. In contrast, the NARDL model reveals a hidden nexus in which reductions in income inequality significantly decrease the ecological footprint, highlighting the importance of decomposing variables into their + and – components to uncover hidden dynamics. These results highlight the potential oversight of critical relationships using traditional models and emphasize the value of disaggregated data to provide deeper insights into the interactions between economic variables and environmental outcomes. In addition, other findings from the NARDL model align with those obtained from the ARDL model, reinforcing the robustness of our analysis.

Originality/value – Unlike prior research, this study reveals the asymmetric impacts of income inequality on ecological outcomes, offering a fresh perspective on integrating economic disparities into sustainable development strategies.

Keywords Ecological footprint, Income inequality, South Africa, NARDL method

Paper type Research article

1. Introduction

According to the most recent data from the Global Footprint Network (2023), the global per capita ecological footprint (EF) will exceed the biocapacity in 2022, resulting in an ecological deficit of approximately 1 gha. Meaning that the world’s population exhibits consumption habits that surpass the rate at which renewable natural resources are provided, leading to an increase in EF and a decrease in self-renewal capacity, i.e. natural biocapacity. Thus, ecological restoration is paramount for establishing sustainable societies. Policymakers are searching for alternative policies aimed at alleviating ecological pressure. Despite the existence of emission reduction protocols within the framework of international agreements and collaborations (Widerberg and Pattberg, 2015), these efforts are often insufficient. Therefore, it is imperative to identify non-traditional determinants of EF (Omri *et al*., 2019). Given the complex and multifaceted nature of environmental challenges, it is essential to look beyond conventional economic factors. Thus, adopting a holistic approach that look beyond pure economic phenomena has the potential to play a pivotal role in achieving development goals through sustainable practices in business activities alongside facilitating ecological restoration (Zhu *et al*., 2024; Agyemang *et al*., 2025).

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Literature focusing on the fundamental determinants of environmental degradation (ED) has significantly advanced intellectual and academic knowledge related to the environment, contributing to a profound understanding of the subject. Within this framework, although the impact of economic gains on the environment has been extensively studied, the impact of income inequality (GINI) on the environment quality or ED has not received sufficient attention (Uzar, 2024). Understanding the nexus between GINI, societal well-being, and environmental sustainability is critical for developing holistic and effective environmental policies. This new perspective necessitates considering not only economic growth (GDP), but also social justice and political participation in solving environmental issues. The neoliberal transformation post-1980 has exacerbated GINI by dismantling previous social and economic gains (Stockhammer, 2011). This transformation has been characterized by the proliferation of free-market policies, reductions in public spending, and weakening of social safety nets. Among the significant factors contributing to GINI are the effects of privatization, deregulation, and globalization (Piketty, 2014). While income disparities between low- and high-income countries have narrowed, GINI within developed and developing countries has become increasingly pronounced (Makhlouf, 2023). These processes have widened the gap between the rich and the poor and exposed lower-income groups to greater ED. Consequently, understanding the complex relationship between GINI and ED is critical for both environmental and social justice.

Consequently, the purpose of this study is to investigate the impact of GINI on environmental quality, explicitly focusing on South Africa, where income distribution is highly unequal. Assessing the potential trade-offs between these objectives is essential to enhancing the effectiveness of sustainable development initiatives. This study aims to address the research gap by exploring the link between GINI and environmental quality, an area that remains underexplored in the context of asymmetric shocks. Understanding the linkages between reducing GINI and preserving environmental quality can offer a more holistic approach to designing environmental and economic policies. The key research questions addressed in this study include: 1) How does GINI affect environmental quality in South Africa? 2) Are there asymmetric effects between GINI and environmental quality? 3) What role do traditional economic determinants, such as GDP, energy consumption (ENE), financial development (FD), and trade openness (TRA), play in explaining environmental quality in South Africa? While most previous studies indicate that GINI assume a symmetric nexus with environmental variables (see Uzar, 2024; Andersson, 2024; Uzar and Eyuboglu, 2023; Kazemzadeh *et al.*, 2022), this work provides a novel contribution to the academic discourse by employing the Nonlinear Autoregressive Distributed Lag (NARDL) method, which accounts for asymmetric effects. Moreover, this is done by considering the unique case of South Africa context, where income inequality is extreme. While this study critically emphasizes the central importance of GINI, a factor of pivotal importance for South Africa, it does not overlook the traditional economic determinants of EF. By including these economic control variables, this study ensures a more comprehensive understanding of environmental quality factors and strengthens its contribution to the existing body of knowledge. In this context, the model includes GDP, ENE, FD, and TRA, which are the most frequently associated economic determinants of EF (Fan *et al.*, 2024; Dada *et al.*, 2023). Including these economic control variables in the model ensures a more comprehensive explanation of EF and avoids omitted variable bias.

The remainder of this paper is structured as follows. The next section presents a concise overview of the existing literary sources pertaining to the connection between the environment and its associated independent variables. The subsequent section delves into the specifics of the econometric models and the data collection process. The final two sections of the study comprise the empirical findings, along with conclusions and policy recommendations.

2. Theoretical justification

The theoretical literature suggests that the dynamics of income distribution can have opposing effects on environmental quality (Berthe and Elie, 2015; Grunewald *et al.*, 2017). There are two attempts to explain this concept, and the first, pioneered by Boyce (1994), was the Political Economy Framework (PEF). The idea is rooted in the 'power-weighted social decision rule' and suggests that the unequal distribution of economic and political power in society can lead to harmful environmental consequences (Boyce, 2007). It posits that a more equitable income distribution improves environmental quality by reducing power inequality among different segments of society. The connection between economic and political influence and national policymaking is evident in situations where wealthy groups use their power to push for environmentally harmful projects, even in countries with unequal income distribution (Uzar and Eyuboglu, 2023). In this context, the power asymmetry between the rich and poor facilitates the consideration of the interests of specific groups in the design of environmental policies. This approach argues that a deteriorating income distribution leads to worse environmental outcomes. On the other hand, modifications in income distribution may affect the purchasing choices of households with diverse income levels (Scruggs, 1998). With increasing and equitably distributed income, the demand for high-energy consumption and high-emission products has increased. Consequently, increases in ENE, natural resource use, and production can exacerbate ED.

Moreover, changes in consumption patterns are assessed for their environmental consequences through the Marginal Properties to Emit (MPE) (Uzar and Eyuboglu, 2019). In other words, shifts in household spending patterns may have an impact on MPE and consequently lead to environmental outcomes. The fundamental factors shaping consumption habits here are income level and distribution (Scruggs, 1998). The increase in GINI, with wealth shifting from higher to lower-income groups, intensifies ecological stress by promoting consumerism. This occurs because the rise in income among lower-income individuals results in heightened consumption patterns owing to their greater marginal propensity to consume, thereby enhancing the MPE (Kazemzadeh *et al.*, 2022; Jorgenson *et al.*, 2017). As the poor tend to have higher marginal consumption rates, any increase in income leads to greater environmental expenses compared with the affluent. It remains unclear whether there is a trade-off between income distribution and environmental quality. In other words, there is no consensus on the relationship between these two critical development goals, presenting a complex puzzle.

2.1 Empirical literature review and hypotheses

A notable portion of the literature has yielded results that support the first theoretical approach, namely, PEF. For instance, Çatık *et al.* (2024) examined 49 countries from 1995 to 2018 using the augmented mean group (AMG) and Common Correlated Effects Mean Group (CCEMG) and found that inequality increases EF. Andersson (2024) investigated the impact of income and wealth distribution on EF in four developed countries from 1962 to 2021. The findings suggest that the connection between GINI and the carbon footprint shifted from negative in the 1960s to positive in the late 1980s. Wang (2024) concluded that GINI may exert pressure on EF in over 150 countries, but this pressure is contingent upon the level of renewable energy. Gimba *et al.* (2023) examined the GINI–EF relationship in Africa (1995–2018), finding support for the PEF hypothesis. Uzar and Eyuboglu (2023) analyzed the impact of income dynamics on EF in the US, suggesting that inequality intensifies environmental pressure. Similarly, Sun *et al.* (2023) studied EF in developing countries (1990–2018) and concluded that higher inequality leads to increased EF. Khan *et al.* (2022) focus on 18 Asian countries over a short period from 2006 to 2017. These findings indicate that GINI harms environmental quality in Asia.

On the other hand, studies demonstrating the validity of MPE are also present in the earlier studies. For instance, Langnel *et al.* (2021) found that an increase in GINI between 1984 and 2016 led to a reduction in EF, thereby alleviating ecological pressure in ECOWAS countries. Similarly, Ehigiamusoe *et al.* (2022) reported that rising inequality negatively affects ED indicators, including EF, contributing to a decrease in environmental stress in developed nations. Dada *et al.* (2023) investigated the relationship between GINI and EF across 29 African countries over the period 2000–2017. They concluded that GINI reduced EF from the 70th percentile onwards. Altıntaş *et al.* (2023), in their study focusing on Turkey, found that while the years 2002–2005 support PEF, an increase in GINI reduces EF from 2006 to 2016. In addition to studies supporting these two approaches, studies that fail to find a significant relationship are also noteworthy. For example, Espoir *et al.* (2024) investigated the determinants of EF in 39 African countries during the period 1996 to 2018. These findings indicated that GINI did not have a strong impact on EF. Uzar (2024) examined trade-off between GINI and EF in E7 countries. While the coefficient is negative, supporting PEF, it is not significant.

Meanwhile, Idrees and Majeed (2022) investigated the asymmetric relationship between GINI and environment in Pakistan. The results supported PEF while confirming a nonlinear relationship between the two variables. Uzar and Eyuboglu (2024) is one of the rare studies in the literature examining the asymmetric relationship between GINI and the EF in Turkey. The work identified an asymmetric nexus between GINI and EF in Turkey, finding that an enhancement in inequality diminishes EF while a decrease in inequality increases it. As evident, studies testing the nexus between GINI and ecological pressure have proliferated in recent years. However, this study focuses on the asymmetric relationship between GINI and EF. In this context, the main hypothesis of the study can be stated as follows:

Main Hypothesis. In South Africa, the relationship between GINI and EF is asymmetric, with increases and decreases in GINI producing different effects on EF.

2.2 Contribution to literature

This study contributes to the literature on the nexus between GNI and environmental quality based on the selection of the primary independent variable, country, and methodology. Firstly, while the existing literature on ED primarily focuses on well-known traditional drivers, this study further explores non-traditional factors by utilizing a comprehensive EF measure. The second contribution of this study pertains to country selection. South Africa has one of the highest global GINI rates and the highest emitter of carbon dioxide in Africa (Hundenborn *et al.*, 2019; International Energy Agency, 2023). This makes South Africa an ideal case for examining the environmental impact of GINI. Despite South Africa's vast natural resources, the country has a broad economic and social spectrum (Masocha, 2019) and faces significant environmental challenges (Death, 2014). This context makes it more meaningful to analyze the environmental impacts of the GINI within its historical and political framework. The third contribution lies in methodological progress. While asymmetric relationships are often overlooked (Islam *et al.*, 2023), this study employs the ARDL and NARDL approaches to investigate the hidden asymmetric relationships between basic GINI and EF. Presenting the hidden asymmetric relationship between GINI and EF provides fresh evidence for the literature in this area, which has seen limited exploration.

3. Data and methodology

3.1 Data

The relationship between GINI and EF in South Africa is examined for the period 1980–2017. This timeframe was selected based on data availability, with GINI data ending in 2017 and FD data starting from 1980. In this analysis, GINI is the main independent variable, while EF per capita represents the dependent variable. To improve the model's explanatory capacity, additional variables such as FD, GDP per capita (constant 2015 US$), primary energy consumption, and trade openness (measured as the ratio of the sum of exports and imports to GDP) are incorporated. FD captures the level of financial sector development, which can influence environmental outcomes by affecting investment patterns and resource use (Saud *et al.*, 2020). GDP accounts for the scale impact of economic activity on the environment, providing insights into the relationship between income levels and ED (Çakmak and Acar, 2022). ENE reflects the overall ENE in the economy, which is a direct contributor to the EF (Uzar and Eyuboglu, 2024). TRA controls the impact of globalization and trade on environmental outcomes (Kongbuamai *et al.*, 2020).

All series are converted into logarithmic forms to address the potential issue of heteroscedasticity and ensure unbiased and efficient estimators. The dataset comprises six key variables. Ecological footprint (EF), measured as consumption per capita, is obtained from the Global Footprint Network database. Income inequality is represented by the GINI coefficient, sourced from the Standardized World Income Inequality Database (SWIID). Financial development (FD) is captured using the Financial Development Index provided by the International Monetary Fund (IMF). Energy consumption (ENE) refers to primary energy use and is retrieved from the Energy Institute. Economic growth is measured by GDP per capita (constant 2015 US$), and trade openness (TRA) is defined as the total value of goods and services traded as a percentage of GDP; both variables are sourced from the World Development Indicators (WDI) (2024).

3.2 Methodology

3.2.1 Pre-tests. This study applies the Augmented Dickey-Fuller (ADF) unit root test, developed by Dickey and Fuller (1981), to assess the presence of unit roots in the time series data. To account for potential structural breaks that may lead to misleading inferences, the Fourier Augmented Dickey-Fuller (FADF) test, proposed by Christopoulos and León-Ledesma (2010), is also employed. This test incorporates trigonometric terms to flexibly capture smooth structural shifts in the data. Furthermore, when structural breaks are identified, the BDS test for nonlinearity, introduced by Broock *et al.* (1996), is utilized to detect possible nonlinear dependencies within the time series. This test is helpful when the information does not adhere to a consistent distribution pattern, as it mandates a flexible asymmetric structure to effectively capture any changes in form and nonlinear connections between the factors (Rahman and Ahmad, 2019).

3.2.2 Linear and non-linear ARDL approaches. The following equation represents the long-term linkages among the series:

$$\mathrm{lEF_t} = f\,(\mathrm{lGINI_t}, \mathrm{lFD_t}, \mathrm{lENE_{t,}}\ \mathrm{lGDP_t}, \mathrm{lTRA_{t,}}) \tag{1}$$

The ARDL approach, introduced by Pesaran *et al.* (2001), is widely employed due to its capacity to simultaneously estimate both short-run dynamics and long-run equilibrium relationships. A key advantage of the ARDL framework lies in its flexibility with respect to the order of integration of the variables, as it accommodates a mix of I(0) and I(1) series. However, it is unsuitable for variables integrated at the second order, I(2). The general specification of the ARDL model is presented as follows:

$$\begin{aligned}\Delta \mathrm{EF}_t = \alpha_0 &+ \sum_{t=1}^{m} \mathrm{b}_i \Delta \mathrm{EF}_{t-i} + \sum_{t=1}^{n} \mathrm{c}_i \Delta GINI_{t-i} + \sum_{t=1}^{O} \mathrm{d}_i \Delta FD_{t-i} + \sum_{t=1}^{p} \mathrm{e}_i \Delta ENE_{t-i} \\ &+ \sum_{t=1}^{r} \mathrm{f}_i \Delta GDP_{t-i} + \sum_{t=1}^{r} \mathrm{g}_i \Delta \mathrm{TRA}_{t-1} + \lambda_1 \mathrm{EF}_{t-1} + \lambda_2 \mathrm{GINI}_{t-1} + \lambda_3 \mathrm{FD}_{t-1} \\ &+ \lambda_4 \mathrm{ENE}_{t-1} + \lambda_5 \mathrm{GDP}_{t-1} + \lambda_6 \mathrm{TRA}_{t-1} + \varepsilon \mathrm{i}\end{aligned} \tag{2}$$

In this specification, Δ denotes the first-difference operator, while the coefficients $\mathrm{b_i}$, $\mathrm{c_i}$, $\mathrm{d_i}$, $\mathrm{e_i}$, $\mathrm{f_i}$, and $\mathrm{g_i}$ capture the short-run dynamics of the model. The parameters associated with the level variables reflect the long-run equilibrium. To assess the existence of cointegration among the variables, the computed F-statistic is evaluated against the critical bounds suggested by Pesaran *et al.* (2001). Given the relatively small sample size in this study (30–80 observations), the critical values proposed by Narayan (2005) are employed, as they are more appropriate for small samples. Upon confirmation of a cointegrating nexus, the short-run interactions among the variables are examined through the following error correction model:

$$\Delta EF_t = \partial_0 + \sum_{i=1}^{m} c_i \Delta EF_{t-1} + \sum_{i=1}^{n} d_i \Delta GINI_{t-1} + \sum_{i=1}^{o} e_i \Delta FD_{t-1} + \sum_{i=1}^{p} f_i \Delta ENE_{t-1} + \sum_{i=1}^{r} g_i \Delta GDP_{t-1} + \sum_{i=1}^{s} h_i TRA_{t-1} + \gamma ECT_{t-1} + \mu \quad (3)$$

In this context, μ_t represents the residual, γ denotes the coefficient, and the *ECT* term signifies convergence to its long-run equilibrium

While the ARDL approach is commonly employed to determine long-term connections between variables, it fails to account for potential nonlinear dynamics resulting from its linear structure. To address this issue, Shin *et al*. (2014) suggested the NARDL method. The NARDL method distinguishes itself from other time series techniques by breaking down explanatory variables into + and − partial sums, thus enabling the examination of nonlinear trends. One notable strength of NARDL is its robustness against residual correlation, which reduces the risk of bias from omitted lag terms in the model's outcomes. NARDL methodology has several advantages over ARDL. First, it enables us to analyze asymmetries, thereby disregarding the assumption of linearity. Second, NARDL examines the potential for asymmetric effects of the explanatory variable(s) on the dependent variable in the long and short term. Third, NARDL also enables the capture of cointegration within a single equation framework, in contrast to the linear ARDL model. This method enables the examination of unique reactions to the + and − shocks originating from the regressors. NARDL contends that a time series is the sum of its + and − fluctuations from the first observation and beyond. Specifically,

$$x_t = x_o + x_t^+ + x_t^- \quad (4)$$

The representation of the partial sums of + and − changes of variables can be conveyed using + and −signs, respectively.

$$x_t^+ = \sum_{j=1}^{t} \Delta x_j^+ = \sum_{j=1}^{t} \max\left(\Delta x_j, 0\right)$$

$$x_t^- = \sum_{j=1}^{t} \Delta x_j^- = \sum_{j=1}^{t} \min\left(\Delta xj, 0\right) \quad (5)$$

The asymmetric framework allows for the expression of the relationship between the two variables over an extended period using the following equation:

$$y_t = \beta_o + \beta^+ x_t^+ + \beta x_t^- + \varepsilon_t \quad (6)$$

To summarize, the NARDL model, which captures both short- and long-run asymmetries, is derived from Equation (7) and is expressed accordingly.

$$\Delta IEF_t = \beta_0 + \beta_1 IEF_{t-1} + \beta_2^+ lGINI_{t-1}^+ + \beta_3^- lGINI_{t-1}^- + \beta_4 IFD_{t-1} + \beta_5 ENE_{t-1} + \beta_6 lGDP_{t-1} + \beta_7 lTRA_{t-1} + \sum_{i=1}^{k} \omega i \Delta IEF_{t-i} + \sum_{i=1}^{m} \sigma_{2i}{}^{+} \Delta GINI_{t-i}^+ + \sum_{i=1}^{n} \sigma_{3i}{}^{-} \Delta GINI_{t-i}^- + \sum_{i=1}^{o} \sigma_{4i} \Delta IFD_{t-i} + \sum_{i=1}^{u} \lambda_{5i} \Delta ENE_{t-i} + \sum_{i=1}^{v} \mu_{6i} \Delta GDP_{t-i} + \sum_{i=1}^{v} \vartheta_{7i} \Delta TRA_{t-i} \quad (7)$$

In this context, Δ signifies the differenced series for periods k, m, n, p, o, u, v, and y, respectively, represent their corresponding lag orders. β_1, β_2^+, β_3^-, β_4, β_5, β_6, β_7 define the coefficients of the long-run changes of regressors on EF. While $\sum_{i=1}^{m}\sigma 2_i^{+}\Delta GINI_{t-i}^{+}$ and $\sum_{i=1}^{n}\sigma 3_i^{-}\Delta GINI_{t-i}^{-}$, and denote the short-run + and − effects of GINI, respectively. $\sum_{i=1}^{o}\sigma 4_i\Delta IFD_{t-i}$, $\sum_{i=1}^{u}\lambda 5_i\Delta ENE_{t-i}$, $\sum_{i=1}^{v}\mu 6_i\Delta GDP_{t-i}$, $\sum_{i=1}^{v}\vartheta 7_i\Delta TRA_{t-i}$ indicate the short-run effects of FD, ENE, GDP, and TRA on EF.

The development of NARDL encompasses a sequence of pivotal stages that demand strict adherence. An essential preliminary step in time series analysis is to ensure that none of the variables are integrated beyond the first order, I(1), as the presence of I(2) series may lead to invalid or misleading inferences. Subsequently, this refined model facilitates an exhaustive exploration of the enduring relationships among the series under the designated hypotheses. The identification of a sustained connection between series can be scrutinized through the ensuing hypotheses. H_0: $\beta_1 = \beta_2^{+} = \beta_3^{-} = \beta_4 = \beta_5 = \beta_6 = \beta_7$ and the alternative hypothesis, H_1: $\beta_1 \neq \beta_2^{+} \neq \beta_3^{-} \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq \beta_7$. Pesaran *et al*. (2001) established critical values for the F statistic. If the calculated F-statistic exceeds the upper bound of the critical values, the null hypothesis of no long-run relationship is rejected. Once cointegration is confirmed, the model can proceed to estimate the long-run parameters.

Following the establishment of long-run relationships among the variables, the study aims to examine the asymmetric effects of GINI and the symmetric influences of FD, ENE, GDP, and TRA on EF. To investigate asymmetries in both the short and long-run, the Wald test is employed. To ensure the robustness and reliability of the empirical findings, a series of diagnostic tests are conducted, including checks for autocorrelation, heteroscedasticity, and the normality of residuals, the latter assessed using the Jarque-Bera test.

4. Results

4.1 Preliminary results

Table 1 provides descriptive statistics for the series. The means of EF, GINI, FD, ENE, GDP, and TRA are 1.214, 4.115, −0.993, 1.414, 8.556, and 3.855, respectively. Jarque-Bera statistics suggest that the distribution is not significantly different from the normal distribution for all variables. In the first phase of the analysis, it was crucial to perform unit root testing on all the series. We employed an ADF test to evaluate the stationary nature of the series. Outcomes of the test are denoted in Table 2. According to our analysis, the series is not stationary in its levels. After taking the first difference, all series exhibit the integration of I(1).

When conducting traditional unit root tests, such as the ADF test, it is important to consider the possibility of structural breaks within the series. Failure to account for these breaks can lead to misleading results. To remove this issue, the FADF test is applied, which is detailed in Table 3. Fourier-based unit root tests offer a significant advantage by identifying structural breaks endogenously, without the need to specify their number or timing in advance. As presented in Table 3, the outcomes of the FADF test confirm that all variables are stationary at the first differences.

Table 1. The descriptive statistics

	lEF	lGINI	lFD	lENE	lGDP	lTRA
Mean	1.214	4.115	−0.993	1.414	8.556	3.855
Maximum	1.392	4.151	−0.533	1.673	8.742	4.189
Minimum	1.045	4.083	−1.425	0.844	8.359	3.536
Std. Deviation	0.090	0.023	0.295	0.213	0.128	0.161
Skewness	0.047	0.173	0.018	−0.654	0.119	−0.154
Kurtosis	2.085	1.477	1.446	2.806	1.642	2.356
Jarque-Bera	1.339	3.865	3.825	2.769	3.010	0.806
Observations	38	38	38	38	38	38

Source(s): Authors' own work

Table 2. ADF test

Series	Intercept	Trend and intercept
lEF	−1.895	−2.404
lGINI	−1.789	−1.971
lFD	−0.341	−1.658
lENE	−1.544	−2.412
lGDP	−0.656	−2.737
lTRA	−1.792	−3.025
ΔlEF	−6.730***	−6.787***
ΔlGINI	−2.985**	−3.229**
ΔlFD	−5.141***	−5.065***
ΔlENE	−7.064***	−7.467***
ΔlGDP	−3.361**	−4.071**
ΔlTRA	−5.548***	−5.541***

Note(s): ***, ** denote significance at the 1% and 5%

Source(s): Authors' own work

Table 3. FADF test

Series	minSSR	$\hat{k}$	FADF	F(k)	Result
lEF	0.082	1	−3.047(0)		nonstationary
lGINI	0.004	1	−2.016(1)		nonstationary
lFD	0.975	1	−1.475(2)		nonstationary
lENE	0.773	1	−3.136(0)		nonstationary
lGDP	0.022	1	−2.745(1)		nonstationary
lTRA	0.234	1	−3.337(0)		nonstationary
ΔlEF	0.092	1	−7.764(0)***	1.378	stationary
ΔlGINI	0.001	1	−3.886(0)**	11.78***	stationary
ΔlFD	0.061	4	−6.655(0)***	6.312**	stationary
ΔlENE	0.058	2	−7.678(0)***	1.850	stationary
ΔlGDP	0.013	1	−5.952(0)***	14.89***	stationary
ΔlTRA	0.253	4	−6.005(0)***	1.946	stationary

Note(s): ***, ** denote statistical significance at the 1% and 5% levels, respectively. Values in parentheses indicate the selected optimal lag lengths

Source(s): Authors' own work

Upon confirming that none of the variables were integrated of order two, I(2), the ARDL Bounds testing approach was employed. As shown in Table 4, the results provide strong evidence of a long-run relationship among the variables. Specifically, the calculated F-statistic exceeds the 1% critical value, thereby leading to the rejection of the null hypothesis of no cointegration. This outcome affirms the presence of a stable long-term nexus among the series. Furthermore, diagnostic checks indicate that the model is well-specified, with no evidence of autocorrelation, heteroscedasticity, or non-normality in the residuals.

4.2 The ARDL result

Following the establishment of cointegration, the long-term impacts of GINI, FD, ENE, GDP, and TRA on EF are assessed. The results, as shown in Table 5, indicate that GINI does not have a statistically significant symmetric effect on EF in South Africa. The lack of a significant symmetric relationship between GINI and EF in the long-run can be attributed to the complex

Table 4. Bound test

Model	Optimal lag length	F-statistic
$lEF_t = lGINI_t + lFD_t + lENE_t + lGDP_t + lTRA_t$	(1,3,3,0,0,0)	6.941***
LM(1) = 1.393		ARCH(1) = 1.149
RESET(1) = 0.221		NORMALITY = 1.664
CUSUM= Stable		CUSUMSQ= Stable

Note(s): *** shows significance at the 0.01

Source(s): Authors' own work

Table 5. Long-run outcomes

	Coefficient	Std. error	t-stat	p-value
lGINI	−0.006	0.032	−0.191	0.849
lFD	−0.328	0.118	−2.775	0.011
lENE	0.404	0.230	1.754	0.093
lGDP	0.566	0.175	3.230	0.003
lTRA	0.276	0.111	2.473	0.021

Source(s): Authors' own work

and non-linear factors influencing environmental outcomes. In this context, GINI may not exert a consistent, uniform effect on EF, as changes in inequality may lead to varying impacts depending on other socio-economic and political conditions. This suggests that the nexus among GINI and EF is more nuanced, requiring an exploration of asymmetric effects rather than assuming symmetry.

The results show that FD has a negative and statistically significant effect on EF. The negative and significant influence of FD on EF suggests that, as the financial sector grows and matures, it potentially facilitates investments in environmentally friendly technologies and sustainable practices. This could be due to better access to funding for green projects, improved financial mechanisms that incentivize lower carbon emissions, and enhanced regulatory frameworks that promote environmental sustainability. Furthermore, ENE, GDP, and TRA exhibit a statistically significant positive relationship with EF in the long-run, suggesting that increases in ENE, GDP, and TRA contribute to a larger EF. The positive association between ENE and EF implies that greater ENE-particularly from non-renewable sources-intensifies ED due to higher emissions of greenhouse gases and pollutants. Similarly, GDP is positively linked to EF, indicating that economic expansion, through increased industrial production, manufacturing, and consumption, leads to greater resource depletion and waste generation. This result highlights the inherent tension between GDP and environmental sustainability. Therefore, the adoption of sustainable development approaches, such as green growth strategies, is crucial to ensuring that economic advancement does not come at the expense of environmental integrity. The positive impact of the TRA on EF suggests that increased trade activities contribute to the ED. This can be attributed to several factors, including the transportation of goods (which often relies on fossil fuels), the potential for trade to encourage environmentally harmful practices in pursuit of competitive advantage, and the increased production demands that accompany higher trade volumes. This emphasizes the need to implement sustainable trade practices and policies to reduce the environmental impact of the TRA. As presented in Table 6, the error correction term (−0.776) signifies that deviations in EF from its long-run equilibrium are corrected at an annual

Table 6. Error correction model

Variables	Coefficient	Standard error	*t*-statistic	*p*-value
c	−4.069	0.567	−7.165	0.000
ΔlGINI	0.018	0.053	0.343	0.734
ΔlGINI(−1)	0.015	0.058	0.268	0.791
ΔlGINI(−2)	0.126	0.050	2.489	0.020
ΔlFD	−0.209	0.104	−2.000	0.058
ΔlFD (−1)	−0.109	0.099	−1.100	0.282
ΔlFD (−2)	−0.233	0.101	−2.314	0.030
ECM(−1)	−0.776	0.108	−7.149	0.000

Source(s): Authors' own work

adjustment speed of 77.6%, indicating a relatively rapid convergence toward equilibrium in response to changes in GINI, FD, ENE, GDP, and TRA in South Africa.

4.3 The NARDL result

The non-linearity was assessed using the BDS test developed by Broock *et al*. (1996). The results, presented in Table 7, test results revealed that non-linearity occurs in all the series.

Consequently, we apply the NARDL model to account for these nonlinearities and better reveal the asymmetric nexus among the series. Following the identification of structural breaks and nonlinearity within the dataset, the NARDL model was employed. Optimal lag lengths were determined using the Akaike Information Criterion (AIC), ensuring the most appropriate model specification. The results of the NARDL model are illustrated in Table 8. The F-statistic exceeds the upper critical value, indicating cointegration between the series. The coefficient values are listed in Table 8. Specifically, the GINI coefficients for + and − shocks are −0.056 and 0.284, respectively. $GINI^{-}$ is statistically significant at the 1% level, indicating that a 1% decrease in GINI is associated with a 0.284% decrease in EF. In addition, the W_{LR} is significant for GINI. In South Africa, when testing the symmetric ARDL model, we found no significant effect of GINI on EF. However, after decomposing GINI into its + and − components, we discovered that diminishes in GINI significantly contribute to a reduction in the EF. Traditional approaches, such as symmetric models, may fail to capture the asymmetric effects of income distribution on environmental outcomes. By disaggregating GINI into its + and − components, hidden patterns can be unveiled, and the true drivers of environmental changes can be uncovered.

This study demonstrated a significant relationship between FD and EF, as an increase in FD was associated with a decrease in EF of 0.195. Moreover, higher FD levels contribute to

Table 7. BDS test

Series	D2	D3	D4	D5	D6
lEF	0.097***	0.170***	0.208***	0.214***	0.208***
lGINI	0.192***	0.318***	0.396***	0.442***	0.466***
lFD	0.180***	0.300***	0.379***	0.428****	0.465***
lENE	0.181***	0.313***	0.414***	0.480***	0.528***
lGDP	0.157***	0.253***	0.304***	0.319***	0.312***
lTRA	0.117***	0.168***	0.179***	0.168***	0.148***

Note(s): *** denotes significance at the 1% level. where D represents the dimension

Source(s): Authors' own work

Table 8. NARDL (2, 0, 1, 2, 1, 2) model

Series	Coefficient	Std. error	*t*-stat	*p*-value
Long-term				
lGINI$^+$	−0.056	0.065	−0.86	0.396
lGINI$^-$	0.284	0.056	5.047	0.000
lFD	−0.195	0.069	−2.813	0.009
lENE	0.447	0.106	4.209	0.000
lGDP	0.677	0.125	5.438	0.000
lTRA	0.292	0.076	3.856	0.001
Asymmetries	Value			*p*-value
W_{LR} (GINI)	7.471			0.013
*F statistics = 7.119****				
Short-term				
ΔlEF(−1)	0.239	0.123	1.946	0.063
ΔlFD	−0.218	0.105	−2.076	0.042
ΔlENE	0.295	0.098	3.005	0.006
ΔlENE(−1)	0.085	0.106	0.802	0.430
ΔlGDP	0.640	0.178	3.590	0.001
ΔlTRA	0.188	0.050	3.749	0.001
ΔlTRA(−1)	0.199	0.061	3.243	0.003
ECT(−1)	−0.634	0.085	−7.458	0.000
Adjusted R^2	0.898			
LM	1.802			
ARCH	0.626			
Durbin-Watson stat	2.008			
Jarque-Bera	1.006			
CUSUM	Stable			
CUSUMSQ	Stable			

Note(s): *** indicates statistical significance at the 1%. The F-statistic reflects the results of the bounds test. W_{LR} is equivalent to the Wald test, which evaluates the null hypothesis of long-term asymmetry for the GINI variable

Source(s): Authors' own work

improved environmental management practices. In addition, ENE, GDP, and TRA have a positive impact on EF, implying that a 1% increase in ENE, GDP, and TRA would lead to a 0.447%, 0.677%, and 0.292% increase in EF, respectively in the long-term. Similar short- and long-term findings have been observed. Improvements in FD have a negative and statistically significant impact on EF. ENE, GDP, and TRA have positive and statistically significant effects on EF, suggesting that increased energy use, GDP, and trade activities lead to higher EF in the short term. The error correction term was negative and significant, indicating a strong adjustment mechanism. The adjusted R2 for our model is 0.898, thus indicating that the model is free from omitted variable bias. Table 8 shows the results of the diagnostic tests. The model presents no serial correlation, misspecification, or heteroskedasticity, and the residuals are normally distributed.

5. Discussion of findings

This section provides a comprehensive discussion of the results for South Africa. The findings of the ARDL indicate that the effect of GINI on EF was insignificant. As explained in the findings section, this lack of symmetry could be attributed to the non-linear nature of the relationship between income inequality and environmental outcomes, where increases and decreases in GINI are likely to exert differing effects on EF. To explore this potential hidden relationship, the analysis can be extended by using the NARDL approach. The NARDL method allows for the examination of asymmetric effects by decomposing the GINI into its + and − components and assessing their impacts on the EF. This more nuanced analysis can reveal whether changes in GINI, either increasing or decreasing, have differential effects on environmental outcomes. Preliminary NARDL outcomes show that, while the + component of the GINI does not have a statistically significant effect on EF, the negative component does. Specifically, a decrease in GINI, representing a reduction in income inequality, significantly reduces EF. This suggests that improvements in the income distribution dynamics can lead to meaningful environmental benefits. Given these insights, the NARDL approach provides a sophisticated framework for understanding the complex interactions between the GINI and environmental sustainability. By identifying and analyzing these asymmetric relationships, policymakers can develop targeted strategies that address both economic and environmental objectives in South Africa. This finding indicates a supportive relationship between income distribution and environmental quality in South Africa during the study period, aligning with the PEF approach. In this context, the results of this study are consistent with the findings of Andersson (2024) and Çatık *et al*. (2024) for panel countries and Uzar and Eyuboglu (2023) for the US. Additionally, the evidence provided by Gimba *et al*. (2023) and Ekeocha (2021), supporting the PEF for the African continent, underscores the significance of the results for South Africa in reflecting broader African dynamics.

Furthermore, Idrees and Majeed (2022) identified an asymmetric relationship between the GINI and EF in Pakistan, supporting the PEF. Therefore, the finding related to the negative component of GINI in South Africa is highly consistent with these studies. This alignment with the existing literature reinforces the robustness of the conclusion that improving income distribution can lead to significant environmental benefits in South Africa, further validating the relevance of the PEF approach in diverse geographical and socio-economic contexts. The reduction of EF through GINI in South Africa is plausible and can be justified in several ways. First, South Africa’s current level of inequality is exceedingly high. The stark income disparity among groups inevitably affects the distribution of societal power, concentrating it within a smaller elite segment. In this context, reducing GINI can alter the economic and political power dynamics within society. As noted by Wolde-Rufael and Idowu (2017), improvements in income distribution can diminish the power of wealthy minorities and weaken their monopolistic control over resources. This shift would enhance the participation of a broader segment of the population in the decision-making processes, ensuring that environmental policies are developed with the general interests of society in mind. Moreover, Torras and Boyce (1998) argue that powerful and affluent minorities, often through large corporations, are more likely to engage in environmentally detrimental activities. Reducing GINI can lead to stricter regulation and oversight of such activities. Uzar and Eyuboglu (2023) also emphasize that the equitable distribution of income and power enables institutions to function more effectively. Increased societal scrutiny and transparency can help to curb environmentally harmful practices (Zhou *et al*., 2024). This, in turn, fosters greater public participation in democratic and political processes, strengthening societal resistance against large-scale projects that negatively affect the environment, and increasing demands for environmental protection. In this framework, the improvement in income distribution in South Africa by reducing power asymmetry can indeed be a compelling explanation for stronger environmental protection. The broader participation of the populace in environmental governance and enhanced accountability of powerful entities can lead to more sustainable environmental outcomes.

Second, the reduction of GINI not only facilitates a more equitable distribution of economic resources but also contributes to the spread of environmental awareness and eco-friendly behaviors. Fairer income distribution enhances access to education and healthcare services, thereby increasing individuals’ sensitivity to environmental issues. When economic concerns are alleviated and environmental awareness heightened, individuals are more likely to support societal efforts against environmentally harmful economic activities. Gimba *et al*. (2023) argue that the increase in environmental consciousness, resulting from reduced GINI, can be a significant catalyst in reducing the EF across the African continent. Moreover, in societies where people are healthier, better educated, and more environmentally conscious, the adoption of sustainable economic models becomes easier. Studies, such as those by Kazemzadeh *et al.* (2022), Khan *et al.* (2022), and Uzar and Eyuboglu (2019) emphasize that broader societal segments demand economic growth that aligns with environmental sustainability. This societal pressure can lead to the development of more effective policies aimed at conserving natural resources and preventing ED. In this context, improving the income distribution in South Africa can significantly enhance public engagement in environmental governance and foster greater accountability among powerful entities. The resulting societal demand for sustainability can drive the implementation of policies that not only address GDP but also ensure environmental preservation, thereby supporting the broader goals of sustainable development.

Finally, the reduction in GINI in South Africa can foster social solidarity and enhance collective action awareness. Islam (2015) and Laurent (2015) highlight that reducing GINI can bolster social cohesion and strengthen collective environmental movements. As inequality decreases in South Africa, cooperation among different segments of society may increase, leading to the development of more effective policies and practices for environmental sustainability. Uzar (2024), in his study of seven developing countries, noted that the solidarity and collective action consciousness emerging from reduced GINI allows for more effective implementation of environmental policies in developing nations. Thus, reducing inequality and creating a more equitable society in South Africa can increase support for environmental regulation and sustainability policies. This enhanced societal backing can contribute significantly to reducing EF. By promoting social solidarity, the reduction of GINI can facilitate a united societal effort towards environmental goals. This collective approach can drive the adoption of sustainable practices and ensure that environmental policies are implemented more efficiently, ultimately contributing to the overall reduction in EF.

The environmental implications of FD are as multifaceted as those related to income distribution. FD can drive GDP by alleviating resource constraints, as highlighted by Greenwood *et al.* (2013). However, this growth often comes at an environmental cost, as the associated economic activities typically depend on energy and natural resource consumption. This reliance can lead to adverse outcomes such as increased greenhouse gas emissions, deforestation, excessive water resource exploitation, and intensified mining activities, thereby exacerbating ecological pressures (Rjoub *et al.*, 2021). Conversely, FD also has the potential to mitigate environmental challenges. One significant pathway is through the promotion of green finance. By channeling investments into sustainable projects, FD can support initiatives that reduce environmental harm while delivering social benefits (Cao *et al.*, 2022; Hasan and Du, 2023). This includes fostering the growth of green financing sectors and encouraging sustainable investment practices. In the context of globalization, the development of financial markets in South Africa has become increasingly vital for safeguarding environmental quality.

In the ARDL and NARDL analyses, the impact of FD on EF is negative and significant. This implies that in South Africa, FD can finance green initiatives and environmental technologies, thereby reducing environmental pressure. These findings align well with the study by Khoza and Biyase (2024), which also indicates that FD enhancement improves environmental quality in South Africa. However, this result contrasts with the results of Godil *et al.* (2020), who reported that an increase in FD raised the EF in Turkey. This discrepancy can be attributed to differing financial and environmental dynamics in different countries. In summary, the positive impact of FD on environmental quality in South Africa suggests that FD, when aligned with sustainable investment and green financing, can play a crucial role in improving environmental quality. This underscores the importance of promoting financial policies to support sustainable development and environmental protection. Khoza and Biyase (2024) also found that increases in FD improve environmental quality, and this study reaches a similar conclusion, indicating the positive effects of green finance in South Africa. Several key factors may explain why FD reduces the EF in South Africa. First, as emphasized by Cao *et al.*

(2022), FD can increase investment in environmentally friendly technologies and sustainable energy sources, thereby reducing reliance on fossil fuels and lowering carbon emissions. Second, as Hasan and Du (2023) explain, diversification of green investment opportunities is critical. The development of financial institutions and markets can promote investment strategies that consider environmental risks and sustainability factors, leading to the adoption of greener and more sustainable business models. With a population of nearly 60 million, South Africa has significant potential for adopting such sustainable business models. Furthermore, FD can facilitate compliance with environmental regulations and financing green projects, supporting both companies and individuals in adopting environmentally conscious practices. By improving access to capital for sustainable investments and encouraging the incorporation of environmental considerations into financial decision-making, FD can play a crucial role in promoting environmental sustainability. In conclusion, the findings from Khoza and Biyase (2024), alongside the results of this study, highlight the importance of green finance in enhancing environmental quality in South Africa. FD not only supports the reduction of the EF but also promotes broader adoption of sustainable practices and technologies, contributing to the overall goal of sustainable development.

Finally, it is evident that the key economic factors included in the model, namely, GDP, ENE, and TRA, are the most significant determinants of ecological pressure in South Africa. Although these factors were examined without being decomposed into their components, findings from both the ARDL and NARDL analyses indicate that all three variables positively and significantly affect EF. Thus, the current economic structure and growth model are associated with increased environmental pressure in South Africa. As emphasized by Nathaniel (2021) and Nathaniel *et al.* (2021), rapid urbanization and reliance on fossil fuel-based ENE in South Africa contribute to the increase in both growth and ENE, consequently elevating EF. These findings are consistent with the conclusions of previous studies. Undoubtedly, as Twum *et al.* (2024) pointed out, the transition to renewable resources plays a crucial role in reducing EF. Although there have been some developments in renewable energy in recent years, data indicates that growth in South Africa still relies heavily on traditional energy sources, as indicated by the Energy Institute (2023).

Furthermore, the TRA in South Africa appears to affect EF through scale effects rather than composition or technique effects. This result aligns with the findings of Aydin and Turan (2020), who concluded that the TRA is a factor contributing to increased EF in South Africa. TRA may lead to higher fossil fuel consumption in production and transportation processes. Additionally, it can incentivize the overexploitation of natural resources, adversely affecting biological diversity and ecosystems. An increase in foreign investments and trade may relax environmental regulations and facilitate the expansion of industries with detrimental environmental impacts. Consequently, the TRA has the potential to exert significant pressure on the EF in South Africa.

6. Conclusion

Most studies examining the drivers of ED have traditionally focused on well-known economic factors. While these studies delve into the effects of GDP and ENE on the environment, they often overlook a critical element that lies at the intersection of economic, social, and political issues: GINI. Limited research that focuses on GINI typically relies on symmetric relationship assumptions, providing only a superficial examination of its environmental consequences and disregarding asymmetric effects. This gap in the understanding of the potential asymmetric impacts of GINI on the environment has led to a significant deficiency in the literature. The lack of evidence on how injustices in income distribution may impact ED in different ways is particularly concerning, creating a notable gap in the literature.

Initially, the symmetric relationship between variables was explored using ARDL. The results indicate that GDP, ENE, and TRA have positive and significant impacts on EF. Consequently, GDP, ENE, and TRA appear to be the strongest factors contributing to the increased ecological pressure in South Africa. In contrast, FD is identified as a negative and significant factor that reduces ecological pressure. However, the GINI did not have a significant impact on EF. This suggests that while traditional economic factors, such as GDP, ENE, and TRA, contribute to increased ecological pressure, FD acts as a mitigating factor. The findings underscore the importance of considering the GINI alongside these traditional economic determinants when examining environmental sustainability in South Africa.

Following the identification of symmetric relationships, the NARDL approach was employed to examine the influence of both the + and − components of the GINI on EF. The + component of the GINI was found to be statistically insignificant, whereas the negative component exhibited a statistically significant effect on EF. This indicates that a decrease in GINI reduces EF, thus enhancing environmental quality. In other words, findings regarding the negative components of GINI support PEF. This emphasizes the significance of utilizing disaggregated data to unveil the underlying dynamics between GINI and environmental sustainability. By employing this methodology, our objective was to offer a more precise understanding of how alterations in income distribution can impact environmental outcomes, thus contributing to enhanced policy formulation. While the overall GINI may not directly influence EF, the mitigation of its adverse components demonstrates a substantial correlation with a reduction in environmental impact. This underscores the crucial necessity of analyzing disaggregated data to comprehend the intricate linkages between income distribution and environmental sustainability.

Like the ARDL results, the NARDL results indicated that an increase in FD significantly reduced EF, thereby improving environmental quality. Consequently, a reduction in financial constraints and diversification of financial instruments may raise opportunities for green financing. Furthermore, positive and significant effects of GDP, ENE, and TRA on EF are observed. The NARDL findings for the three control variables indicate that these factors are the primary suspects of ED, confirming the results obtained from ARDL.

6.1 Policy recommendations and practical implications

The findings of this study provide significant insights into the policy implications. First, evidence indicating that a reduction in GINI improves environmental quality presents a win-win opportunity for South Africa. In this regard, South African policymakers can simultaneously address the critical issue of GINI while concurrently reducing ecological pressure, thus achieving two important development goals. First, comprehensive social and economic reforms should be implemented to make income distribution more equitable. Undoubtedly, reducing inequality is a long-term endeavor that requires steadfast policies. In addition to reform efforts, policymakers can focus on micro-level categories with the potential to reduce both inequality and ED. For example, the implementation of green workforce programs can provide employment opportunities for low-income individuals in sectors such as recycling and sustainable agriculture. Organizing educational and awareness campaigns to increase environmental consciousness in low-income areas can be highly effective. This would raise awareness about energy conservation, water management, and recycling while fostering a sense of social responsibility and justice. High-energy-efficiency and sustainable housing projects can be developed for low-income families, thereby reducing energy and water consumption. Moreover, tax incentives and financial support can be provided to facilitate access to eco-friendly products and services among low-income individuals. Supporting community gardens and urban farming projects in low-income areas of cities can increase local food production and reduce carbon footprints.

Considering the positive impact of FD, policymakers can implement various measures to promote green finance. For instance, tax incentives or exemptions can be provided to encourage investments in green projects. Additionally, incentivizing regulations can be established to facilitate the issuance of green bonds and financial products. Banks and financial institutions can be incentivized to provide loans for green projects and support green investments. Thus, the development of green finance can contribute to providing necessary funding for environmental projects and promoting sustainable development. Finally, increasing renewable ENE in South Africa and considering the environmental costs of the GDP process are crucial. This is because ENE and GDP are major drivers of environmental pressure, and their impact on the environment should be reduced.

6.2 Limitations and future research directions

It is essential to remember that every scientific study has limitations. One of the most significant limitations of this study is the restriction of the GINI data to 2017. The inability to access more recent GINI data may lead to missing the impact of the current developments. Second, this study used the GINI coefficient as a single inequality indicator. Although the GINI coefficient is a widely used and reliable measure, the impact of inequality on EF can be examined using different indicators. Future research may address the constraints of current investigations and build upon the existing corpus of literature by focusing on diverse countries. For example, analyzing different countries with updated data, as well as examining the effects of different inequality indicators such as the share of income in the top 1% and wealth distribution on ED, could be explored in future research endeavors.

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