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Race to carbon neutrality in South Africa: What role does environmental technological innovation play?

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HIGHLIGHTS

- This study explored nexus between environmental pollution, economic growth, and environmental technological innovation in South Africa
- Utilisation of Autoregressive distributed lag (ARDL) estimators were employed
- Agricultural activities dampens environmental sustainability in South Africa
- Green growth policies should be pursued in South Africa energy mix

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ABSTRACT

Governments worldwide have prioritized carbon reduction and neutrality to address the escalating threat of climate change. These goals are in line with the United Nations Sustainable Development Goals (UNSDG-13). These goals stress taking action on climate change to lessen the bad effects of human activities and using fossil fuels for energy. To this end, the present study investigates the connection between conventional energy usage, agricultural practices, economic growth, and their impact on environmental sustainability in South Africa. Additionally, it explores the role of renewable energy consumption and environmental technological innovation in mitigating these effects. To achieve the study objectives, a carbon-income function is fitted with an annual frequency data from 1975 to 2020. The present study leverages on Pesaran's Autoregressive distributed lag (ARDL) method and for robustness analysis the dynamic ARDL simulations method to simultaneously explore the short and long-run coefficients of the study's outlined variables. Empirical analysis, confirmed by bounds testing for cointegration, reveals a long-term equilibrium relationship among the variables considered. Notably, economic growth, fossil fuel energy consumption, and agricultural activities have adverse effects on environmental sustainability in South Africa, indicating a trade-off between economic growth and environmental quality. Dynamic ARDL simulations provide further evidence of an Environmental Kuznets Curve (EKC) phenomenon. However, renewable energy consumption and environmental technological innovation positively influence environmental quality. These findings highlight the imperative for South Africa and its stakeholders to adopt green growth policies and transition to cleaner energy alternatives.

1. Introduction

The world faces an unprecedented challenge escalating climate change resulting from a surge in carbon dioxide (CO_2) emissions primarily attributed to human activities [9,43]. Boden et al. [13] and Adebayo et al. [1] reveal that global CO_2 emissions have surged by nearly 90% since 1970, with fossil fuel combustion and industrial activities responsible for about 78% of this increase. Moreover, agriculture, deforestation, and land-use alterations represent significant contributors to greenhouse gas emissions [10]. The adverse consequences of rising CO_2 levels are profound and include air pollution, responsible for seven million premature deaths a year, and environmental disasters like flooding and forest fires [27,81].

Despite contributing only 3% of global CO_2 emissions, African nations, led by South Africa, bear the brunt of climate change, with devastating impacts like floods [77]. Flooding, resulting from CO_2

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accumulation, has severely impacted the economies of Mozambique, Madagascar, and South Africa [69]. Additionally, South Africa's exposure to climate change is starkly evident; in 2019, 750,000 people were affected by drought, and 4500 were displaced due to floods [82]. Although the share of GDP lost to flooding in South Africa is minimal, the monetary value of climate disasters amounts to an estimated $4.5 billion [82]. Therefore, the pursuit of carbon neutrality—a reduction in CO2 emissions using renewable energy and technological innovations—is vital for South Africa.

South Africa's heavy reliance on fossil fuels, especially coal, further exacerbates the carbon emissions problem [36,50]. In 2022, fossil fuels accounted for approximately 94.24% of the country's energy consumption, with coal alone constituting 84.4% [69]. This reliance on coal makes South Africa a major contributor to Africa's CO_2 emissions [45,48]. Unbridled use of fossil fuels, such as oil, coal, and gas, intensifies CO2 emissions [47,48,77].

Additionally, the agricultural sector has been scrutinized as a significant source of CO2 emissions [16,67]. Agricultural activities like deforestation, mechanization, and the destruction of carbon-sequestering trees contribute to emissions [71,73]. Notably, South Africa's agricultural sector, comprising both commercial and small-scale agriculture, contributes approximately 10% of the nation's greenhouse gas emissions (GHGs) [5]. High agricultural productivity in South Africa necessitates energy-intensive processes powered by fossil fuels, further increasing CO2 emissions [74].

The relationship between economic growth and CO_2 emissions is a subject of debate, with the Environmental Kuznets Curve (EKC) theory suggesting that as GDP grows, CO_2 emissions initially rise before declining with technological adoption [27,76]. South Africa's growing economy, with the third-largest GDP in Africa, stands to expand further, driven by industrialization and urbanisation [69]. This economic growth, while promising prosperity, also threatens environmental quality due to potential CO2 increases.

Despite being Africa's leading CO_2 emitter, South Africa has committed to reducing carbon emissions and achieving carbon neutrality by 2050 to combat climate change . To attain this goal, South Africa must transition to renewable energy sources and embrace eco-friendly innovations, effectively reducing CO_2 emissions [21]. The country boasts significant renewable energy potential, including solar and hydropower opportunities [7,8]. Embracing environmentally friendly technologies like carbon capture and energy-efficient appliances will further support carbon reduction [23].

Aligned with the United Nations' Sustainable Development Goals (SDGs), South Africa's commitment to sustainability necessitates a substantial reduction in CO2 emissions [30,31,66]. Achieving the SDGs and South Africa's National Development Plan requires a significant reduction in CO2 emissions [61].

This research investigates the combined impact of agriculture, fossil fuels, and economic growth on carbon neutrality in South Africa. It also explores how renewable energy consumption and environmental and technological innovations contribute to carbon reduction. Our study makes a holistic assessment of the drivers of CO_2 emissions in South Africa, an essential endeavour as the highest emitter in Africa. Moreover, it evaluates the role of renewable energy and ecological technologies in emissions reduction. Finally, this study utilizes the Pesaran's autoregressive distributed lag (ARDL) methodology combined with dynamic ARDL simulations to provide short-term and long-term strategies for carbon neutrality.

Therefore, the organisation of this paper follows thus; following the introduction, part 2 is the literature review, part 3 is the methodology, part 4 presents empirical analysis, and part 5 presents the research conclusion and implications.

2. Literature review

2.1. Theoretical review

The theory that is relevant to our study is the Environmental Kuznet Curve (EKC) theory based on the argument of Grossman and Krueger [25]. According to the EKC theory, the quality of the environment and real production have a non-linear connection that is defined by an upward curve and a falling curve. Dogan and Turkekul [19] noted that, up until a particular GDP level, environmental degradation occasioned by productivity first rises as economic activity (as measured by GDP) rises. Beyond this point, continued economic expansion is linked to a reduction in environmental damage [72]. The argument of the EKC indicates that environmental disasters occasioned by CO_2 have a quadratic function with economic growth, which represents economic productive activities that need energy use [9].

The EKC provides a theoretical understanding of the race towards carbon neutrality by adopting renewable energy use, environmental technology, and innovation through economic growth, fossil fuel and agricultural productivity channels. Based on the assumption of the EKC, the initial rise in environmental pollution due to excessive discharge of CO_2 because of output productivity can be driven by fossil fuel energy, agricultural productivity and overall GDP growth. According to Mthembu [48] and Mesagan et al. [43], fossil fuel consumption releases carbon discharge into the atmosphere, negatively affecting environmental quality. Jahanger et al. [31] also emphasised that carbon is present in substantial amounts in fossil fuels. For instance, carbon is the main component of coal. When these substances are burned, carbon atoms join with oxygen to create CO_2, which releases energy. Therefore, since South Africa is a coal-dependent nation, the EKC provides insight as to why it is the largest emitter of CO_2 in Africa [48]. Furthermore, agricultural productivity has been identified in the literature as a key contributor to CO2 emission [16,67]. South Africa's agricultural sector has evolved rapidly in recent years into a dual sector which is largely mechanised. Tagwi [71] emphasised that mechanised farming requires energy intensity, and South Africa has utilised fossil fuels to power machines to increase productivity. Therefore, as farm operations rise, emission from the process increases CO_2 accumulation. Also, the overall GDP growth will worsen pollution for South Africa since it is still in a state of convergence with the developed economies, as argued in the EKC that, at the initial stage of growth, CO_2 pollution rises [18].

The EKC argued that environmental pollution reverses as economic productivity increases in the long run. Jahanger et al. [31] noted that, at this stage, the incorporation of renewable energy and environmental technology and innovation in the production processes aids the decline in pollution since they support energy and carbon efficiency. Moreover, Ibekilo and Emmanuel [28] posited that technological innovation can reverse unpleasant environmental circumstances that emanate from production processes. Also, evidence from Feng [23] and Wen et al. [79] supports the role of renewable energy use in lowering carbon releases. Therefore, incorporating renewable energy and environmental technology and innovation following the EKC argument can aid the analysis of the significance of renewable energy use. Environmental technology and innovation is driving carbon neutrality via fossil fuel energy, agricultural productivity and GDP growth in South Africa.

2.2. Empirical review

This section of the literature review explores related study areas. The review is organised in two strands. The first strand reviews evidence that has considered the effect of fossil fuel, agricultural output and economic growth on CO_2 release, while the second strand explores evidence on the role of renewable energy consumption and environmental technology and innovation in driving carbon neutrality. For the first strand, Lin and Xu [39] showed that fossil fuel energy use caused CO_2 emission to surge in 30 Chinese provinces between 1990 and 2017 but has a non-linear linkage with the GDP expansion of the country using the nonparametric additive regression model. Also, Udeagha and Breitenbach [77] focused on South African Community Development member countries between 1960 and 2014 and established fossil fuel energy use and industrial development increased CO_2 emissions, which deteriorated the environment, but trade flow and innovation reduced environmental pollution. Similarly, Mesagan et al. [43] presented evidence for 46 African countries and documented that, using the Pool Mean Group (PMG) technique, fossil energy consumption and industrial productivity that support economic growth increased pollution.

Furthermore, Raihan and Tuspekova [62] explored how fossil energy, agricultural sector productivity, urbanisation pace and GDP growth impacted CO2 rise in Kazakhstan between 1996 and 2020. The analytical tool employed for the study is cointegration regressions (DOLS, FMOLS and CCR) which were used for the estimate. The study established that the use of fossil energy, economic expansion and urban growth increased the discharge of CO2, but agricultural output and forest areas lowered CO_2 emission in Kazakhstan. Also, they established a long-run linkage among the variables based on the ARDL bound calculation. In a similar study for Turkey, Raihan and Tuspekova [63] used the DOLS estimation technique and time series data between 1990 and 2020 to show that energy use, GDP, industrial growth, and tourism increased CO_2 emissions, but agricultural output and renewable energy supported CO_2 reduction in Turkey. Also, for Brazil, Raihan and Tuspekova [64], using the same analytical style, concluded that economic growth, agricultural output, fossil energy, GDP and tourism caused CO2 to surge in Brazil while renewable energy use increase and improved forest area supported CO_2 emission decline. Furthermore, Gyimah et al. [26] concentrated on Ghana between 1990 and 2018 for analysis of fossil energy and renewable energy on CO_2 growth. They employed the 2-stage least squares, robust OLS, and GMM techniques for the data examination. The study discovered that both forms of energy increased CO_2 emissions.

On the second strand, [86] analysed the impact of the Renewable Energy Independent Power Producer Procurement Program (REIPPPP) in promoting renewable energy generation. From their investigation, the authors noted that the programme had stimulated investment in renewable energy projects, resulting in a significant increase in renewable energy capacity and reduced carbon emissions. The importance of renewable energy in the economy of South Africa prompted Marquard et al. [41] to explore the possible areas of diversification of energy sources. The authors analysed wind power technology and the energy sector in South Africa and observed that deploying wind power has contributed to diversifying the energy mix, reducing reliance on fossil fuels and lowering carbon emissions. The authors highlighted the potential of wind power technology to contribute to carbon neutrality in the country.

Analysing the issue of technological innovation on CO_2 emission as related to environmental sustainability in South Africa. Udeagha and Ngepah [76] looked at the asymmetric relationship of the study, employing the quantile autoregressive distributed lag model approach; the authors observed that technological advancements contribute to the reduction of CO_2 emissions both in the immediate future and in the long run. The technique reduces CO2 emissions while the scale effect increases them, hence validating the EKC hypothesis. Environmental quality is significantly impacted by energy use, foreign direct investment (FDI) and industrial expansion. Furthermore, although trade openness brings short-term benefits, its long-term consequences are detrimental to the environment. In a similar study, Wang et al. [80] made three observations; to attain carbon neutrality, current global development mechanisms may need to be reformed to reduce greenhouse gas emissions and boost CO_2 capture. The reliance on fossil fuels may be eliminated if we harness the potential of renewable and carbon-neutral resources to produce electricity and other fossil-based alternatives. And climate change can be mitigated by conserving natural carbon sinks and fostering CO_2 capture, utilisation and storage.

Analysing the role of green finance and technological innovations in offsetting the carbon footprint of renewable energy production for long-term environmental sustainability, Feng [23] employed Markov switching regression and the fully modified OLS approaches. The estimated outcomes demonstrate the important role of green financing, green energy, transparency and R&D investments in improving environmental quality. Urbanisation and economic development in China have similar negative effects on the country's ecology. The selected variables' causal associations show a two-way causal relationship involving openness, green finance, emissions and openness, and R&D expenditures. Interesting findings can also be found in the other direction of the correlation. Udeagha and Breitenbach [75] observed new policy lessons from re-examining the relationship between fiscal decentralisation and carbon dioxide emissions in South Africa. Both in the short and long term, fiscal decentralisation reduced CO_2 emissions, demonstrating the prevalence of the “race to the top” strategy. Due to the scale effect, economic development has degraded ecological quality. However, the environmental Kuznets curve hypothesis is supported by the fact that its square (as reflected by the technique impact) helped increase ecological protection. Energy use, trade liberalisation, industrial value-added, and FDI contributed to rising CO_2 emissions, while technological progress bolstered environmental sustainability. The study's conclusions indicate that, to maintain South Africa's ecological sustainability, additional fiscal decentralisation should be performed by devolving more power to local bodies, especially in environmental policy. To further the energy-saving functions of fiscal expenditures, South Africa should adopt policies to increase environmental sustainability. This can be done by bolstering a lower government tier and clarifying national and local obligations.

Summarising the literature gap, evidence in the literature tends to be consistent on the increasing effect of fossil energy use and economic growth (See [39,45,62,77]). This implies that fossil fuel energy increases CO_2 and does not support a neutrality agenda. On the other hand, the effect of agriculture on CO_2 emission is mixed. For instance, Raihan and Tuspekova [62,63] showed that agricultural productivity promotes carbon neutrality for Turkey and Kazakhstan, but they also established [64] that agricultural productivity increased CO_2 in Brazil. Since South Africa is a developing economy that is fossil fuel dependent and operates large-scale agriculture, it is important to analyse how these variables affect their carbon footprint due to their desire for carbon neutrality by 2050. Furthermore, in identifying the role of renewable energy and environmental technology and innovation in reducing the carbon footprint in South Africa. However, evidence in the literature, such as Marquard et al. [41], Udeagha and Ngepah [76], and Udeagha and Breitenbach [75] revealed that renewable energy utilisation and technology adoption can curtail CO2 rise in South Africa, but none of these studies has taken a holistic approach of examining the channel through which CO2 is rising before suggesting that renewable energy and technology can reduce carbon discharge. Therefore, the crux of this study is to explore the importance of renewable energy use and ecological technology and innovation as pathways through which South Africa can close the discharge of emissions using fossil fuel, agricultural output and economic growth.

3. Methodological sequence

3.1. Model specification and data

Our study's model is developed following the theory of EKC as presented by [25]. Therefore, the EKC proposition, which proposed a quadratic nexus between environmental damages and economic output expansion is the underpinning theory for our study. More so, Dogan and Turkekul [19] and Udeagha and Breitenbach [75] pointed out that the relationship between environmental deterioration and output productivity that EKC describe can be in the form of a U-shape. This means that as economic growth and pollution rise together at the early stage of economic expansion due to the use of unclean energy as economic output continues to rise, economic prosperity increases and nations can acquire clean energy and technologies which mitigate CO_2 rise, thereby lowering pollution. Therefore, following the argument of the EKC, its mathematical function is presented as thus;

$$CO2_t = f\left(GDP_t, GDP_t^2\right) \tag{1}$$

Eq. (1) presents the mathematical function of the argument of the EKC theory where CO_2 represents carbon emission, which captures population, GDP is economic growth which, if it rises, CO_2 also increases [77], GDP^2 denotes the squared of GDP which is expected to have a negative sign with CO_2 [43,77], and *t* indicates time factor showing that the variables move with time.

Therefore, we transform Eq. (1) into an empirical model following the evidence of Udeagha and Breitenbach [77], Raihan and Tuspekova [64], and Udeagha and Breitenbach [75] as thus to accommodate the effect that fossil fuel (FF) and agriculture (Agric) has on CO2 in South Africa as thus;

$$CO2_t = \theta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 Agric_t + \beta_4 FF_t + \varepsilon_t \tag{2}$$

Eq. (2) captures the effect of fossil fuel, agriculture and economic growth on CO2 emission in South Africa. Where the intercept is depicted by θ_0, the independent variables are represented by $\beta_1, \beta_2, \beta_3$, and β_4 and the error term is denoted by ε_t. According to Udeagha and Breitenbach [77] and Raihan and Tuspekova [63], we expect that FF, Agric, and GDP should cause CO2 to surge while GDP^2 is expected to slow CO_2 based on the EKC argument. Furthermore, we incorporate renewable energy consumption (REC) and environmental technology and innovation (ECO) into Eq. (2), to explore the significance of renewable energy use and ecological technology and innovation as pathways through which South Africa can close the discharge of emission through the use of fossil fuel, agricultural output and economic growth and further transformed in the logged forms in Eq. (3) as thus;

$$ln(\mathrm{CO}_2)_t = \theta_0 + \beta_1 \mathrm{lnGDP}_t + \beta_2 ln\mathrm{GDP}_t^2 + \beta_3 ln\mathrm{Agric}_t + \beta_4 \mathrm{lnFF}_t + \beta_5 ln\mathrm{REC}_t + \beta_6 \mathrm{lnECO}_t + \varepsilon_t \tag{3}$$

The model in Eq. (3) is often associated with the twin problem of endogeneity and serial correlations; this situation occurs when there is a zero correlation in the error term and in the explanatory variables in a case where they are not independent. This leads to the underlying violations of the least squares assumption of finite samples, which suggests that the residual's two problems of endogeneity and serial correlation must be addressed. Hence, to address this problem, as suggested by Onwe et al. [60], the autoregressive distributed lag (ARDL) model is employed.

Furthermore, the current study examines the relation of immediate drivers of low carbon emissions in South Africa to environmental-related technologies. Therefore, the study employed annual time series data from 1975 to 2020. Table 1 shows all variables, their description and source.

3.2. Method

3.2.1. ARDL bounds testing method

In the early 2000s, there were several techniques for cointegration analysis but the most popular was the one advanced by Pesaran et al. [57] who originally proposed the ARDL bound test to evaluate if employed variables are cointegrated in the long run. When variables have breaks in I(2) but are integrated in mixed order, such as first order of integration I(1) or at level I(0), this technique can be used. Pesaran and Smith [58] and Kripfganz et al. [38] state that this suggests that the dependent variable must be integrated with I(1) for the ARDL bounds procedure.[1] Given that the conditions for cointegration are satisfied and the unconstrained error correction term is present, the ARDL bound test model is defined as in Eq. (2).

$$\begin{aligned}\Delta ln(\mathrm{CO}_2)_t = {} & \delta_0 + \delta_1 ln\mathrm{CO}_{2t-1} + \delta_2 ln\mathrm{GDP}_{t-1} + \delta_3 ln\mathrm{GDP}_{t-1}^2 + \delta_4 ln\mathrm{AGRIC}_{t-1} \\ & + \delta_5 ln\mathrm{LFF}_{t-1} + \delta_6 ln\mathrm{REC}_{t-1} + \delta_7 ln\mathrm{LECO}_{t-1} + \sum_{i=1}^{p}\beta_1 \Delta ln\mathrm{CO}_{2t-1} \\ & + \sum_{i=1}^{p}\beta_2 \Delta ln\mathrm{GDP}_{t-i} + \sum_{i=1}^{p}\beta_3 \Delta ln\mathrm{GDP}_{t-i}^2 + \sum_{i=1}^{p}\beta_4 \Delta \mathrm{lnAGRIC}_{t-i} \\ & + \sum_{i=1}^{p}\beta_5 \Delta ln\mathrm{FF}_{t-i} + \sum_{i=1}^{p}\beta_6 \Delta \mathrm{lnREC}_{t-i} + \sum_{i=1}^{p}\beta_7 \Delta \mathrm{lnECO}_{t-i} + \varepsilon_t\end{aligned} \tag{4}$$

Eq. (4) depict the ARDL bound equation, where the variance operator is symbolised by the intercept is shown by the δ_0, the short-run coefficients are shown by$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ *and* β_6 the long-run coefficients are shown by the long-run parameters are illustrated by δ_1 *to* δ_7 the error term is denoted by ε_t.Below is a representation of the alternate and null hypotheses in Case II (limited intercept and no trend):

$$H_{null}: \delta_0 = \delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta_5 = \delta_7 = 0. H_{alternative}: \delta_0 \neq \delta_1 \neq \delta_2 \neq \delta_3 \neq \delta_4 \neq \delta_5 \neq \delta_6 \neq \delta_7 \neq 0$$

If the estimated F-statistic is greater than the critical values of the upper bounds established by Pesaran et al. [57], the null hypothesis of zero cointegration can be rejected. Otherwise, there is no long-term relationship between the variables.

3.2.2. DYANMIC ARDL

The complicated model definition incorporates elements typical of ARDL modelling, such as the lagged differences of the series at the first difference and the lag structure. On the other hand, it is challenging in ARDL modelling to examine the explanatory variable's short- and long-term impacts on the dependent variables with their initial differences and lag length. In order to include the dynamic error correction term (ECT) in the model, [85] developed the dynamic model of ARDL. The DARDL technique can produce graphs to forecast hypothetical alterations in one explanatory variable and their effect on the response variable while other regressors are constant. To use the DARDL approach, the series must be integrated at I(1) and exhibit mutual cointegration [85]. In this study, 5000 simulations were used. The dynamic ARDL model's equation form, which takes the error correction component into account, is as follows:

$$\begin{aligned}\Delta ln(\mathrm{CO}_2)_t = {} & \varphi_0 + \theta_0 ln\mathrm{CO}_{2t-1} + \beta_1 \Delta ln\mathrm{GDP}_t + \theta_1 ln\mathrm{GDP}_{t-i} + \beta_2 \Delta ln\mathrm{GDP}_t^2 \\ & + \theta_2 ln\mathrm{GDP}_{t-i}^2 + \theta_3 \mathrm{lnAGRIC}_t + \beta_3 \Delta \mathrm{lnAGRIC}_{t-1} + \theta_4 ln\mathrm{FF}_t \\ & + \beta_4 \Delta ln\mathrm{FF}_{t-1} + \beta_5 \Delta ln\mathrm{REC}_t + \theta_5 \Delta \mathrm{lnREC}_{t-1} + \beta_6 \Delta \mathrm{lnECO}_t \\ & + \theta_6 ln\mathrm{ECO}_{t-1} + \xi \mathrm{ECT}_{t-1} + + \mu_t\end{aligned} \tag{5}$$

[1] The dependent variable should be integrated of order 1. ~I(1). That is, the dependent variable should be stationary (stable) which is supported in the econometric literature.

The Eq. (5) is the DARDL empirical model for short and long-run parameter stimulations. Although ARDL approach's strength in generating consistent and robust estimates by handling the twin problem of endogeneity and serial correlations, it is not without a drawback. For instance, Hossain et al. [34] and Maduka et al. [40] showed that selecting the appropriate lag length for the ARDL can be challenging and if the correct structure is not used, the parameter estimates from the ARDL may become unreliable. Therefore, to check the robustness of the ARDL calculation, we employ the novel dynamic ARDL (DARDL) following the argument of Sarkodie and Owusu [65] to confirm the reliability and accuracy of the ARDL for policy formulation on carbon neutrality for South Africa.

4. Empirical results and discussion

Table 2 presents the unit root test result used to ascertain the soundness of the dataset used in the study; the study employed the Augmented Dickey-Fuller (ADF) and the Philip Peron (PP) tests at both levels and first difference, respectively. The results indicate that the log of CO_2 (Ln CO_2), Fossil Fuel (LnFF), Gross Domestic Product (LnGDP) and Renewable Energy (LnREN) are all non-stationary at levels for both the ADF and PP unit root tests. However, at the first difference, there is strong proof that unit roots are absent in the dataset for the above-mentioned variables. (See Table 1.)

However, the log of Agriculture (LnAGRIC) and Eco-innovation (LnECO) show significant stationary status at the level form, implying the absence of unit root in the data for these variables even though the first difference outcome proves otherwise. Overall, the significance of the variables at different levels indicates that the variables in this study are all stationary. Furthermore, the diverse nature of the unit root outcomes supports the application of the bound F-statistics test for investigating the existence of cointegration between the regressors and the dependent variable.

Table 3 presents the description of the dataset for each variable used in the study and reveals that LnCO_2 has a mean value of 2.1577 and ranges between 1.9937 and 2.2975; LnAGRIC has a mean value of 22.398 and ranges between 21.878 and 22.969; LnECO has a mean value of 2.3101 which ranges between 1.4586 and 2.8284. Similarly, LnFF has a mean value of 10.114, falling within the range of 9.9412 and 10.242; LnGDP has a mean of 8.5667, which ranges between 8.3592 and 8.7424, while LnREN has a mean of 4.8746, and ranges between 2.3176 and 6.6026.

The outcome of the descriptive statistics shows that there are no cases of extreme values based on the range except for LnREN. Moreover, except for LnECO, LnFF and LnREN, the variables used in this study are positively skewed and with all standing below their mean values. Furthermore, Table 3 reveals that LnECO and LnREN are leptokurtic. In contrast, the rest of the variables are platykurtic, implying that the chances of having outliers in the model of this study are slim or impossible. Thus, the dataset for the study is deemed feasible and reliable.

The bound test for the study is presented in Table 4, and from every indication, there is a significant long-run relationship between the regressand and the regressors. This is as the bound F value of 13.227 portrays. The bound F value is statistically significant at 0.01, higher than the upper bound's critical value [40]. With this, we move on to estimating the cointegrating equation with (ECM) capacity, which, all other things being equal, will eventually restore equilibrium.

Table 5 present the long-run and short-run ARDL result for the study. Firstly, LnAGRIC has a positive and significant impact on environmental deterioration (LnCO_2) in both the short and long run, implying that every one unit increment in LnAGRIC will deteriorate the environment by 0.0912% and 0.0912% in the short and long run, respectively. The short-run and long-run impacts of LnAGRIC on LnCO_2 are similar, as indicated in the coefficient values. The economic intuition is that as South Africa's agricultural productivity rises, it triggers the acceleration of CO_2, perhaps due to the use of fossil energy to power farm machinery. Similarly, LnFF has a positive impact on LnCO_2 in the short run as well as in the long run. A similar outcome was observed for LnGDP in the short run and long run, only that the short-run outcome is statistically insignificant. By implication, increasing LnFF by just one unit will equally increase LnCO_2 by 0.1197% in the short run and 0.9351% in the long run if every other factor is held constant. Moreover, increasing LnGDP by one unit will increase LnCO_2 by 0.3660% in the long run, but the short case will remain unchanged. This implies that the LnFF, in the long run and short run, as well as LnGDP in the long run, encourages the destruction of the environment in South Africa via their respective contribution to the emission of CO_2. This implies that, in both the short and long run, fossil fuel and the growth of GDP in South Africa cause the CO_2 discharge to rise. This is expected because South Africa is fossil fuel dependent (i.e. coal) for providing electricity for homes and businesses.

Moreover, the evidence shows that renewable energy consumption (LnREC) positively affects CO_2 emission in the short run but, over the long run, causes it to decline. Based on the parameter estimate, changes in LnREC by 1% increase CO_2 by 1.7% in the short period, but over the long period, CO_2 declines by 2.1%. This evidence for South Africa implies that renewable energy use has a long-run carbon neutralisation effect. Considering the role of environmental technology and innovation, the result revealed that LnECO negatively and significantly impacts LnCO_2 in South Africa. This is true for the long and short run and connotes that when eco-innovation is increased by one unit, CO_2 will decrease by −0.1235% in the long run and − 0.0894%, and vice versa if other factors are constant. The implication of the negative nexus between LnECO and CO_2 in short and long periods is that adopting environmental technology and innovations in the production process in South Africa can substantially mitigate CO_2 discharge in the short and long periods, thereby supporting the carbon neutrality agenda. This may be because eco-technologies are energy efficient with minimal or zero carbon. The detailed economic intuition of the evidence is presented in the results discussion subsection.

The error correction term (ECT) is negative and significant, as expected, indicating that about −0.8644% of the disequilibrium in the short run will be corrected in the long run. The constant term is equally negative and significant, portending that some other factors or variables significantly promote the environmental sustainability in South Africa that were not explicit in the model of this study but are encapsulated in the constant term; an example is carbon taxes and other environmental regulation policies. Furthermore, Fig. 1 highlights a schematic of the study variables under review.

Table 6 presents the result of the diagnostic tests, validating the regression outcome's robustness. Accordingly, the results show that the model is normal, with the JB *p*-value indicating that the null hypothesis

Table 2
Unit root test results.

	LnCO_2	LnAGRIC	LnECO	LnFF	LnGDP	LnGDP^2	LnREC
ADF	−2.3426	−4.4344***	−5.1805***	−1.5441	−1.6966	−1.46925	−2.9299
ΔADF	−6.8330***	−7.7038***	−6.7647***	−6.6542***	−4.7943***	−3.0450**	−8.7393***
PP	−2.4328	−4.3892***	−5.1805***	−1.5441	−1.5259	−1.5267	−2.8942
ΔPP	−6.8311***	−7.4679***	−5.1806***	−6.6507***	−4.8495***	−4.839***	−9.6416***

Note: ***, ** and * denotes 1%, 5% and 10% level of significance, respectively.

Table 3
Descriptive statistics.

	$LnCO_2$	LnAGRIC	LnECO	LnFF	LnGDP	$LnGDP^2$	LnREC
Mean	2.1577	22.398	2.3101	10.114	8.5667	73.40346	4.8746
Median	2.1565	22.381	2.3584	10.116	8.5605	73.28306	4.8171
Maximum	2.2975	22.969	2.8284	10.242	8.7424	76.4301	6.6026
Minimum	1.9937	21.878	1.4586	9.9412	8.3592	69.8778	2.3176
Std. Dev.	0.0853	0.2758	0.2981	0.0750	0.1222	2.094348	0.8043
Skewness	0.0005	0.1828	−0.6983	−0.6713	0.0084	0.024778	−0.0972
Kurtosis	2.1231	2.2965	3.6467	2.9224	1.7707	1.7652	4.4030
Jarque-Bera	1.4735	1.2049	4.5406	3.4674	2.8968	2.9272	3.8455
Probability	0.4786	0.5475	0.1032	0.1766	0.2349	0.5475	0.1462

Table 4
ARDL bounds test result.

F-Bounds Test		Null Hypothesis: No levels of relationship		
	Value	Signif.	I(0)	I(1)
F-statistic	13.227***	10%	2.26	3.35
K	5	5%	2.62	3.79
		2.5%	2.96	4.18
		1%	3.41	4.68

Note: *** denotes 1% level of significance.

is rejected; the Breusch-Gedfrey Serial correlation and heteroscedasticity tests equally show that there is no problem of serial correlation and heteroscedasticity, respectively. There is no reason to support the omission of crucial variables in the current study, as revealed by the Ramsey reset test outcome.

Furthermore, upon the verification of the presence of long-term cointegrating dynamics, as ascertained by the bounds test outcome displayed in Table 4, the dynamic autoregressive distributed lag (ARDL) model is subsequently simulated as a robustness analysis. The ARDL simulation is presented in Table 7. The results corroborate with the environmental Kuznets curve (EKC) phenomenon in South Africa over the study period. This EKC phenomenon highlights the assertion that South Africa is still at her scale stage, i.e., the South Africa economy prioritises economic growth relative to environmental quality. This preposition aligns with the empirical study of Adebayo [2] for the case of Mexico. This result raises the need for more environmental stringent regulation to aid environmental education in the form of investment in research and development. From the dynamic ARDL robustness analysis, it corroborates with the results of the conventional ARDL baseline regression that outlines the detrimental role of South African agricultural activities. The plausible explanation is linked due to the use of fossil energy to power farm machinery. The trend of detrimental effect of economic growth and fossil fuel-based energy on environmental quality aligns with previous results in Table 5. However, renewable energy, i.e., alternative, and clean energy sources such as wind, solar, photovoltaic, hydro among others clean energy sources were suggested to arrive at a clean and sustainable environment which can help mitigate climate change action (SDG-13) in South Africa. This can further be achieved via investment in eco-innovation in clean technologies. In summary, both the conventional and novel dynamic ARDL simulation both corroborate each other. Fig. 3 further illustrates the capability of the dynamic ARDL technique to project the projected effects of the counterfactual shocks to an independent variable of interest on the dependent variable, which is a fundamental characteristic of this analysis. The predicted positive impact of one standard deviation counterfactual shock to CO_2 by agriculture is positive for positive external shock and likewise the same for negative shock. Similar trend is experienced across all independent variables (fossil-fuel energy consumption, agriculture, economic growth) except for (eco-innovation and renewable energy consumption) that highlights an inverse relationship from external positive and negative on carbon emission shock, as also outlined by the dynamic ARDL simulation in Table 7.

Finally, the outcome of the CUSUM and CUSUM squared test outlined in Fig. 2a and b shows that the study model is highly stable as the dual indicates the trend (blue) line in each running through and within the 0.05 limit.

4.1. Discussion of findings

The evidence from this study provides valuable insights for policy discussions. Our research highlights that economic growth, fossil fuel energy, and agricultural output significantly contribute to environmental deterioration in South Africa, mainly through increased CO_2 emissions. This observation aligns with South Africa's heavy reliance on fossil fuels, particularly coal, as the primary energy source for driving both economic productivity and agricultural machinery operations. In fact, fossil fuel energy accounts for approximately 94.24% of the primary energy sources in South Africa, with coal representing around 84.4% of the fossil fuel energy mix. This reliance on coal has positioned South Africa among the top three carbon emitters in Africa.

The notable environmental impact of GDP growth, fossil fuel consumption, and agricultural productivity underscores the need for more effective environmental policies in South Africa, especially as the observed effects are consistent in both the short run and the long run. This suggests that existing environmental policies in the country may not be sufficient to promote sustainable economic growth and a healthier agricultural sector.

Furthermore, the intensified use of natural resources in agriculture

Table 5
ARDL long and short-run results.

	Long-Run Estimates			
Variable	Coefficient	Std. Error	t-Statistic	Prob
LnAGRIC	0.0912*	0.0522	1.7469	0.0902
LnECO	−0.1235**	0.0579	−2.1330	0.0407
LnFF	0.9351***	0.1436	6.5104	0.0000
LnGDP	0.3660*	0.2116	1.7292	0.0934
LnREC	−0.0212	0.0196	−1.0813	0.2856
	Short-Run Estimates			
LnAGRIC	0.0912*	0.0448	2.0332	0.0504
LnECO	−0.0894*	0.0468	−1.9098	0.0651
LnFF	0.1197**	0.0464	2.5800	0.0147
LnGDP	0.6759	0.8319	0.8125	0.4211
LnREC	0.0176*	0.0090	1.9348	0.0619
ECT (−1)	−0.8644***	0.0902	−9.5793	0.0000
C	−4.6247	1.0501	−4.4040	0.0001

Note: ***, ** and * denote 1%, 5% and 10%, levels of significance, respectively.

Table 6
Post-estimations of tests results.

	Value	*P* value
Normality Test	1.1634	0.5583
Breusch-Godfrey Serial Correlation LM Test	0.0592	0.9426
Heteroscedasticity Test: Breusch-Pagan-Godfrey	1.1493	0.3590
Ramsey RESET Test	0.52029	0.6066

Table 7
Results of dynamic ARDL simulation (robustness analysis).

Dependent variable dLnCO_2	Coefficient	Std. err.	t	P > t	[95% conf. interval]	
Short-run estimates						
ECT(−1)	−0.8705***	0.19105	−4.56	0.000	−1.264	−0.477
LnAGRIC	16.9232**	6.62429	2.55	0.017	3.28018	30.5661
LnGDP	0.116	0.27854	0.42	0.681	0.6897	0.45767
lnGDP2	−374.61**	147.609	−2.54	0.018	−678.62	−70.609
LnFF	0.9787***	0.16275	6.01	0.000	0.64348	1.31385
LnREC	−0.0066	0.01135	−0.58	0.566	−0.03	0.01676
LnECO	−0.0123	0.02304	−0.53	0.599	−0.0597	0.03519
LnGDP(−1)	0.55385	0.35633	1.55	0.133	−0.18	1.28773
lnAGRIC(−1)	0.24636**	0.07652	3.22	0.004	0.08877	0.40395
lnGDP2 (−1)	4.15687**	1.51822	2.74	0.011	1.03005	7.2837
L1D_LnFF (−1)	−0.0526	0.16557	−0.32	0.753	−0.3936	0.2884
Long-run estimates						
LnAGRIC	18.4677**	7.61113	2.43	0.023	2.79228	34.1431
LnGDP	0.1437	0.1005	1.43	0.165	0.3507	0.06328
lnGDP2	−417.31**	170.683	−2.44	0.022	−768.83	−65.778
LnFF	1.13882***	0.28202	4.04	0.000	0.55799	1.71965
LnREC	−0.0087	0.01251	−0.7	0.492	−0.017	0.03451
LnECO	−0.02187	0.02983	−0.73	0.470	−0.0396	0.0833
Constant	875.206**	359.714	2.43	0.022	134.36	1616.05

Note: **,and *** denote 5% and 1% level of significance, respectively.

and the degradation of the environment due to land conversion, deforestation, and soil erosion exacerbate the environmental challenges. Given the critical role of ecosystems in supporting South African agriculture, these activities have led to the deterioration of critical ecological services such as soil fertility, water availability, and pollination.

To mitigate these negative impacts, our study examines the potential of renewable energy and eco-technology. The results reveal that renewable energy consumption has a significant long-term effect on reducing CO_2 emissions in South Africa. This suggests that integrating renewable energy into various sectors can contribute to long-term CO_2 mitigation and promote environmental sustainability.

However, the observed effect is not significant in the short term, possibly due to fluctuations in renewable energy policies. South Africa's ambitious plans to increase renewable energy investments by 19 GW by 2030 could face challenges related to the pace of implementation. Hence, consistent and aggressive efforts are required to maintain environmental sustainability.

Additionally, the study highlights the significant role of eco-innovation in reducing CO_2 emissions and mitigating environmental damage in South Africa. These findings underscore the ongoing efforts within the country to leverage eco-technologies to combat environmental challenges. The adoption of eco-technologies across various sectors of the economy holds promise for reducing pollution associated with agriculture, energy, and industrial activities.

5. Conclusion and policy suggestions

The carbon neutrality goal is a global agenda. However, each nation tends to adopt a unique but varying policy approach depending on the nation's socioeconomic peculiarity. South Africa, a country richly endowed with coal and whose economy is driven by the industrial sector, among others, with many environmental policy prospects, will need to choose to arrive at the most potent and desirable policy for the country's economic status. Therefore, the current study examined the role of eco-innovation in achieving carbon neutrality in South Africa.

The study's key findings showed that economic growth, fossil fuel and agricultural productivity increase CO_2 emission in both the short and long run in South Africa. Considering the mitigating role of renewable energy use and eco-technologies, our study shows that renewable energy has a negative and insignificant long-run effect on CO_2 while eco-technology has a negative and significant effect on South Africa's CO_2 emission in both the short and long run.

Table 1
Data description.

Variables information and source			
Indicators	Variable	Measurement	Source
GDP	Economic Growth	GDP per capita (constant 2015 US$)	World Bank Database
GDP^2	Economic Growth Squared	The squared of GDP per capita	Derived
AGRIC	Agriculture	Agriculture, forestry, and fishing, value added (constant 2015 US$)	World Bank Database
CO_2	Carbon Emissions	Metric Tonnes Per Capita	Ourwordindata Database
FF	Fossil Fuel	Fossil fuels per capita (kWh)	Ourwordindata Database
REC	Renewable Energy	Renewables per capita (kWh - equivalent)	Ourwordindata Database
ECO	Eco-innovation	Patent on environmental technologies	Ourwordindata Database

Author's computation.

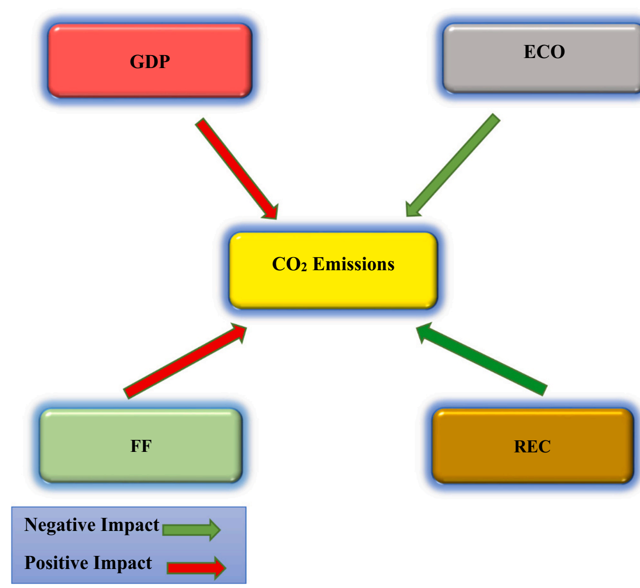

Fig. 1. Diagrammatic schematic of variable flow.

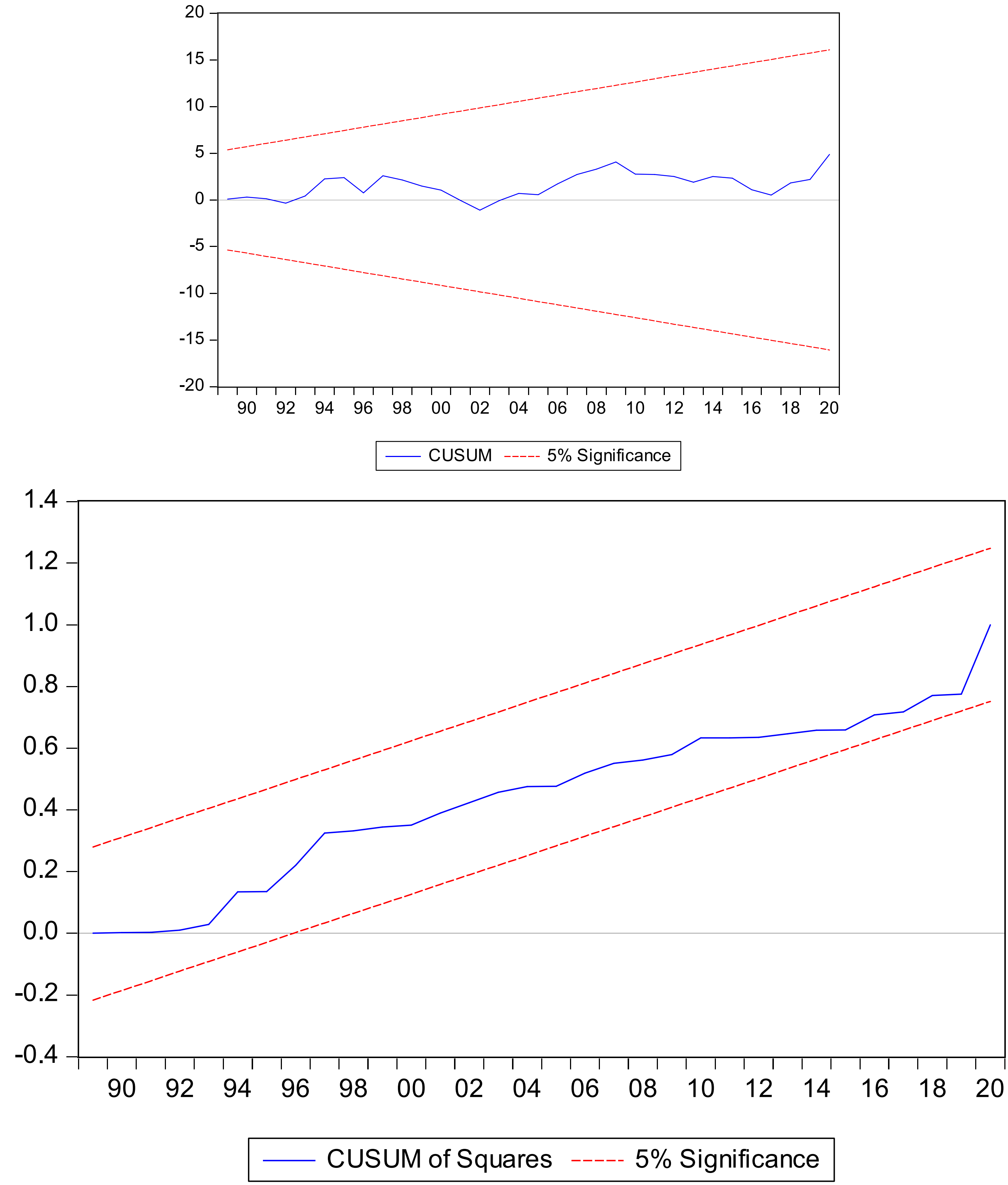

Fig. 2. a. CUSUM.
b. CUSUM of square.

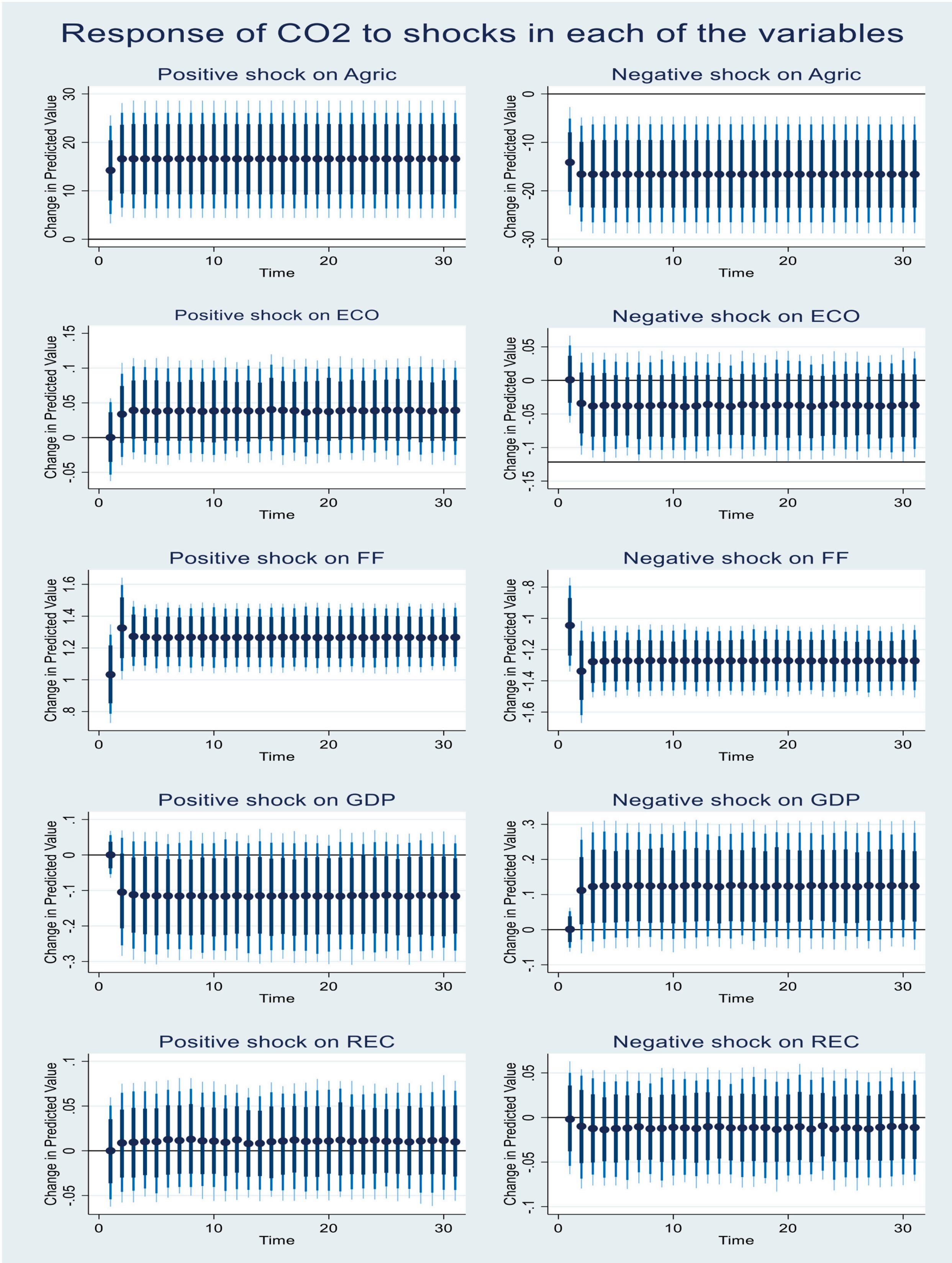

Fig. 3. Response of CO_2 to shocks in each of the variables under review.

Following the evidence of our study, it provides insight for policy suggestions. Since economic growth, fossil fuel and agricultural productivity increase CO_2 emission in South Africa, The present suggest that, to achieve the carbon neutrality target, South Africa should adopt carbon taxation measures to checkmate and control the carbon footprint emanating from economic activities focusing on the agricultural sector and industrial activities. Therefore, applying carbon taxation will discourage the extensive exploration of fossil fuels and will, in turn, motivate switching to renewable energy use. Also, the fact that renewable energy use has a long-run carbon reduction effect in Africa, there is a need for an aggressive investment in renewable energy in South Africa.

The current 19 GW renewable energy investment goal for 2030 is expected to be funded by the public sector. The pace of this investment may be slow due to fiscal revenue pressure on the government. Therefore, South Africa should create opportunities that allow private investors in renewable energy technologies, such as off-grid solar and wind energy, to accelerate renewable energy deployment in the country. Additionally, based on the fact that eco-technologies can lower CO_2 emissions in Africa, the government can consolidate this by introducing energy efficiency labelling on appliances and equipment used by households, businesses and firms across the sector. This will encourage energy-efficient practices, accelerating the country's pace towards carbon neutrality. Furthermore, since South Africa is very rich in coal, we are not making a case for the abandonment of their natural endowment, but we suggest that they adopt eco-technology like carbon capture storage and sequestration (CCSS) to capture the emissions from the use of coal, thereby making coal cleaner energy, which is crucial for the carbon neutrality journey.

The outcome of the study presents policy implications for carbon neutrality reduction. Despite the novelty, it is not without limitation. We have considered the role of renewable energy, environmental technology and innovation in lowering environmental damages caused through economic growth, fossil fuel use and agriculture in South Africa. The crucial challenge for renewable energy and eco-technology adoption is financing but in the present study, did not consider the issue of financing options for these technologies to combat CO_2 rise. Therefore, while renewable energy and eco-technology adoption can help lower CO_2, funding can be a hindrance. Hence, this opens an opportunity for future researchers to consider the role of finance in aiding renewable energy and eco-technology adoption towards carbon neutrality. Additionally, future study can also account for the role of institutional quality such as rule of law and corruption in the chase to drive a clean and favourable environment in the South African economy. Despite these study's limitation, the findings contribute significantly towards policy discussion on decarbonisation targets.

CRediT authorship contribution statement

Festus Victor Bekun: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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