RESEARCH ARTICLE

Does trade openness mitigate the environmental degradation in South Africa?

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Abstract

The debate over the role international trade plays in determining environmental outcomes has considerably generated more heat than light. Theoretical work has been successful in identifying a series of hypotheses linking openness to trade and environmental quality, but the empirical verification of these hypotheses has seriously lagged. This study revisits the dynamic relationship between trade openness and environmental quality in South Africa using time series data over the period 1960–2020. The recently developed novel dynamic autoregressive distributed lag (ARDL) simulation framework has been used. The outcomes of the analysis indicate that (i) trade openness deteriorates environmental quality in the long run, although it is environmentally friendly in the short run; (ii) the scale effect increases CO_2 emissions, whereas the technique effect contributes to lower it, thus validating the presence of an environmental Kuznets curve (EKC) hypothesis; (iii) energy consumption, foreign direct investment, and industrial value-added contribute to environmental deterioration; (iv) technological innovation improves environmental quality; (v) the pollution haven hypothesis (PHH) exists; and (vi) InSE, InTE, InOPEN, InEC, InFDI, InTECH, and InIGDP Granger-cause InCO$_2$ in the medium, long, and short run suggesting that these variables are important to influence CO_2 emissions. In light of our empirical evidence, this paper suggests that the international teamwork to lessen carbon emissions is immensely critical to solve the growing trans-boundary environmental decay and other associated spillover consequences.

Keywords Trade openness · CO_2 emissions · Dynamic ARDL simulations · Energy consumption · EKC · Cointegration · Economic growth · Industrial value-added · South Africa

JEL Classifications F18, F13, Q56 · O13 · F1 · F41

Introduction

Environmental degradation is now a global issue since every nation is exposed to such threats. The notion that environmental degradation poses a threat to only the industrialised countries and not the less developed countries is no longer valid today at least in terms of consequences (Shahbaz et al. 2013c). Greenhouse gas (GHG) emissions like carbon dioxide (CO_2) are seen as the driving factor for climate change, which happens due to internal changes within the climate system. The accumulation of GHG emissions in the surface of the earth is significantly affecting every nation across the world, both industrialised and less developed, notwithstanding the country which is responsible for such emissions. The tsunami in Japan, the earthquake in Haiti, the outburst of flood in Australia and Pakistan, and the burn out of fire in Russia are just few major disasters witnessed in the recent past that could be attributed to the repercussions of environmental degradation (Zerbo 2017). Such events brought about destructions to infrastructure, natural resources like agricultural land and produce, wildlife, forests, and most importantly to precious human lives. Although environmental deterioration is a global issue, and the entire world is exposed to threats arising from deterioration of environmental quality, the responsibility to save the world from such threats is largely dependent on nations like China, India, Russia, Brazil, OECD group, and USA, who are considered

the key GHG emitters (Shahbaz et al. 2013c). More importantly, the successful international efforts to minimise the global CO_2 emissions is substantially dependent on the commitment of these key emitters. However, difficulties arise for countries when the CO_2 emissions are related to energy production because energy works as an engine of economic growth. In such cases, curbing carbon dioxide emissions would mean to ultimately retard their economic growth, for which these countries are very reluctant to either comply or commit to programmes to minimise these emissions. This calls for finding better approaches in which sustainable economic growth and improved environmental quality could be attained. Therefore, trade openness is one of the ways that could help to accomplish these objectives.

South Africa has remarkably adopted comprehensive unilateral trade policy reforms during the early 1990s (Inglesi-Lotz 2018). This was subsequently followed by ambitious programs of free trade agreements (FTAs) with the European Union (EU), greater tariff liberalisation as part of its offer in the General Agreement on Tariffs and Trade (GATT) Uruguay round, regional integration, the Southern Africa Development Community (SADC), and more modest trade agreements with the European Free Trade Association (EFTA) states and MERCOSUR.[1]The period also coincided with the democratic election of the new government in 1994 that implemented a good number of reforms aimed at shifting the country's development strategy from export promotion with import controls to greater trade openness. In addition, the reforms led to a significant rationalisation and simplification of South Africa's tariff structure, where the list of prohibited imports was removed and the number of tariff lines decreased substantially from 12,000 during the early 1990s to 6,420 in 2006 (Edwards et al. 2009). Non-ad valorem tariff rates that were often applied during the early 1990s were substituted with ad valorem rates. Non-tariff barriers, import surcharges, and export subsidies were all removed. This evidence of such trade policy reforms makes South Africa a good candidate for this case study to ascertain their environmental effect. Furthermore, South Africa is an interesting case because it has made a significant progress in reducing "most favoured nation" (MFN) tariff rates from 17.9% in 1994 to 9.6% in 2019, thereby considerably decreasing anti-export bias and effective protection rates for many sectors (Udeagha and Breitenbach 2021). In South Africa, the implementation of these trade policy reforms has further led to a greater openness to international goods markets being a fundamental mechanism that brings about higher economic growth; permits the full exploitation of her

comparative advantage resulting in high returns to capital in her unskilled labour-abundance sectors; stimulates efficiency in resource allocation leading to improved economic growth; leads to transformation into larger factor accumulation, knowledge spillovers, and technology diffusion; enables the importation of investment and intermediate goods needed to boost her domestic production; and leads to openness to innovations and ideas. South Africa has equally witnessed improved technological innovations, which result in greater entrepreneurship via improved market access and higher competition; greater new investment opportunities, enhancing productivity, stimulating employment, and real wages.

On the other hand, South Africa is one of the major emitters of CO_2 emissions (1.09 of the world emissions) (World Bank 2021). The country is currently ranked 15th in terms of annual carbon dioxide emissions. The obvious reason for this is the use of coal, a major ingredient of CO_2 emissions, in energy production. Currently, South Africa holds 35,053 million tons (MMst) of proven coal reserves at the end of 2020, ranking 8th in the world and accounting for about 3.68% of the world's total coal reserves of 1,139,471 million tons (MMst).[2] South Africa has proven reserves equivalent to 173.3 times its annual consumption. South Africa is heavily dependent on energy sector where coal consumption is dominant in production activity. Almost 77% of the country's primary energy needs are provided by coal, whereas 53% of the coal reserves are used in electricity generation, 33% in petrochemical industries, 12% in metallurgical industries, and 2% in domestic heating and cooking. These characteristics further make South Africa a compelling candidate for a separate study. While considering the gains from trade policy reforms in South Africa, its environmental impact has received a less attention.

What does the evidence tell us? Just a few empirical studies have attempted to explicitly explore this link in the South African context. The most notable case is the recent paper by Aydin and Turan (2020), who show that trade openness has brought about a significant improvement in South Africa's environmental quality by reducing the growth of energy pollutants. Previous studies which investigated the relationship between trade openness and CO_2 emissions have one thing in common. They all proxied trade openness by using trade intensity (TI) and applying a simple ARDL methodology. The TI-based proxy conventionally defined as the ratio of trade (sum of exports and imports) to GDP only captures the trade of a country in relation to its share of income (GDP), although it is not contrived.[3] While it is intuitively sensible,

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[1] Mercado Commun del Cono Sur (Southern Common Market) consists of Venezuela, Uruguay, Paraguay, Brazil and Argentina as full members.

[2] For more details (see BP Statistical Review of World Energy 2021).

[3] This proxy is in sharp contradiction with other measures of trade openness, which have been used by earlier works such as the arbitrary binary (1,0) measure suggested by Sachs and Warner (1995).

the proxy does not help to resolve the ambiguity on how trade is measured and defined. Its main shortcoming is that it reflects only one dimension focusing on the comparative position of trade performance of a country linked to its domestic economy. In other words, this proxy only focuses on the question of how enormous the income contribution of a country in international trade is. Consequently, it woefully fails to address another crucial dimension of trade openness that is how important the explicit level of trade of a country to global trade is. This suggests that the proxy is unable to truly reflect the correct idea of trade openness and accurately capture the precise environmental impact of trade. Also, the use of the proxy penalises bigger economies like Germany, the USA, France, China, Japan, and so many others because they are being classified as closed economies due to their larger GDPs, whereas the poor countries such as Zimbabwe, Zambia, Venezuela, Uganda, Ghana, Nigeria, Togo, and many others are grouped as open economies due to their small GDPs (Squalli and Wilson 2011). Given this, the proxy therefore fails to reflect credibly the exact idea of trade openness because it does not capture the advantages a country enjoys while engaging enormously in global trade (Squalli and Wilson 2011). In addition, the diverse findings and conflicting evidence on the trade-CO_2 emission relationship are blamed on different methodologies and misspecification problems.

In this context, the current study contributes to scholarship and is different from previous studies in the following ways: First, identifying environmental consequences of international trade has a crucial role in constructing and planning strategies of any country like South Africa that is currently witnessing a significant increase in trade openness; however, little efforts are made to investigate the environmental consequences of trade openness in South Africa. Moreover, to the best of our knowledge, no study so far has empirically assessed the dynamic relationship between trade openness and environmental quality by incorporating potential factors such as energy consumption, foreign direct investment, technological innovation, and industrial value-added for South Africa. This is an important gap that this study intends to fill. Second, the work adopts an innovative measure of trade openness proposed by Squalli and Wilson (2011), which captures trade share in GDP as well as size of trade relative to the global trade. Therefore, employing the Squalli and Wilson proxy of trade openness in this study remarkably differentiates our paper from others, which predominantly used TI-based measure of trade openness. Third, previous studies, which examined the trade-environment nexus, have widely used the simple ARDL approach proposed by Pesaran et al. (2001) and other cointegration frameworks that can only estimate and explore the long- and short-run relationships between the variables. However, this study contributes to the extant literature on methodological

front by using the novel dynamic ARDL simulation model proposed by Jordan and Philips (2018), which overcomes the limitations of the simple ARDL approach. The novel dynamic ARDL simulation model can effectively and efficiently resolve the prevailing difficulties and result interpretations associated with the simple ARDL approach. This newly developed framework is capable of simulating and plotting to predict graphs of (positive and negative) changes in the variables automatically and also estimate their relationships for long run and short run. Therefore, the adaptation of this method in this present study enables us to obtain unbiased and accurate results. Fourth, it uses the frequency domain causality (FDC) approach, the robust testing strategy suggested by Breitung and Candelon (2006), which permits us to capture permanent causality for medium term, short term, and long term among the variables under review. This test is also used for robustness check in this study. To the best of our knowledge, previous studies have not used this test in the trade-environment nexus especially in the context of South Africa. Lastly, it employs the second-generation econometric procedures accounting robustly for the multiple structural breaks which have been considerably ignored in earlier studies.[4] In light of this, the paper uses the Narayan and Popp's structural break unit root test since empirical evidence shows that structural breaks are very persistent in empirical literature and many macroeconomic variables like CO_2 emissions and trade openness are affected by structural breaks.

To visually observe the link between trade openness and environmental quality (proxied by CO_2 emissions) in South Africa, we plot them in Fig. 1, which shows the trends in trade openness and CO_2 emissions in South Africa over the period 1960–2020. To link these two variables, the study divides the time series data into two categories namely "period before trade policy reforms between 1960 and 1988" and "period after trade policy reforms with greater trade openness between 1989 and 2020." The trends depicted show a downward trend in trade openness during the 1960s, followed by an upward trend during the 1970s. This upward trend in trade openness coincides with the period after the implementation of export promotion industrialisation in South Africa, which was incepted in 1972. South Africa's trade openness, however, declined considerably during the early 1980s and again during the early 1990s, particularly between 1990 and 1992. However, from 1993 onwards, trade openness showed a steady upward trend, reaching a peak of 72.9% in 2008. Following the decline in the world trade as

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[4] Perhaps, these procedures have been largely ignored by previous studies due to the limited data observations since an application of structural break analysis requires the span of time series to be quite long.

Fig. 1 Trends in trade openness and CO_2 emissions in South Africa, 1960–2020. While the period between 1960 and 1988 was before trade policy reforms, the period between 1989 and 2020 was charac-terised by trade policy reforms with greater trade openness. Source: Constructed from World Bank World Development Indictors (2020)

a result of the 2008 global recession, South Africa's trade openness dropped sharply to 55.4% in 2009, before rising again in 2010. During the period between 2011 and 2020, South Africa's trade openness has remained slightly above 60% (World Bank 2021; Dauda et al. 2021).

Concerning CO_2 emissions, Fig. 1 shows an upward trend in CO_2 emissions over the period 1960–2020. Since South Africa is the world's 14th largest emitter of GHG emissions, carbon emissions are gradually increasing and its CO_2 emissions are principally due to a heavy reliance on coal (World Bank 2021). However, a recently released draft electricity plan proposes a significant shift away from the fuel, towards gas and renewables. While coal would continue to play a role for decades, the plan would see no new plants built after 2030 and four-fifths of capacity closed by 2050. South Africa has pledged to peak its emissions between 2020 and 2025, allowing them to plateau for roughly a decade before they start to fall.

The remainder of the paper is organised as follows. "Literature review" reviews the relevant literature on trade-environment nexus. "Material and methods" outlines the material and methods, while "Empirical results and their discussion" discusses the results. "Conclusions and policy implications" concludes with policy implications.

Literature review

The theoretical underpinning on the environmental effect of trade openness was earlier developed by Copeland and Taylor (1994) and Grossman and Krueger (1995), Grossman and Krueger (1995). Antweiler et al. (2001), who later amplified it, highlight the various factors influencing carbon emissions and channels through which trade openness can affect the environment. The study thus divides the environmental impacts into composition, technique, and scale effects. The structural composition of a country's industrial production determines the level of environmental degradation. Composition effect therefore reflects the environmental effect of this structural composition. A country with more carbon-intensive production structure will always generate more environmental pollution compared to its counterpart whose production structure is less carbon-intensive. So, the nature of a country's industrial composition and structural arrangement determines the level of that country's environmental quality. Scale effect, on the other hand, is an effect on emissions brought about by a rise in income. As income increases, it deteriorates environmental quality because of intensive production. The technique effect arises due to the enforcement of environmental laws, which force private sector to comply with the adoption of greener, cleaner, and updated production processes improving environmental quality. The technique effect results in a better environmental quality because of people's predisposition for a clean environment as well as the enforcement of more stringent environmental standards as income increases (Kebede 2017). In summary, Antweiler et al. (2001) stress that the overall composition effect will be determined by the magnitude of a country's openness to international trade, the resource abundance, comparative advantage, and the enforcement of environmental standards. Developed countries with high environmental standards usually produce less carbon-intensive goods; however, their less developed counterparts with

feeble and compromised environmental laws always specialise in production of more pollution-intensive products.

Turning to empirical literature, a good number of works have investigated the relationship between trade and the environmental quality. However, the findings of these studies are mostly contradictory and unsettled across various methodological frameworks and countries scrutinised. While some works concluded that trade openness brings about improvement in environmental quality through various channels (Ding et al. 2021; Ibrahim and Ajide 2021b, 2021c; Khan et al. 2020), a few studies contended that trade openness results in worsening environmental condition (Khan et al. 2021a; Khan and Ozturk 2021; Ibrahim and Ajide 2021a; Van Tran 2020; Ali et al. 2020). On the contrary, another group of works found robust evidence that trade openness has no impact on the environment (Gulistan et al. 2020; Oh and Bhuyan 2018).

Empirical study by Ding et al. (2021), who use cross-sectional autoregressive distributed lag (CS-ARDL) and augmented mean group (AMG) methods, finds that higher trade openness contributes to improve environmental quality for G-7 economies. Also, Ibrahim and Ajide. (2021b), who use common correlated effect mean group (CCEMG), and mean group (MG) in case of G-20 countries, find that trade openness reduces environmental deterioration. Similarly, Ibrahim and Ajide. (2021c), who use trade facilitation (TF) as a measure of trade openness for 48 Sub-Saharan African countries for the period spanning 2005–2014, observe that TF is environmentally friendly and promotes environmental quality in the region. Using AMG and CCEMG methods, Khan et al. (2020) find evidence for the enhancing role of trade openness.

In contrast, empirical study by Khan et al. (2021a) reveal that trade openness deteriorates the environmental condition in Pakistan. This empirical evidence is also corroborated by Ibrahim and Ajide (2021a), who find that trade openness contributes to increase CO_2 emissions in G-7. Similar results were observed by Van Tran (2020), who shows that trade openness worsens the environmental condition in 66 developing economies over the period 1971–2017. Using the difference and system generalised method of moments, Khan and Ozturk (2021) find that trade openness increases CO_2 emissions for 88 developing countries over the period 2000–2014. Equally, Ali et al. (2020) find that openness to international goods market has a damaging effect and contributes greatly to worsen the environmental conditions of OIC[5] countries. This evidence is further supported by the study of Aydin and Turan (2020) for China and India over the period 1996–2016.

For South Africa's case, empirical evidence is also conflicting and largely mixed (Udeagha and Ngepah 2019; Menyah and Wolde-Rufael 2010; Kohler 2013; Shahbaz et al. 2013c; Zerbo 2015; Zerbo 2017; Khobai and Le Roux 2017; Hasson and Masih 2017; Mapapu and Phiri 2018; Inglesi-Lotz 2018). The recent study by Udeagha and Ngepah (2019) reveals that, in the long run, openness to international goods markets contributes to deteriorate the environment of South Africa, although there is strong evidence that trade openness can contribute to improve the country's environment in the short run. The authors' findings further reveal evidence of strong asymmetric behaviour between trade openness and CO_2 emissions.

Material and methods

This part starts by presenting the functional framework (EKC hypothesis framework), data, and its sources used in the study, with an analysis of the most important statistical characteristics; then, it moves to define the model specification and presents the variables used in the study and the reasons for choosing these variables. The final section in this part explains the novel dynamic ARDL simulation model versus the ARDL model.

Functional form

This work follows the robust empirical approach widely used in earlier studies by adopting the usual EKC hypothesis framework to revisit the trade-CO_2 emission nexus for South Africa. In its standard form, following Udeagha and Breitenbach (2021), Udeagha and Ngepah (2019), Cole and Elliott (2003), and Ling et al. (2015), the standard EKC hypothesis is thus presented as follows:

$$CO_2 = F(SE, \ TE) \tag{1}$$

where CO_2 represents CO_2 emissions per capita (in metric tons), an environmental quality measure; SE denotes scale effect, a proxy for economic growth; and TE represents technique effect, which captures the square of economic growth. When Eq. (1) is log-linearised, the following is thus obtained:

$$InCO_{2t} = \alpha + \varphi InSE_t + \beta InTE_t + \varepsilon_t \tag{2}$$

Scale effect (economic growth) deteriorates environmental quality as income increases; however, technique effect improves environmental quality due to the enforcement of environmental laws and people's predisposition for a clean environment (Cole and Elliott 2003; Ling et al. 2015). Given this background, for EKC hypothesis to be present, the theoretical expectations require that $\varphi > 0$ and $\beta < 0$. Following

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[5] Organization of Islamic Cooperation.

literature, as control variables in the trade-CO_2 emission equation, we use foreign direct investment, energy consumption, technological innovation, and industrial value-added. Accounting for these variables as well as trade openness, Eq. (2) is thus augmented as follows:

$$\ln CO_{2t} = \alpha + \varphi \ln SE_t + \beta \ln TE_t + \rho \ln OPEN_t + \pi \ln EC_t$$
$$+ \delta \ln FDI_t + \tau \ln TECH_t + \omega \ln IGDP_t + U_t \quad (3)$$

where $\ln OPEN_t$ represents trade openness, $\ln EC_t$ denotes energy consumption, $\ln FDI_t$ captures foreign direct investment, $\ln TECH_t$ is technological innovation, and $\ln IGDP_t$ denotes industrial value-added. All variables are in natural log. $\varphi, \beta, \rho, \pi, \delta, \tau,$ and ω are the estimable coefficients capturing different elasticities, whereas U_t captures the stochastic error term with standard properties.

Variables and data sources

This paper uses yearly times series data covering the period 1960–2020. CO_2 emission, as the proxy for environmental quality, is the dependent variable. Economic growth proxied by scale effect and the square of economic growth capturing the technique effect are used to validate the presence of EKC hypothesis. Trade openness proxied by a composite trade intensity (CTI) is calculated as below. The other variables controlled for, following literature, are as follows: energy consumption (EC), foreign direct investment (FDI), technological innovation (TECH), and industrial value-added to GDP (IGDP).

Following Squalli and Wilson (2011), this work uses CTI as a measure of trade openness to robustly account for trade share in GDP and size of trade relative to global trade. Using this way to measure trade openness enables us to effectively address the shortcomings of conventional trade intensity (TI) widely used in earlier studies. More importantly, the novel CTI contains more crucial information pertaining to a country's trade contribution share in terms of global economy, which intuitively captures TI adjusted by the share of level of trade in relation to global trade. The novelty of CTI in this work is that it mirrors trade outcome reality because it contains two dimensions of a country's ties with the rest of the world. The CTI is presented thus as follows:

$$CTI = \frac{(X+M)_i}{\frac{1}{n}\sum_{j=1}^{n}(X+M)_j} \frac{(X+M)_i}{GDP_i} \quad (4)$$

where i reflects South Africa and j captures her trading partners. In Eq. (4), the first portion represents global trade share, whereas the second segment denotes trade share of South Africa.

The justifications on the variables controlled for in the trade-CO_2 emissions equation are summarily presented as follows: energy consumption as utilised by many studies

(Khan et al. 2021b; Kongkuah et al. 2021; Li et al. 2021) is used in this study to track energy consumption effect on CO_2 emissions since energy sector causes 75% of the global GHC emissions (International Energy Association 2015). Foreign direct investment, although plays a pivotal role in boosting the development and growth of an economy, especially when the domestic reserves are not enough to fulfil the local investment requirements, may deteriorate the host country's environmental quality (Mukhtarov et al. 2021). Therefore, following Mahalik et al. (2021) and An et al.(2021a, b), the study uses foreign direct investment to capture its environmental effect since inflow of FDI propagates more economic activities and thus increases CO_2 emissions (Islam et al. 2021). Technological innovation is seen as a key factor that brings about minimum energy consumption, boosts energy efficiency, and fosters environmental quality (Ibrahim and Vo 2021; Destek and Manga 2021). An improved application of technological innovations is crucial to facilitate green economies and helps to reduce the growing levels of CO_2 emissions. Therefore, following Guo et al. (2021) and Anser et al. (2021), the study includes technological innovation as one of the determinants of CO_2 emissions to explore its impact since it can contribute to transform energy resources such as renewables from conventional to more efficient and sustainable sources. The country's environmental and total carbon footprints are an important element of the economic exposure to industrialisation (Rehman et al. 2021). When industrialisation grows, natural resources tend to be absorbed more rapidly, and this impacts not only on the general well-being of the large population but also the environment. Therefore, following Khan et al. (2021b) and Appiah et al. (2021), industrial value-added is used to track the effect of industrialisation on CO_2 emissions.

Table 1 therefore summarises the variable definition and data sources.

Narayan and Popp's structural break unit root test

As a first step, before implementing the novel dynamic ARDL simulations model, it is important to conduct a stationarity test on the variables under review to ascertain their order of integration. Thus, this work employs Dickey-Fuller GLS (DF-GLS), Phillips-Perron (PP), Augmented Dickey-Fuller (ADF), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) unit root tests to confirm the asymptotic behaviour and order of integration of all variables under review. This process helps to resolve the issues of spurious regressions. In the second step, the Narayan and Popp's structural break unit root test is used since empirical evidence shows that structural breaks are very persistent in empirical literature and many macroeconomic variables like CO_2 emissions and trade openness are likely to be affected.

Table 1 Definition of variables and data sources

Variable	Description	Expected sign	Source
CO_2	CO_2 emissions (kg per 2010 US\$ of GDP)	N/A	WDI
EC	Energy consumption, million tonnes oil equivalent	Positive	BP Statistical Review of World Energy
OPEN	Trade openness computed as composite trade intensity introduced by Squalli and Wilson (2011) capturing trade effect	Positive or negative	WDI, Authors
SE	Real GDP per capita capturing scale effect	Positive	WDI
TE	Real GDP per capita squared capturing technique effect	Negative	WDI, Authors
FDI	Foreign direct investment, net inflows (% of GDP)	Positive	WDI
TECH	Technological innovation measured by total patent applications	negative	WDI
IGDP	Industry, value added (% of GDP)	Positive or negative	WDI

N/A not available, *WDI* World Development Indicator

ARDL bounds testing approach

This paper employs the bound test to examine the nexus among the variables under review for long run. The ARDL bound testing approach, following Pesaran et al. (2001), is presented as follows:

$$\Delta \text{InCO}_{2t} = \gamma_0 + \sum_{i=1}^{n} \gamma_{1i}\Delta\text{InCO}_{2t-i} + \sum_{i=0}^{n} \gamma_{2i}\Delta\text{InSE}_{t-i} + \sum_{i=0}^{n} \gamma_{3i}\Delta\text{InTE}_{t-i}$$
$$+ \sum_{i=0}^{n} \gamma_{4i}\Delta\text{OPEN}_{t-i} + \sum_{i=0}^{n} \gamma_{5i}\Delta\text{EC}_{t-i}$$
$$+ \sum_{i=0}^{n} \gamma_{6i}\Delta\text{InFDI}_{t-i} + \sum_{i=0}^{n} \gamma_{7i}\Delta\text{InTECH}_{t-i}$$
$$+ \sum_{i=0}^{n} \gamma_{8i}\Delta\text{InIGDP}_{t-i}$$
$$+ \theta_1\text{InCO}_{2t-i} + \theta_2\text{InSE}_{t-i}$$
$$+ \theta_3\text{InTE}_{t-i} + \theta_4\text{InOPEN}_{t-i} + \theta_5\text{InEC}_{t-i}$$
$$+ \theta_6\text{InFDI}_{t-i} + \theta_7\text{InTECH}_{t-i} + \theta_8\text{InIGDP}_{t-i} + \varepsilon_t \quad (5)$$

where Δ represents the first difference, InCO$_2$, InSE, InTE, InOPEN, InEC, InFDI, InTECH, and InIGDP, respectively. Meanwhile, $t-i$ denotes the optimal lags selected by Schwarz's Bayesian Information Criterion (SBIC), and γ and θ are the estimated coefficients for short run and long run, respectively. The ARDL model for the long and short run will be approximated if variables are cointegrated. The null hypothesis, which tests for long-run relationship, is as follows: ($H_0 : \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = \theta_7 = \theta_8 = 0$) against the alternative hypothesis ($H_1 : \theta_1 \neq \theta_2 \neq \theta_3 \neq \theta_4 \neq \theta_5 \neq \theta_6 \neq \theta_7 \neq \theta_8 \neq 0$).

Rejection or acceptance of null hypothesis depends on the value of the calculated *F*-statistic. If the value of calculated *F*-statistic is greater than the upper bound, we reject the null hypothesis and conclude that the variables are having a long-run relationship or there is evidence of cointegration. However, cointegration does not exist if the value of calculated *F*-statistic is less than the lower bound. In addition, if the value of the calculated *F*-statistic lies between lower and upper bounds, the bound test becomes inconclusive. If the variables are having a long-run relationship, then the long-run ARDL model to be estimated is as follows:

$$\Delta \text{InCO}_{2t} = \beta_0 + \sum_{i=1}^{q} \omega_1\text{InCO}_{2t-i} + \sum_{i=1}^{q} \omega_2\text{InSE}_{t-i}$$
$$+ \sum_{i=1}^{q} \omega_3\text{InTE}_{t-1} + \sum_{i=1}^{q} \omega_4\text{InOPEN}_{t-i} + \sum_{i=1}^{q} \omega_5\text{InEC}_{t-1} + \sum_{i=1}^{q} \omega_6\text{InFDI}_{t-1} \quad (6)$$
$$+ \sum_{i=1}^{q} \omega_7\text{InTECH}_{t-1} + \sum_{i=1}^{q} \omega_8\text{InTECH}_{t-1} + \varepsilon_t$$

ω denotes the long-run variance of variables in Eq. (6). In choosing the correct lags, the paper uses the SBIC. For short-run ARDL model, the error correction model used is as follows:

$$\Delta \text{InCO}_{2t} = \beta_0 + \sum_{i=1}^{q} \pi_1\Delta\text{InCO}_{2t-i} + \sum_{i=1}^{q} \pi_2\Delta\text{InSE}_{t-i}$$
$$+ \sum_{i=1}^{q} \pi_3\Delta\text{InTE}_{t-1} + \sum_{i=1}^{q} \pi_4\Delta\text{InOPEN}_{t-i} + \sum_{i=1}^{q} \pi_5\Delta\text{InEC}_{t-1}$$
$$+ \sum_{i=1}^{q} \pi_6\text{In}\Delta\text{FDI}_{t-1} + \sum_{i=1}^{q} \pi_7\Delta\text{InTECH}_{t-1} \quad (7)$$
$$+ \sum_{i=1}^{q} \pi_8\Delta\text{InTECH}_{t-1} + \text{ECT}_{t-i} + \varepsilon_t$$

In Eq. (7), π reflects the short-run variability of the variables, whereas ECT denotes the error correction term that captures the adjustment speed of disequilibrium. The estimated coefficient for ECT ranges from −1 to 0. This work further uses the diagnostic tests for model stability. The Breusch Godfrey LM test is used to check for serial corrections; the Breusch-Pagan-Godfrey test and the ARCH test are both employed to test for heteroscedasticity; the Ramsey RESET test is used to ensure that the model is correctly specified, and the Jarque–Bera Test is used to test whether the estimated residuals are normally distributed. To check for structural stability, this paper employs the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMSQ).

Table 2 Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. Dev	Skewness	Kurtosis	J-B Stat	Probability
CO_2	0.264	0.238	0.477	0.084	0.120	0.217	1.652	4.682	0.196
SE	7.706	7.959	8.984	6.073	0.843	−0.511	2.156	4.102	0.129
TE	60.316	63.754	80.717	36.880	12.663	−0.387	2.082	3.422	0.181
OPEN	6.060	6.512	7.665	2.745	1.329	0.636	2.077	5.757	0.156
EC	4.220	4.422	4.840	3.177	0.527	−0.558	1.921	5.621	0.160
FDI	13.203	13.286	14.659	11.913	0.738	0.056	2.463	0.702	0.704
IGDP	3.513	3.580	3.813	3.258	0.161	−0.215	1.697	4.474	0.107
TECH	9.360	9.255	10.545	8.210	0.766	0.082	1.634	4.499	0.105

Source: Authors' calculations

Dynamic autoregressive distributed lag simulations

Previous studies, which investigated the trade-CO_2 emission nexus, have widely used the simple ARDL approach proposed by Pesaran et al. (2001) and other cointegration frameworks that can only estimate and explore the short- and long-run relationships between the variables. To address the shortcomings which characterise the simple ARDL model, Jordan and Philips (2018) recently developed the novel dynamic ARDL simulation model that can effectively and efficiently resolve the prevailing difficulties and result interpretations associated with the simple ARDL approach. This newly developed framework is capable of simulating and plotting to predict graphs of (positive and negative) changes in the variables automatically and estimate the relationships for short run and long run. The major advantage of this framework is that it can predict, simulate, and immediately plot probabilistic change forecasts on the dependent variable in one explanatory variable while holding other regressor constant. In this study, based on the multivariate normal distribution for the parameter vector, the dynamic ARDL error correction algorithm uses 1000 simulations. We employ the graphs to examine the actual change of an explanatory variable as well as its influence on the dependent variable. The novel dynamic ARDL simulation model is presented as follows:

$$
\begin{aligned}
\Delta \ln CO_{2t} = \alpha_0 &+ \upsilon_0 \ln CO_{2t-1} + \varphi_1 \Delta SE_t + \rho_1 SE_{t-1} \\
&+ \varphi_2 \Delta TE_t + \rho_2 TE_{t-1} + \varphi_3 \Delta OPEN_t + \rho_3 OPEN_{t-1} \\
&+ \varphi_4 \Delta EC_t + \rho_4 EC_{t-1} + \varphi_5 \Delta FDI_t + \rho_5 FDI_{t-1} \\
&+ \varphi_6 \Delta TECH_t + \rho_6 TECH_{t-1} + \varphi_7 \Delta IGDP_t + \rho_7 IGDP_{t-1} + \varepsilon_t
\end{aligned}
\tag{8}
$$

Frequency domain causality test

This paper uses the frequency domain causality (FDC) approach, the robust testing strategy suggested by Breitung and Candelon (2006) to explore the causal relationships among the variables under scrutiny. Unlike the traditional Granger causality approach where it is extremely impossible to predict the response variable at a particular time frequency, FDC enables that and further permits to capture permanent causality for medium term, short term, and long term among the variables under examination. This test is also used for robustness check in this study.

Empirical results and their discussion

Summary statistics

The summary statistics of the variables used in this work are analysed and scrutinised before discussing the results. Table 2 reports the overview of statistics showing that the CO_2 emission average value is 0.264. The technique effect (TE), the square of GDP per capita, has the average mean of 60.316 greater than other variables. This is followed by foreign direct investment (FDI) which has 13.203. In addition to characterising the summary statistics, Table 2 uses kurtosis to represent the peak, while the Jarque–Bera test statistics is used to check for normality of our data series. The table shows that the scale effect, trade openness, energy consumption, foreign direct investment, industrial value-added, and technological innovation show a positive trend, while technique effect has a negative trend. The variance in technique effect (TE) is the highest of all the variables showing the high level of volatility in this variable. The variance in CO_2 emissions is less relative to technique effect showing that CO_2 emissions are far more stable. Also, the variations in trade openness (OPEN), scale effect (SE), and technological innovation

Table 3 Unit root analysis

Variable	Dickey-Fuller GLS	Phillips-Perron	Augmented Dickey-Fuller	Kwiatkowski-Phillips-Schmidt-Shin	Narayan and Pop (2010) unit root test			
					Model 1		Model 2	
	(DF-GLS)	(PP)	(ADF)	(KPSS)	Break-year	ADF-stat	Break-year	ADF-stat
Level	Test – Statistics value							
$lnCO_2$	− 0.570	− 0.464	− 1.152	0.966	1982:1985	− 3.132	1987:1994	− 8.160***
lnSE	− 0.116**	− 0.079	− 1.308	0.833***	1979:1988	− 2.914	1982:1990	− 7.601***
lnTE	− 0.112*	− 0.076	− 1.268	0.848***	1979:1990	− 1.939	1982:1994	− 6.791***
lnOPEN	− 0.072	− 0.082	− 1.335	1.080*	1996:2001	− 3.053	2003:2009	− 7.318***
lnEC	− 0.011	− 0.014	− 0.366	1.300***	1982:1989	− 4.372**	1985:1991	− 8.521***
lnFDI	− 0.032*	− 0.001	− 0.012	0.640	2001:2006	− 2.021	2004:2010	− 8.362***
lnTECH	− 0.254***	− 0.284***	− 2.999	0.255***	1995:2000	− 4.318	2008:2011	− 7.821***
lnIGDP	− 0.046	− 0.071*	− 1.718	1.060**	1972:1985	− 3.815	1982:1991	− 7.521***
First difference					Critical value (1%, 5%, and 10%)			
$\Delta lnCO_2$	− 0.995***	− 0.996***	− 7.176***	0.705***	1999:2005	− 4.801**	1980:1991	− 5.832***
Δ lnSE	− 0.695***	− 0.707***	− 5.319***	0.585***	1983:1997	− 5.831***	1985:1995	− 6.831***
Δ lnTE	− 0.694***	− 0.707***	− 5.316***	0.589***	1991:2000	− 8.531***	1987:1996	− 5.893***
Δ lnOPEN	− 0.935***	− 0.938***	− 6.699***	0.626***	1996:2004	− 6.842**	2001:2007	− 8.942***
Δ lnEC	− 1.105***	− 1.121***	− 8.142***	0.586***	1985:1993	− 5.921***	1989:1997	− 7.942***
Δ lnFDI	− 0.207**	− 0.209**	− 6.443***	0.609***	2005:2008	− 6.831***	2001:2008	− 6.973***
Δ lnTECH	− 1.023***	− 1.034***	− 7.473***	0.424***	1999:2003	− 4.841**	2006:2010	− 5.983***
Δ lnIGDP	− 0.799***	− 0.801***	− 5.878***	0.431***	1975:1990	− 7.742***	1988:1992	− 7.892***

Source: Authors' calculations

*, **, and *** denote statistical significance at 10%, 5%, and 1% levels, respectively. MacKinnon's (1996) one-sided p-values. Lag length based on SIC and AIC. Probability-based on Kwiatkowski-Phillips-Schmidt-Shin (1992). The critical values for Narayan-Popp unit root test with two breaks are followed by Narayan and Pop (2010). All the variables are trended

Table 4 Lag length criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	178.453	NA	3.2e − 12	− 6.594	− 6.331	− 6.493
1	607.095	857.28	1.5e − 18	− 21.195	− 19.094*	− 20.390*
2	661.093	108	1.4e − 18	− 21.388	− 17.448	− 19.877
3	719.755	117.32	1.2e − 18*	− 21.759	− 15.981	− 19.544
4	784.113	128.72*	1.3e − 18	− 22.350*	− 14.733	− 19.430

Source: Authors' calculations

[*]Lag order selected by the criterion

(TECH) are quite greater. In addition, the Jarque–Bera statistics shows that our data series are normally distributed.

Order of integration of the respective variables

Table 3 reports the results of DF-GLS, PP, ADF, and KPSS showing that after first differencing all variables which are non-stationary in level become stationary at I (1). This implies that all the series under review are either $I(1)$ or $I(0)$ and none is $I(2)$. The traditional unit root tests reported above do not account for structural breaks. Therefore, this work implements a testing strategy which is able to account

for two structural breaks in the variables. The paper hence uses the Narayan and Popp's unit root test with two structural breaks, and the results are also reported in the right-hand panel of Table 3. The empirical evidence shows that the null hypothesis of unit root cannot be rejected. Consequently, all data series are integrated of order one and prospective application for the dynamic ARDL bound testing approach.

Table 5 ARDL bounds test analysis

Test statistics	Value	K	H_0	H_1		
F-statistics	14.341	7	No level relationship	Relationship exists		
t-statistics	−8.752					
Kripfganz and Schneider (2018) critical values and approximate p-values y						
Significance	F-statistics		t-statistics		p-value F	
	1 (0)	1 (1)	1 (0)	1 (1)	1 (0)	1 (1)
10%	2.12	3.23	−2.57	−4.04	0.000***	0.000***
5%	2.45	3.61	−2.86	−4.38	p-value t	
1%	3.15	4.43	−3.43	−4.99	0.000***	0.002**

*, ** and *** respectively represent statistical significance at 10%, 5%, and 1% levels. The respective significance levels suggest the rejection of the null hypothesis of no cointegration. The optimal lag length on each variable is chosen by the Schwarz's Bayesian information criterion (SBIC)

Table 6 Diagnostic statistics tests

Diagnostic statistics tests	X^2(p values)	Results
Breusch Godfrey LM test	0.3812	No problem of serial correlations
Breusch-Pagan-Godfrey test	0.2610	No problem of heteroscedasticity
ARCH test	0.6837	No problem of heteroscedasticity
Ramsey RESET test	0.5183	Model is specified correctly
Jarque–Bera Test	0.2715	Estimated residual are normal

Source: Authors' calculations

Lag length selection results

Table 4 reports the findings of different test criteria for lags selection. The use of HQ, AIC, and SIC is documented in empirical literature as the most popular for selecting appropriate lags. In this study, SIC is used for lag selection. Based on this tool, lag one is suitable for our model. This is because the lowest value is obtained at lag one when SIC is used unlike others.

Cointegration test results

Table 5 displays the results of the cointegration test utilising the surface-response regression suggested by Kripfganz and Schneider (2018). Since the F- and t-statistics are greater than the upper bound critical values at various significance levels, we reject the null hypothesis. Thus, our empirical evidence suggests that cointegration exists among the variables under consideration.

Diagnostic statistics tests

To ensure that our chosen model is reliable and consistent, the study therefore uses different diagnostic statistics tests and their empirical results are reported in Table 6. The empirical results suggest that the used model is well fitted having passed all the diagnostic tests. The model does not suffer from the problems of serial correlation and autocorrelation as confirmed by the Breusch Godfrey LM test. The Ramsey RESET test is used, and evidence shows that the model does not suffer from misspecification. The Breusch-Pagan-Godfrey test and ARCH test are both employed to test if there is evidence of heteroscedasticity in the model. The empirical findings suggest that heteroscedasticity is moderate and not a problem. Finally, the Jarque–Bera test result shows that the model's residuals are normally distributed.

Dynamic ARDL simulations model results

The dynamic ARDL simulation model results are reported in Table 7. Our findings show that the scale effect (InSE) and technique effect (InTE) positively and negatively affect CO_2 emissions, respectively. The scale effect representing economic growth deteriorates environmental quality, whereas the technique effect has a mitigating effect on the environment. The empirical evidence therefore suggests that the EKC hypothesis holds in the case of South Africa, where real income grows until a certain threshold level, whereas CO_2 emissions start to decline. In the initial stage of economic growth, the environmental quality decreases, whereas after reaching the optimum level, environmental quality starts improving in South Africa. This supports the inverted U-shaped relationship between economic growth and environmental quality. The findings are justifiable for South Africa and associated with structural change and

Table 7 Dynamic ARDL simulations analysis

	Estimations using composite trade intensity (CTI) as a proxy of trade openness			Estimations using traditional trade intensity (TI) as a proxy of trade openness		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Coefficient	St. error	t-value	Coefficient	St. error	t-value
Cons	− 1.2162	1.1524	− 0.70	− 1.2030	1.1702	− 0.51
InSE	0.2042***	0.1710	4.72	0.1730**	0.1603	2.40
Δ InSE	0.3041***	0.2081	2.83	0.4102**	0.1305	2.20
InTE	− 0.6173**	0.8172	− 2.41	− 0.6040***	0.5072	− 3.50
Δ InTE	− 0.7051	0.1430	− 1.63	− 0.5102	0.1318	− 1.01
InOPEN	0.1210***	0.0415	5.01	0.9816**	0.6103	2.51
Δ InOPEN	− 0.2316**	0.0513	− 2.61	− 0.4032*	0.1302	− 1.99
InEC	0.2057***	0.1603	3.06	0.1401**	0.1267	2.57
Δ InEC	0.4814*	0.1615	1.99	0.4035**	0.1028	2.48
InFDI	0.9071	0.0835	1.14	0.9102	0.0710	1.05
Δ InFDI	0.2801**	0.2641	2.48	0.1704***	0.5047	3.81
InTECH	− 0.7166***	0.5317	− 3.01	0.8014	0.1331	1.40
Δ InTECH	− 0.2210	0.0715	− 0.25	0.3010	0.0521	0.59
InIGDP	0.3414**	0.1542	2.52	0.4402*	0.1401	1.98
Δ InIGDP	0.5935	0.2270	0.10	0.4103	0.2110	0.25
ECT(− 1)	− 0.8521***	0.1364	− 3.14	− 0.7140**	0.1482	− 2.55
R-squared	0.898			0.510		
Adj R-squared	0.860			0.4904		
N	59			59		
P val of F-sta	0.0000***			0.0000***		
Simulations	1000					
Root MSE	0.081			0.271		

Source: Authors' calculations

*, **, and *** denote statistical significance at 10%, 5%, and 1% levels, respectively

technological advancement in the country. Environmental awareness increases among the people as income grows, so environmental regulations are enforced to use energy-efficient technologies to mitigate pollution. These results coincide with the work of Udeagha and Breitenbach (2021), who highlight the existence of EKC hypothesis for the Southern African Development Community (SADC) over the period 1960–2014. Alharthi et al. (2021) also find similar results that EKC hypothesis exists for the Middle East and North Africa (MENA) countries. Likewise, Bibi and Jamil (2021), who examine the association between air pollution and economic growth, find a support for the EKC hypothesis, which suggests an inverted U-shaped link between air pollution and economic growth in six different regions including Latin America and the Caribbean, East Asia and the Pacific, Europe and Central Asia, South Asia, the Middle East and North Africa, and Sub-Saharan Africa. Udeagha and Ngepah (2020, 2019) also find that the EKC hypothesis exists for South Africa. Our results further reciprocate the findings of Isik et al. (2021) for 8 Organisation for Economic Co-operation and Development (OECD) countries, Liu et al.

(2021) for China, Sun et al. (2021) for China, Naqvi et al. (2021) for 155 countries of four different income groups, and Murshed (2021) for six South Asian economies. However, the findings contradict with Minlah and Zhang (2021), who find that the Environmental Kuznets Curve for carbon dioxide emissions for Ghana is upward sloping, contrary to the standard Environmental Kuznets Curve theory which postulates an inverted "U"-shaped relationship between economic growth and environmental degradation. Ozturk and Al-Mulali (2015), Sohag et al. (2017), Tedino (2017), and Mensah et al. (2018) also find similar results showing that the EKC hypothesis does not hold.

The estimated coefficient for long run on trade openness (InOPEN) is found to be statistically significant and positive suggesting that an upsurge in trade openness by 1% increases CO_2 emissions by 0.121% ceteris paribus. The detrimental effect of openness on the environmental condition of South Africa in the long run undeniably reiterates the concern against trade liberalisation. The type of products forming the bulk of South Africa's exports is part of the possible reason that could explain why trade openness impedes her

environment. For instance, since the country has a comparative advantage in export and production of natural resource-intensive goods such forest products, antimony, tin, copper, manganese minerals, phosphates, vanadium, rare earth elements, natural gas, nickel, iron ore, nickel, coal, chromium, diamond, platinum, and gold, a rise in the demand of these products will certainly lead to worsening South Africa's environmental condition. This is because harvesting these products continuously to meet the growing international markets significantly deteriorates South Africa's environmental quality. Also, our findings could be explained by the theoretical framework of Lopez (1994) that energy-based activities that consume a high amount of energy mainly driven from trade liberalisation such as transportation and manufacturing produce pollution. Additionally, our results are also consistent with the pollution haven hypothesis (Taylor 2004) that developing countries like South Africa have a comparative advantage in pollution-intensive production while developed ones have a comparative advantage in producing clean products (Wagner 2010). Therefore, developed countries tend to transfer pollution to developing countries via international trade (Cole 2004; Wagner 2010). Our empirical evidence is also supported by and aligned with the results obtained by Khan and Ozturk (2021) suggesting that developing countries tend to release a high amount of pollutants due to relying on dirty industries. Our result is consistent with Khan et al. (2021a), who suggested that trade openness is injurious and has extensively contributed to worsen the environmental condition in Pakistan. This empirical evidence is further corroborated by Ibrahim and Ajide (2021a), who find that trade openness contributes to increase CO_2 emissions in G-7. Similar results were observed by Van Tran (2020), who show that trade openness worsens the environmental condition in 66 developing economies. The negative view of environmental impacts of trade openness is in line with the findings from Aydin and Turan (2020) and Ali et al. (2020), who found that trade has a harmful effect on environmental quality through releasing carbon dioxide emissions. However, our findings contradict with Ibrahim and Ajide (2021b), Ibrahim and Ajide (2021c), and Ding et al. (2021), who found that higher trade openness contributes to improve environmental quality in G-20 countries, 48 Sub-Saharan African countries, and G-7 economies respectively.

For energy consumption (InEC), the estimated coefficients for short run and long run are statistically significant and positive suggesting that energy consumption considerably contributes to increase CO_2 emissions in South Africa. Coal consumption as a major source of energy use in South Africa, although is crucial to support production and enhance economic development, is a major contributor to deterioration of environmental quality as South Africa is the seventh biggest country which heavily consumes coal

to meet energy demand (World Bank 2021). It is observable that a 1% increase in energy consumption raises CO_2 emissions by 0.205% in the long run. South Africa is heavily dependent on energy sector where coal consumption is dominant in production activity. Almost 77% primary energy supply and 93% electricity production are from coal reserves in South Africa (Udeagha and Breitenbach 2021). Due to continuous rise in energy demand in South Africa, CO_2 emissions have significantly increased over the years, which have severe implications for the environment and a significant contributor to global climate change. Our empirical evidence is supported by Adebayo et al. (2021), who find that energy consumption triggers CO_2 emissions in South Korea. Similarly, Aslan et al. (2021) find that energy consumption deteriorates environmental quality for 17 Mediterranean countries. Doğanlar et al. (2021) also report that energy consumption escalates CO_2 emissions for Turkey. Likewise, Hongxing et al. (2021) conclude that energy consumption increases carbon emissions for 81 Belt and Road Initiative (BRI) economies. A study by Hu et al. (2021) also finds that aggregate energy consumption increases carbon emissions for Guangdong, China. Our results are contrary to those found by Ponce and Khan (2021), Khan et al. (2021c), He et al. (2021), Hao et al. (2021), Irfan (2021), and Baye et al. (2021), who observe that energy consumption improves environmental quality.

The short-run estimated coefficient on foreign direct investment (InFDI) is statistically significant and positive. However, the estimated value for long run, although positive, is not statistically significant. Our results therefore suggest that an upsurge in FDI leads to worsening environmental decay in South Africa. The results support the "pollution have hypothesis" for South Africa. Since South Africa has a comparative advantage in export and production of dirty products, this has massively attracted FDI inflows, which considerably contribute to worsen the country's environmental condition. The detrimental effect of FDI on South Africa's environment suggests that FDI inflows enable the country to become one of the "havens" for the highly intensive-pollution industries of the world. Our results are consistent with the findings of Copeland and Taylor (2013), who argued that the highly polluting industries which produce dirty goods have migrated to less developed nations, thereby transferring the pollution problems of the developed nations to these poor countries, and this immensely contributes to worsen their existing environmental decay. Also, owing to ineffective environmental standard and corrupt institutions, South Africa has become dirtier as the country specialises in production of dirty goods that significantly escalate the growing levels of environmental dilapidation. FDI inflows have indeed facilitated to transform South Africa into a highly polluted factory of the world, which exports much of what it produces back to the global

markets. This empirical evidence reflects the true nature of the South African economy which is known to be among the fast-emerging economies in Africa. Thus, the policymakers and the stakeholders need to do more to ensure that foreign investors adopt updated, greener, and cleaner technologies to shift from non-renewable energy sources to renewable or less carbon-intensive ones so as to ensure proficiency in the production processes. Meanwhile, the substitution of non-renewable energy types with alternative sources such as solar power will considerably reduce CO_2 emissions in South Africa. This will ultimately promote lasting value for reductions of GHG emissions and constantly support the establishment of new technologies, which improve the South Africa's environmental condition and safeguard the global environment. Our results reciprocate the findings of Abdouli and Hammami (2017), who drew a similar conclusion in the case of MENA countries that FDI has contributed enormously to increase CO_2 emissions and there is evidence of pollution haven hypothesis. This empirical finding is further supported by Farooq (2021), Muhammad et al. (2021), Khan et al (2020), Ngepah and Udeagha (2018), Shahbaz et al. (2018), Paramati et al. (2016), Lee (2013), Ming Qing and Jia (2011), Haisheng et al. (2005), Tamazian and Rao (2010), Shahbaz et al. (2014a, b), Ren et al.(2014), Seker et al. (2015), Naz et al. (2019), Gorus and Aslan (2019), Ngepah and Udeagha (2019), and Hanif et al. (2019). However, the findings contradict with Joshua et al. (2020) and Omri et al. (2014).

The estimated coefficient on technological innovation (InTECH) is statistically significant and negative in the long run. Our empirical finding shows that a 1% increase in technological innovation brings about a reduction in CO_2 emissions by 0.72% in the long run. Technological innovations in South Africa effectively reduce CO_2 emissions, which could be seen as eco-friendly technological innovation. It supports efficient energy utilisation and facilitates renewable energy sources at cheaper costs; thus, leading to minimum carbon emissions in South Africa. Technological innovations improve South Africa's environmental quality through the following ways: (i) setting up of end-of-pipe technology crucial for reduction of carbon emissions, (ii) use of production technologies which are more energy efficient, and (ii) changes in fuel mix. Innovations in technology through these channels lead to an increase in energy efficiency, which substantially improves environmental quality in the country. Meanwhile, South Africa's enormous investments in R&D and changes in technology are among reasons why innovations in technology have immensely contributed to improve the country's environmental quality. Also, as part of the major key to mitigate the growing levels of carbon emissions, South Africa has implemented several policies aimed at developing robust technologies, which are crucial to minimise the intensity of emissions from production processes

and other economic activities connected to high levels of emissions. Sohag et al. (2015) illustrated that technological innovation creates an avenue which permits a reduction in energy consumption, facilitates energy efficiency, and substantially reduces carbon emissions. Our results are consistent with the findings of Ibrahim and Vo (2021); Destek and Manga (2021), An et al. (2021a, b), Guo et al. (2021), Baloch et al. (2020), Shan et al. (2021), Yang et al. (2021), Anser et al. (2021), Erdogan (2021), Töbelmann and Wendler (2020), Rafique et al. (2020), Ibrahiem (2020), Ahmad and Raza (2020), Zameer et al. (2020),Godil et al. (2020), Khan et al. (2020), and Altinoz et al. (2020). However, the findings contradict with Usman and Hammar (2021), Dauda et al. (2021), Atsu et al. (2021), Arshad et al. (2020), Usman et al. (2020), Khattak et al. (2020), Demir et al. (2020), Villanthenkodath and Mahalik (2020), and Faisal et al. (2020).

The long-run estimated coefficient on industrial value-added share of GDP (InIGDP) is statistically significant and positive showing that industrial sector growth significantly contributes to deteriorate South Africa's environmental quality in the long run. The growing industrial sector in South Africa is primarily responsible for an upward trend of CO_2 emissions. Over the years, South Africa has adopted several policies aimed at pursuing structural transformation and industrialisation to reduce poverty and ensure inclusive growth. Structural transformation of the economy from low-productivity agriculture to high-productivity industrialisation is seen as a requisite to achieve sustainable economic growth, job creation and poverty reduction. However, the growing industrial sector in South Africa has brought about an upward trend of CO_2 emissions. The large-scale industrialisation and associated environmental alteration and its impact on biodiversity pose a threat to human existence through basic necessities, recreation, and the ecological functions. It is evident that pollution from various sources, particularly from industries, has a negative impact on the environment, irreversible in nature, and causes extinction of species resulting in the loss of unique genetic resources of great use. Our findings are consistent with those of Al Mamun et al. (2014) and Sohag et al. (2017), who observed that the thriving industrial sectors are primarily responsible for an upward trend of CO_2 emissions. Also, Tian et al (2014) stated that heavy manufacturing is the source of CO_2 emissions at the domestic level. Our results are further supported by Cherniwchan (2012); Hossain (2011), Poumanyvong and Kaneko (2010), Nejat et al. (2015), Asane-Otoo (2015), Ozturk and Al-Mulali (2015), Lin et al. (2009), Garcia and Sperling (2010), Shahbaz and Lean (2012), and Li and Xia (2013). However, the findings contradict with Lin et al. (2015), who suggested that there is no evidence that industrial sector growth increases carbon emissions in Nigeria. Similar studies such as Shahbaz et al. (2014b), Shafiei
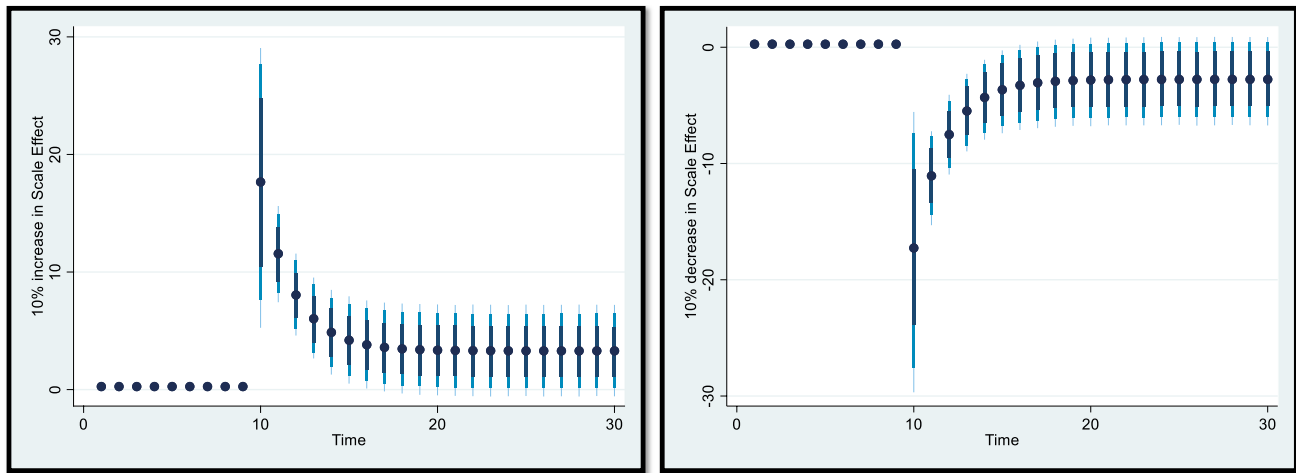
Fig. 2 The impulse response plot for scale effect (economic growth) and CO_2 emissions. Figure 2 shows a 10% increase and a decrease in scale effect and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

and Salim (2014), Zhou et al. (2013), Xu and Lin (2015), Zhang and Lin (2012), Dhami et al. (2013), Ahuti (2015), Kavzo (2008), Lin et al. (2017), Wang et al. (2014), Shahbaz et al (2015), and Ewing and Rong (2008) found evidence that industrial sector growth reduces CO_2 emissions.

The error correction term (ECT) captures the speed of adjustment. The estimated coefficient is negative and statistically significant confirming that a steady long-run relationship exists among the variables under review. The ECT estimated value of -0.85 suggests that in the long run, 85% of disequilibrium is corrected. *R*-squared value shows that 89% variations in CO_2 emissions are brought about by the explanatory variables used in this work. The estimated *p* value of *F*-statistics suggests that the model is a good fit.

While keeping other explanatory variables constant, the dynamic ARDL simulations automatically plot the forecasts of actual regressor change and its impact on the dependent variable. The effect of explanatory variables, that is, scale effect, technique effect, trade openness, energy consumption, foreign direct investment, technological innovation, and industrial value-added, on CO_2 emissions is forecasted to increase and decrease by 10% in South Africa.

Figure 2 shows the impulse response plot of relationship between scale effect (economic growth) and CO_2 emissions. The plot captures the transition of scale effect and its impact on CO_2 emissions. A 10% increase in scale effect denotes a positive effect of economic growth on CO_2 emissions in the short run and long run; however, a 10% decrease in scale effect implies a negative influence of economic growth on CO_2 emissions, but the impact of 10% increase is higher than 10% decrease in scale effect. This implies that an increase in scale effect (economic growth) contributes to deteriorate the environmental quality, whereas a decrease in scale effect

improves the environmental condition in both the short run and long run in South Africa.

Figure 3 illustrates the impulse response plot of technique effect and CO_2 emissions in South Africa. The technique effect graph demonstrates that a 10% increase is closely associated with a negative influence on CO_2 emissions in the long run and short run. However, a 10% decrease has a positive effect on CO_2 emissions in the long run and short run. This suggests that an increase in technique effect (square of economic growth) improves the environmental quality, but a decrease in technique effect deteriorates the environmental condition in both the short and long run in South Africa.

Figure 4 displays the impulse response plot connecting the relationship between trade openness and CO_2 emissions. The plot shows that a 10% increase in trade openness positively influences CO_2 emissions in the long, but negatively affects it in the short run. In contrast, a 10% decrease in trade openness has a negative influence on CO_2 emissions in the long, but positive effect in the short run. This suggests that an increase in trade openness improves South Africa's environmental quality in the short run, but deteriorates it in the long run. However, a decrease in trade openness has a beneficial impact on South Africa's environment in the long, but deteriorates it in the short run.

Figure 5 shows the impulse response plot of relationship between energy consumption and CO_2 emissions. The plot capturing the energy consumption impact on CO_2 emissions shows that a 10% increase in energy consumption has a positive impact on CO_2 emissions in the short run and long run; however, a 10% decrease in energy consumption has a negative influence on CO_2 emissions. This implies that an increase in energy consumption contributes to deteriorate the environmental quality, whereas a decrease in energy
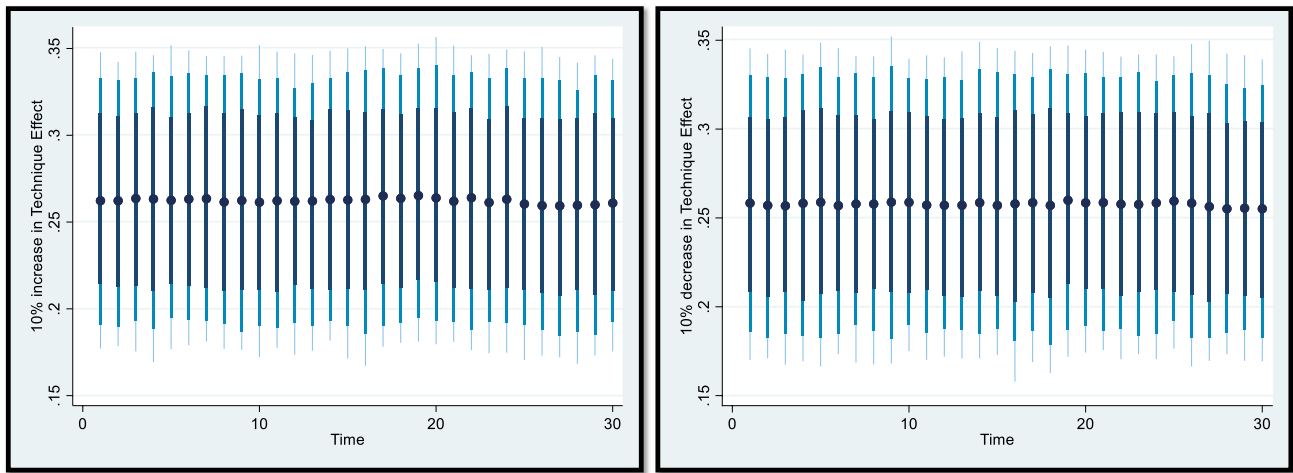
Fig. 3 The impulse response plot for technique effect and CO_2 emissions. Figure 3 shows a 10% increase and a decrease in technique effect and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively
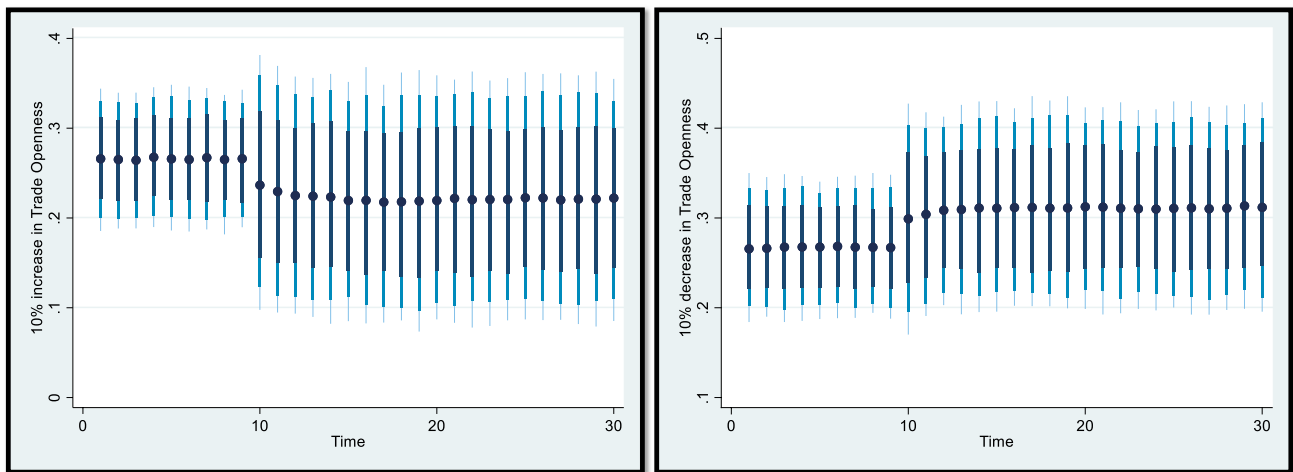

Fig. 4 The impulse response plot for trade openness and CO_2 emissions. Figure 4 shows a 10% increase and a decrease in trade openness and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

consumption improves the environmental condition in both the short run and long run in South Africa.

Figure 6 illustrates the impulse response plot of foreign direct investment and CO_2 emissions in South Africa. The foreign direct investment graph demonstrates that a 10% increase in foreign direct investment is closely associated with a positive influence on CO_2 emissions in the long run and short run. However, a 10% decrease has a negative effect on CO_2 emissions in the long run and short run. This suggests that an increase in foreign direct investment deteriorates the environmental quality in both the short and long run in South Africa.

In Fig. 7, the impulse response plot between technological innovation and CO_2 emissions in South Africa is presented. The graph reveals that a 10% increase in technological innovation has a negative influence on CO_2 emissions in the long run and short run. However, a 10% decrease in technological innovation brings about a positive effect on CO_2 emissions in the long run and short run. This suggests that an increase in technological innovation improves South Africa's environmental quality, whereas a decrease in technological innovation deteriorates the environmental condition in both the short and long run in South Africa.
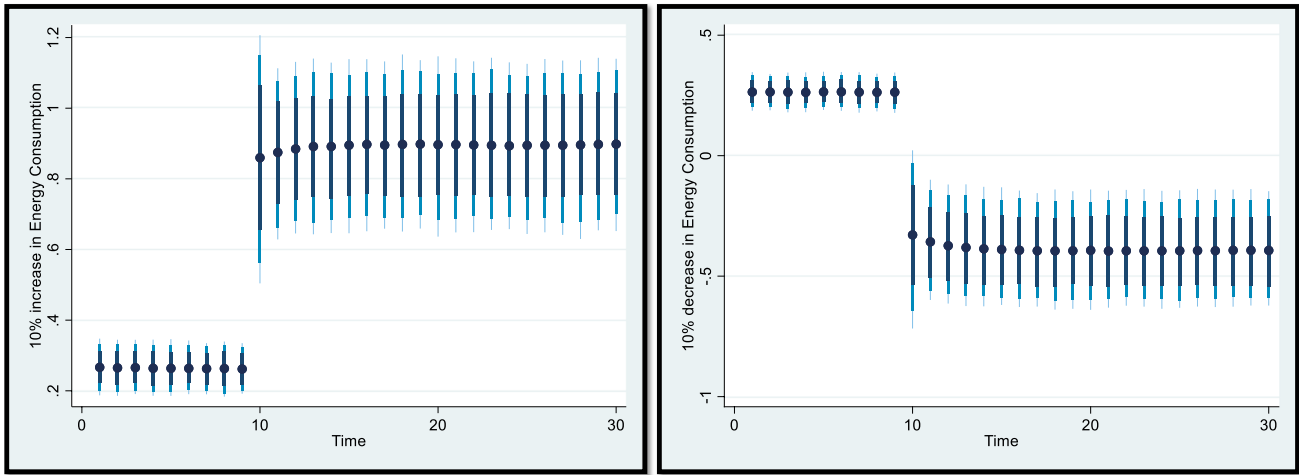
Fig. 5 The impulse response plot for energy consumption and CO_2 emissions. Figure 5 shows a 10% increase and a decrease in energy consumption and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively
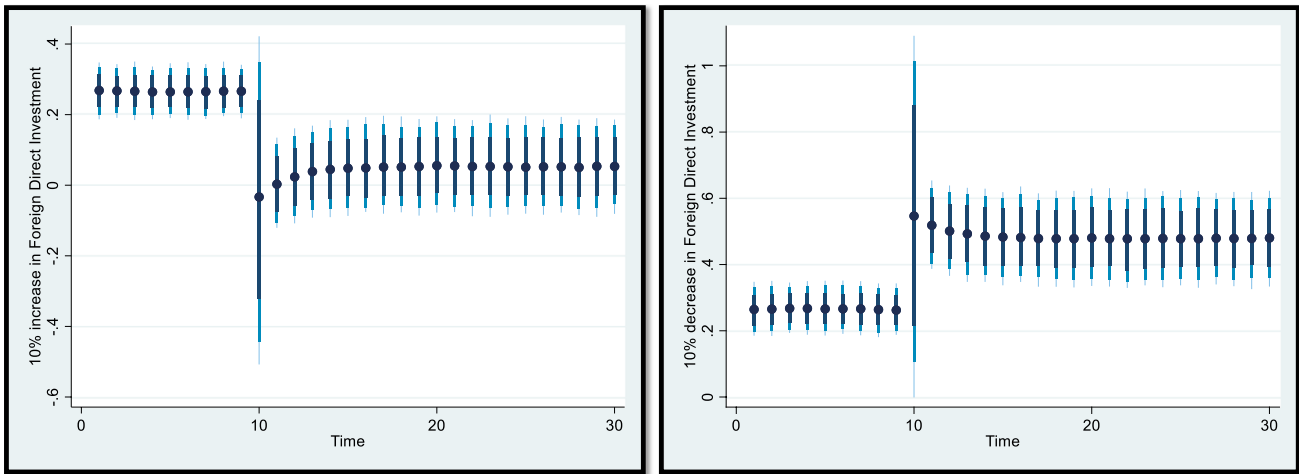

Fig. 6 The impulse response plot for foreign direct investment and CO_2 emissions. Figure 6 shows a 10% increase and a decrease in foreign direct investment and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

Figure 8 presents the impulse response plot of relationship between industrial value-added and CO_2 emissions. The plot shows that a 10% increase in industrial value-added has a positive impact on CO_2 emissions in the short run and long run; however, a 10% decrease in industrial value-added has a negative influence on CO_2 emissions. This suggests that an increase in industrial value-added contributes to deteriorate the environmental quality, whereas a decrease in industrial value-added improves the environmental condition in both the short run and long run in South Africa.

This work also uses the frequency domain causality test proposed by Breitung and Candelon (2006) to explore the causality between InSE, InTE, InOPEN, InEC,

InFDI, InTECH, InIGDP, and $InCO_2$ in South Africa. Table 8 (see Appendix) shows that InSE, InTE, InOPEN, InEC, InFDI, InTECH, and InIGDP Granger-cause $InCO_2$ in the short, medium, and long run for frequencies $\omega_i = 0.05$, $\omega_i = 1.50$, $\omega_i = 2.50$. This implies that InSE, InTE, InOPEN, InEC, InFDI, InTECH, and InIGDP significantly affect CO_2 emissions in short, medium, and long terms in South Africa. Our empirical evidence is compatible with the findings of Udeagha and Ngepah (2019), Udeagha and Ngepah (2021), Al Mamun et al. (2014), and Sohag et al. (2017).

This study further applies the structural stability evaluation of the model to validate its robustness. To this end,
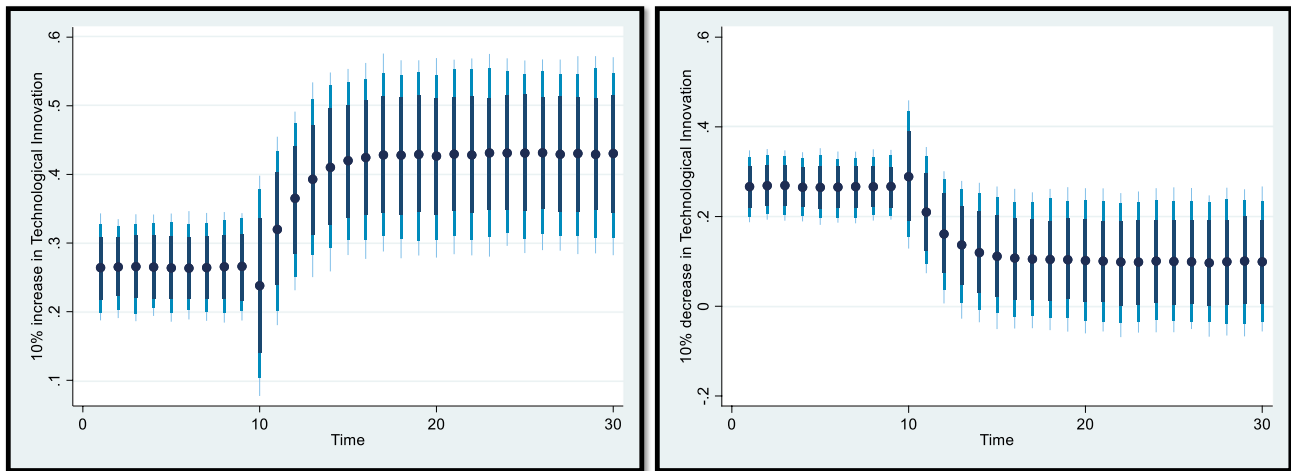
Fig. 7 The impulse response plot for technological innovation and CO_2 emissions. Figure 7 shows a 10% increase and a decrease in technological innovation and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively
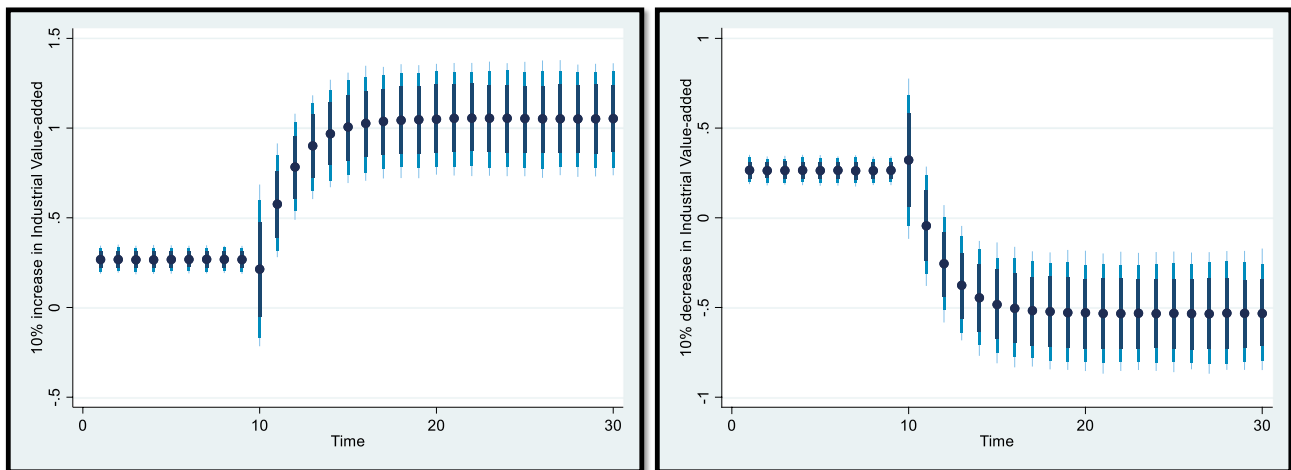

Fig. 8 The impulse response plot for industrial value-added and CO_2 emissions. Figure 8 shows a 10% increase and a decrease in industrial value-added and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residual (CUSUMSQ) proposed by Pesaran and Pesaran (1997) are used. Figures 9 and 10 (see Appendix) present a visual representation of CUSUM and CUSUMSQ. Conventionally, there is a stability of model parameters over time if plots are within a critical bound level of 5%. Based on the model trend shown in Figures A1 and A2, since CUSUM and CUSUMSQ are within the boundaries at a 5% level, we can conclude that the model parameters are stable over time.

Robustness

This study uses three tests to evaluate the robustness of the Squalli and Wilson (2011) measure (i.e. composite trade intensity—CTI) over traditional trade intensity (TI) measure. First, using the Penn World Tables (PWT) data for 2000, the study verifies the robustness of the world rankings by comparing the performance of the CTI and TI-based measures. Second, using several indicators of liberal trade policies and capital flows, the work compares partial correlation coefficients between CTI and TI. Third, our models are re-estimated using the TI measure to prove the supposition by testing and checking the extent to which

the findings are sensitive to the measurements used. To this end, the TI measure is captured as the ratio of total trade (exports plus imports) to GDP.

Rankings

Previous studies have extensively used the TI-based measure to investigate the effect of trade openness on environmental quality. Astonishingly, a striking anomaly occurs when this proxy is used to rank countries to ascertain their degree of openness to trade benefits. Table 9 (see Appendix) shows that with TI measure, the bottom five and most closed economies are Japan, Argentina, Brazil, the USA, and India. Using the TI-based measure, the largest trading economies of the world are relatively closed because their trade shares of total economic activities are very low using the world standards. But how sensible is it to categorise a country particularly the USA, the world's dominant trading country, as a closed economy? The apparent explanation is that the TI-based measure is a one-dimensional measure that looks only at the comparative position of trade performance of a country in relation to her domestic economy. In doing so, it tends to penalise bigger economies (because of their potentially large GDP), thus, classifying them as closed. Penn World Tables (PWT) data for 2000 shows that South Africa is ranked 107th when TI measure is used, but 37th with CTI measure. Given this background, this study therefore argues that trade openness is a two-dimensional measure; the first one captures the proportion of total income of a given country that is connected to international trade and the second one deals with a country's interconnectedness and interaction with the rest of the world. Using this way to measure openness, this study suggests a way to rectify the anomaly seen in the rankings by using CTI measure to capture two dimensions which together describe the real trade openness and focus on actual trade flows instead of potential trade flows. In so doing, bigger economies such as Russia, France, Germany, South Africa, the UK, the USA, and China will have their trade openness proxies increased significantly compared with the traditional TI-based measure.

Correlations

The second test used in this study to assess the robustness of CTI over TI is to conduct a partial correlation analysis between CTI and TI with several indicators of liberal trade policies and capital flows. Following Squalli and Wilson (2011), the proxies of liberal trade policies used for this analysis include foreign direct investment (FDI) inflows and outflows (as percentage of GDP), taxes on international trade (as percentage of revenue), customs and other import duties (as percentage of tax revenue), and

number of registrations of new businesses (as percentage of total). Data for all these proxies are from World Bank world development indictors. It is expected that customs and other import duties on trade to have a negative correlation with CTI and TI measures, while other proxies of liberal trade policies are expected to have positive correlations with them.

As expected, Table 10 (see Appendix) shows that the customs and other import duties on international trade are negatively correlated with both CTI and TI measures of trade openness estimated at -0.43 versus -0.04. However, the correlation with CTI is stronger than that of TI. Similarly, there is a negative correlation with taxes on international trade estimated at -0.31 versus -0.22, where CTI's correlation also appears to be stronger than that of TI. For other proxies used, CTI has a positive correlation, while TI is positively correlated with only FDI net inflows and the number of registration of new businesses. Again, the correlation between CTI and new business registrations is stronger and larger than that of TI; thus, providing further evidence that supports the robustness of CTI. On the contrary, TI's correlation with FDI net inflows is stronger than that of CTI estimated at 0.69 versus 0.30 for CTI, but is negatively correlated with FDI net outflows. This evidence appears curious and casts further doubt on the consistency and use of TI measure of trade openness.

Are the findings sensitive to the measurements?

The third robustness test deals with the test to prove the supposition that CTI is superior to TI and check the extent to which the findings are sensitive to the measurements used. This is carried out by re-estimating our models using TI in lieu of CTI. The results reported in the columns (4)–(6) of Table 7 show that when TI is used, there is a significant reduction in explanatory power, where the reported R^2 value substantially decreases from 0.898 to 0.510. Also, using TI measure, the root-mean-squared error (RMSE) significantly increases from 0.081 to 0.271 in the models. Furthermore, the results of Table 7 show that the estimated coefficient on the variable of interest (i.e. trade openness) is substantially higher when TI is used in lieu of CTI. More importantly, the difference in magnitude between CTI and TI estimates suggests that using TI may result in overstating the impact of our variable of interest on environmental quality in South Africa. In addition, our findings are very sensitive when TI is used in place of CTI. Based on the results, the long-run estimated coefficient on technological innovation (InTECH) is not only statistically insignificant, but also has an opposite sign. In summary, given the aforementioned facts and tests, the estimation of the models is evidently statistically

superior with the use of CTI measure and this evidence not only casts doubt on the use of TI measure but also provides statistical supports while CTI measure is used in this paper.

Conclusions and policy implications

This study revisited the dynamic relationship between trade and CO_2 emissions in South Africa over the period 1960–2016 by using the recently developed novel dynamic ARDL simulation model proposed by Jordan and Philips (2018) that can estimate, stimulate, and plot to predict graphs of (positive and negative) changes in the variables automatically as well as their short-and long-run relationships. Using this approach permits us to identify the positive and negative relationships between InSE, InTE, InOPEN, InEC, InFDI, InTECH, InIGDP, and $InCO_2$ in South Africa, thereby overcoming the limitations of the simple ARDL approach in earlier studies. For robustness check, we used the frequency domain causality (FDC) approach, the robust testing strategy suggested by Breitung and Candelon (2006) which permits us to capture permanent causality for medium term, short term, and long term among variables under consideration. This paper further contributed to empirical literature by employing an innovative measure of trade openness proposed by Squalli and Wilson (2011) capturing trade share in GDP and the size of trade relative to the global trade for South Africa. We used the Dickey-Fuller GLS (DF-GLS), Phillips-Perron (PP), Augmented Dickey-Fuller (ADF), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) unit root tests to confirm the asymptotic behaviour and order of integration of all variables under review. This process helps to resolve the issues of spurious regressions. Further, the Narayan and Popp's structural break unit root test was used since empirical evidence shows that structural breaks are very persistent in empirical literature and many macroeconomic variables like CO_2 emissions and trade openness are likely to be affected. Consequently, empirical evidence from all the tests validated that the data series were integrated into order one, that is, $I(1)$, and there is no evidence of any $I(2)$. SBIC was utilised to identify the optimal lag length. For South Africa, our empirical results revealed that the scale effect contributes to deteriorate the environmental condition, whereas the technique effect is environmentally friendly. This evidence therefore confirms the presence of EKC hypothesis for South Africa. Foreign direct investment, industry value-added, and energy consumption deteriorate environmental quality; however, technological innovation contributes to lower CO_2 emissions in South Africa. The FDC results also revealed that InSE, InTE, InOPEN, InEC, InFDI, InTECH, and InIGDP

Granger-cause $InCO_2$ in the medium term, long term, and short term suggest that these variables are important to influence CO_2 emissions in South Africa.

In addition, regarding the relationship between trade openness and CO_2 emissions, our empirical results showed that in the long run, higher trade openness is highly injurious to the environment of South Africa, although it is environmentally friendly in the short run. Our empirical evidence is in line with the findings of Udeagha and Ngepah (2019) that, in the long run, trade openness contributes to deteriorate the country's environmental quality, but beneficial in the short run. These findings were further supported by Tayebi and Younespour (2012) that validated the presence of pollution haven hypothesis in case of many developing countries. The comparative advantage of South Africa in export and production of pollution-intensive products has enabled the migration of industries from developed countries to the country, thereby making the country the "havens" for the highly intensive-pollution industries of the world. Such a migration has considerably led to a shift in the pollution problems of these developed countries to South Africa, and this has contributed significantly to worsen the current environmental deterioration. Added to this are the country's inefficient environmental laws and weak institutions due to corruption. Consequently, South Africa becomes dirtier as it continues to specialise in the production of dirty products, which highly contribute to deteriorate her environmental quality. Inevitably, trade openness has enabled to make South Africa to become an extremely polluted factory of the world.

In light of our empirical evidence, the following policy considerations are suggested: (i) South Africa's government and policymakers should take prompt initiatives to mandate foreign investors to use cleaner, greener, and updated technologies, which can promote efficiency in the production processes and curtail CO_2 emissions in South Africa. (ii) International teamwork to improve environmental quality is immensely critical to solve the growing trans-boundary environmental decay and other associated spillover consequences. In light of this, the government should work together to build robust global teamwork with other countries with the purpose of sharing technology. (iii) The government should integrate all-inclusive environmental chapters into the country's trade agreement policies to enable a transition into low-carbon economy and greener industries, thus encouraging production of cleaner products. (iv) Lastly, trade policy reform could be supported by other developmental policies to ensure long-lasting value for reductions of carbon emissions and continuously enable the development of new technologies that can boost the country's environmental quality and protect the global environment.
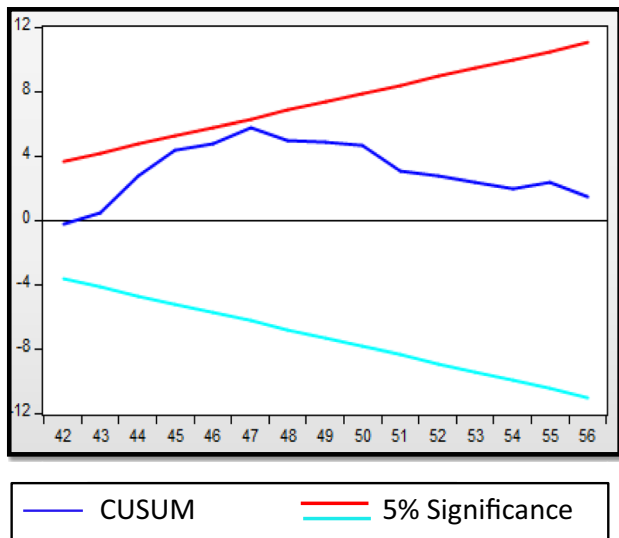
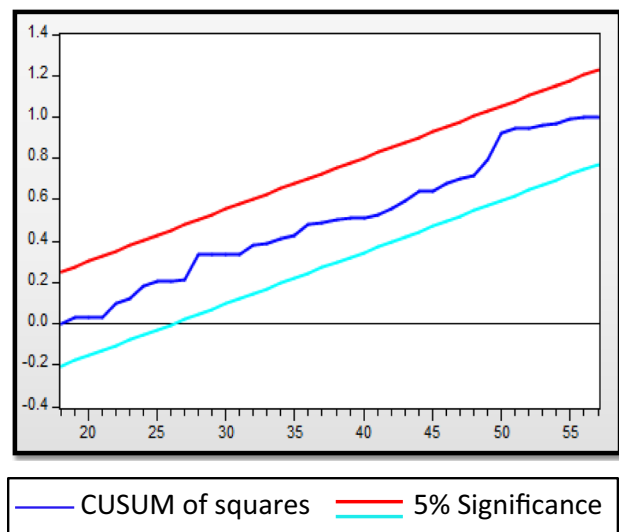**Fig. 9** Plot of cumulative sum of recursive residuals (CUSUM)

Fig. 10 Plot of cumulative sum of squares of recursive residuals (CUSUMSQ)

Appendix

Table 8 Frequency-domain causality test

Direction of causality	Long-term	Medium-term	Short-term
	$\omega_{i=0.05}$	$\omega_{i=1.50}$	$\omega_{i=2.50}$
$lnSE \rightarrow lnCO_2$	<8.31>	<8.50>	<9.96>
	(0.02)**	(0.00)***	(0.00)***
$lnTE \rightarrow lnCO_2$	<4.89>	<6.49>	<6.93>
	(0.07)*	(0.03)**	(0.04)**
$lnOPEN \rightarrow lnCO_2$	<8.94>	<8.73>	<7.28>
	(0.00)***	(0.00)***	(0.01)**
$lnEC \rightarrow lnCO_2$	<5.12>	<6.49>	<6.73>
	(0.08)*	(0.04)**	(0.03)**
$lnFDI \rightarrow lnCO_2$	<8.20>	<8.08>	<8.62>
	(0.01)**	(0.03)**	(0.00)***
$lnTECH \rightarrow lnCO_2$	<4.84>	<5.14>	<7.83>
	(0.06)*	(0.04)**	(0.02)**
$lnIGDP \rightarrow lnCO_2$	<5.46>	<8.82>	<8.89>
	(0.07)*	(0.00)**	(0.00)**

Source: Authors' calculations

*, **, and *** denote statistical significance at 10%, 5%, and 1% levels, respectively

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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Table 9 Penn World Tables (PWT) trade openness measures and ranks; $n = 136$, 2000

Countries	TI	Rank	CTI	Rank	Countries	TI	Rank	CTI	Rank
Albania	59.42	96	251.98	109	Germany	67.07	86	50,565.79	5
Algeria	64.35	90	4397.08	43	Ghana	118.75	30	2142.40	60
Antiqua	150.32	12	158.25	116	Hong Kong	295.19	2	94,491.06	1
Argentina	22.22	135	1226.62	73	India	30.45	132	14,458.98	23
Armenia	47.93	70	374.72	101	Indonesia	69.21	82	23,263.88	16
Australia	45.60	117	6195.90	36	Italy	55.59	106	23,342.66	15
Austria	101.22	43	11,803.85	24	Japan	20.1	136	7603.43	35
Azerbaijan	79.08	66	1023.41	78	Luxembourg	285.59	3	10,083.46	27
Bangladesh	33.22	129	1466.20	66	Malaysia	230.33	4	66,527.34	3
Barbados	106.68	40	304.61	104	Netherlands	129.59	21	39,390.81	8
Belarus	140.36	16	9851.67	29	New Zealand	71.82	75	2261.49	57
Belgium	169.33	7	42,056.33	6	Nigeria	93.12	51	5202.25	40
Belize	110.66	37	120.52	119	Philippines	104.11	42	19,045.97	19
Benin	44.45	118	86.81	124	Poland	69.27	81	10,247.45	26
Bolivia	42.64	119	254.11	108	Portugal	74.91	71	5487.75	39
Brazil	23.03	134	4003.69	46	Romania	74.03	72	3532.91	48
Bulgaria	121.53	27	4385.04	44	Russia	70.68	77	41,574.34	7
Burkina Faso	40.33	121	103.38	121	Rwanda	32.33	130	49.65	131
Burundi	30.54	131	22.46	134	Senegal	70.08	80	450.01	98
Cameroon	57.44	100	645.90	89	Seychelles	164.76	9	146.86	117
Canada	86.80	60	38,072.67	10	Sierra Leone	50.52	111	53.87	130
Cape Verde	85.05	63	78.44	127	Singapore	341.59	1	76,812.24	2
Chad	48.60	112	99.72	122	Slovenia	121.75	26	2862.60	53
Chile	62.52	92	3533.10	47	South Africa	55.15	107	5969.26	37
China	48.36	113	64,724.01	4	Spain	62.22	93	16,830.83	22
Colombia	42.33	120	2512.50	55	Sri Lanka	90.21	54	3460.93	49
Comoros	57.52	99	19.24	135	St Lucia	121.24	29	89.48	123
Congo	132.5	18	767.59	86	Swaziland	146.31	15	645.73	91
Costa Rica	94.48	50	1142.73	74	Sweden	89.02	56	9903.01	28
Cote d'Ivoire	85.22	62	1348.69	69	Switzerland	87.93	57	8963.29	30
Croatia	95.64	49	2187.81	58	Syria	68.59	84	1889.69	62
Czech Republic	146.62	14	18,749.05	20	Tajikistan	165.37	8	1331.56	70
Denmark	80.12	65	5593.44	38	Tanzania	37.93	125	135.91	118
Dominica	114.86	35	45.63	132	Thailand	127.61	23	37,984.57	11
Dominican Republic	69.06	83	1291.38	72	Togo	85.41	61	174.92	114
Ecuador	73.36	73	1448.05	67	Tunisia	91.58	53	3271.14	51
Egypt	38.81	123	2428.66	56	Turkey	54.98	108	8567.41	32
El Salvador	70.12	79	815.85	83	Uganda	35.66	126	166.32	115
Equatorial Guinea	153.05	10	630.81	93	Ukraine	118.24	31	20,374	18
Estonia	179.93	5	2756.36	54	UK	57.91	97	27,798.85	13
Ethiopia	46.08	116	562.32	95	USA	26.2	133	38,517.96	9
Finland	76.03	68	4178.57	45	Uruguay	39.98	122	313.77	103
France	55.9	103	25,505.43	14	Venezuela	46.3	115	2143.42	59
Gabon	71.79	76	282.08	105	Yemen	91.95	52	1094.34	76
Gambia	108.92	38	117.54	120	Zambia	70.45	78	240.86	111
Georgia	84.05	64	1079.06	77	Zimbabwe	62.61	91	730.10	88
Germany	67.07	86	50,565.79	5	Nigeria	93.12	51	5202.25	40
Ghana	118.75	30	2142.40	60	Norway	77	67	4888.75	42
Greece	57.91	98	3150.76	52	Pakistan	34.57	127	2036.74	61
Grenada	136.17	17	66.62	128	Panama	71.97	74	562.70	94

Table 9 (continued)

Countries	TI	Rank	CTI	Rank	Countries	TI	Rank	CTI	Rank
Guatemala	47.76	114	643.87	92	Paraguay	55.7	104	468.27	97
Guinea	57.15	101	410.17	99	Peru	33.81	128	805.23	84
Guinea-Bissau	89.69	55	40.69	133	Philippines	104.11	42	19,045.97	19
Honduras	98.76	46	774.85	85	Poland	69.27	81	10,247.45	26
Hong Kong	295.19	2	94,491.06	1	Portugal	74.91	71	5487.75	39
Hungary	127.24	24	10,269.28	25	Romania	74.03	72	3532.91	48
Iceland	75.81	69	249.01	110	Russia	70.68	77	41,574.34	7
India	30.45	132	14,458.98	23	Rwanda	32.33	130	49.65	131
Indonesia	69.21	82	23,263.88	16	Sao Tome and Principe	115.32	34	14.82	136
Iran	55.69	105	8133.67	33	Senegal	70.08	80	450.01	98
Ireland	175.56	6	18,156.82	21	Seychelles	164.76	9	146.86	117
Israel	86.87	59	5151.90	41	Sierra Leone	50.52	111	53.87	130
Italy	55.59	106	23,342.66	15	Singapore	341.59	1	76,812.24	2
Jamaica	99.33	45	514.76	96	Slovak Republic	149.56	13	8719.69	31
Japan	20.1	136	7603.43	35	Slovenia	121.75	26	2862.60	53
Jordan	110.96	36	1473.70	65	South Africa	55.15	107	5969.26	37
Kazakhstan	105.63	41	7905.90	34	Spain	62.22	93	16,830.83	22
Kenya	61.71	94	862.75	80	Sri Lanka	90.21	54	3460.93	49
Korea, Republic of	87.18	58	30,697.46	12	St. Kitts and Nevis	131.49	19	59.30	129
Kyrgyzstan	97.67	47	859.55	81	St Lucia	121.24	29	89.48	123
Latvia	100.08	44	1128.60	75	St. Vincent and Grenadines	128.76	22	85.57	125
Lebanon	50.83	110	389.47	100	Swaziland	146.31	15	645.73	91
Lesotho	116.81	32	237.00	112	Sweden	89.02	56	9903.01	28
Lithuania	96.72	48	1660.10	64	Switzerland	87.93	57	8963.29	30
Luxembourg	285.59	3	10,083.46	27	Syria	68.59	84	1889.69	62
Macao	151.21	11	1324.25	71	Tajikistan	165.37	8	1331.56	70
Macedonia	107.8	39	743.36	87	Tanzania	37.93	125	135.91	118
Madagascar	59.52	95	275.75	106	Thailand	127.61	23	37,984.57	11
Malawi	64.48	89	198.06	113	Togo	85.41	61	174.92	114
Malaysia	230.33	4	66,527.34	3	Trinidad and Tobago	116.23	33	1379.33	68
Mali	65.34	87	263.52	107	Tunisia	91.58	53	3271.14	51
Mauritius	130.55	20	1665.73	63	Turkey	54.98	108	8567.41	32
Mexico	64.69	88	22,598.55	17	Uganda	35.66	126	166.32	115
Moldova	126.86	25	871.98	79	Ukraine	118.24	31	20,374	18
Morocco	68.41	85	3303.47	50	UK	57.91	97	27,798.85	13
Mozambique	54.63	109	336.24	102	USA	26.2	133	38,517.96	9
Nepal	55.96	102	645.86	90	Uruguay	39.98	122	313.77	103
Netherlands	129.59	21	39,390.81	8	Venezuela	46.3	115	2143.42	59
New Zealand	71.82	75	2261.49	57	Yemen	91.95	52	1094.34	76
Nicaragua	121.32	28	831.29	82	Zambia	70.45	78	240.86	111
Niger	38.53	124	82.99	126	Zimbabwe	62.61	91	730.10	88

Source: Squalli and Wilson (2011)

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Table 10 Correlation analysis

Proxy	CTI	TI
FDI net outflows	0.69	−0.32
FDI net inflows	0.30	0.69
Taxes on international trade	−0.31	−0.22
Customs and other import duties	−0.43	−0.04
Business entry	0.27	0.08

(i) Data for the above-mentioned proxies as well as CTI and TI are from WDI. (ii) The time period of all data is 1993–2019. (iii) Foreign direct investment (FDI) net outflows and inflows are as a percentage of GDP. (iv) Taxes on international trade are as a percentage of revenue. (v) Custom duties and other import duties are as a percentage of tax revenue. (vi) Business entry denotes the registration of new businesses (as percentage of total). (iv) Business entry denotes the registrations of new businesses (as percentage of total. Source: Authors' calculations

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