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Exploring the moderating role of financial development in environmental Kuznets curve for South Africa: fresh evidence from the novel dynamic ARDL simulations approach

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Abstract

The extant literature has produced mixed evidence on the relationship between financial development and ecological sustainability. This work addresses this conundrum by investigating financial development's direct and indirect consequences on ecological quality utilizing the environmental Kuznets curve (EKC) methodological approach. Our empirical analysis is based on the novel dynamic autoregressive distributed lag simulations approach for South Africa between 1960 and 2020. The results, which used five distinct financial development measures, demonstrate that financial development boosts ecological integrity and environmental sustainability over the long and short terms. In the instance of South Africa, we additionally confirm the validity of the EKC theory. More importantly, the outcomes of the indirect channels demonstrate that financial development increases energy usage's role in causing pollution while attenuating the detrimental impacts of economic growth, trade openness, and foreign direct investment on ecological quality. Moreover, the presence of an inadequate financial system is a requirement for the basis of the pollution haven hypothesis (PHH), which we examine using trade openness and foreign direct investment variables. PHH for both of these variables disappears when financial development crosses specified thresholds. Finally, industrial value addition destroys ecological quality while technological innovation enhances it. This research provides some crucial policy recommendations and fresh perspectives for South Africa as it develops national initiatives to support ecological sustainability and reach its net zero emissions goal.

Keywords: Financial development, Trade openness, CO_2 emissions, Dynamic ARDL simulations, Energy consumption, EKC, Cointegration, Economic growth, Foreign direct investment, Industrial value-added, South Africa

JEL Classification: F18, F13, Q56, O13, F1, F41

Introduction

In industrialized and emerging economies, growing carbon emissions and ecological deterioration are significant issues today (Udeagha and Ngepah 2022a, b), and human activities are to blame for rising carbon emissions and ecological deterioration. World

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Bank (2021) shows that contemporary carbon emissions and environmental deterioration are 50% more than during the industrial period. This deterioration is wreaking havoc on the ecosystem in practically every country on the planet, representing a significant concern that must be tackled from various perspectives. In its broadest sense, environmental quality describes the characteristics of the atmosphere, river, and earth, particularly in the context of overall sustainability. The ecosystem is regarded as sustainable and healthy without emissions, implying no threats such as carbon pollution, chemical toxins, fire, or allergens in the domain (Udeagha and Muchapondwa 2022; Zia et al. 2021). By minimizing greenhouse gas (GHG) emissions, a healthy ecosystem enhances ecological integrity and environmental conservation, suggesting that ecological sustainability supports people's health and that all countries have practical habitat preservation (Zeeshan et al. 2021).

Environmental degradation has become a growing issue and a significant public health concern, as it affects every country and many industrialized economies, including India, Russia, Japan, Germany, the United States, and China, which have been identified as major GHG producers and have obligations to maintain the planet (World Bank 2021). Their sacrifices and collaborations are crucial to tackling global environmental degradation; however, reducing CO_2 emissions reduces production. This reduction could hinder productivity expansion since reducing CO_2 emissions is connected to energy utilization, which is essential for economic development (Tahir et al. 2021). Due to this circumstance, it is very challenging for these nations to subscribe to or carry out initiatives that aim to lower global CO_2 emissions, which necessitates better ways to achieve ecofriendly economic growth and better ecological conditions. In this pursuit, some policymakers worldwide have adopted various strategies to mitigate environmental deterioration and global warming (Li et al. 2022; Musa et al. 2021; Kumar et al. 2021; Habiba et al. 2021; Ganda 2021). Financial development is believed to be an effective pathway among these strategies for improving environmental quality.

Various arguments have been proposed in the theoretical literature to explain the relevance of financial development in promoting ecological integrity. Financial development, for example, lowers intermediate costs and decreases risk diversification, making it easier for private and public sector investors to engage in clean energy projects (Nasir et al. 2019). Frankel and Romer (1999) showed that well-organized financial sector development promotes foreign direct investment, which triggers research and development (R&D) projects, resulting in increased revenue and less environmental damage. The authors also acknowledged that substantial foreign direct investment in less industrialized economies promotes the adoption of innovative technologies, thereby improving regional and global environmental sustainability.

South Africa's financial development has accelerated historically, accompanied by increased CO_2 emissions. Following a transition to a democratically constitutional regime in 1994, the country enacted several initiatives to bolster its financial institutions, resulting in a solid financial base (Udeagha and Muchapondwa 2022; Adebayo et al. 2021; Adebayo and Odugbesan 2021). This increasing trend persisted until 2007 when the country experienced a substantial financial meltdown due to the 2007–2008 worldwide financial crisis. (Adewuyi and Awodumi 2021). Since then, South Africa has maintained a progressively increasing trend in economic and fiscal growth and CO_2

emissions levels. Financial resources are routinely leveraged in South Africa to improve economic and financial development. Meanwhile, the country's improved financial system—which is heavily reliant on financial resources—enables energy and technological advancements, boosts investment efficiency, expands business opportunities, improves enterprise performance, facilitates increased energy efficiency, and mitigates environmental degradation (Kohler 2013). Thus, one of the key policy options that many administrations have followed since 1994 to limit environmental deterioration has been to expand the country's energy industry by providing sufficient financial assistance (Haseeb et al. 2018). South Africa's financial system increases credit allocation, investment rates, economic development, and more environmentally friendly initiatives, all of which help to mitigate environmental deterioration (Adebayo et al. 2021; Adebayo and Odugbesan 2021; Adewuyi and Awodumi 2021). Furthermore, the country's improved, robust, and productive financial intermediary quality attracts foreign direct investment, contributing significantly to economic growth and development. The government has recently introduced several major policies to encourage foreign firms to invest more in R&D and employ more robust practices to promote ecologically sustainable activities and energy-efficient production. These ecoinnovative strategies have shifted the country's industrial structure from high-energy-consuming manufacturing to production methods that require much less energy, consequently improving ecological integrity (Shahbaz et al. 2013; Udeagha and Ngepah 2019). More fundamentally, South Africa's financial system helps to minimize CO_2 emissions by increasing product competitiveness, lowering production costs, minimizing energy costs, and championing energy-efficient technologies. Finally, the country's financial system is well-organized and developed, with solid banking rules and a financial sector that ranks top ten worldwide. Because of these features, South Africa is a good reference point for analyzing the moderating influence of financial development in the standard environmental Kuznets curve (EKC) architecture through economic growth, energy supply, trade openness, and foreign direct investment inflows.

As the largest CO_2 producer in Africa, with an expected 390 million metric tons in 2020, South Africa is the 15th largest CO_2 producer globally (1.09% of worldwide pollution) (World Bank 2021). The use of coal seems to be the main factor contributing to the nation's rising emission levels and ecological damage (Udeagha and Ngepah 2022c; Shahbaz et al. 2013). In South Africa, coal is the primary power source and a significant contributor to pollutant emissions. Coal produces approximately 77% of all electricity, of which domestic energy production consumes 2%, 12% for the iron and steel industry, 33% for industrial plants, and 53% for cogeneration (Udeagha and Breitenbach 2021). With 35,053 million metric tons (MMst) of known coal reserves as of 2020, South Africa is significantly dependent on the energy sector, with the share of coal driving production operations. Because of these qualities, South Africa is an excellent fit for investigating how financial development influences environmental quality through economic growth, energy consumption, foreign direct investment, and trade openness.

In South Africa, only a few empirical studies have examined the implications of financial development. For example, Rafindadi and Ozturk (2017) investigated the dynamic impacts of financial development on energy consumption, revealing that a competent financial system is a tool that enables energy demand in South Africa. Salahuddin and

Gow (2016) assessed the effects of financial development on economic growth and determined that financial development helps to increase economic growth in South Africa. Similarly, Nyasha and Odhiambo (2015) investigated the effects of financial development on economic growth in South Africa using both market- and bank-based indicators, concluding that financial development helps increase the country's economic growth. Additionally, Phiri (2015) used a momentum threshold autoregressive model to investigate the nexus between financial development and economic growth. They found that financial development facilitates responsiveness and increases the overall efficiency of the public sector in service delivery, thereby enhancing economic development and reducing regional disparities in South Africa. Adebayo and Odugbesan (2021) showed that the finance-pollution nexus in South Africa adds to the escalation of environmental deterioration in the country, while Adewuyi and Awodumi (2021) investigated the ecological implications of financial development in South Africa and found similar results. Adebayo et al. (2021) used the autoregressive distributed lag (ARDL) methodology to indicate that financial development reduces CO_2 emissions in South Africa. Similarly, Shahbaz et al. (2013) evaluated the effects of financial development on environmental quality and showed that financial development enhanced environmental quality in South Africa.

Although past research on the relationship between financial development and ecological quality has made progress, it has also raised several significant problems. The current study includes these elements, adds to the growing research, and indicates five ways financial development affects the environment. First, to the best of our knowledge, this paper represents the first attempt to empirically assess the moderating impact of financial development in the EKC framework in South Africa. The study uses the EKC framework to investigate whether financial development affects ecological sustainability in South Africa; it also investigates whether creating a well-organized financial sector may offset the adverse environmental effects of income (economic growth). Second, this study uses the EKC framework and financial development as a moderating factor to assess whether a greater degree of financial development mediates the negative impacts of energy use, foreign direct investment, and trade openness on South Africa's ecological sustainability. It is important to note that since these factors have been used to examine whether the pollution haven hypothesis (PHH) applies to less developed nations, it is crucial to research how financial growth may indirectly affect ecological integrity through these variables. Although there is conflicting and inconsistent empirical evidence supporting the PHH (Kong 2021; Hsu et al. 2021; Aljadani 2022), this study is the first to attempt to outline the conditions under which the theory may be valid or erroneous for South Africa. Thus, our research provides a solution to the empirical conundrum regarding the PHH for South Africa and the rest of the developing world. Third, to graphically represent the ecological implications of financial development as shown in economic growth, energy consumption, foreign direct investment, and trade openness, this work uses the reliable approach developed by Brambor et al. (2006). With the help of this method, we can assess the marginal environmental effects of each of these variables at various levels of financial development and systematically determine the financial development thresholds necessary to reduce the negative effects of economic growth, energy supply, foreign direct investment, and trade openness. Despite the robust modeling approach that Brambor et al. (2006) proposed, no prior studies have used it to investigate the proposed relationship. Fourth, earlier research on the relationship between finance and CO_2 emissions in a broader sense (including the studies mentioned above) frequently used Pesaran et al. (2001)'s basic ARDL model and other cointegration strategies, which could only examine the short- and long-term relationships between all of the model's variables. In contrast, this study adds to the scant methodological literature by addressing the shortcomings and drawbacks of applying the conventional ARDL approach using sophisticated econometric analysis: Jordan and Philips (2018)'s novel dynamic ARDL simulations framework. By conveniently simulating and depicting forecast plots of (negative and positive) variations in the factors and observing the accompanying short- and long-run relationships between variables under evaluation, the novel dynamic ARDL simulations framework effectively addresses the issues and constraints in the output explanations of the simple ARDL approach. As a result, using this original method in this inquiry yields reliable and open results. Lastly, prior research that examined the relationship between finance and CO_2 emissions in the context of trade openness has been criticized for using a one-dimensional trade approximation that failed to account for the ecological effects of global commerce. By carefully using Squalli and Wilson (2011)'s new trade openness measure to reflect two components of trade openness—emphasizing trade's contribution to gross domestic product (GDP) and recognizing the magnitude of trade, particularly in comparison to foreign markets—this research adds to the body of research already aggressing the relationship between financial development and ecological sustainability. We differ from extant research that evaluated and broadly described trade openness using standard trade intensity by utilizing the Squalli and Wilson (2011) trade openness indicator.

The remainder of the research is organized as follows. "Literature review and research gaps" section reviews the literature on the link between financial development and environmental quality. "Material and methods" section discusses the material and methodological framework, and "Empirical results and their discussion" section presents the findings. The conclusion and policy consequences are presented in "Conclusion and policy implications" section.

Literature review and research gaps

This section comprises two different headings. The theoretical and empirical works on the nexus between financial development and environmental quality are discussed and presented in the first section. The second section presents the knowledge gaps in the present work to the existing literature on the effects of financial development on ecological sustainability.

Review of previous literature

The extant theoretical literature provides various arguments describing the importance of financial development in supporting ecological integrity (Dagar et al. 2022; Islam 2022; Sheraz et al. 2021). For example, financial development lowers intermediate costs, decreases risk diversification, and makes it easier for private and public sector investors to engage in clean energy projects (Nasir et al. 2019). Frankel and Romer (1999) showed that well-organized financial sector development promotes foreign direct investment, which triggers R&D projects, resulting in increased revenue and less environmental damage. The authors also acknowledged that substantial foreign direct investment inflows in less developed countries promote the adoption of innovative technologies, improving regional and global environmental sustainability.

The environmental effects of financial development have been studied extensively; however, the results have been controversial and inconsistent throughout various experimental techniques and examined economies. According to specific investigations, financial development helps to minimize pollution by allowing businesses to employ more robust techniques that promote ecoinnovative and energy-efficient production (Zeeshan et al. 2021; Xuezhou et al. 2022; Usman et al. 2021; Li et al. 2022; Le and Hoang 2022; Khan et al. 2021b, 2022a, b; Godil et al. 2021; Hsu et al. 2021; Kong 2021; Zhuo and Qamruzzaman 2022). Countries using these ecoinnovative strategies can shift their industrial structure to ecofriendly production processes, helping to enhance the sustainability of the environment. Moreover, according to these studies, an improved financial system strengthens ecological integrity by enabling energy and technology improvement, increasing investment efficiency, expanding business opportunities and enterprise performance, facilitating an increase in energy efficiency, increasing product competitiveness, lowering production costs, minimizing energy costs, and promoting energy-efficient techniques. All of these make significant contributions to lowering CO_2 emissions.

Zeeshan et al. (2021) looked at the relationship between financial development and environmental quality in 20 developed nations from 2001 to 2018, revealing that financial development considerably improved the environment. Xuezhou et al. (2022) used the panel vector autoregressive-generalized method of moment framework (PVAR-GMM) to investigate the role of financial development in fostering environmental quality. They observed that financial development improved environmental quality by lowering CO_2 emissions in the Sub-Saharan African countries studied. Similarly, Usman et al. (2021) used the pooled mean group-autoregressive distributive lag model (PMG-ARDL), revealing that financial development helped minimize environmental pollution for 52 advanced and emerging economies from 1995 to 2017. In addition, Li et al. (2022) used the asymmetric ARDL framework to analyze the asymmetric influence of financial development on ecosystems in China from 1981 to 2019 and found that financial development resulted in a decrease in CO_2 emissions. Le and Hoang (2022) found similar results when they utilized the gravity model to investigate the impacts of financial development on CO_2 emissions in emerging, transition, and industrialized nations. Similarly, Khan et al. (2022a, b) found that global financial development enhanced environmental sustainability from 2002 to 2019, while Khan et al. (2021a, b, c) demonstrated that financial development improved environmental quality in 184 nations. Additionally, Godil et al. (2021) used the Quantile ARDL framework to explore the ecological impacts of financial development, concluding that financial development accelerated ecological integrity in Pakistan from 1990 to 2018.

In contrast, according to a different set of research, financial development weakens environmental sustainability (Zia et al. 2021; Yang et al. 2021a, b; Weili et al. 2022; Usman and Hammar 2021; Tahir et al. 2021; Sharma et al. 2021; Musa et al. 2021; Li et al. 2022; Kumar et al. 2021; Khaskheli et al. 2021; Kahouli et al. 2022; Idrees and Majeed 2022;

Habiba et al. 2021; Ganda 2021; Fakher et al. 2021a, b; Dagar et al. 2022; Aljadani 20221; Musah et al. 2021; Zafar et al. 2021; Khan et al. 2022a, b; Islam 2022). This group also claims that better-organized and higher-quality financial intermediation results in more financial projects, allowing both household members and enterprises (or industrialists) to access high-energy-demanding items and lowering ecological integrity. Increased energy consumption by industrialists (or enterprises) and family members leads to increased environmental deterioration. Therefore, financial development contributes to eroding ecological protection via energy consumption. This school of thought has also recognized the route of foreign direct investment inflows as another factor for financial development's pollution-increasing impact. Financial development draws foreign direct investment, which substantially adversely affects ecosystems, particularly in developing countries. Environmentally damaging products tend to move due to increased levels of trade liberalization and significant foreign direct investment in less developed countries, while pollution-intensive multinational businesses seek out countries with inadequate environmental requirements for their investments. These pollution-intensive multinational firms relocate their operations because it is more flexible and less expensive to comply with lax environmental regulations than strict environmental standards that guide production activities in developed countries. This situation escalates environmental degradation in these less developed countries (Habiba et al. 2021; Ganda 2021).

Zia et al. (2021) used the dynamic simulated ARDL framework to analyze the ecological effect of financial development in China from 1985 to 2018. They noted that financial development degraded ecological integrity. Yang et al. (2021a) revealed that financial development contributed significantly to rising CO_2 emissions in BRICS (Brazil, Russia, India, China, and South Africa) nations utilizing the dynamic seemingly unrelated regression model and fully modified ordinary least squares approach. Furthermore, from 2000 to 2019, Weili et al. (2022) observed that financial development impaired ecological sustainability in Belt and Road nations. Usman and Hammar (2021) obtained similar findings for Asia Pacific Economic Cooperation (APEC); Tahir et al. (2021) for South Asian economies; Sharma et al. (2021) for 8 South and Southeast Asian nations; Musa et al. (2021) for EU-28 countries; Li et al. (2022) for Belt and Road countries; Kumar et al. (2021) for 33 developing countries; Khaskheli et al. (2021) for low-income countries; Kahouli et al. (2022) for Saudi Arabia; Idrees and Majeed (2022) for Pakistan; Habiba et al. (2021) for G20 countries; Ganda (2021) for BRICS economies[1]; Fakher et al. (2021b) for OPEC countries[2]; and Dagar et al. (2022) for OECD countries.[3]

For further cross-national and cross-regional assessments, Table 1 offers an overview of research examining the link between financial development and ecological sustainability.

Summarizing literature gaps

Given the extensive popularity of previous studies, several vital gaps remained unaddressed, which this inquiry considers, including the following huge gaps. First, although

[1] Brazil, Russia, India, China, and South Africa.

[2] Organization of the Petroleum Exporting Countries.

[3] Organisation for Economic Co-operation and Development.

Table 1 Synopsis of studies

S/N	Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
1	Zia et al. (2021)	1985–2018	China	Dynamic simulated ARDL	Financial development triggers CO_2 emissions
2	Zeeshan et al. (2021)	2001–2018	20 Developed countries	Dynamic Penal GMM, CCEMG, Dynamic Fixed Effect	Financial development reduces the level of emissions
3	Yang et al. (2021a)	1990–2016	BICS countries	DSUR, FMOLS	Financial development deteriorates environmental quality
4	Xuezhou et al. (2022)	1980–2017	Sub-Saharan African region	PVAR-GMM	Financial development improves environmental quality
5	Weili et al. (2022)	2000–2019	Belt and Road countries	GMM, GLS	Financial development increases carbon emissions
6	Usman and Hammar (2021)	1990–2017	APEC	STIRPAT model	Financial development accelerates environmental quality
7	Usman et al. (2021)	1995–2017	52 Developed and developing countries	PMG-ARDL	Financial development improves environmental quality
8	Tahir et al. (2021)	1990–2014	South Asian economies	FMOLS, DOLS, PMG	Financial development increases carbon emissions
9	Sharma et al. (2021)	1990–2015	8 South and Southeast Asian nations	CS-ARDL	Financial development escalates carbon emissions
10	Rout et al. (2022)	1990–2018	BRICS	PMG	Financial development does not have any effect on carbon emissions
11	Musa et al. (2021)	2002–2014	EU-28 countries	GMM	Financial development worsens the level of emissions
12	Li et al. (2022)	1981–2019	China	Asymmetric ARDL	Financial development improves environmental quality
13	Li et al. (2022)	1991–2017	BRI	MG	Financial development increases carbon emissions
14	Le and Hoang (2022)	1995–2018	Developing transition and, developed countries	Gravity model	Financial development mitigates carbon emissions
15	Kumar et al. (2021)	2011–2017	33 Developing countries	Dynamic technique system GMM	Financial development worsens environmental quality
16	Khaskheli et al. (2021)	1990–2016	Low-income countries	PSTR	Financial development deteriorates environmental quality at a low regime but improves it as the economy progresses to the high regime
17	Khan et al. (2021a)	2002–2019	Global perspective	GMM	Financial development improves environmental quality
18	Kahouli et al. (2022)	1980–2019	Saudi Arabia	ARDL, VECM	Financial development worsens environmental quality

Table 1 (continued)

S/N	Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
19	Idrees and Majeed (2022)	1972–2018	Pakistan	Linear and nonlinear ARDL	Financial development deteriorates environmental quality
20	Habiba et al. (2021)	1981–2017	G20 countries	CCEMG	Financial development increases carbon emissions
21	Ganda (2021)	2000–2018	BRICS economies	Fixed effect panel threshold model	Financial development increases the level of emissions
22	Fakher et al. (2021b)	2010–2019	OPEC countries	System GMM	Financial development increases the level of emissions
23	Fakher et al. (2021a)	1985–2018	OPEC and OECD countries	System GMM	Financial development deteriorates environmental quality in OPEC countries but improves it in OECD countries
24	Dagar et al. (2022)	1995–2019	OECD countries	Difference GMM, system GMM	Financial development worsens environmental quality
25	Aljadani (2022)	1970–2016	Saudi Arabia	STIRPAT, ARDL model	Financial development deteriorates environmental quality
26	Musah et al. (2021)	1990–2016	West Africa	CS-ARDL, CS-DL, CAEC	Financial development intensifies level of emissions
27	Zafar et al. (2021)	1990–2017	Asian countries	FMOLS	Financial development worsens environmental quality
28	MK. Khan et al. (2021a)	1989–2020	Canada	Dynamic ARDL model	Financial development increases environmental degradation
29	Islam (2022)	1980–2018	Five South Asian economies	LSDVC	Financial development deteriorates environmental quality
30	Yang et al. (2021b)	1990–2017	GCC	FMOLS	Financial development deteriorates environmental quality
31	Khan et al. (2021b)	2002–2019	180 countries	OLS, Fixed effect, GMM	Financial development deteriorates environmental quality
32	Khan et al. (2021b)	1990–2017	184 countries	GMM estimator	Financial development mitigates the level of emissions
33	Sheraz et al. (2021)	2003–2018	Belt and Road countries	GMM	Financial development increases the level of emissions
34	Godil et al. (2021)	1980–2018	Pakistan	QARDL	Financial development reduces carbon emissions
35	Hsu et al. (2021)	2000–2018	28 Chinese provinces	OLS	Financial development improves environmental quality
36	Kong (2021)	1985–2016	China	ARDL framework	Financial development improves environmental quality
37	Zhuo and Qamruzzaman (2022)	2000–2016	China	DSUR	Financial development improves environmental quality

Table 1 (continued)

S/N	Investigator (s)	Timeframe	Nation (s)	Technique(s)	Findings
38	Zeraibi et al. (2020)	1985–2016	5 Southeast Asian countries	CS-ARDL	Financial development worsens environmental quality
39	Uche and Effiom (2021)	2000–2018	Nigeria	MTNARDL	Financial development intensifies environmental degradation
40	Adebayo et al. (2021)	1980–2017	Latin American countries	FMOLS, DOLS	Financial development does not have any effect on environmental quality
41	Khan et al. (2021a)	1980–2019	Malaysia	Dynamic simulated ARDL	Financial development worsens environmental quality

BICS Brazil, India, China, and South Africa, *ARDL* autoregressive distributed lag, *DOLS* dynamic ordinary least squares, *FMOLS* fully modified ordinary least squares, *MTNARDL* multiple threshold nonlinear autoregressive distributed lag model, *DSUR* dynamic seemingly unrelated regression, *PVAR-GMM* panel vector autoregressive-generalized method of moment framework, *PMG* pooled mean group, *MG* mean group, *GMM* generalised method of moments, *GLS* generalized least square model, *APEC* Asia Pacific Economic Cooperation countries, *STIRPAT* Stochastic Impacts by Regression on Population, Affluence and Technology model, *PMG-ARDL* pooled mean group-autoregressive distributed lag model, *QARDL* quantile autoregressive distributed lag model, *PSTR* panel smooth transition regression model, *VECM* vector error correction model, *CS-DL* cross-sectional augmented distributed lag, *CAEC* cross-sectional augmented error correction, *CS-ARDL* cross-sectional augmented autoregressive distributed lag, *OECD* Organisation for Economic Co-operation and Development, *OPEC* Organization of the Petroleum Exporting Countries, *CS-ARDL* cross-sectional augmented autoregressive distributed lag, *BRICS* Brazil, Russia, India, China and South Africa, *CCEMG* common correlated effect mean group, *BRI* belt and road initiative, *GCC* Gulf Cooperation Council

there are significant direct and indirect interconnections between financial development and environmental quality, the extant literature has not conducted empirical research on the indirect influence of financial development that manifests via foreign direct investment, energy supply, economic growth, and trade openness. Therefore, it is crucial to emphasize the relevance of examining the indirect consequences of financial development on environmental protection via trade openness, and foreign direct investment in particular, given that these variables have been extensively utilized to investigate the validity of the PHH for developing countries like South Africa (Kong 2021; Hsu et al. 2021; Aljadani 2022). Environmentally damaging items allegedly relocate to countries with emerging economies because of their low environmental laws due to rising trade openness and globalization. Because of this, emerging nations like South Africa may experience environmental deterioration due to increased trade and foreign direct investment. Even though many investigations have examined the empirical validity of PHH, the results provide a confusing picture of the situation. As a result, the indirect consequences of trade openness, economic growth, energy supply, and foreign direct investment (primarily in South Africa) have gone unresearched concerning the link between finance and environmental integrity. Our work examines the moderating influence of financial development on the link between CO_2 emissions and these two variables (trade openness and foreign direct investment), representing the first attempt to propose circumstances under which PHH may or may not hold for South Africa. Second, studies on the relationship between financial development and environmental damage have frequently employed the conventional ARDL model developed by Pesaran et al. (2001) and alternative cointegration techniques. None of the extant literature used the novel dynamic ARDL simulations approach; thus, those investigations failed to account for the shortcomings and inefficiencies in the fundamental ARDL procedure by flawlessly visualizing and plotting to accurately predict graphs of (positive and negative) variations in the data and exploring the respective short- and long-run relationships of the variables under evaluation. Third, little research has used the robust method developed by Brambor et al. (2006) to graphically represent the ecological effects of financial development as manifested in economic growth, energy supply, foreign direct investment, and trade openness. Finally, research examining the connection between financial development and CO_2 emissions in the context of trade openness has questioned the use of a one-dimensional trade measurement that does not adequately capture the ecological impact of trade openness. Since no research employed the composite trade intensity (CTI) proposed by Squalli and Wilson (2011), earlier works failed to consider two components of trade openness: the trade share in the GDP and the trade size compared to global trade.

Material and methods

This research uses the novel dynamic ARDL simulations paradigm to systematically examine the moderating impact of financial development on ecosystems in South Africa between 1960 and 2020. We first conduct stationarity on the variables to investigate their order of integration using the Dickey–Fuller GLS (DF-GLS), Phillips–Perron (PP), Augmented Dickey–Fuller (ADF), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests. Because structural fractures are frequent, failing to account for them could lead to inaccurate results; thus, this paper uses the method described by Narayan and Popp (2010). The variables' long- and short-run coefficients are investigated using the novel dynamic ARDL simulations model. Finally, the study applies the advanced modeling approach developed by Brambor et al. (2006) to visualize the environmental effects of financial development as shown in trade openness, energy supply, economic growth, and foreign direct investment.

Functional form

This study used the established EKC hypothesis framework and methodologically rigorous approach in prior research to examine the moderating impact of financial development on ecosystems in South Africa. The EKC hypothesis holds that climate change worsens as economies develop, especially in the initial phases of a dramatic shift. Thus, environmental deterioration increases with income since the nation is more focused on reaching faster economic growth than on cutting emissions. This idea emphasizes the strong and fundamental connection between ecological sustainability and income. Meanwhile, the rapidly industrializing stage of expansion causes more significant environmental deterioration. Ecological destruction increases as the economy grows and shifts away from manufacturing processes characterized by agricultural production. Consequently, people have become more concerned with environmental challenges, deploying stiffer pollution standards to improve ecosystems and biodiversity. Thus, throughout the highly industrialized era of social transition, the propensity for a suitable environment and the government's implementation of more stringent environmental regulations substantially contributed to enhancing ecological integrity; as income (economic growth) increases, environmental deterioration declines. This idea explains the negative association between the technique effect (square of economic growth) and the ecological environment.

Following Cole and Elliott (2003), Udeagha and Ngepah (2019, 2021a, b), and Udeagha and Breitenbach (2021) and, we provide the conventional EKC hypothesis as follows:

$$CO2_t = F(SE, TE) \tag{1}$$

where CO_2 is a measure of ecological quality, SE is a scale effect that reflects economic growth (income), and TE is a technique effect that records growth in the economy squared. When Eq. (1) is log-linearized, we have the following:

$$\text{In}CO2_t = \alpha + \varphi InSE_t + \beta InTE_t + \varepsilon_t \tag{2}$$

As pollution rises due to increased income, the SE degrades ecological integrity; on the other hand, the TE strengthens ecological sustainability and integrity as stricter pollution controls are adopted to curb rising emissions (Cole and Elliott 2003; Ling et al. 2015). As a result, the correctness of the EKC hypothesis necessitates that: $\varphi > 0$ and $\beta < 0$. The model accounts for industrial value-added and technological innovation, as the literature suggests. Thus, the following equation defines our benchmark modeling approach, which contains the primary effects excluding multiplicative interaction terms:

$$\begin{aligned}\text{In}CO2_t = \alpha + \vartheta\,\text{In}CO2_{t-1} + \varphi InSE_t + \beta InTE_t + \psi InFD_t + \pi InEC_t + \delta InFDI_t \\ + \tau InOPEN_t + \omega InIGDP_t + \rho InTECH_t + U_t\end{aligned} \tag{3}$$

where $InFD_t$ denotes financial development; $InIGDP_t$ stands for industrial value-added; $InOPEN_t$ signifies trade openness, $InFDI_t$ denotes foreign direct investment; $InEC_t$ signifies energy consumption; $InTECH_t$ is technological innovation; all variables are in their natural log. $\varphi, \beta, \psi, \rho, \pi, \delta\tau,$ and ω are the estimable parameters in the model representing different elasticities while U_t is the stochastic error term. This paper employs the first lag of the dependent variable ($\text{In}CO2_{t-1}$) to reflect the dynamic influence of CO_2 emissions in the model.

While verifying the prevalence of the EKC hypothesis, Eq. (3) hypothesizes the standalone (direct) ecological effect of financial development. This research first suggests that financial development can act as a moderating component in the relationship between economic expansion and ecological sustainability (see Khan and Ozturk 2021; Sheraz et al. 2021; Gill et al. 2019). Equation (3) is supplemented by including the multiplicative interaction term of financial development and economic growth (SE) to account for this effect. The following is the equation:

$$\begin{aligned}\text{In}CO2_t = \alpha + \vartheta\,\text{In}CO2_{t-1} + \beta InTE_t + \psi InFD_t + \varphi InSE_t + \varphi^* In(SE_t * FD_t) + \pi InEC_t \\ + \delta InFDI_t + \tau InOPEN_t + \omega InIGDP_t + \rho InTECH_t + U_t\end{aligned} \tag{4}$$

The multiplicative interaction term captures the moderating effect of financial development on the connection between economic growth and environmental sustainability (see Khan and Ozturk 2021; Chen et al. 2019; Chen and Myagmarsuren 2013; Cohen and Cohen 1983). Thus, the existence of higher-quality financial intermediation only acts as a moderating element in the link between economic growth and ecological sustainability if φ is positive and statistically significant and φ^* is negative and statistically significant. As a result, the multiplicative interaction factor in Eq. (4) should be statistically significant, indicating that financial development plays a moderating function in the economic growth-pollution association (Le and Hoang 2022; Jahanger 2022).

Similarly, the following relation can be used to investigate the moderating effect of financial development on the energy-pollution relationship:

$$\begin{aligned} \text{In}CO2_t = \alpha + \vartheta \text{In}CO2_{t-1} + \varphi InSE_t + \beta InTE_t + \psi InFD_t + \pi InEC_t + \pi^* In(EC_t * FD_t) \\ + \delta InFDI_t + \tau InOPEN_t + \omega InIGDP_t + \rho InTECH_t + U_t \end{aligned} \quad (5)$$

Equally, the moderating influence of financial development on the link between foreign direct investment and ecological sustainability may be evaluated using the following relation:

$$\begin{aligned} \text{In}CO2_t = \alpha + \vartheta \text{In}CO2_{t-1} + \varphi InSE_t + \beta InTE_t + \psi InFD_t + \pi InEC_t + \delta InFDI_t \\ + \delta^* In(FDI_t * FD_t) + \tau InOPEN_t + \omega InIGDP_t + \rho InTECH_t + U_t \end{aligned} \quad (6)$$

Similarly, to account for the moderating effect of financial development on ecosystems via the trade openness channel, we add the multiplicative interaction term of financial development and trade openness to our benchmark equation as follows:

$$\begin{aligned} \text{In}CO2_t = \alpha + \vartheta \text{In}CO2_{t-1} + \varphi InSE_t + \beta InTE_t + \psi InFD_t + \pi InEC_t + \delta InFDI_t \\ + \tau InOPEN_t + \tau^* In(OPEN_t * FD_t) + \omega InIGDP_t + \rho InTECH_t + U_t \end{aligned} \quad (7)$$

Finally, the research employs the sophisticated analytical methodology of Brambor et al. (2006) to visually show and quantify the cumulative effects of economic growth, energy supply, foreign direct investment, and trade openness at various degrees of financial development.

Measuring trade openness

This research uses the CTI developed by Squalli and Wilson (2011) to successfully solve the drawbacks of trade intensity (TI) in prior works. The CTI accurately accounts for two components of trade openness: the contribution of trade in GDP and the extent of trade regarding the international market. As a result, introducing the Squalli and Wilson measure of trade openness differentiates our approach from earlier research, which used the standard TI to quantify and approximate trade openness. Additionally, leveraging this wide-ranging approach to quantifying trade openness accounts for the deficiencies of the popular TI. In effect, the innovative CTI contains additional critical components of a nation's trade, contributing to the global market (Squalli and Wilson 2011). Furthermore, because it includes two components of a nation's relationships with the world, this revolutionary measure for trade openness considers trade outcome reality. As suggested by Squalli and Wilson (2011), we show the CTI as follows:

$$CTI = \frac{(X+M)_i}{\frac{1}{n}\sum_{j=1}^{n}(X+M)_j}\frac{(X+M)_i}{GDP_i} \quad (8)$$

where i denotes South Africa, j reflects her trading partners, X represents exports, and M denotes imports. In Eq. (8), the first segment captures the world trade share, and the second portion accounts for South Africa's trade share.

Variables and data sources

This research uses annual time series data that span the years 1960 through 2020. CO_2 emissions, the dependent variable in this study, serve as a proxy for environmental quality; kg per US dollar (USD) of GDP in 2015 served as the unit of CO_2 emissions. The World Bank World Development Indicators gave data on CO_2 emissions from 1960 to 2020. We employ the SE—which captures economic growth—and the TE—which represents the square of economic growth—to confirm the existence of the EKC hypothesis. Both SE and TE were measured at the current USD exchange rate. Data for SE and TE between 1960 and 2020 were gathered from the World Bank World Development Indicators. The research employs five metrics percentages of GDP to assess financial development, including liquid liabilities (M3GDP), total bank deposit (TDGDP), domestic credit to the private sector (DCPS), domestic credit provided by the financial sector (DCFS), and financial system deposits (FSDGDP). The World Bank World Development Indicators gave data on five metrics of financial development used in this inquiry from 1960 to 2020. The variables of interest include economic growth (represented by SE), energy supply (EC), foreign direct investment (FDI), and trade openness (OPEN). The unit of energy consumption (EC) was kg of oil equivalent per capita, and relevant data from 1960 to 2020 were sourced from the World Bank World Development Indicators. The unit of FDI was in a percentage of GDP, and the World Bank World Development Indicators provided data on FDI from 1960 to 2020. The unit of OPEN was in a percentage of GDP, computed using a CTI as illustrated above, with observations from 1960 to 2020 sourced from the World Bank World Development Indicators. The control variables were measured as percentages of GDP following empirical studies, including industrial value-added to GDP (IGDP) and technological innovation (TECH), using gross domestic spending on R&D. Both variables were sourced from the World Bank World Development Indicators from 1960 to 2020. Table 2 summarily presents the definition of variables as well as the sources of data.

Narayan and Popp's structural break unit root test

To initially analyze the order of integration, we use a unit root test on the variables before using the novel dynamic ARDL simulations framework. This paper incorporates the conventional stationarity tests, such as Dickey–Fuller GLS (DF-GLS), Phillips–Perron (PP), Augmented Dickey–Fuller (ADF), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS). The investigation accounts for structural breaks with the method suggested by Narayan and Popp (2010), as failing to do so might result in inaccurate and conflicting outcomes.

ARDL bounds testing approach

This study investigates the moderating effect of financial development on South Africa's ecological integrity using the bounds testing methodology. Equation (3), our benchmark framework without multiplicative connecting components, is used as an example before

Table 2 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
FD	Financial development is proxied using five measures, which include as follows:		
M3GDP	Liquid liabilities;	Positive or negative	WDI
TDGDP	Total bank deposit;	Positive or negative	WDI
DCPS	Domestic credit to private sector;	Positive or negative	WDI
DCFS	Domestic credit provided by financial sector; and	Positive or negative	WDI
FSD	Financial system deposits	Positive or negative	WDI
TECH	Technological innovation is measured by gross domestic spending on R&D (% GDP)	negative	WDI
OPEN	Trade openness is 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
IGDP	Industry, value added (% of GDP)	Positive or negative	WDI

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

employing frameworks with multiplicative interacting elements. We provide the traditional ARDL bounds methodology in the format below, following Pesaran et al. (2001):

$$\begin{aligned}\Delta InCO2_t = {} & \gamma_0 + \theta_1 InCO2_{t-i} + \theta_2 InSE_{t-i} + \theta_3 InTE_{t-i} + \theta_4 InFD_{t-i} \\ & + \theta_5 InTECH_{t-i} + \theta_6 InEC_{t-i} + \theta_7 InFDI_{t-i} + \theta_8 InOPEN_{t-i} + \theta_9 InIGDP_{t-i} \\ & + \sum_{i=1}^{q} \gamma_{1i} \Delta InCO2_{t-i} + \sum_{i=1}^{q} \gamma_{2i} \Delta InSE_{t-i} + \sum_{i=1}^{q} \gamma_{3i} \Delta InTE_{t-i} + \sum_{i=1}^{q} \gamma_{4i} \Delta InFD_{t-i} \\ & + \sum_{i=1}^{q} \gamma_{5i} \Delta TECH_{t-i} + \sum_{i=1}^{q} \gamma_{6i} \Delta EC_{t-i} + \sum_{i=1}^{q} \gamma_{7i} \Delta InFDI_{t-i} + \sum_{i=1}^{q} \gamma_{8i} \Delta InOPEN_{t-i} \\ & + \sum_{i=1}^{q} \gamma_{9i} \Delta InIGDP_{t-i} + \varepsilon_t\end{aligned} \tag{9}$$

where Δ represents the first difference of InFD, InIGDP, InOPEN, InFDI, InEC, InTECH, InTE, InSE, and $InCO_{2,}$ and ε_t denotes the white noise. Furthermore, $t-i$ signifies the optimal lags chosen by Schwarz's Bayesian Information Criterion (SBIC), and θ and γ are the coefficients to be estimated for the long and short run, respectively. If the variables are cointegrated, the ARDL model for the long and short runs is approximated. The null hypothesis for long-run nexus is ($H_0 : \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6 = \theta_7 = \theta_8 = \theta_9 = 0$) against the alternative hypothesis ($H_1 : \theta_1 \neq \theta_2 \neq \theta_3 \neq \theta_4 \neq \theta_5 \neq \theta_6 \neq \theta_7 \neq \theta_8 \neq \theta_9 \neq 0$).

Additionally, the value of the calculated F-statistic determines whether the null hypothesis can be accepted or rejected. The null hypothesis is rejected when the value of the calculated F-statistic is above the upper bound, and we conclude that the variables are cointegrated. In contrast, when the value of the calculated F-statistic is below the lower bound, we accept the null hypothesis and conclude that the variables are not cointegrated; the ARDL bounds test becomes inconclusive when the value of the calculated F-statistic lies between lower and upper bounds. The estimable long-run ARDL model is presented as follows:

$$\begin{aligned} InCO2_t = \beta_0 &+ \sum_{i=1}^{q} \omega_1 InCO2_{t-i} + \sum_{i=1}^{q} \omega_2 InSE_{t-i} + \sum_{i=1}^{q} \omega_3 InTE_{t-i} \\ &+ \sum_{i=1}^{q} \omega_4 InFD_{t-i} + \sum_{i=1}^{q} \omega_5 InTECH_{t-i} + \sum_{i=1}^{q} \omega_6 InEC_{t-i} \\ &+ \sum_{i=1}^{q} \omega_7 InFDI_{t-i} + \sum_{i=1}^{q} \omega_8 InOPEN_{t-i} + \sum_{i=1}^{q} \omega_9 InIGDP_{t-i} + \varepsilon_t \end{aligned} \tag{10}$$

In Eq. (10), ω denotes the variables' long-run variability. The SBIC is utilized to choose the appropriate lags. We present the short-term error-correction framework as follows:

$$\begin{aligned} \Delta InCO2_t = \beta_0 &+ \sum_{i=1}^{q} \pi_1 \Delta InCO2_{t-i} + \sum_{i=1}^{q} \pi_2 \Delta InSE_{t-i} + \sum_{i=1}^{q} \pi_3 \Delta InTE_{t-1} \\ &+ \sum_{i=1}^{q} \pi_4 \Delta InFD_{t-i} + \sum_{i=1}^{q} \pi_5 \Delta InTECH_{t-i} + \sum_{i=1}^{q} \pi_6 \Delta InEC_{t-1} \\ &+ \sum_{i=1}^{q} \pi_7 In\Delta FDI_{t-1} + \sum_{i=1}^{q} \pi_8 \Delta InOPEN_{t-1} + \sum_{i=1}^{q} \pi_9 \Delta InIGDP_{t-1} \\ &+ \emptyset ECT_{t-i} + \varepsilon_t \end{aligned} \tag{11}$$

In Eq. (11), π represents the short-run variance of the parameters, and error-correction term (ECT) stands for the error-correction term, representing the imbalance adjustment process. We employ some diagnostic testing procedures to further verify the model's reliability. The Breusch Godfrey LM analysis determines whether the model contains serial correlations. The ARCH and Breusch–Pagan–Godfrey assessments determine whether the model contains heteroscedasticity. The Ramsey RESET analysis determines whether the model's specification is accurate, while the Jarque–Bera test determines whether the residuals are normally distributed. Structural strength is assessed using the cumulative sum of squares of recursive residuals (CUSUMSQ) and the cumulative sum of recursive residuals (CUSUM).

Dynamic autoregressive distributed lag (dynamic ARDL) simulations model

Earlier studies on the relationship between finance and ecological sustainability often used the simple ARDL framework proposed by Pesaran et al. (2001) and other cointegration methodologies, which could only inspect and explore the short- and long-run linkage among the variables tested. To circumvent the impediments and deficiencies in deploying the uncomplicated ARDL methodology, Jordan and Philips (2018) established a novel dynamic ARDL simulations paradigm, which this research adopts to significantly contribute to the body of methodological knowledge. The novel dynamic ARDL simulations framework can instantaneously visualize and graph to forecast diagrams of (negative and positive) adjustments in the different factors, explore the inexorably intertwined short- and long-run association between the variables evaluated, efficaciously improve the accuracy, and provide possible solutions in the outcome understandings of the simple ARDL approach. Consequently, the technique used in this study produces accurate and objective findings. The approximately Gaussian distributions of the sample space necessitate the usage of 1000 simulation results in this paper's dynamic ARDL error-correction approach. This study's diagrams are also used to explore the variations in the predictor factors and how they impact the outcomes. Using Eq. (3) as our baseline model and following Jordan and Philips (2018), we provide the novel dynamic ARDL simulations framework as follows:

$$\begin{aligned} \Delta InCO2_t = {} & \alpha_0 + \rho_0 InCO2_{t-1} + \varphi_1 \Delta \text{In}SE_t + \rho_1 InSE_{t-1} + \varphi_2 \Delta \text{In}TE_t \\ & + \rho_2 InTE_{t-1} + \varphi_3 \Delta \text{In}FD_t + \rho_3 InFD_{t-1} + \varphi_4 \Delta \text{In}TECH_t + \rho_4 InTECH_{t-1} \\ & + \varphi_5 \Delta \text{In}EC_t + \rho_5 InEC_{t-1} + \varphi_6 \Delta \text{In}FDI_t + \rho_6 InFDI_{t-1} + \varphi_7 \Delta InOPEN_t \\ & + \rho_7 InOPEN_{t-1} + \varphi_8 \Delta \text{In}IGDP_t + \rho_8 InIGDP_{t-1} + \delta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{12}$$

One of this paper's research objectives is to investigate the moderating effect of financial development on the growth-pollution nexus in South Africa. To achieve this goal, Eq. (4) is revised as follows in the novel dynamic ARDL simulations approach to examine the moderating effect of financial development on the ecosystem via the economic growth platform:

$$\begin{aligned} \Delta InCO2_t = {} & \alpha_0 + \rho_0 InCO2_{t-1} + \varphi_1 \Delta InSE_t + \rho_1 InSE_{t-1} + \varphi_1^* \Delta \text{In}(SE_t * FD_t) \\ & + \rho_1^* \text{In}(SE_{t-1} * FD_{t-1}) + \varphi_2 \Delta \text{In}TE_t + \rho_2 InTE_{t-1} + \varphi_3 \Delta \text{In}FD_t \\ & + \rho_3 InFD_{t-1} + \varphi_4 \Delta InTECH_t + \rho_4 InTECH_{t-1} + \varphi_5 \text{In} \Delta EC_t \\ & + \rho_5 InEC_{t-1} + \varphi_6 \Delta \text{In}FDI_t + \rho_6 InFDI_{t-1} + \varphi_7 \Delta InOPEN_t \\ & + \rho_7 InOPEN_{t-1} + \varphi_8 \Delta \text{In}IGDP_t + \rho_8 InIGDP_{t-1} + \delta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{13}$$

To examine the moderating effect of financial development in the relationship between energy utilization and ecological sustainability, Eq. (5) in the novel dynamic ARDL simulations framework could be written in the following form:

$$\begin{aligned} \Delta InCO2_t = {} & \alpha_0 + \rho_0 InCO2_{t-1} + \varphi_1 \Delta \text{In}SE_t + \rho_1 InSE_{t-1} + \varphi_2 \Delta \text{In}TE_t \\ & + \rho_2 InTE_{t-1} + \varphi_3 \Delta InFD_t + \rho_3 InFD_{t-1} + \varphi_4 \Delta \text{In}TECH_t + \rho_4 InTECH_{t-1} \\ & + \varphi_5 \Delta InEC_t + \rho_5 InEC_{t-1} + \varphi_5^* \Delta \text{In}(EC_t * FD_t) + \rho_5^* \text{In}(EC_{t-1} * FD_{t-1}) \\ & + \varphi_6 \Delta InFDI_t + \rho_6 InFDI_{t-1} + \varphi_7 \Delta InOPEN_t + \rho_7 InOPEN_{t-1} + \varphi_8 \Delta InIGDP_t \\ & + \rho_8 InIGDP_{t-1} + \delta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{14}$$

The moderating effect of financial development could also be quantified in the link between FDI and ecological sustainability by revising Eq. (6) in the novel dynamic ARDL simulations model as follows:

$$\begin{aligned} \Delta InCO2_t = {} & \alpha_0 + \rho_0 InCO2_{t-1} + \varphi_1 \Delta InSE_t + \rho_1 InSE_{t-1} + \varphi_2 \Delta InTE_t \\ & + \rho_2 InTE_{t-1} + \varphi_3 \Delta \text{In}FD_t + \rho_3 InFD_{t-1} + \varphi_4 \Delta \text{In}TECH_t + \rho_4 InTECH_{t-1} \\ & + \varphi_5 \Delta InEC_t + \rho_5 InEC_{t-1} + \varphi_6 \Delta InFDI_t + \rho_6 InFDI_{t-1} + \varphi_6^* \Delta \text{In}(FDI_t * FD_t) \\ & + \rho_6^* \text{In}(FDI_{t-1} * FD_{t-1}) + \varphi_7 \Delta \text{In}OPEN_t + \rho_7 InOPEN_{t-1} + \varphi_8 \Delta \text{In}IGDP_t \\ & + \rho_8 InIGDP_{t-1} + \delta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{15}$$

Table 3 Descriptive statistics

Variables	Mean	Median	Maximum	Minimum	Std. Dev	Skewness	Kurtosis	J-B Stat	Probability
CO_2	0.361	0.338	0.477	0.084	0.120	0.217	1.652	4.682	0.196
SE	7.706	7.159	8.984	6.073	0.843	−0.511	2.156	4.102	0.129
TE	63.316	62.754	80.717	36.880	12.663	−0.387	2.082	3.422	0.181
M3GDP	3.836	2.914	5.714	2.610	0.610	−0.214	1.581	3.703	0.193
TDGDP	4.714	3.720	6.103	1.719	1.105	−0.162	1.520	4.204	0.267
DCPS	3.856	3.617	5.925	1.835	0.514	−0.157	2.103	3.102	0.102
DCFS	4.213	4.052	5.104	2.042	0.173	−0.140	1.410	2.415	0.154
FSDGDP	5.052	4.941	5.719	2.710	0.184	−0.205	1.302	3.103	0.193
TECH	9.360	9.255	10.545	8.210	0.766	0.082	1.634	4.499	0.105
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
OPEN	6.060	6.512	7.665	2.745	1.329	0.636	2.077	5.757	0.156

Source: Authors' calculations

Finally, by modifying Eq. (7) in the novel dynamic ARDL simulations framework, the moderating effect of financial development on the ecosystem via the trade openness pathway is tested as follows:

$$\begin{aligned}\Delta InCO2_t = {} & \alpha_0 + \rho_0 InCO2_{t-1} + \varphi_1 \Delta InSE_t + \rho_1 InSE_{t-1} + \varphi_2 \Delta InTE_t \\ & + \rho_2 InTE_{t-1} + \varphi_3 \Delta \mathrm{In}FD_t + \rho_3 InFD_{t-1} + \varphi_4 \Delta InTECH_t + \rho_4 InTECH_{t-1} \\ & + \varphi_5 \Delta InEC_t + \rho_5 InEC_{t-1} + \varphi_6 \Delta \mathrm{In}FDI_t + \rho_6 InFDI_{t-1} + \varphi_7 \Delta InOPEN_t \\ & + \rho_7 InOPEN_{t-1} + \varphi_7^* \Delta \mathrm{In}(OPEN_t * FD_t) + \rho_7^* \mathrm{In}(OPEN_{t-1} * FD_{t-1}) \\ & + \varphi_8 \Delta \mathrm{In}IGDP_t + \rho_8 InIGDP_{t-1} + \delta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{16}$$

Equations (12), (13), (14), (15), and (16) are the appropriately chosen models utilized in our investigation. This work employs five financial development proxies extensively utilized in empirical literature for robustness verification, as the novel dynamic ARDL stimulations approach is applied in these estimable equations.

Empirical results and their discussion

Summary statistics

Before providing and analyzing the results, we first investigate the descriptive analysis of the employed elements. Table 3 presents the assessment of descriptive information, in which the mean quantities of CO_2 emissions (the minimum) and TE (the maximum) are, in comparison with other elements, 0.361 and 60.316, respectively. According to the findings, FDI has the second-highest mean value at 13.203. Table 3 uses kurtosis to illustrate how significantly the tails of distributions deviate from those of normally distributed data, and the Jarque–Bera diagnostic analysis assesses our data's normality. Technology innovation (TECH), industrial value-added (IGDP), FDI, EC, trade openness (OPEN), and all metrics of financial development show positive trends, whereas TE has a negative trend. The biggest variation is related to TE, indicating that this variable is the most volatile compared to others. CO_2 emissions, on the other hand, have a minimal variance, indicating that this variable is relatively steady. Furthermore, the Jarque–Bera statistics demonstrate the normal distribution of our data series.

Table 4 Unit root analysis

Variable	Dickey-fuller GLS	Phillips–Perron	Augmented Dickey-fuller	Kwiatkowski–Phillips–Schmidt–Shin	Narayan and Pop (2010) unit root test			
	(DF-GLS)	(PP)	(ADF)	(KPSS)	Model 1		Model 2	
Level	Test—statistics value				Break-year	ADF-stat	Break-year	ADF-stat
$\ln CO_2$	− 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***
lnM3GDP	− 0.027**	− 0.041	− 1.172	0.715**	1981:1992	− 1.825	1986:1996	− 8.413***
lnTDGDP	− 0.052***	− 0.162*	− 1.291	0.057**	1992:2001	− 2.504	2008:2011	− 7.619***
lnDCPS	− 0.196*	− 0.176	− 0.052	0.527***	1994:1999	− 2.619	2009:2014	− 8.157***
lnDCFS	− 0.017**	− 0.062	− 1.162	0.502***	1980:1987	− 1.825	2006:2016	− 7.624***
lnFSDGDP	− 0.183*	− 0.170	− 1.148	0.340***	1987:2001	− 1.724	2005:2011	− 8.710***
lnTECH	− 0.254***	− 0.284***	− 2.999	0.255***	1995:2000	− 4.318	2008:2011	− 7.821***
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***
lnOPEN	− 0.072	− 0.082	− 1.335	1.080*	1996:2001	− 3.053	2003:2009	− 7.318***
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%)			
$\Delta \ln CO_2$	− 0.995***	− 0.996***	− 7.176***	0.705***	1999:2005	− 4.801**	1980:1991	− 5.832***
Δ lnSE	− 0.695***	− 0.707***	− 5.319***	0.502***	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 lnM3GDP	− 0.502***	− 0.264***	− 6.162***	0.410***	1982:1989	− 8.024***	2001:2014	− 7.920***
Δ lnTDGDP	− 0.710***	− 0.617***	− 5.719***	0.518***	1985:1989	− 5.814***	2002:2011	− 7.424***
Δ lnDCPS	− 0.417***	− 0.316***	− 7.392***	0.614***	1990:1998	− 6.417***	2005:2014	− .8.261***
Δ lnDCFS	− 0.813***	− 0.602***	− 5.815***	0.537***	1991:1999	− 5.892***	2000:2015	− 5.824***
Δ lnFSDGDP	− 0.714***	− 1.150***	− 7.251***	0.451***	1990:1996	− 7.517***	2001:2018	− 6.618***
Δ lnTECH	− 1.023***	− 1.034***	− 7.473***	0.424***	1999:2003	− 4.841**	2006:2010	− 5.983***
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 lnOPEN	− 0.935***	− 0.938***	− 6.699***	0.626***	1996:2004	− 6.842**	2001:2007	− 8.942***
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

Order of integration of the respective variables

After providing the descriptive information, we analyze the research elements' unit root characteristics, employing four stationarity tests: KPSS, ADF, PP, and DF-GLS. Table 4 presents the results of these experiments. When different unit root tests are used, we observed that lnSE, lnTE, $\ln M_3 GDP$, lnTDGDP, lnDCPS, lnDCFS, lnFSDGDP, lnTECH, lnFDI, and lnIGDP are stationary at either *I(1)* or *I(0)* or both; however, our investigation shows that $\ln CO_2$, lnEC, and lnOPEN are only stationary at *I(1).* Moreover, the variables with a nonstationary level after the first differencing become stationary at *I(1).* This scientific finding suggests that none of the elements examined is *I(2)* and that all are either *I(1)* or *I(0).*

Table 5 Lag length criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	176.451	NA	3.2e−12	−5.591	−5.331	−6.493
1	604.091	757.28	1.5e−18	−20.192	−18.097*	−20.390*
2	665.091	105	1.4e−18	−20.384	−16.442	−19.877
3	714.750	121.30	1.2e−18*	−20.757	−15.985	−18.546
4	781.112	123.72*	1.3e−18	−21.354*	−13.736	−18.435

Source Authors' calculations

* Indicates lag order selected by the criterion

Table 6 ARDL bounds test analysis

Test statistics	Value	K	H_0	H_1		
F-statistics	14.618	9	No level relationship	Relationship exists		
t-statistics	−10.032					
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 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)

Nevertheless, the commonly employed unit root tests do not consider the impact of structural breaks. The Narayan and Popp's unit root test is a thorough testing approach that considers two structural breaks in the variable; this test is used to successfully remedy this deficiency, and the findings are shown in the right-hand panel of Table 4. We cannot rule out the unit root null hypothesis based on the findings, which indicate the usage of the dynamic ARDL bounds testing technique and reveals that variables are integrated of order one.

Lag length selection results

Table 5 shows the outcomes of several tests for choosing acceptable lags. The SIC, AIC, and HQ approaches have been extensively employed in empirical literature to select the proper lags; this research utilizes the SIC approach for lag selection as it has the greatest performance. Since the SIC yields the lowest value compared to other procedures, lag one is the most applicable in our study, as shown by this strategy.

Cointegration test results

Table 6 summarizes the output of the cointegration test utilizing the surface-response regression analysis suggested by Kripfganz and Schneider (2018). The null hypothesis of no cointegration is rejected because the F- and t-statistics are greater than the upper bound critical values at different significance levels (5% and 1%), suggesting that the investigated variables are cointegrated and have a long-run relationship.

Table 7 Diagnostic statistics tests

Diagnostic statistics tests	X^2(*p* values)	Results
Breusch Godfrey LM test	0.2314	No problem of serial correlations
Breusch–Pagan–Godfrey test	0.2115	No problem of heteroscedasticity
ARCH test	0.5135	No problem of heteroscedasticity
Ramsey RESET test	0.4282	Model is specified correctly
Jarque–Bera Test	0.1317	Estimated residual are normal

Source: Authors' calculations

Diagnostic statistics tests

This paper used several diagnostic statistic tests to assess model precision and accuracy, and Table 7 presents the results. Our model is well fitted, as seen by the outputs of these test results, since it satisfies all the screening procedures. The Breusch Godfrey LM result demonstrates that serial correlation and autocorrelation do not affect the proposed model. The test also shows that the model has no heteroscedasticity, as verified by the ARCH and Breusch–Pagan–Godfrey assessment. Furthermore, the chosen model is devoid of model misspecification. Finally, the Jarque–Bera assessment demonstrates that the residuals are appropriately dispersed.

Dynamic ARDL simulations model results

This part is separated into two subsections for proper and efficient evaluation of the outcomes. The first subcategory illustrates and explores the direct effects of financial development and other influencing factors on South Africa's ecosystem. The second subdivision focuses solely on the discussions of financial development's moderation effects (indirect effects) on ecological sustainability through the lenses of economic growth, energy use, trade openness, and FDI inflows.

Direct effects of financial development on environmental quality (baseline results)

Columns (1)–(5) of Table 8a present the findings of the direct impact of financial development on environmental protection using the dynamic ARDL simulations model. We discovered that the estimated values for long- and short-term economic growth (income) (represented by SE, InSE) are positive and statistically significant using five different metrics of financial development. This empirical finding shows a positive connection between South Africa's economic growth and ecological degradation. The results of the computations for both the long and short runs on the square of economic growth (income) (expressed by TE, InTE) are negative and statistically significant, demonstrating that InTE contributes to improving South Africa's ecological integrity. The outcome experimentally demonstrates the validity of the EKC hypothesis in South Africa; CO_2 emissions increase as the economy grows, but there comes the point where greater economic activity causes the environment to become healthier. South Africa has an inverted U-shaped relationship between income and carbon pollution due to several variables, including technical advancement, economic restructuring, and the strict implementation of environmental regulations. Additionally, as the economy expands, so does environmental awareness, resulting in tougher environmental regulations that demand

Table 8 Dynamic ARDL simulations analysis

Dependent variable: $lnCO_2$	Direct effects of financial development on CO_2 emissions					Moderating role of financial development (FD) on CO_2 emissions through economic growth (represented by scale effect, SE) channel				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
a										
Cons	− 1.0613** (− 2.41)	− 1.0628*** (− 3.02)	− 1.0701 (0.82)	− 1.0743** (− 2.51)	− 1.0680 (− 1.01)	− 1.0051** (− 2.50)	− 1.0606* (− 0.85)	− 1.0742 (0.51)	− 1.0615*** (− 3.90)	− 1.0609** (− 2.46)
$\ln SE_{t-1}$	0.2014*** (4.67)	0.2182** (2.41)	0.2517*** (3.10)	0.2370*** (3.64)	0.2014** (2.58)	0.2190 (0.34)	0.2035** (2.38)	0.2402 (0.51)	0.2195 (1.71)	0.2071** (2.62)
$\Delta lnSE_t$	0.3613** (2.31)	0.2614*** (3.93)	0.3182** (2.53)	0.3505** (2.40)	0.2915** (2.52)	0.3014** (2.48)	0.2501** (2.43)	0.3053 (1.53)	0.3213 (1.37)	0.2908 (0.43)
$lnTE_{t-1}$	− 0.7152*** (− 5.10)	− 0.7203** (− 2.42)	− 0.7188*** (− 3.85)	− 0.6920** (− 2.49)	− 0.7094** (− 2.10)	− 0.7024*** (− 3.61)	− 0.7174*** (− 3.06)	− 0.7073 (− 0.31)	− 0.7001 (− 0.83)	− 0.7060 (− 0.44)
$\Delta \ln TE_t$	− 0.6284** (− 2.32)	− 0.6180 (− 1.48)	− 0.6207*** (− 3.51)	− 0.5013** (− 2.51)	− 0.6172** (− 2.60)	− 0.6106 (− 0.84)	− 0.6043 (− 0.61)	− 0.6103 (− 1.42)	− 0.5916** (− 3.35)	− 0.6180** (− 2.38)
$lnM3GDP_{t-1}$	− 0.0517** (− 2.51)					0.0613*** (3.44)				
$\Delta lnM3GDP_t$	− 0.1526*** (− 4.65)					0.2010 (0.51)				
$ln(M3GDP_{t-1} * SE_{t-1})$						− 0.0317*** (− 3.51)				
$\Delta ln(M3GDP_t * SE_t)$						− 0.0103** (− 2.72)				
$lnTDGDP_{t-1}$		− 0.0814 (− 1.36)					0.0715*** (3.17)			
$\Delta lnTDGDP_t$		− 0.1150 (− 0.58)					0.1802** (2.40)			
$ln(TDGDP_{t-1} * SE_{t-1})$							− 0.0317*** (− 3.51)			
$\Delta ln(TDGDP_t * SE_t)$							− 0.0103** (− 2.72)			
$lnDCPS_{t-1}$			− 0.1030** (− 2.58)					0.0901 (1.31)		

Table 8 (continued)

Dependent variable: lnCO_2	Direct effects of financial development on CO_2 emissions					Moderating role of financial development (FD) on CO_2 emissions through economic growth (represented by scale effect, SE) channel				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\Delta lnDCPS_t$			−0.1027** (−2.41)					0.1624 (1.48)		
$ln(DCPS_{t-1} * SE_{t-1})$								−0.0251 (−1.20)		
$\Delta ln(DCPS_t * SE_t)$								−0.0204 (−1.53)		
$lnDCFS_{t-1}$				−0.0415*** (−3.20)					0.0517*** (3.54)	
$\Delta lnDCFS_t$				−0.1203** (−2.54)					0.2074** (2.49)	
$ln(DCFS_{t-1} * SE_{t-1})$									−0.0328*** (−3.51)	
$\Delta ln(DCFS_t * SE_t)$									−0.0163** (−2.30)	
$lnFSDGDP_{t-1}$					−0.0853** (−2.32)					0.0726*** (3.03)
$\Delta lnFSDGDP_t$					−0.1071** (−2.51)					0.2206 (0.51)
$ln(FSDGDP_{t-1} * SE_{t-1})$										−0.0295*** (−3.83)
$\Delta ln(FSDGDP_t * SE_t)$										−0.0263** (−2.50)
$lnTECH_{t-1}$	−0.6142*** (−3.61)	−0.6186 (−0.50)	−0.6061*** (−3.29)	−0.6103*** (−3.61)	−0.5915** (−2.42)	−0.6103** (−2.40)	−0.6105 (−0.37)	−0.5910*** (−3.01)	−0.6168*** (−3.04)	−0.5814** (−2.38)
$\Delta lnTECH_t$	−0.1523** (−2.39)	−0.1075 (−1.52)	−0.1420** (−2.41)	−0.1026** (−2.53)	−0.1416** (−2.51)	−0.2021** (−2.51)	−0.1152 (−1.03)	−0.1301 (−0.72)	−0.1143** (−2.49)	−0.1420** (−2.47)
$lnEC_{t-1}$	0.3584** (2.35)	0.3103** (2.49)	0.3062** (2.47)	0.2851** (2.52)	0.3063 (0.51)	0.3017 (0.52)	0.3028** (2.47)	0.3010** (2.32)	0.2610** (2.53)	0.3010 (0.42)
$\Delta lnEC_t$	0.6142** (2.54)	0.6068 (0.95)	0.6103 (0.84)	0.6052** (2.62)	0.6010** (2.47)	0.6001*** (3.93)	0.6184** (2.48)	0.6036** (2.41)	0.6003*** (3.80))	0.6163** (2.51)

Table 8 (continued)

Dependent variable: $lnCO_2$	Direct effects of financial development on CO_2 emissions					Moderating role of financial development (FD) on CO_2 emissions through economic growth (represented by scale effect, SE) channel				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$lnFDI_{t-1}$	0.4284*** (3.74)	0.4052*** (4.14)	0.4102*** (3.06)	0.4001 (0.41)	0.4180*** (4.01)	0.4291*** (3.10)	0.4190** (2.48)	0.4205** (2.51)	0.4514 (0.62)	0.4106** (2.48)
$\Delta lnFDI_t$	0.1720* (1.99)	0.1701 (0.92)	0.1851** (2.40)	0.1742* (1.99)	0.1691** (2.53)	0.1751** (2.52)	0.1400 (0.41)	0.1730* (1.99)	0.1701 (0.84)	0.1530** (2.45)
$lnOPEN_{t-1}$	0.5810 (1.48)	0.5015** (2.36)	0.5271** (2.41)	0.5014** (2.39)	0.5805*** (3.60)	0.5217** (2.42)	0.5082** (2.40)	0.5050 (1.38)	0.5029** (2.58)	0.5822*** (3.31)
$\Delta lnOPEN_t$	0.2576 (0.72)	0.2062** (2.51)	0.2503 (0.69)	0.2142** (2.59)	0.2504 (0.81)	0.2503** (2.57)	0.2014** (2.45)	0.2361*** (3.37)	0.2103** (2.42)	0.2301** (2.50)
$lnIGDP_{t-1}$	0.1052 (0.16)	0.1140** (2.51)	0.1083** (2.39)	0.1001 (0.84)	0.1304 (0.36)	0.1061*** (3.71)	0.1027** (2.33)	0.1162** (2.52)	0.1284** (2.35)	0.1315** (2.27)
$\Delta lnIGDP_t$	0.2149** (2.41)	0.2305** (2.49)	0.2204 (0.67)	0.2062** (2.58)	0.2100** (2.36)	0.2618** (2.62)	0.2201** (2.26)	0.2271 (0.51)	0.2170** (2.43)	0.2073** (2.29)
ECT(− 1)	− 0.8261*** (− 3.76)	− 0.8274*** (− 3.43)	− 0.8102*** (− 3.80)	− 0.8025*** (− 3.62)	− 0.8201*** (− 3.01)	− 0.8160*** (− 3.03)	− 0.8016*** (− 3.85)	− 0.8119*** (− 3.13)	− 0.8163*** (− 3.24)	− 0.8070*** (− 3.01)
R-squared	0.7603	0.7502	0.7624	0.7481	0.7563	0.7501	0.7306	0.7520	0.7305	0.7410
Adj R-squared	0.7251	0.7183	0.7270	0.7062	0.7301	0.7016	0.7027	0.7103	0.7006	0.7204
N	60	60	60	60	60	60	60	60	60	60
p Val of F-sta	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
Simulations	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Dependent variable: $lnCO_2$	**Moderating role of financial development (FD) on CO_2 emissions through energy consumption (EC) channel**					**Moderating role of financial development (FD) on CO_2 emissions through foreign direct investment (FDI) channel**				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
b										
Cons	− 0.0631** (− 2.44)	− 1.0652*** (− 3.15)	− 1.0751 (0.41)	− 1.0760** (− 2.37)	− 1.0672 (− 1.63)	− 1.0042** (− 2.38)	− 1.0673* (− 0.61)	− 1.0750 (0.32)	− 1.0674*** (− 3.88)	− 1.0653** (− 2.51)
$lnSE_{t-1}$	0.2081*** (3.42)	0.2101 (1.30)	0.2509*** (3.26)	0.2303*** (3.16)	0.2016 (1.37)	0.2150** (2.41)	0.2004** (2.41)	0.2461*** (3.20)	0.2155*** (3.03)	0.2015** (2.03)

Table 8 (continued)

Dependent variable: $lnCO_2$	Moderating role of financial development (FD) on CO_2 emissions through energy consumption (EC) channel					Moderating role of financial development (FD) on CO_2 emissions through foreign direct investment (FDI) channel				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
$\Delta lnSE_t$	0.1420 (1.62)	0.1314 (0.91)	0.1382 (0.75)	0.1505** (2.38)	0.1315** (2.48)	0.1414* (1.98)	0.1201** (2.53)	0.1353** (2.42)	0.1413** (2.41)	0.3208** (2.33)
$lnTE_{t-1}$	− 0.4152** (− 2.21)	− 0.4003 (− 1.38)	− 0.4188*** (− 3.31)	− 0.4020 (− 1.35)	− 0.4194*** (− 5.23)	− 0.4124*** (− 3.03)	− 0.4074*** (− 3.05)	− 0.4173*** (− 3.04)	− 0.4201 (− 0.80)	− 0.4060*** (− 3.41)
$\Delta lnTE_t$	− 0.3205 (− 1.14)	− 0.3080** (− 2.41)	− 0.3107 (− 1.50)	− 0.3013 (− 0.70)	− 0.3372** (− 2.51)	− 0.3106** (− 2.48)	− 0.3243** (− 2.52)	− 0.3103** (− 2.41)	− 0.3316 (− 0.31)	− 0.3080** (− 2.31)
$lnM3GDP_{t-1}$	− 0.0362** (− 2.61)					0.0665*** (3.51)				
$\Delta lnM3GDP_t$	− 0.1571 (− 1.30)					0.2081** (2.49)				
$ln(M3GDP_{t-1} * EC_{t-1})$	0.0251*** (3.71)									
$\Delta ln(M3GDP_t * EC_t)$	0.0142** (2.34)									
$ln(M3GDP_{t-1} * FDI_{t-1})$						− 0.0582** (− 2.49)				
$\Delta ln(M3GDP_t * FDI_t)$						− 0.0315 (− 1.45)				
$lnTDGDP_{t-1}$		− 0.0871*** (− 3.92)					0.0738*** (3.83)			
$\Delta lnTDGDP_t$		− 0.1169** (− 2.63)					0.1819 (0.37)			
$ln(TDGDP_{t-1} * EC_{t-1})$		0.0271*** (3.90)								
$\Delta ln(TDGDP_t * EC_t)$		0.0138 (1.43)								
$ln(TDGDP_{t-1} * FDI_{t-1})$							− 0.0448*** (− 3.14)			

Table 8 (continued)

Dependent variable: $lnCO_2$	Moderating role of financial development (FD) on CO_2 emissions through energy consumption (EC) channel					Moderating role of financial development (FD) on CO_2 emissions through foreign direct investment (FDI) channel				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\Delta ln(TDGDP_t * FDI_t)$							− 0.0251** (− 2.75)			
$lnDCPS_{t-1}$			− 0.1051** (− 2.48)					0.0901*** (3.01)		
$\Delta lnDCPS_t$			− 0.1038** (− 2.35)					0.1624 (1.48)		
$ln(DCPS_{t-1} * EC_{t-1})$			0.0226*** (3.12)							
$\Delta ln(DCPS_t * EC_t)$			0.0133 (1.37)							
$ln(DCPS_{t-1} * FDI_{t-1})$								− 0.0242*** (− 3.36)		
$\Delta ln(DCPS_t * FDI_t)$								− 0.0213** (− 2.49)		
$lnDCFS_{t-1}$				− 0.0403* (− 1.99)					0.0583*** (3.16)	
$\Delta lnDCFS_t$				− 0.1281 (− 0.80)					0.2003 (0.32)	
$ln(DCFS_{t-1} * EC_{t-1})$				0.0214*** (3.16)						
$\Delta ln(DCFS_t * EC_t)$				0.0194** (2.41)						
$ln(DCFS_{t-1} * FDI_{t-1})$									− 0.0305*** (− 3.26)	
$\Delta ln(DCFS_t * FDI_t)$									− 0.0108** (− 2.42)	
$lnFSDGDP_{t-1}$					− 0.0804** (− 2.46)					0.0708*** (3.17)

Table 8 (continued)

Dependent variable: $lnCO_2$	Moderating role of financial development (FD) on CO_2 emissions through energy consumption (EC) channel					Moderating role of financial development (FD) on CO_2 emissions through foreign direct investment (FDI) channel				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
$\Delta lnFSDGDP_t$					− 0.1073** (− 2.42)					0.2214 (0.48)
$ln(FSDGDP_{t-1} * EC_{t-1})$					0.0271*** (3.15)					
$\Delta ln(FSDGDP_t * EC_t)$					0.0184 (1.49)					
$ln(FSDGDP_{t-1} * FDI_{t-1})$										− 0.0203*** (− − 3.02)
$\Delta ln(FSDGDP_t * FDI_t)$										− 0.0214** (− 2.43)
$lnTECH_{t-1}$	− 0.6161*** (− 3.37)	− 0.6101 (− 0.43)	− 0.6001*** (− 3.01)	− 0.6151*** (− 3.31)	− 0.5987** (− 2.38)	− 0.6162** (− 2.52)	− 0.6182 (− 0.45)	− 0.5974*** (− 3.51)	− 0.6141*** (− 3.72)	− 0.5894** (− 2.52)
$\Delta lnTECH_t$	− 0.1041 (− 1.42)	− 0.1935 (− 1.64)	− 0.1030* (− 1.98)	− 0.1156** (− 2.03)	− 0.1596* (− 1.98)	− 0.2981** (− 2.42)	− 0.1842 (− 1.03)	− 0.1441 (− 0.72)	− 0.1913** (− 2.50)	− 0.1870** (− 2.39)
$lnEC_{t-1}$	0.3073** (2.52)	0.3943** (2.50)	0.3412** (2.31)	0.2021* (1.99)	0.3173 (0.34)	0.3637 (0.30)	0.3198* (1.99)	0.3240** (2.32)	0.2830* (1.98)	0.3790 (0.42)
$\Delta lnEC_t$	0.6101 (0.16)	0.6083 (0.92)	0.6181 (0.54)	0.6052** (2.62)	0.6062** (2.48)	0.6082** (0.98)	0.6121** (2.30)	0.6087** (2.57)	0.6082*** (3.27))	0.6149** (2.52)
$lnFDI_{t-1}$	0.3684*** (3.01)	0.3152*** (4.06)	0.3802 (1.02)	0.3101 (0.40)	0.3780*** (4.70)	0.3091*** (3.01)	0.3290* (1.99)	0.3505** (2.42)	0.3814 (0.61)	0.3206** (2.51)
$\Delta lnFDI_t$	0.2020** (2.46)	0.2501 (0.90)	0.2051** (2.51)	0.2942* (1.98)	0.2791 (0.91)	0.2551 (0.83)	0.2700** (2.44)	0.2630** (2.50)	0.2501** (2.52)	0.2230*** (3.81)
$lnOPEN_{t-1}$	0.5030** (2.53)	0.5065** (2.40)	0.5841 (1.32)	0.5854** (2.48)	0.5915*** (3.05)	0.5887 (1.36)	0.5732** (2.51)	0.5830** (2.59)	0.5639** (2.44)	0.5752*** (3.84)
$\Delta lnOPEN_t$	0.1676 (0.40)	0.1862** (2.49)	0.1003 (0.68)	0.1542* (1.98)	0.1604 (0.82)	0.1903** (2.26)	0.1814** (2.38)	0.1761** (2.30)	0.1503** (2.40)	0.1901** (2.44)
$lnIGDP_{t-1}$	0.2652 (0.18)	0.2040** (2.43)	0.2483** (2.41)	0.2701 (0.81)	0.2804 (0.30)	0.2161** (2.49)	0.2327** (2.41)	0.2562** (2.54)	0.2084** (2.30)	0.2515*** (3.23)

Table 8 (continued)

Dependent variable: lnCO$_2$	**Moderating role of financial development (FD) on CO$_2$ emissions through energy consumption (EC) channel**					**Moderating role of financial development (FD) on CO$_2$ emissions through foreign direct investment (FDI) channel**				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**	**(10)**
$\Delta lnIGDP_t$	0.2029** (2.43)	0.2745** (2.41)	0.2174 (0.60)	0.2742* (1.99)	0.2730** (2.30)	0.2558** (2.66)	0.2031** (2.24)	0.2831 (0.50)	0.2920** (2.40)	0.2513** (2.24)
ECT (− 1)	− 0.8202*** (− 3.71)	− 0.8284*** (− 3.48)	− 0.8119*** (− 3.83)	− 0.8004*** (− 3.61)	− 0.8288*** (− 3.84)	− 0.8141*** (− 3.42)	− 0.8073*** (− 3.66)	− 0.8175*** (− 3.15)	− 0.8101*** (− 3.26)	− 0.8082*** (− 3.84)
R-squared	0.7617	0.7581	0.7605	0.7466	0.7581	0.7594	0.7388	0.7515	0.7343	0.7451
Adj R-squared	0.7242	0.7180	0.7216	0.7004	0.7325	0.7077	0.7001	0.7153	0.7042	0.7211
N	60	60	60	60	60	60	60	60	60	60
p Val of F-sta	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
Simulations	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Dependent variable: lnCO$_2$	**Moderating role of financial development (FD) on CO$_2$ emissions through trade openness (OPEN) channel**				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
c					
Cons	− 1.0652** (− 2.38)	− 1.0671*** (− 3.41)	− 1.0781 (0.51)	− 1.0795** (− 2.69)	− 1.0655 (− 1.26)
$\ln SE_{t-1}$	0.1814 (1.01)	0.1582** (2.55)	0.1317*** (3.59)	0.1770*** (3.04)	0.1414** (2.47)
$\Delta lnSE_t$	0.2013** (2.04)	0.1414** (2.49)	0.2682 (0.70)	0.1805** (2.41)	0.1815** (2.58)
$lnTE_{t-1}$	− 0.3052*** (− 5.11)	− 0.3103** (− 2.44)	− 0.3088*** (− 3.05)	− 0.3320 (− 0.59)	− 0.3294*** (− 5.40)
$\Delta \ln TE_t$	− 0.2084 (− 1.37)	− 0.2480 (− 1.41)	− 0.2107*** (− 3.52)	− 0.2213** (− 2.40)	− 0.2472** (− 2.60)
$lnM3GDP_{t-1}$	− 0.0311** (− 2.52)				
$\Delta lnM3GDP_t$	− 0.2826*** (− 4.03)				

Table 8 (continued)

Dependent variable: lnCO_2	**Moderating role of financial development (FD) on CO_2 emissions through trade openness (OPEN) channel**				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
$ln(M3GDP_{t-1} * OPEN_{t-1})$	− 0.0283*** (− 3.06)				
$\Delta ln(M3GDP_t * OPEN_t)$	− 0.0204** (− 2.25)				
$lnTDGDP_{t-1}$		− 0.0820*** (− 3.46)			
$\Delta lnTDGDP_t$		− 0.1193** (− 2.52)			
$ln(TDGDP_{t-1} * OPEN_{t-1})$		− 0.0271*** (− 3.02)			
$\Delta ln(TDGDP_t * OPEN_t)$		− 0.0275** (− 2.46)			
$lnDCPS_{t-1}$			− 0.1061** (− 2.58)		
$\Delta lnDCPS_t$			− 0.1053** (− 2.41)		
$ln(DCPS_{t-1} * OPEN_{t-1})$			− 0.0204*** (− 3.80)		
$\Delta ln(DCPS_t * OPEN_t)$			− 0.0263** (− 2.51)		
$lnDCFS_{t-1}$				− 0.0441*** (− 3.31)	
$\Delta lnDCFS_t$				− 0.1252 (− 0.74)	
$ln(DCFS_{t-1} * OPEN_{t-1})$				− 0.0261 (− 1.84)	
$\Delta ln(DCFS_t * OPEN_t)$				− 0.0267 (− 0.51)	

Table 8 (continued)

Dependent variable: lnCO_2	Moderating role of financial development (FD) on CO_2 emissions through trade openness (OPEN) channel				
	(1)	(2)	(3)	(4)	(5)
$lnFSDGDP_{t-1}$					−0.0753** (−2.22)
$\Delta lnFSDGDP_t$					−0.1571** (−2.82)
$ln(FSDGDP_{t-1} * OPEN_{t-1})$					−0.0298*** (−3.06)
$\Delta ln(FSDGDP_t * OPEN_t)$					−0.0271** (−2.48)
$lnTECH_{t-1}$	−0.5042*** (−3.05)	−0.5286 (−0.42)	−0.5861*** (−3.26)	−0.5003*** (−3.01)	−0.5415** (−2.30)
$\Delta lnTECH_t$	−0.2023 (−0.99)	−0.2175 (−1.60)	−0.2020** (−2.59)	−0.2226** (−2.48)	−0.2016** (−2.42)
$lnEC_{t-1}$	0.3501** (2.42)	0.3179** (2.45)	0.3081** (2.43)	0.2895* (1.99)	0.3001 (0.58)
$\Delta lnEC_t$	0.6106 (0.86)	0.6072 (0.84)	0.6174 (0.95)	0.6017** (2.53)	0.6080* (1.99)
$lnFDI_{t-1}$	0.3184*** (3.70)	0.3852*** (4.18)	0.3702*** (3.17)	0.3101 (0.42)	0.3380*** (4.11)
$\Delta lnFDI_t$	0.1420** (2.59)	0.1401 (0.91)	0.1451** (2.41)	0.1542** (2.39)	0.1491 (0.92)
$lnOPEN_{t-1}$	0.5884** (2.40)	0.5058** (2.36)	0.5202** (2.41)	0.5060** (2.37)	0.5814*** (3.61)
$\Delta lnOPEN_t$	0.2542 (0.75)	0.2010** (2.52)	0.2552** (2.69)	0.2171 (1.93)	0.2515 (0.82)
$lnIGDP_{t-1}$	0.2252 (0.10)	0.2340** (2.52)	0.2683** (2.30)	0.2701 (0.81)	0.2504 (0.34)
$\Delta lnIGDP_t$	0.2185** (2.41)	0.2314** (2.49)	0.2287 (0.67)	0.2092* (1.98)	0.2164** (2.36)

Table 8 (continued)

Dependent variable: $lnCO_2$	Moderating role of financial development (FD) on CO_2 emissions through trade openness (OPEN) channel				
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
ECT(− 1)	− 0.8270*** (− 3.71)	− 0.8251*** (− 3.44)	− 0.8182*** (− 3.84)	− 0.8024*** (− 3.60)	− 0.8204*** (− 3.05)
R-squared	0.7651	0.7559	0.7605	0.7467	0.7572
Adj R-squared	0.7266	0.7191	0.7261	0.7051	0.7374
N	60	60	60	60	60
p Val of F-sta	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
Simulations	1000	1000	1000	1000	1000

Source: Authors' calculations

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

T-values in parentheses

energy-efficient technology to stop environmental destruction. Our findings agree with those of Udeagha and Ngepah (2019, 2022c), Alharthi et al. (2021), and Udeagha and Breitenbach (2021); however, the observations contradict (Alola and Donve 2021; Bandyopadhyay and Rej 2021; Minlah and Zhang 2021).

In 4 out of 5 scenarios in columns (1)–(5) of Table 8a, financial development stays negative and significant in the short and long term. These negative coefficients illustrate the direct influence of financial development on enhancing South Africa's ecological integrity, as these results reflect the solitary consequences of financial development. The negative link indicates that South Africa's financial industry has attained a level of sophistication, as it distributes resources to ecofriendly projects and supports enterprises in employing new developmental techniques to improve production efficiency. Furthermore, financial deepening makes obtaining finance for environmentally friendly energy capabilities easier and boosts the energy sector's productivity levels in South Africa. Our findings are consistent with those of Zeeshan et al. (2021), who demonstrated that financial deepening improved ecological integrity in 20 developed nations from 2001 to 2018. Xuezhou et al. (2022) observed that financial development helps the environment by cutting CO_2 emissions in the Sub-Saharan African nations studied, which supports this empirical evidence. Likewise, Usman et al. (2021) showed that financial development helps reduce pollution in 52 developed and developing nations. Furthermore, Li et al. (2022) looked at the asymmetric influence of financial development on environmental quality in China, determining that financial development results in lower CO_2 emissions. Le and Hoang (2022) found the same for developing, transitioning, and developed nations; Khan et al. (2022a) for global viewpoint; Khan et al. (2021b) for 184 countries; and Godil et al. (2021) for Pakistan. However, our findings contradict Zia et al. (2021) for China, Yang et al. (2021a, b) for BICS, and Weili et al. (2022) for Belt and Road countries. These studies found that a well-organized and higher-quality financial intermediation provides more financial projects that enable both members of households and firms (or industrialists) to access high-energy-demanding products, resulting in the deterioration of environmental quality. Increased EC by industrialists (or enterprises) and household members leads to increased environmental deterioration; thus, financial development contributes to deteriorating environmental quality through the EC channel. Similar findings were obtained by Usman and Hammar (2021) for APEC; Tahir et al. (2021) for South Asian economies; Sharma et al. (2021) for 8 South and Southeast Asian nations; Musa et al. (2021) for 28 EU countries; Li et al. (2022) for Belt and Road countries; Kumar et al. (2021) for 33 developing countries; Khaskheli et al. (2021) for low-income countries; Kahouli et al. (2022) for Saudi Arabia; Idrees and Majeed (2022) for Pakistan; Habiba et al. (2021) for G20 countries; Ganda (2021) for BRICS economies; Fakher et al. (2021b) for OPEC countries; and Dagar et al. (2022) for OECD countries.

The long- and short-run estimated coefficients for technological innovation (lnTECH) are negative and statistically significant in most financial development metrics. Our findings demonstrate that when liquid liabilities as a percentage of GDP (M3GDP) are used as a proxy for financial growth, a 1% increase in technical innovation decreases CO_2 emissions by 0.614% over the long run. South Africa recently implemented several regulations to strengthen the nation's ecological integrity to promote innovative ideas. Environmentally responsible technical advancements in South Africa encourage less energy use, increase accessibility to renewable energy sources, and improve environmental health. Technological advancements contribute to lower CO_2 emissions in South Africa by maximizing energy efficiency through various outlets, including changing the fuel system, adopting energy-efficient techniques, and leveraging end-of-pipe solutions. Essentially, South Africa's significant R&D expenditures and technical advancements make technological advances beneficial to the nation's ecological health. The nation has implemented several initiatives to increase the government's involvement in R&D, gradually transitioning its industrial activities away from high-energy-intensive coal-based technologies and toward high-energy-efficient processes sparked by technical advancements. These forward-thinking changes support technology innovation and have significantly helped South Africa reduce its carbon emissions. Our empirical results are complemented by the findings of Erdogan (2021) and Guo et al. (2021), who demonstrated that technology advancements create an environment that reduces EC, boosts energy efficiency, and considerably aids in pollution abatement. Udeagha and Ngepah (2022d), who discovered that environmentally friendly technical advancements in the BRICS nations encourage efficient energy usage, give people access to renewable energy sources at lower prices, and enhance the environment, also corroborate these findings. Yang et al. (2021a) and Anser et al. (2021) for BRICS economies and EU countries, respectively obtained similar results. Regarding South Africa, Udeagha and Muchapondwa (2022) came to a similar conclusion that technological development helps achieve the goal of reducing emissions. Similarly, Kou et al. (2022) demonstrated that technological progress plays an important part in developing a novel problem-solving blueprint of ground-breaking greenhouse gas reduction initiatives for transportation investment opportunities. They also found that electric vehicles play an increasingly important role in overcoming a considerable amount of carbon dioxide released into the environment because of using nonrenewable sources in transport vehicles. Still, our results differ from Dauda et al. (2021), who concluded that the advancement of technology in Sub-Saharan African countries compromises ecological integrity. Ngepah and Udeagha (2018) found similar results for sub-Saharan Africa, indicating that technological innovations lead to climate change.

The computed elasticities for short- and long-run EC (InEC) are statistically significant and positive in most financial development indicators. This information demonstrates that energy use in South Africa has a significant role in increasing CO_2 emissions. Coal consumption, as a primary source of energy in South Africa, is a significant component of the degradation of ecosystems; however, it is required to accommodate growth and business expansion. South Africa is the seventh largest economy in the world and requires a large amount of coal to meet its power requirements (World Bank 2021). For example, when liquid liabilities—as a percentage of GDP (M_3GDP)—are employed as a proxy for financial development, a 1% increase in EC boosts CO_2 emissions by 0.358% in the long term. South Africa's economy strongly relies on the energy industry, with coal consumption dominating manufacturing. South Africa's share of coal provides over 77% of power generation and 93% of power output (Udeagha and Breitenbach 2021). Pollutants in South Africa have proliferated over time due to the country's constant increase in EC, which has serious environmental consequences and is a key source of emissions. Adebayo et al. (2021) found that energy use generates carbon footprints in South

Korea, which supports our empirical results, while Aslan et al. (2021) demonstrate that energy usage adversely impacts the ecosystem in 17 Mediterranean nations. Doğanlar et al. (2021) reportedly claimed that Turkey's energy use is increasing carbon footprints, and Hongxing et al. (2021) found that energy use raises pollution levels in 81 Belt and Road Initiative countries. According to research by Hu et al. (2021), energy use enhances greenhouse gases in Guangdong, China. In contrast, our findings contradict Baye et al. (2021) and Ponce and Khan (2021), who showed that increasing energy usage enhances ecological integrity.

In many financial development measures employed, the short- and long-run computed elasticities on FDI (lnFDI) are positively significant. As a result, our findings imply that more FDI contributes to deteriorating climate change in South Africa. In the case of South Africa, the findings support arguments for the "pollution have theory." Because South Africa has a strategic strength in exporting and manufacturing filthy commodities, it has drawn a large amount of FDI, contributing significantly to the nation's carbon emissions. The adverse impact of FDI on the ecosystem in South Africa shows that FDI inflows help the nation to be among the globe's "enclaves" for environmentally damaging corporations. Our findings follow those of Copeland and Taylor (2013). They alleged that environmentally hazardous manufacturers in economically advanced countries that make dirty commodities have relocated to less industrialized economies, consequently relocating the environmental issue of industrialized economies to such developing countries, contributing significantly to the worsening of their pollution problems. South Africa has also got dirtier due to weak pollution regulations and an unscrupulous system; the country specializes in manufacturing unclean commodities, contributing considerably to rising issues, such as ecological destruction. FDI inflows have aided South Africa's transformation into a heavily polluted globalized production plant that sells most of its output to the world market. This real fact portrays the deep character of the South African economy, which is often regarded as one of Africa's fastest-growing economies. Consequently, regulators and decision-makers should do more to confirm that overseas companies use the latest, smarter, and relatively clean methods to transition from fossil fuel-based energy sources to renewables to improve ecological integrity and sustainability and sustain the growth of ecofriendly industrial activities. However, South Africa's CO_2 emissions will be significantly reduced when fossil fuel-based resources are replaced with potential substitutes, including renewable resources. Doing so will, in the end, help promote the long-term usefulness of decarbonization and continue to encourage the development of innovative solutions that enhance South Africa's quality of the environment while also managing climate change. Our findings corroborate those of Abdouli and Hammami (2017), who concluded that overseas investment has significantly increased carbon footprints in MENA nations and that proof of the pollution haven theory exists. Muhammad et al. (2021), Udeagha and Ngepah (2020, 2021b) validated these research findings; however, the observations counter Omri et al. (2014) and Joshua et al. (2020), who found that overseas investment contributed substantially to improving ecological integrity and sustainability.

The long- and short-run parameter estimates for trade openness (lnOPEN) are considerably positive across most financial development variables. This empirical conclusion suggests that a 1% increase in trade openness leads to a 0.501% increase in CO_2

emissions over the long run when total bank deposits to GDP (TDGDP) are used to measure financial growth. Our findings were supported by Udeagha and Ngepah (2021a, b), who claimed that trade openness negatively affected the South African ecosystem. Concerns about South Africa's officials and policymakers' escalating economic liberalization plans are inevitably raised by the trade liberalization's tendency to increase emissions. Although trade openness promotes economic expansion, its environmental effects have largely gone unnoticed. Because South Africa exports various goods to other countries, trade openness is primarily bad for the country's ecology; thus, these globally traded goods demand a lot of energy, which worsens the country's environmental problems. For instance, South Africa has a market advantage in the shipping and mining natural resources, including precious gems, palladium, aluminum, magnetite, propylene, plutonium, and other mineral resource energy commodities. The nation's ecology has suffered considerably due to the constant extraction of these goods to meet the expanding demand of overseas markets. Our conclusions are supported by Ibrahim and Ajide (2021a) for the G-7 countries, ZA. Khan et al. (2021c) for Pakistan, Udeagha and Muchapondwa (2022) for South Africa, and Udeagha and Breitenbach (2021) for the SADC region. In contrast, our results contradict Ding et al. (2021), who acknowledge that trade openness aids the G-7 countries in enhancing environmental health. A similar result was reached by Ibrahim and Ajide (2021b), who demonstrated how trade openness improves the atmosphere for G-20 countries. Similarly, Ibrahim and Ajide (2021c), who examined how trade openness affected 48 Sub-Saharan African nations' efforts to promote a green environment, concluded that it is both environmentally sustainable and ecologically responsible.

In most financial development indicators, the short- and long-run coefficient estimates on industrial value addition to GDP (InIGDP) are statistically significantly positive, indicating that industrialization significantly contributes to the long-term deterioration of South Africa's ecosystem. An upsurge in ecological destruction in South Africa is primarily due to the expansion of the manufacturing industry. South Africa has implemented various reforms to achieve industrialization and technological progress to minimize hunger and improve sustainable growth in the last few decades. A fundamental economic system transition from agricultural production to greater industrialization has been considered a requirement for higher living standards, employment generation, and social protection. Nevertheless, in South Africa, the rise of the manufacturing industries has increased atmospheric carbon dioxide emissions and ecological degradation. Increasing industrial activities, concomitant ecological degradation, and accompanying influence on the ecosystem represent a danger to sustaining life on earth via basic needs, leisure, and maintaining biodiversity. It is evident that carbon emissions from myriad perspectives, notably factories, have a detrimental influence on the uncertain ecosystem and contribute to ecological collapse, leading to the destruction of economically valuable endowments. Our results agree with those of Sohag et al. (2017) and Al Mamun et al. (2014), who found that growing manufacturing industries are the primary cause of rising ecological destruction and climate change. According to Tian et al. (2014), intense industrialization contributes to climate change on a local and national scale. Still, our observations contrast Ling et al. (2015), who claimed that rapid industrialization facilitates ecological sustainability and decarbonization in Nigeria. Likewise,

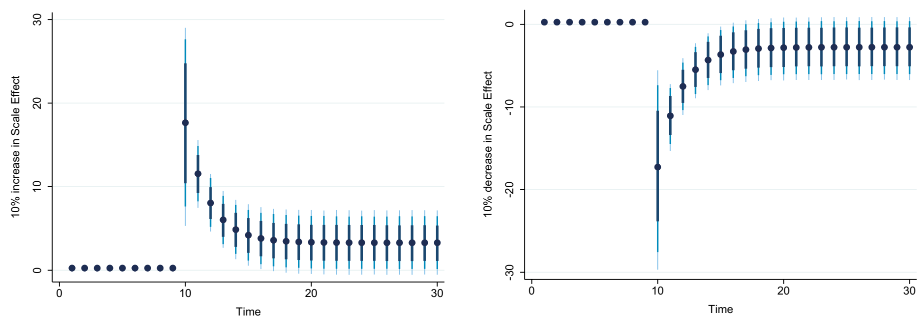

Fig. 1 The impulse response plot for scale effect (economic growth) and CO_2 emissions. This figure shows a 10% increase and a decrease in scale effect and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

Ngepah and Udeagha (2019) observed that rising industrialization aided in accomplishing Sub-saharan Africa's carbon reduction target.

The ECT captures the adjustment rate. Table 8a shows that the expected result is statistically significantly negative, indicating that the factors investigated have a long-term association. For example, the ECT calculated result of − 0.826 in column (1) of Table 8a indicates that 83% of disharmony is rectified over a long period. According to the R-squared statistic, the regressors included in this study are responsible for 76% of CO_2 emissions. The F-statistics estimated p-value shows that the model is an appropriate match for this investigation.

The dynamic ARDL simulations model instantly visualizes the predictions of exact variation in the explanatory variable and its influence on the criterion variable while holding relevant regressors constant. In South Africa, the impact of regressors such as industrial value-added, FDI, EC, trade openness, technological innovation, financial development, SE, and TE on CO_2 emissions is anticipated to fluctuate by 10%.

The impulse response diagram illustrating the link between the SE (economic growth) and Fig. 1 shows the environmental quality. The shift of the SE and its effects on pollution are depicted in this graph. A 10% upsurge in SE indicates that economic growth has a positive long- and short-term impact on pollution; notwithstanding, a 10% reduction in SE indicates that economic growth negatively impacts pollution; moreover, the impact of a 10% rise in SE is greater than that of a 10% drop in SE. This means that a rise in SE (economic expansion) in South Africa deteriorates ecological integrity; however, a drop in SE enhances ecological integrity in the short and long run.

Figure 2 shows the impulse response graph of the TE and pollution in South Africa. The TE figure shows that a 10% rise is deeply connected to a negative impact on environmental quality in the short and long term. Conversely, a 10% reduction has a positive short-term and long-term impact on pollution. This implies that a rise in the TE (square of economic growth) in South Africa enhances ecological integrity; however, a drop in the TE lowers environmental sustainability in the short and long run.

Figure 3 shows an impulse response graph of financial development (as measured by liquid liabilities as a percentage of GDP) and pollution in South Africa. The chart illustrates that a 10% growth in financial development has a negative short-term and

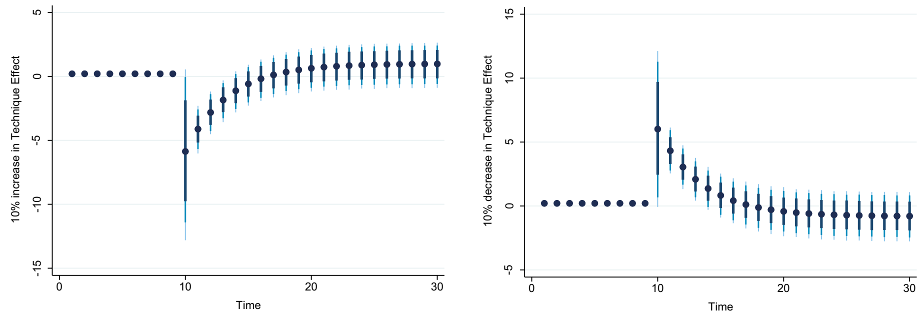

Fig. 2 The impulse response plot for technique effect and CO_2 emissions. This figure shows a 10% increase and a decrease in technique effect and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

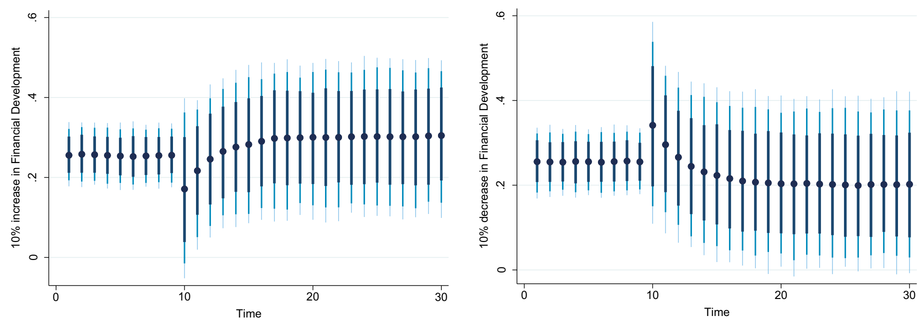

Fig. 3 The impulse response plot for financial development (proxied by liquid liabilities as % of GDP) and CO_2 emissions. This figure shows a 10% increase and a decrease in financial development and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

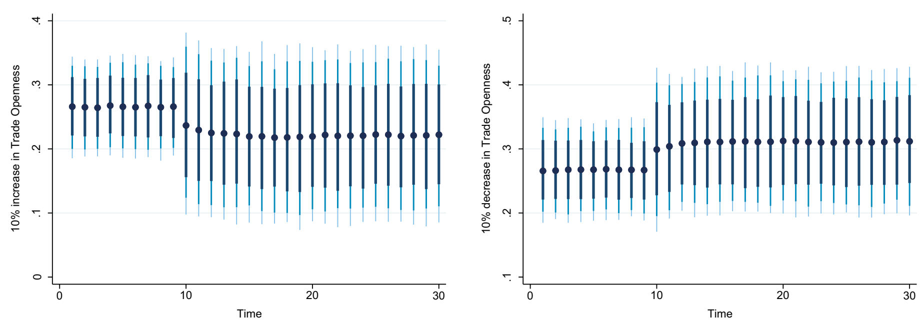

Fig. 4 The impulse response plot for trade openness and CO_2 emissions. This figure shows a 10% increase and a decrease in trade openness and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval,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

long-term impact on environmental quality; however, a 10% reduction in financial development positively impacts pollution in the short and long run. This shows that increasing financial development enhances South Africa's ecological integrity but decreasing that worsens the ecosystem in both the long and short term.

The impulse response curve depicted in Fig. 4 shows the link between trade openness and pollution. The graph illustrates that a 10% increase in trade openness has a long-term positive impact on environmental quality but a short-term negative

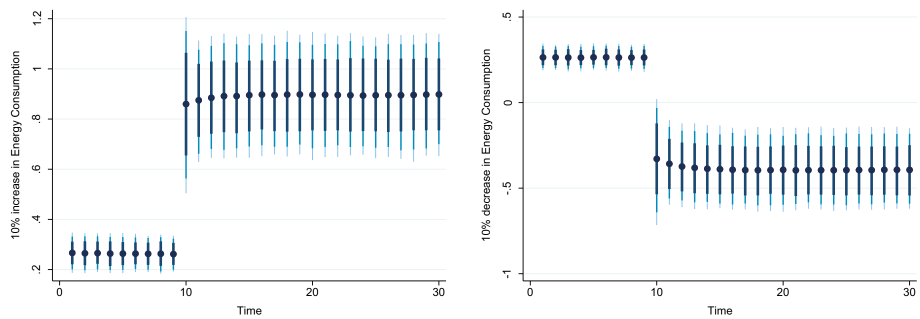

Fig. 5 The impulse response plot for energy consumption and CO_2 emissions. This figure shows a 10% increase and a decrease in energy consumption and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

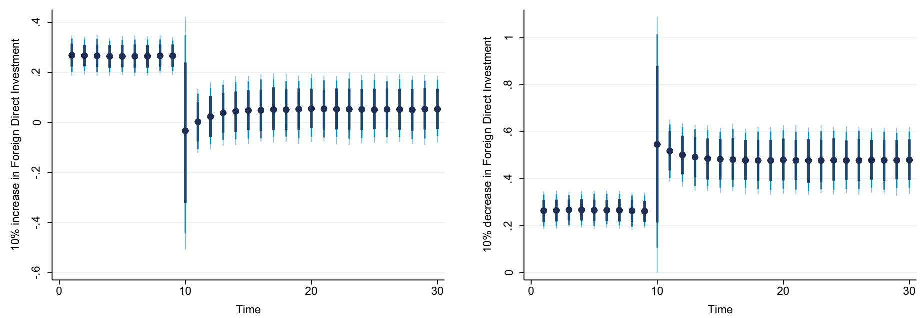

Fig. 6 The impulse response plot for foreign direct investment inflows and CO_2 emissions. This figure shows a 10% increase and a decrease in foreign direct investment and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75,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

impact. In contrast, a 10% reduction in trade openness has a long-term negative impact on pollution but a short-term positive impact, showing that increasing trade openness enhances South Africa's ecological integrity in the short term but degrades it over time. Conversely, reduced trade openness has a profound long-term influence on South Africa's ecosystem but has a short-term detrimental effect.

Figure 5 shows the impulse response graph that links energy use and pollution. The figure depicting the impact of energy utilization on ecological integrity indicates that a 10% increase in energy use has a positive long-term and short-term impact on pollution; conversely, a 10% reduction in energy usage negatively affects ecological sustainability. This means that increasing energy use worsens ecological integrity, and reducing energy use promotes sustainability of the environment in the long and short term in South Africa.

Figure 6 shows the impulse response curve of FDI and pollution in South Africa. The chart of FDI shows that a 10% expansion in FDI is strongly linked to a positive impact on pollution in the short and long term. Nevertheless, a 10% reduction negatively impacts environmental quality in the long and short term. This shows that more FDI in South Africa degrades ecological integrity in the short and long term, but reducing it has the opposite effect in the short and long term.

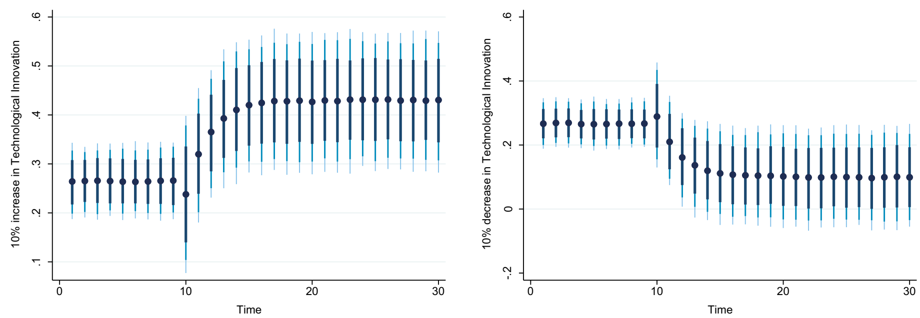

Fig. 7 The Impulse Response Plot for technological innovation and CO_2 emissions. This figure shows a 10% increase and a decrease in technological innovation and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95% confidence interval, respectively

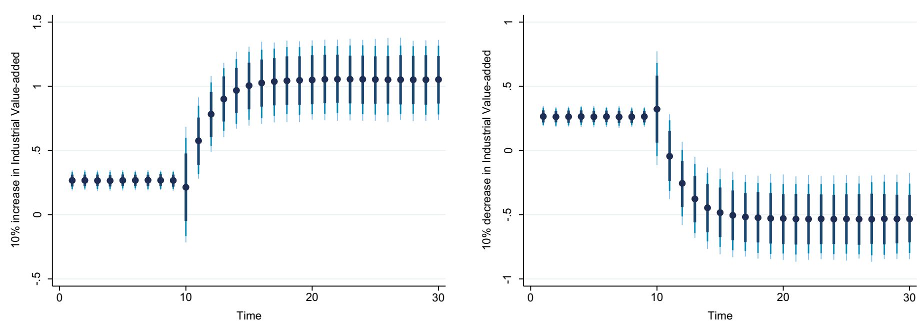

Fig. 8 The Impulse Response Plot for industrial value-added and CO_2 emissions. This figure shows a 10% increase and a decrease in industrial value-added and its influence on CO_2 emissions where dots specify average prediction value. However, the dark blue to light blue line denotes 75, 90, and 95%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

Figure 7 shows a visualization of the impulse response between technological innovations and pollution in South Africa. The graph shows that a 10% growth in technological innovations has a negative short-term and long-term impact on pollution; however, in the short and long run, a 10% reduction in technological innovations positively influences pollution. This shows that increasing technological innovations enhances South Africa's ecological integrity, but decreasing technological innovations worsens the long- and short-term ecosystems.

Figure 8 depicts the impulse response graph illustrating the relationship between industrialization and pollution. A 10% upsurge in industrialization brings about a positive long- and short-term influence on ecological sustainability, while a 10% decline results in a negative impact on pollution. This implies that a rise in industrialization in South Africa degrades ecological sustainability, but a drop enhances ecosystems in both the long and short term.

Moderating role (indirect effects) of financial development on environmental quality

In Table 8a, columns (6)–(10) show the results of moderating impacts of financial development (as measured by five distinct indicators: M3GDP, TDGDP, DCPS, DCFS, and FSDGDP) on environmental quality via the economic growth (income) channel, as measured by SE. This paper empirically tests the validity of financial development's moderating role on environmental quality via the economic growth channel using the multiplicative interaction terms of financial development and economic growth, i.e., In(M3GDP*SE), In(TDGDP*SE), In(DCPS*SE), In(DCFS*SE), and In(FSDGDP*SE). The estimated coefficients for the long and short run on the majority of multiplicative interaction terms are statistically significant and negative, implying that South Africa's well-organized and efficient financial development mitigates the adverse impact of economic growth on environmental quality. In other words, South Africa's robust financial system reduces environmental degradation by reducing pollutants and enhancing the importance of economic growth. Our findings align with earlier research, suggesting that financial development moderates environmental quality via the economic growth channel (Khan and Ozturk 2021; Katircioğlu and Taşpinar 2017; Chen et al. 2019; Cohen and Cohen 1983).

These effects are recorded in columns (1)–(5) of Table 8b using the multiplicative interaction terms between financial development and energy consumption to empirically test the validity of financial development's moderating role on environmental quality through the energy consumption channel: In(M3GDP*EC), In(TDGDP*EC), In(DCPS*EC), In(DCFS*EC), and In(FSDGDP*EC). The estimated long- and short-run coefficients on most multiplicative interaction terms are statistically significant and positive, implying that a strong financial system significantly contributes to the escalation of environmental deterioration in South Africa via the EC channel. On the one hand, because of South Africa's well-organized and higher-quality financial intermediation, more financial projects are readily accessed by members of households, allowing them to purchase high-energy-demanding items, further aggravating environmental deterioration in the country. On the other hand, South Africa's enhanced financial system significantly improves enterprises' access to greater financial backing for their operations and investments. These financial aids from the financial sector invariably enable industrialists and businesses to acquire high-energy-demanding items, which significantly increase EC and, as a result, harm the environment. Increased EC by industrialists (or enterprises) and household members leads to increased environmental deterioration. As a result, financial development deteriorates environmental quality in South Africa via the EC channel. In contrast, Katircioğlu and Taşpinar (2017) found statistically insignificant evidence of moderating the role of financial development on environmental quality through EC channels in Turkey.

Columns (6)–(10) of Table 8b, c present the results of the moderating influence of financial development on environmental quality via the foreign direct investment channel—captured by In(M3GDP*FDI), In(TDGDP*FDI), In(DCPS*FDI), In(DCFS*FDI), and In(FSDGDP*FDI) and trade openness channel using In(M3GDP*OPEN), In(TDGDP*OPEN), In(DCPS*OPEN), In(DCFS*OPEN), and In(FSDGDP*OPEN). Our model also considers the indirect impacts of financial development on environmental quality through FDI inflows and trade openness. As previously stated, financial development has a moderating influence on environmental quality through economic growth, energy usage, and other significant determinants of environmental quality, such as FDI and trade openness. The energy-pollution literature focuses on the environmental implications of FDI inflows and trade openness in South Africa to evaluate the empirical reality of the PHH. Conversely, this study examines and tests moderating effects of financial development on environmental quality via FDI inflows and trade openness channels. The estimated coefficients for the long and short run for most multiplicative interaction terms for FDI inflows are statistically significant and negative, as shown in columns (6)–(10) of Table 8b. As a result, this empirical evidence demonstrates that South Africa's robust financial system helps to mitigate the detrimental effects on the environment of FDI inflows. This is because South Africa's well-organized and higher-quality financial intermediation attracts FDI, improves the use of funds received in FDI, and reduces environmental damage. Thus, financial development improves environmental quality by mediating FDI inflows' role as a pollution enhancer. Financial development enhances ecological quality by reducing pollution and enhancing the influence of FDI inflows on ecological integrity. Our empirical findings are supported by Khan and Ozturk (2021), who found that financial development immensely contributes to moderating FDI inflows' role as a pollution enhancer in 88 developing countries. Similarly, the long- and short-run estimated coefficients on the majority of multiplicative interaction terms between financial development and trade openness (see Table 8c) are statistically significant and negative, implying that South Africa's efficient and well-organized financial intermediation reduces CO_2 emissions by moderating the pollution-enhancing role of trade openness. According to our assumptions, the empirical evidence confirms the contingency implications of financial development in the FDI-environment nexus and the trade-pollution link. Both interaction components have negative and statistically significant coefficients, indicating that South Africa's efficient financial system decreases CO_2 emissions through FDI inflows and trade openness. Our findings are also similar to Khan and Ozturk (2021), who showed that in 88 developing countries, financial development helps ameliorate the deleterious impacts of trade openness on environmental quality.

Even though the signs and significance for all of the moderating cases support our hypothesis that financial development plays a role in pollution emissions, these findings do not show how our moderating variables (e.g., economic growth, EC, trade openness, and FDI) are related to emission levels at various levels of financial development. We follow Brambor et al. (2006) to obtain a pictorial representation of the association between ecological quality and all of these factors at various degrees of financial development. As a result, this research employs Brambor et al. (2006)'s robust technique to visually depict the environmental implications of financial development via economic growth, EC, trade openness, and FDI. Using this robust method, we can evaluate the marginal ecological effects of these factors at various degrees of financial development and investigate the financial development thresholds required to reduce these variables' negative environmental consequences. Using this method, we can also plot the evolution of the incremental impacts of economic growth, EC, trade openness, and FDI on ecological stewardship at increasing levels of financial development. Their findings are represented visually in Figs. 9, 10, 11, and 12.

These findings show that the marginal impacts of economic growth, EC, trade openness, and FDI in South Africa are all influenced by the country's financial development. For example, Fig. 9 shows that where the moderating variable is liquid liabilities (M3) as a percentage of GDP in the connection between economic growth (proxied by SE)

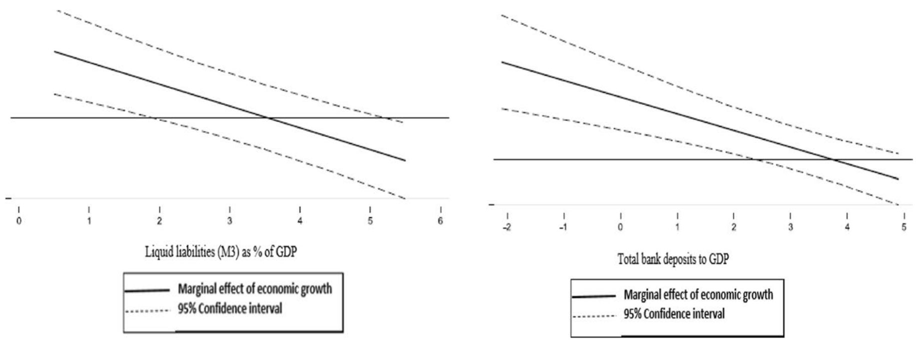

Fig. 9 Effects of economic growth (represented by scale effect, SE) on CO_2 emissions as financial development changes. Dependent variable: CO_2 emissions

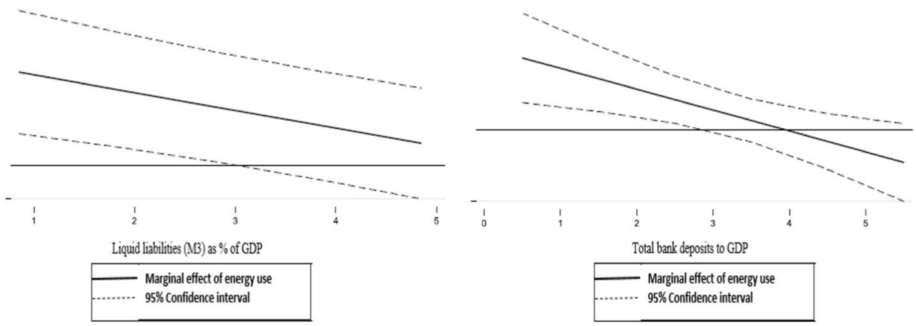

Fig. 10 Effects of energy consumption on CO_2 emissions as financial development changes. Dependent variable: CO_2 emissions

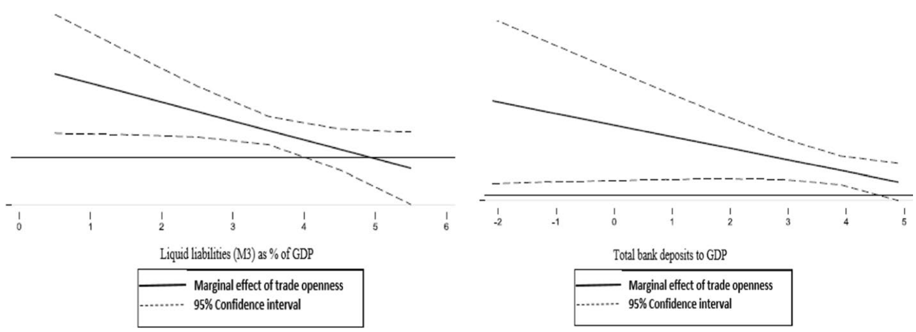

Fig. 11 Effects of trade openness on CO_2 emissions as financial development changes. Dependent variable: CO_2 emissions

and carbon emissions, the impacts of economic growth on carbon emissions are positive for levels of this indicator below two. The detrimental effects of economic growth on ecosystems become insignificant between two and five. Furthermore, when the value of the financial indicator crosses five, the link between economic growth and carbon emissions becomes negative, as predicted by the EKC theory. This supports the nonlinear consequences of financial development as seen through the lens of economic growth. Additionally, the marginal effect of EC on environmental quality (Fig. 10) shows that the

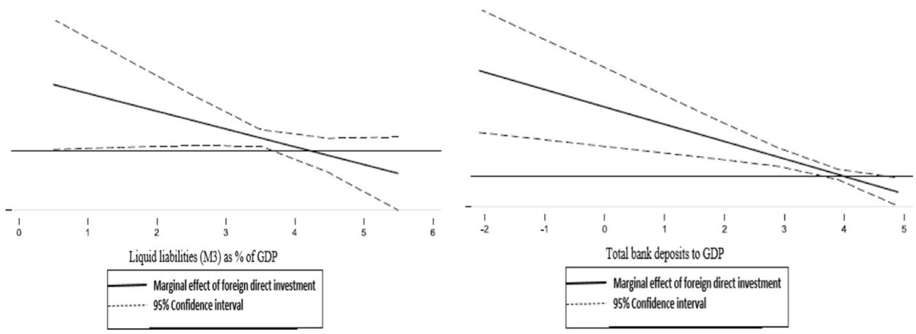

Fig. 12 Effects of foreign direct investment inflows on CO_2 emissions as financial development changes. Dependent variable: CO_2 emissions

effect is statistically significant and positive as financial development increases. More financial projects that enable both members of households and enterprises (or industrialists) to obtain high-energy demanding items are available due to better-organized and higher-quality financial intermediation, resulting in the deterioration of environmental quality in South Africa. Increased EC by industrialists (or enterprises) and household members leads to increased environmental deterioration. Thus, financial development contributes to environmental quality degradation through the EC channel. Similarly, the pollution haven theory is only valid for trade openness and FDI when financial intermediation is inadequate (Figs. 11, 12). However, as financial development reaches a critical point, the detrimental consequences of trade openness and FDI on pollution levels vanish.

The model's impact strength is investigated in this work to ensure its consistency. Pesaran and Pesaran (1997) presented the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residual (CUSUMSQ) methods for this purpose. CUSUM and CUSUMSQ are visually represented in Figs. 13 and 14 (see "Appendix"), respectively. Traditionally, a parameter estimate is considered consistent across the board if a plot is under a 5% critical bound threshold. We may infer that the parameter estimates are consistent and predictable based on the forecast trajectory presented in Figs. 13 and 14 (see "Appendix") because CUSUM and CUSUMSQ are inside the bounds at a 5% level.

Conclusion and policy implications

Conclusion

Several governments and experts have recently widely discussed the challenges of climate change and ecological destruction. Because rising CO_2 emissions are the driving force behind all of these changes, the critical problem for the world today is figuring out how to tackle climate change without sacrificing EC. Switching from nonrenewable to renewable energy usage is one plausible way to solve this issue, although this necessitates a significant implementation of sustainable energy infrastructure. This predicament is especially worrying for emerging markets because, on the one hand, they abuse mineral wealth to drive economic transformation; on the other hand, they lack the means to transition from nonrenewable to renewable energy sources. In light of this, some researchers concur that a country's financial development may contribute to curbing emission levels because financial sector development lowers credit costs, enhances credit allocation, facilitates resources for sustainable energy investments, and aids nations in knowledge creation via overseas investment.

For these driving factors, our research explores the direct and indirect effects of financial development on pollutant emissions in South Africa from 1960 to 2020. We implement Jordan and Philips (2018)'s newly established novel dynamic ARDL simulations framework, which can conveniently assess, replicate, and plot diagrams of (positive and negative) variation, and their long- and short-run connection. Using this concept, we can classify the positive and negative connections between income, income squared, financial development, energy use, trade openness, technological innovation, industrial value-added, and FDI for South Africa, thereby addressing the inadequacies of the standard ARDL framework widely adopted in early studies. This experiment uses the comprehensive modeling technique developed by Brambor et al. (2006) to visually quantify the dynamics of the incremental impacts of economic progress, FDI, trade openness, and energy usage on the ecosystem as financial development rises. This paper contributes to the body of research by utilizing the proposed trade openness indicator constructed by Squalli and Wilson (2011) to satisfactorily address the popularly adopted TI inadequacies. Our results indicate that (1) financial development and technological innovation boost ecological integrity in the short and long run. Furthermore, (2) income worsens the destruction of the environment, but its square accelerates the sustainability of the environment, validating the existence of the EKC hypothesis. Additionally, (3) ecological sustainability is impaired by industrial growth, FDI, trade openness, and energy utilization. Moreover, (4) financial development immeasurably moderates the pollution-enhancing roles of income, EC, FDI, and trade openness. (5) While high financial development mitigates the detrimental impacts of economic expansion, trade openness, and FDI on CO_2 emissions, it exacerbates the pollution-inducing role of energy usage. Finally, (6) the confirmability of the PHH, which is examined using factors like trade openness and FDI, is dependent on a weak financial system. PHH ends for both of these elements when financial development reaches specific limitations.

Policy implications

Our experimental results offer the following policy initiatives. First, financial intermediation has a critical effect in mitigating emission levels in South Africa, as indicated by the negative sign of the financial development variable. As a result, authorities should pay special attention to policies that enable the growth of financial institutions in South Africa. Without a sustained flow of capital to both government and commercial players, a shift from polluting to green power investments will be impossible. Only a stable financial architecture, which lowers the cost of financial intermediaries in the economy, can ensure the supply of such vast funds. The growth literature has previously emphasized the need to target the financial industry's development for long-term economic growth. The same may be said for biodiversity conservation, according to this research.

Second, our examination of the indirect pathways lends credence to these policy concerns. For example, because financial development substantially affects the income–pollution relationship, South African authorities should not wait for spontaneous pollution prevention via income, as the EKC evidence predicts. Even before approaching the historical turning point of the EKC, the nation can lessen the severity of harmful environmental effects of economic expansion (income) by improving its financial development.

Third, the other three indirect mechanisms, energy usage, trade openness, and FDI, are also affected. Our empirical findings suggest that South Africa is now sacrificing its emission regulations to benefit economically from trade and FDI flows; however, the government should not limit foreign trade or overseas investment to improve environmental sustainability because of the "pollution haven" scenario. Indeed, financial development and the productive use of overseas investment can help to reduce the negative environmental consequences of international trade and FDI. Consequently, a well-established financial sector benefits both trade and FDI inflows, resulting in an improved ecosystem in South Africa. These findings demonstrate that evaluating the influence of any macroeconomic performance (for example, FDI and trade openness) on ecological sustainability should not be limited to its direct consequences solely for policy considerations and future investigation. Relying solely on direct routes may misrepresent these macroeconomic variables' full ecological efficacy, which could even result in inaccurate policy recommendations in certain circumstances.

Fourth, South Africa's authorities and policy experts should take additional steps to guarantee the execution of programs that facilitate the transition from nonrenewable to alternative energy sources to improve production efficiency and enhance ecological sustainability. More government and manufacturing industry investments in R&D will be critical to further reducing the country's growing carbon emissions, given that South Africa has several local industries whose business operations significantly contribute to increasing the nation's amounts of pollutants. The South African government should develop strict rules that drive high-polluting sectors to embrace cleaner, green, and innovative products and spend more on R&D, patent protection, and less-polluting techniques. A progressive shift should commence, moving away from coal-intensive energy that is detrimental to the environment and fuels a substantial portion of the South African economy, to alternative sources of energy such as renewable sources, including wind, solar, and photovoltaic energy, which are claimed to be better for the environment and more sustainable.

Fifth, regional cooperation to enhance ecological integrity is vital to address the rising transboundary ecological damage and its accompanying ripple effects. The government should collaborate to form a robust massive network with several nations to share technologies. It is necessary to strengthen adherence to local and internationally ecological accords to put the South African economy on a trajectory of economic progress. This is because attaining income growth should enhance the social welfare of South Africans, as income activity entails a rise in livelihoods. As a result, this study demonstrates that the pursuit of growth and progress should be effectively monitored to reduce environmental deterioration; otherwise, in the long term, the adverse outcomes of growth and prosperity can present severe ecological threats via deterioration, potentially undoing the country's reform agenda.

Sixth, the government of South Africa should facilitate the use of energy-saving technologies in industrial processes by offering low-interest financing and fostering the expansion of companies that produce energy-saving equipment. The use of tax breaks or other nonprice incentives that may not affect the price of fossil fuels can be utilized to promote energy efficiency. Additional incentives, tax breaks, and assistance should be provided to ecologically friendly energy sources to move the energy structure away from fossil fuels. Renewable energy sources must receive more attention to cope with nonrenewable sources. Innovations in energy storage technology should be seen as a vital policy tool and managed alongside renewable energy programs. The potential importance of energy technology in reducing greenhouse gas emissions must also be highlighted. Energy policy should concentrate on energy advancements to reduce the social costs of utilizing fossil fuels.

Seventh, the South African authorities should also strengthen their trade regulations to promote environmental protection; however, the long-term detrimental impact of trade openness on the nation's environment does not justify ongoing actions to restrict the borders because of certain benefits to South Africa's economy. Instead, proper measures should be taken to ensure that international commerce significantly lowers South Africa's growing greenhouse gases. In this reference, South Africa's officials should step up efforts to adopt cutting-edge, environmentally friendly, and nonpolluting innovations that could help the country shift from nonrenewable to greener, less carbon-intensive renewable resources and guarantee the capabilities of its industrial processes. Meanwhile, alternative energy sources like solar power could be considered in place of nonrenewable energy, which produces roughly 90% of the nation's energy. Furthermore, international cooperation in reducing greenhouse gas emissions is required to tackle the increasing global environmental destruction and other knock-on consequences. In this sense, the South African government ought to forge significant ties with the rest of the globe to exchange advanced technologies and lessen emissions. South African policymakers should, more crucially, include sections on carbon emissions management in their trade deal policies to promote the shift to ecologically friendly industries and a low-carbon economy, which encourages the creation of greener products and services. Trade policy may be supplemented with additional policies to further stimulate long-term value for GHG emission reductions and consistently support the development of innovative technologies that improve South Africa's environmental position and safeguard the global environment.

Eighth, given that technological innovation is environmentally beneficial in South Africa, authorities should concentrate immediately on maximizing the ecological impact of sustainable technologies to encourage and enhance sustainability. The South African government should also invest in programs like adopting environmentally friendly practices and concerted efforts to modify all forms of laws to encourage ecological advancements and related technologies. It is necessary to implement green policies, enhance the environment, and adopt technology-friendly laws to promote sustainable growth and tackle ecological and sustainability issues. Controlling the risk factors associated with innovations and technology breakthroughs will be achievable when more and more responsible technical facilities and innovations are established with the incorporation of green initiatives. It is also essential for policymakers to have a collection of guidelines when choosing ecologically sound regulations for technologies that might improve the green environment. To support environmental advancements, a market architecture that enables companies to share cutting-edge innovations and advantages while creating considerable synergies must be created. Policymakers can also encourage investment in environmentally friendly technologies and sustainable renewable energies for greener production.

Lastly, to facilitate a transition to a low-carbon economy and ecofriendly sectors, the authorities should include detailed environmental elements in the nation's trade deal guidelines, thereby boosting the creation of environmentally friendly commodities. More importantly, trade-related reforms may be accompanied by specific programs and projects to assure long-term benefits for carbon emission reductions and to continue to allow technological innovations that can improve the nation's ecological integrity while protecting the planet's climate.

Limitations and potential future study areas

Although the current investigation generated rigorous empirical results in the case of South Africa, the research investigation contains numerous shortcomings that could be considered in future investigative work. One of the critical shortcomings of the investigation is the limited availability of the data outside of the sample period, which reduces the scope of the time series analysis utilized. However, using up-to-date time series data, this research examined the moderating influence of financial development on environmental quality in South Africa through economic growth, EC, trade openness, and FDI. Other emerging economies may be the subject of future investigation using various econometric techniques or micro disaggregated relevant information. Future research can also consider additional growth-related factors that were not considered in this research, including natural resources and institutional quality. Additionally, this study used $CO_2 =$ as a measure of ecological destruction. Additional investigations are needed to ensure better environmental quality in South Africa. Future studies can use consumption-based carbon emissions as an indicator for ecological damage or other metrics of carbon footprints, such as chlorofluorocarbons, volatile organic compounds, hydrocarbons, unburned hydrocarbons, ground-level gaseous pollutants, sulfur compounds, and other short-lived climatological shocks. Even though CO_2 emissions are not the only source of ecological contamination, they are used in the current study to reflect biodiversity loss. Future studies, for instance, of South Africa should examine this link by including additional ecological contamination measures, including water contamination and toxic pollutants. Additional studies might also compare country-specific findings to general panel outputs employing much more complex different methodologies by utilizing time series data in combination with panel estimation methods. This can offer a helpful comparative analysis with the results of this investigation, illuminating the available evidence. Finally, the investigation's limited analysis of one nation is another serious flaw. Future research in the African panel setting and other parts of the world should focus on exploring the moderating impact of financial development on environmental quality through economic growth, EC, trade openness, and FDI for a broader perspective.

Appendix

See Figs. 13 and 14.

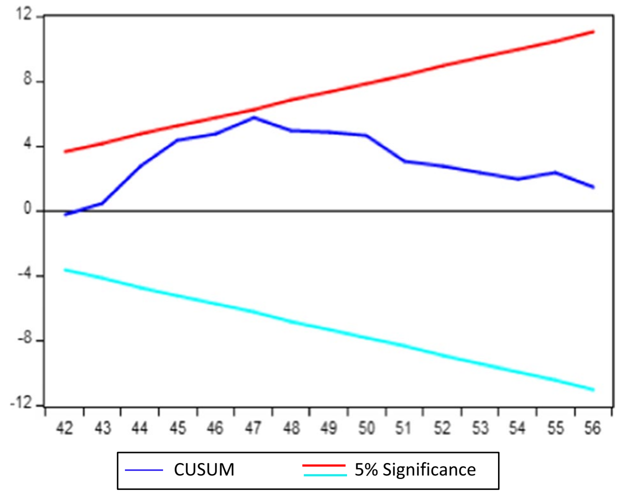

Fig. 13 Plot of cumulative sum of recursive residuals (CUSUM)

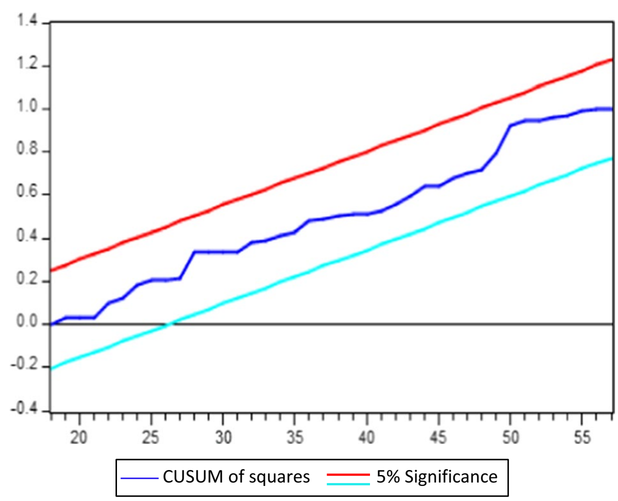

Fig. 14 Plot of cumulative sum of squares of recursive residuals (CUSUMSQ)

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Author contributions
MCU and MCB conceptualised the study idea, drafted the paper, collected data, analysed data, wrote the introduction section, organised the literature review, drafted the methodology section, interpreted the results, and provided the discussions, concluded the study with policy implications and organised the reference list. Both the authors read and approved the final manuscript.

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Availability of data and materials

The data relevant to this research is publicly available from the World Development Indicators or obtained from the authors by making a reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

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