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On the asymmetric effects of trade openness on CO_2 emissions in SADC with a nonlinear ARDL approach

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Abstract
In this study, the expected asymmetric relationship between trade openness and CO_2 emissions is investigated for the Southern African Development Community (SADC). We make use of a nonlinear autoregressive distributed lag (NARDL) framework proposed to capture the short- and long-run asymmetries for increases and decreases in trade openness and its impact on CO_2 emissions over the period 1960–2020. We proxy trade openness using an innovative approach that considers both a country's trade share to GDP and its size of trade relative to world trade. Both short- and long-run nonlinearity are tested by deriving the positive and negative partial sum decompositions of the trade openness variable. The results show mixed evidence of asymmetric behaviour between trade openness and CO_2 emissions. Long-run asymmetry is found for Botswana, Madagascar, Mozambique and Tanzania, while in Comoros, Namibia and South Africa, there is evidence of both short- and long-run asymmetry. The remaining cases (Angola, Democratic Republic of Congo (DRC), Lesotho, Malawi, Mauritius, Seychelles, Zambia and Zimbabwe) show ample evidence of symmetric behaviour and linear long-run relationships between trade openness and CO_2 emissions. The policy implication is that the SADC member countries should amend and reinforce environmental policies that can promote production and trade of environmentally friendly goods. For instance, a "tax or subsidy" policy, which taxes the trading of environmentally damaging goods, while subsidizing the trading of eco-friendly goods, can be implemented.

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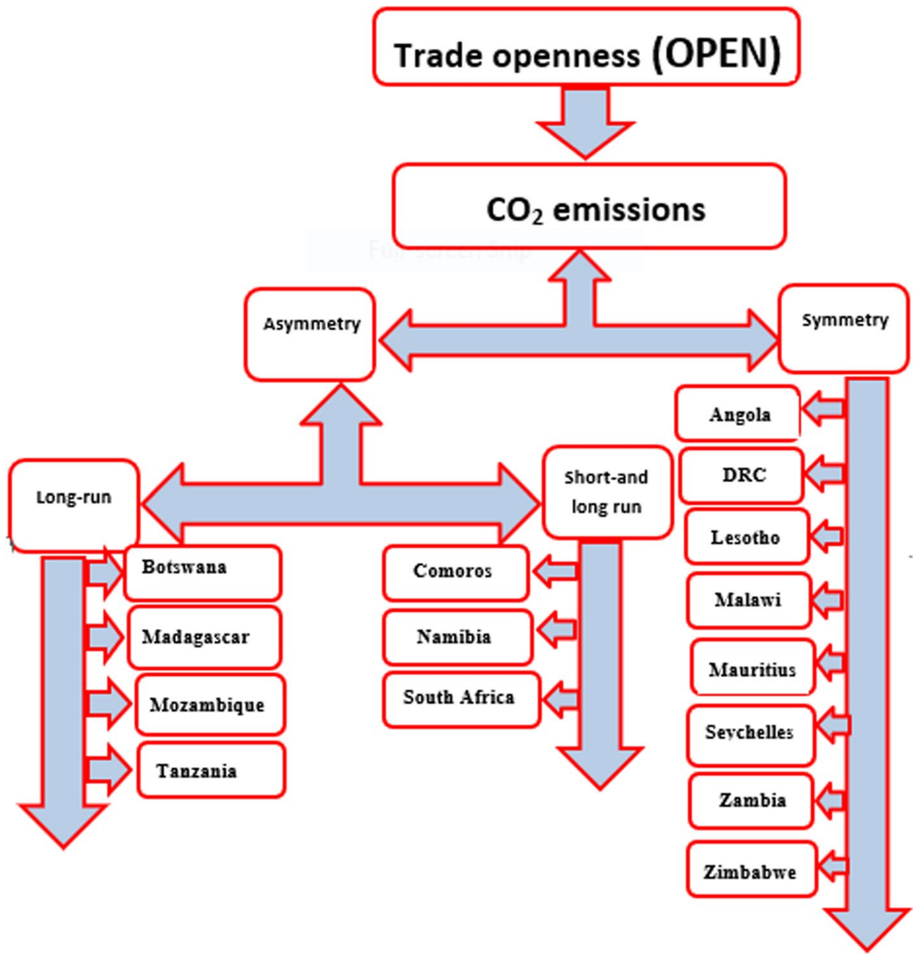
Graphical Abstract



Keywords Trade openness · Asymmetry · CO_2 emissions · Nonlinear ARDL · Symmetric ARDL · Asymmetry cointegration · SADC

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1 Introduction

In recent years, several scholars have looked at how trade openness affects the environment [96, 106]. The theoretical literature has identified a variety of pathways via which trade openness can have an influence on the environment, even though the actual findings on the link between trade openness and the environment remain contradictory [63, 68, 70, 76, 77]. Antweiler et al. [6] present a theoretical framework in which the environmental impacts associated to trade openness are divided into scale, technique, and composition effects. This approach is inspired by the pioneering work of Grossman and Krueger [36, 38]. Extensive literature has resulted from the search for empirical evidence of these many environmental influences, with inconsistent and contradictory findings [79, 80, 82, 83, 85, 86, 90, 91, 107].

A growing number of people are now worried about climate change and global warming because of their detrimental consequences on people. A substantial study priority on the causes and effects of environmental deterioration has resulted from this [95]. It is not shocking that the environment is recognized by Beeson [20] as the defining public policy concern of the era. The policy of environmental protection has garnered the attention of several governments across the world. For instance, from 1980 to 2005, the total amount of CO_2 emissions worldwide attributed to human activity on the African continent was little under 2.5% [106, 110–112]. More recently, the continent is responsible for 5.3% of the world's greenhouse gases (GHGs) from all non-land use sectors and 3.0% of the world's carbon from fossil fuels [1]. These figures support SADC's efforts to cut emissions in accordance with the UN Framework Convention on Climate Change. However, Southern Africa has contributed 31% of Africa's deforested land since 1990, which is the greatest pace in the continent. 54% of the continent's biomass carbon losses result from deforestation in SADC member states. Deforestation and degradation together produce carbon emissions that are more than five times as great as all other sources combined. The region is a strong option for this case study since stopping deforestation and lowering CO_2 emissions are the highest priorities for climate change mitigation in the area. The SADC region is a particularly interesting case because it has pushed for urgent measures to manage and conserve the region's forests sustainably, implemented laws to help people adapt to climate change, and taken part in campaigns to mitigate the effects of rising global temperatures and lessen their potential harm to the region.

Earlier research on the relationship between trade and CO_2 emissions frequently assumes that the cointegrating relationship between the nonstationary stochastic regressors is symmetrically linear; as a result, they frequently fail to consider the possibility of a nonlinear relationship [2, 3, 5, 100, 101]. Thus, their findings imply that an increase in trade openness causes a proportionate increase in CO_2 emissions, but a decrease in trade openness may cause a proportionate decrease in CO_2 emissions. But how accurate is this statement? The existence of nonlinearity has received little to no attention in previous research since the cointegrating connection is frequently represented as linear.

There may be nonlinearity in the link between trade openness and CO_2 emissions due to trade liberalization (such as a reduction in tariff barriers) and technology diffusion [7–14]. Reduced tariffs are expected to stimulate trade and have a positive effect on the environment. According to the theory supporting the existence of a nonlinear and/or asymmetric relationship between trade openness and CO_2 emissions, trade liberalization policies can have a nonlinear impact on the relationship between trade openness and the environment when set against endogenous trade frameworks based on imperfect competition. For instance, nonlinearity is conceivable in the case when a minimal reduction in existing high trade barriers results in an improvement to the environment, while liberalization of low trade barriers results in an increase in welfare [7, 16, 19]. Furthermore, historical trade data reveal that international tariff levels have only slightly decreased despite multiple rounds of multilateral trade discussions at the WTO and GATT. Another significant potential source of nonlinearity in the link between trade openness and the environment is technological diffusion resulting from trade. Since the positive impacts of technology diffusion are susceptible to diminishing returns, it is predicted that increased commerce may have nonlinear consequences on the environment.

In addition, many macroeconomic variables and processes have long been known to have nonlinear interactions. For instance, Keynes [54] made a significant observation that had a lasting impact on the field: "The replacement of a downward for an upward propensity always occurs aggressively and unexpectedly; however, as a rule, there is an absence of such a sharp turning point when an upward for a downward inclination." Recent research in economics and behavioral finance have provided compelling evidence that supports nonlinearity and asymmetry, highlighting how these ideas are pervasive in the social sciences and, thus, essential to understanding human behavior.[1]

Additionally, since the mid-1990s, a large body of literature has included the combined topics of non-stationarity and nonlinearity, which is heavily dominated by three regime-switching models: the threshold ECM of Balke and Fomby [17], the Markov-switching ECM developed by Psaradakis et al. [75], and the smooth transition regression ECM associated with Kapetanios et al. [51]. These works' development demonstrates that there is insufficient data in linear frameworks to draw sound conclusions or make accurate predictions. This research suggests that the presumption of a linear relationship is quite constrictive across a wide variety of economic phenomena, especially when it comes to the connection between trade openness and CO_2 emissions. The literature mentioned above gives us reason to think that trade openness and CO_2 emissions may have an asymmetric and nonlinear connection. If this were to occur, the implications for policy would be considerably different than when this connection is linear.

Additionally, earlier studies that looked at the dynamic interaction between trade and the environment, such as Hussain et al. [42], Hu et al. [41], Abbas et al. [1], Wen et al. [108], and Ali et al. [4], widely employed trade intensity (TI) as a proxy for trade openness. This measure of trade openness, which is often calculated as the total of imports and exports divided by GDP, exclusively considers a nation's trading performance in relation to its own internal economy. The TI-based proxy, which penalizes larger economies owing to their higher GDP by categorizing and portraying them as the closed economies, often overlooks a country's openness to international trade and is unable to represent the precise impact of

[1] See Shiller [87, 88] and Kahneman and Tversky [49] for more detail.

trade openness on the environment [92]. Although this metric makes sense, it is unable to fully address the ambiguity surrounding the notion of actual trade openness and the methods used to quantify it. The main drawback of using the TI-based metric is that it only accurately reflects a country's portion of the income from international trade. The apparent inability of this proxy to account for the importance of a nation's trade in relation to global trade is another sign of its flaw. As a result, the TI-based proxy is unable to accurately reflect the benefits and drawbacks of dealing with other countries, failing to adequately convey the impact of trade openness on the environment.

Against this backdrop, our work makes two contributions: First, by using a flexible and straightforward nonlinear dynamic approach that can concurrently and clearly model the asymmetries between member countries of the SADC region in the effects of trade openness on CO_2 emissions, the paper makes a contribution to the empirical literature. As far as we are aware, there has not been any work done to investigate and model the potential for nonlinearity in the trade-environment interaction for the SADC. Since the assumption of linearity has considerable policy consequences, this is a notable gap in the research. The present research that are based on the assumption of linearity should be reconsidered since their findings may be erroneous and deceptive if the connection between trade openness and CO_2 emissions is genuinely nonlinear. By employing the methodology of Shin et al. [89]'s autoregressive distributed lags (NARDL) framework, this study closes a gap in the literature. By calculating both positive and negative partial sum decompositions of trade, short- and long-run nonlinearities are clearly checked for. Second, in contrast to other research, the current analysis develops and makes use of a novel proxy for trade openness proposed by Squalli and Wilson [92] that takes into consideration both the magnitude of trade relative to global trade in a particular year as well as SADC's trade proportion to GDP. We are better able to capture the environmental consequences of trade openness using this proxy for trade openness than we are using the TI-based proxy, which sets our work apart from comparable studies in SADC and sub-Saharan countries.

The remainder of the work is organized as follows: The trade-environment nexus is covered in detail in Sect. 2 of the relevant literature. The framework for the methodology is covered in Sect. 3 Section 4 discusses the findings, and Sect. 5 ends with implications for policy.

2 Literature review

There are three parts to this section. In the first section, the theoretical literature is discussed. The empirical literature on the connection between trade and CO_2 emissions is reviewed in the second section. The knowledge gaps in the extant literature on the relationship between trade and CO_2 emissions are compiled in the last section.

2.1 Theoretical literature

The environmental Kuznets Curve (EKC) theory was the first to suggest a connection between trade openness and the environment, and it gained prominence in the early 1990s. Among the pioneers in the field, Grossman and Krueger [36–38] and Copeland and Taylor [24] investigated the relationship between trade and the environment. When the environmental effects of the North American Free Trade Agreement (NAFTA) were being researched, Grossman and Krueger [38] provided the fundamental theoretical framework for investigating the EKC hypothesis. However, after the 1992 Earth Summit in Rio de Janeiro, Brazil, literature on the growth-environment nexus began to appear. This was made possible by Shafik and Bandyopadhyay [84]'s monumental work, which served as a crucial background study for the World Development Report. It was stated that environmental improvement is essential for sustainable growth. Since then, there has been a significant body of work examining the link between development and environmental quality, but due to conflicting findings, there is now even less clarity on the true environmental effects of trade openness. Meanwhile, conflicting findings has prompted more research on the subject by a large number of scholars throughout the globe.

Examples are Udeagha and Ngepah [102, 103], who used the EKC hypothesis, and Kearsley and Riddel [52], who used the pollution haven hypothesis (PHH), neither of which were able to draw any firm conclusions on the environmental effects of trade openness. Grether and De Melo [35] discovered that trade openness directly causes environmental degradation due to inflows of trading activities from the affluent nations and indirectly promotes environmental degradation by boosting economic development in third world countries. Dinda [27] stated that because affluent countries' companies frequently confront strict environmental regulations, pollution is shifted to developing nations by their industries when they move to less developed nations with laxer regulations. The well-known pollution haven hypothesis (PHH) and its counterpart, the factor endowment hypothesis (FEH), are two examples of how this notion has acquired popularity. The final point relates to the exodus of polluting, capital-intensive businesses from relatively wealthy nations, which has led to a decline in the environmental quality of emerging nations. A country with a competitive advantage in producing filthy, capital-intensive commodities would constantly boost production to accommodate the expanding export market, which raises pollution levels, according to the argument that trade openness will increase carbon emissions in PHH and FEH [69].

The three trade impacts on environmental quality—scale, technique, and composition effects—were highlighted by Antweiler et al. [6], one of the first writers to present a thorough theoretical framework. The scale effect is the increase in environmental harm and depletion of natural resources brought on by an increase in economic activity and increased demand [37, 60]. The technique effect refers to the potential for enforcing stricter environmental regulations that result in a cleaner production process as income increases. Additionally, an increase in income further stimulates people's desire for a less carbon-intensive environment and better environmental practices [53]. The composition impact, on the other hand, illustrates how the structure of the industry and the composition of output influence the environment, which is primarily influenced by the degree of national openness together with comparative advantage [21]. The net effect of the composition effect due to trade openness might be favorable or negative depending on the relative magnitude of the capital-labor impact and the implications of environmental regulation [50].

2.2 Empirical literature

The trade-environment nexus literature is extensive on the empirical front. But the evidence provided by these investigations is generally contradictory or, at best, equivocal.[2] While some research found that trade openness improves environmental quality through a variety of routes [104], others claimed that trade openness worsens the state of the environment [106]. Contrarily, a different group of studies discovered solid proof that increased trade openness had no effect on the environment [94].

An empirical study by Pata et al. [72] discovered that, for the Association of Southeast Asian Nations (ASEAN) nations between 1995 and 2018, trade openness enhances environmental quality. Mahmood [61] came to the same findings, noting that from 1970 to 2019, trade in Latin America had a net positive environmental impact. Additionally, Ding et al. [114] demonstrated that greater trade openness helps G-7 economies' environmental quality. They did this by using cross-sectional autoregressive distributed lag (CS-ARDL) and augmented mean group (AMG) methodologies. Additionally, Ibrahim and Ajide [115] discovered that trade openness slows down environmental deterioration using the common correlated effect mean group (CCEMG) and mean group (MG) in the instance of G-20 nations. Similar to this, Ibrahim and Ajide [116], who utilized trade facilitation (TF) as a measure of trade openness for 48 Sub-Saharan African nations for the period spanning 2005–2014, note that TF is ecologically friendly and supports environmental quality in the region. Khan et al. [117] provide evidence for the expanding importance of trade openness using the AMG and CCEMG techniques.

In contrast, Suhrab et al. [93], who used annual time series data from 1985 to 2018 to assess the impact of GDP, urbanization, trade openness, financial development, and renewable energy use on CO_2 emissions in Pakistan, discovered evidence that trade openness worsens environmental quality. In a similar vein, Omri and Saadaoui [71] discovered that from 1980 to 2020, environmental deterioration in France was greatly exacerbated by trade openness. In a similar vein, Ibrahim [43] discovered that trade openness contributed significantly to environmental deterioration in G20 nations utilizing a system generalized method of moments (GMM), fully modified ordinary least squares (FM-OLS), and quantile regression estimators. Additionally, when trade openness is increased, environmental degradation is more severe in low middle-income countries than upper middle-income countries, according to Chhabra et al. who studied the impact of trade openness and innovation in reducing CO_2 emissions in middle-income countries. Furthermore, Wenlong et al. [109] discovered that trade openness significantly impacted the decline of environmental quality in 10 Asian economies between 1995 and 2018. Similar to this, an empirical research by Khan et al. [118] shows that trade

[2] Even though a limited number of recent research has generated evidence demonstrating the positive impact of trade openness on the environmental quality [99, 105], a consensus has not been reached in the literature. Because of this, it is yet unknown how reliable these results are [23, 26, 28, 29, 31–34]. These inconsistent findings in the literature are likely the result of the preceding research being hampered by an imprecise concept of trade openness and how it is assessed. The ratio of trade (the sum of exports and imports) to GDP has historically been the main indicator used to study the relationship between trade and the environment. Simply put, this proxy, commonly referred to as "trade intensity (TI)," evaluates how well a nation's trade performance stacks up against the health of its domestic economy. However, the proxy frequently ignores how open a country is to trade internationally, failing to adequately depict how trade affects the environment [92]. The trade-environment relationship has not been fully explored in previous works, in part due to methodological disagreements and problems with misspecification.

liberalization worsens Pakistan's environmental situation. Ibrahim and Ajide [119], who find that trade openness causes a rise in CO_2 emissions in the G-7, also support this empirical evidence. Van Tran [120], who shows that trade openness affects the environmental state in 66 emerging economies during the period of 1971–2017, obtained similar results. Khan and Ozturk [121] conclude that trade openness increases CO_2 emissions for 88 developing countries during the period of 2000–2014 using the difference and system generalized technique of moments. Additionally, according to Ali et al. [122], opening up the OIC[3] nations' markets to foreign goods has a negative impact and significantly worsens their environmental circumstances. The analysis conducted by Aydin and Turan [123] for China and India between 1996 and 2016 lends more credence to this evidence.

2.3 Summarizing literature gaps

Despite the broad prominence of earlier research, a number of significant gaps remained, which are taken into account in this work. The significant gaps that were found are listed below: First, the analysis of the aforementioned empirical literature leads us to the conclusion that there is a wealth of evidence on the linear relationship between trade openness and CO_2 emissions. The asymmetric impact of trade openness on CO_2 emissions, particularly with reference to the SADC area, is not, however, well-examined in the literature. Prior research on the trade-environment interaction mostly neglected the potential of nonlinearity until Awokuse and Christopoulos [7] recently emphasized it. The existence of nonlinearities in the relationships between many macroeconomic variables has been amply supported by a large number of empirical works on related subjects, including GDP growth, oil prices, exchange rates, stock prices, and many others. It has also been shown that this idea is becoming more apparent in research on business cycles and exchange rate dynamics. It is reasonable to anticipate the possibility of nonlinearity in the link between trade and the environment if a business cycle, such as a change in GDP, is likely to display an expressively nonlinear tendency. Because of this, there is still a need for study on the nonlinear/asymmetric consequences of trade openness. Asymmetry and structural breaks are absent from most of the current studies, which is why our research makes a contribution by examining the asymmetric link between trade openness and CO_2 emissions in the SADC area. Finally, a one-dimensional trade proxy that fails to fully reflect the environmental effects of trade openness has been criticized in studies that examined the relationship between trade openness and CO_2 emissions. The trade share in GDP and the magnitude of the trade relative to global trade were two factors that earlier studies failed to consider since they did not use the composite trade intensity (CTI) developed by Squalli and Wilson [92].

3 Methodology and data

3.1 Methodology

The asymmetric link between trade openness and CO_2 emissions among SADC area member nations is investigated in this study using the following methodology. The first stage is the introduction of the dynamic adjustment process, which is frequently utilized to mimic the dynamic interactions between I (1) variables utilizing an error-correction model-ECM [30]. In light of Pesaran et al. [73], the following is the ARDL specification without asymmetry in short- and long-run dynamics:

$$\Delta InCO_{2t} = \mu + \rho InCO_{2t-1} + \pi InOPEN_{t-1} + \sum_{i=1}^{p-1} \alpha_i \Delta InCO_{2t-1} + \sum_{i=0}^{q-1} \beta_i \Delta InOPEN_{t-1} + \varepsilon_t \tag{1}$$

where Δ denotes the first difference operator and ε_t represents the white noise term. The investigation deals with two-step procedures where Schwarz's Bayesian Information Criterion (SBIC) is used to select the optimal lag length and thereafter OLS is used to run the equation [74]. This procedure helps to fix the problems associated with endogeneity. More importantly, Eq. (1) is used to capture only the symmetric relationship between trade openness and CO_2 emissions under the assumption that the fundamental cointegrating relationship is symmetrically linear. In addition, it is expected that the decomposed partial sum processes of positive and negative effects of trade openness are both the same.

[3] Organization of Islamic Cooperation.

However, this approach may provide misleading results and flawed policy conclusions. To fix this problem, the study adopts the nonlinear autoregressive distributed lags (NARDL) modelling strategy proposed by Shin et al. [89] to capture the nonlinearity and asymmetries in the trade-CO_2 emissions nexus. Because of its effectiveness in the presence of mix order of integration, the NARDL methodology is considered more appropriate which follows the lower and upper bound F-values. By considering the first differenced stationary variables i.e. I(1), the upper bound values are provided, whereas by assuming level stationary variables i.e. I(0), the lower bound values are given. Many economic variables are either I(0) or *I(1)*. Also, using this framework permits to test for the asymmetric effects of $InOPEN_t^+$ and $InOPEN_t^-$ on CO_2 emissions for SADC region. Consequently, it enables us to examine the effect of a decrease in trade openness on CO_2 emissions in relation to the effect of a rise in trade openness on CO_2 emissions. This analysis becomes crucial because the size of the effect of a negative change differs from that of a positive change in the absolute terms. Remarkably, this methodology has been fruitfully adopted to model short- and long-run asymmetric cointegrating associations between exchange rates, stock returns and other financial variables for the industrialised and other emerging economies [15, 25, 39, 40, 44–47].

In addition, the NARDL framework can be used to get a unified model that is able to combine nonlinearities in the long-run association and the error correction mechanism coherently unlike other nonlinear frameworks such as the smooth transition regression ECM developed by Kapetanios et al. [51], the Markov-switching ECM of Psaradakis et al. [75] and the threshold ECM associated with Balke and Fomby [17]. Meanwhile, it may be non-trivial[4] in practice to select the regime-switching variables and the transition functional forms (Shin et al. Thus, developing an operational model of this kind may be extremely challenging [55–58, 81]. Given this, in this paper, we use a nonlinear modelling framework based on the ARDL approach that offers a simple and flexible vehicle for the investigation of joint long- and short-run asymmetries. To this end, for instance, a negative shock is likely to have a more absolute impact in the short-run, whereas a positive shock is likely to have a bigger absolute impact in the long-run (or vice-versa). The simple and flexible nature of NARDL methodology makes it an ideal framework used to capture such a complex phenomenon. Thus, it includes a regime-switching cointegrating relationship where regime transitions are controlled by the sign of change in the explanatory variable (Δx_t). Hence, reasoning from this direction suggests that equilibrium does not need to be unique in a universally linear sense·

So, following Shin et al. [89], changes of trade openness variable are decomposed into partial sum processes of positive and negative components to capture their asymmetric impacts on CO_2 emissions. The two components constructed to capture these effects are as follows:

$$InOPEN_t^+ = \sum_{j=1}^{t} \Delta InOPEN_j^+ = \sum_{j=1}^{t} max\left(\Delta InOPEN_j, 0\right) \tag{2}$$

$$InOPEN_t^- = \sum_{j=1}^{t} \Delta InOPEN_j^- = \sum_{j=1}^{t} min\left(\Delta InOPEN_j, 0\right) \tag{3}$$

where Δ denotes the first difference operator; $InOPEN_t^+$ and $InOPEN_t^-$ represent respectively the partial sum processes of positive (increases) and negative(decreases) changes in trade policy in the period t. A more general cointegrating methodology is obtained by extending the ARDL approach in Eq. (1) and replacing the $InOPEN_t$ variable with $InOPEN_t^+$ and $InOPEN_t^-$ to introduce the combined short- and long-run dynamics:

$$\Delta InCO_{2t} = \mu + \rho InCO_{2t-1} + \pi^+ InOPEN_{t-1}^+ + \pi^- InOPEN_{t-1}^- + \sum_{i=1}^{p-1} \alpha_i \Delta InCO_{2t-1} + \sum_{i=0}^{q-1} \left(\beta_i^+ \Delta InOPEN_{t-1}^+ + \beta_i^- \Delta InOPEN_{t-1}^-\right) + \varepsilon_t \tag{4}$$

By applying a similar procedure associated with Eq. (1), Shin et al. [89] demonstrate that Eq. (4) can be run and the nonlinearity is thus added into the model by the partial sum decompositions of trade policy variable. The superscripts (−) and (+) respectively represent the negative and positive partial sum decompositions of lagged levels. The short-run

[4] Take for instance, the case of the threshold ECM where the choice of the transition variable is important both theoretically and empirically. In general, the asymptotic distribution of the test statistic for the null of linearity or symmetry is non-standard and dependent on these transition variables.

adjustments of trade openness to CO_2 emissions are captured by the coefficients β_i^+ and β_i^-. The paper uses the Schwarz's Bayesian Information Criterion (SBIC) to select the optimal lag length specification of the models.

We follow Banerjee et al. [18] t-test, testing $\rho = 0, against \rho < 0$ in Eq. (4). Next, the pragmatic bounds-testing procedure is applied following Pesaran et al. [73]. Thus, using an F-statistic, the joint null hypothesis ($H_0 : \rho = \pi^+ = \pi^- = 0$) is tested against the alternative hypothesis ($H_1 : \rho \neq \pi^+ \neq \pi^- \neq 0$). This modelling methodology is advantageous because of its validity 'regardless of whether the basic regressors are I(0), or I(1) or mutually cointegrated'. The two tests highlighted above are respectively denoted by t_{BDM} and F_{PSS}. Shin et al. [89] demonstrate that the bounds-testing procedure can equally be applied to Eq. (4). Hence, the $InOPEN_t^+$ and $InOPEN_t^-$ variables are seen as one variable[5] in which the same critical values for the F-test used in Eq. (1) are employed, even though Eq. (4) has one additional variable. In general, the appropriate critical value bounds for the F_{PSS} test is dependent on the number of regressors which enter the long-run relationship [89]. The values of k are 1, 2, 2 and 1 for symmetric ARDL, NARDL with combined short- and long-run asymmetry, NARDL with long-run asymmetry and NARDL with short-run asymmetry respectively.

Once the cointegrating relationship is established between the two variables, we subsequently obtain information about three aspects of asymmetric effects following the estimation of Eq. (4). First, we obtain the short-run asymmetry adjustment if $\Delta InOPEN_{t-1}^+$ contains several lags which are different from $\Delta InOPEN_{t-1}^-$. Second, if $\sum_{i=0}^{q-1} \beta_i^+ \neq \sum_{i=0}^{q-1} \beta_i^-$, the short-run asymmetry becomes valid. Lastly, there will be present of the long-run asymmetry if the coefficient on $InOPEN_{t-1}^+$ is different from $InOPEN_{t-1}^-$. Using the Wald test, we test the null hypothesis that $\theta^+ = \theta^-, where\, \theta^+ = \frac{\pi^+}{-\rho}\, and\, \theta^- = \frac{\pi^-}{-\rho}$ in Eq. (4) to draw a conclusion whether asymmetry exits. The model of Eq. (4) will be transformed into the traditional ARDL framework (i.e. Equation (1)) suppose the null hypothesis is accepted, i.e. if symmetry exists in the relationship between trade openness and CO_2 emissions. But, suppose the null hypothesis is rejected, the model is then reduced to the cointegrating NARDL, with short- and long-run asymmetries presented respectively in Eqs. (5), (6) below:

$$\Delta InCO_{2t} = \mu + \rho InCO_{2t-1} + \pi InOPEN_{t-1} + \sum_{i=1}^{p-1} \alpha_i \Delta InCO_{2t-1} + \sum_{i=0}^{q-1} \left(\beta_i^+ \Delta InOPEN_{t-1}^+ + \beta_i^- \Delta InOPEN_{t-1}^-\right) + \varepsilon_t \tag{5}$$

$$\Delta InCO_{2t} = \mu + \rho InCO_{2t-1} + \pi^+ InOPEN_{t-1}^+ + \pi^- InOPEN_{t-1}^- + \sum_{i=1}^{p-1} \alpha_i \Delta InCO_{2t-1} + \sum_{i=0}^{q-1} \beta_i \Delta InOPEN_{t-1} + \varepsilon_t \tag{6}$$

The responses of CO_2 emissions to increases and decreases in trade openness can be quantified through the asymmetric dynamic multipliers as follows:

$$m_h^t = \sum\nolimits_{j=0}^{h} \left(\frac{\partial InCO_{2t+j}}{\partial InOPEN_t^+}\right) \text{and} m_h^- = \sum\nolimits_{j=0}^{h} \left(\frac{\partial InCO_{2t+j}}{\partial InOPEN_t^-}\right), \text{h} = 0, 1, 2, \ldots$$

By construction, when $h \to \infty, m_h^t \to \theta^+, and m_h^- \to \theta^-$, then $\theta^+ and \theta^-$ are the asymmetric long-run coefficients as shown above. We can see, through the estimated multipliers, the direction from the old to the new equilibrium arising from a negative or positive shock and the corresponding period of the temporary disequilibria in the short run.

3.2 Data

The paper uses annual data covering the period 1960–2020. In this paper, CO_2 emissions (kg per 2010 US$ of GDP) represents environmental quality is treated as the dependent variable. The trade openness variable is proxied using the composite trade intensity (CTI) as suggested by Squalli and Wilson [92] and it is demonstrated below. Both variables are sourced from the World Bank World Development Indicators (WDI).

Table 1 presents the descriptive statistics and stochastic properties of both variables together with the results of the normality and unit root tests. Based on top five countries in SADC region, CO_2 emissions have an average value of 1.313 (kg per 2010 US$ of GDP), 1.102, 0.978, 0.471 and 0.385 in South Africa, Lesotho, Zimbabwe, Mozambique and Botswana respectively reach a peak of 1.611 (kg per 2010 US$ of GDP), 1.361, 1.333, 1.421 and 0.592 respectively over the period

[5] Shin et al. [89] argue that, because of dependency between the two variables, such a treatment is crucial.

Table 1 Descriptive statistics

Country	Mean	Median	Max	Min	Std. Dev	Skewness	Kurtosis	JB Stat	ZA		Obs
									At level	At 1st diff	
CO_2emissions											
Angola	0.257	0.251	0.409	0.151	0.082	0.208	1.519	3.452	– 6.197***	– 9.942***	35
Botswana	0.385	0.393	0.592	0.029	0.124	– 1.091	4.400	12.048***	– 4.701	– 8.334***	43
Comoros	0.130	0.126	0.199	0.081	0.031	0.387	2.339	1.511	– 5.263**	– 7.399***	35
DRC	0.128	0.133	0.175	0.059	0.031	– 0.479	2.347	3.083	– 4.619	– 9.121***	55
Lesotho	1.102	1.113	1.361	0.878	0.136	0.031	2.141	0.772	– 20.192***	– 8.519***	25
Madagascar	0.214	0.211	0.334	0.095	0.055	0.012	2.890	0.028	– 5.112**	– 8.920***	55
Malawi	0.237	0.235	0.348	0.145	0.057	0.178	1.959	2.569	– 9.077***	– 13.997***	51
Mauritius	0.337	0.361	0.436	0.200	0.067	– 0.447	1.765	3.781	– 5.262**	– 8.268***	39
Mozambique	0.471	0.321	1.421	0.253	0.294	1.776	5.281	25.997***	– 8.250***	– 9.204***	35
Namibia	0.241	0.242	0.313	0.008	0.057	– 2.720	12.049	116.135**	– 4.169	– 10.959***	25
Seychelles	0.378	0.322	1.026	0.042	0.242	0.705	2.885	4.348	– 4.946*	– 11.678***	52
South Africa	1.313	1.272	1.611	1.086	0.159	0.291	1.684	4.744*	– 4.400	– 8.134***	55
Tanzania	0.207	0.197	0.290	0.156	0.036	0.685	2.622	2.274	– 5.683***	– 8.345***	27
Zambia	0.360	0.308	0.766	0.123	0.184	0.449	1.991	3.875	– 11.296***	– 12.027***	51
Zimbabwe	0.978	0.985	1.333	0.485	0.202	– 0.310	2.313	1.819	– 7.584***	– 9.732***	51
Trade openness											
Angola	62.439	60.669	89.685	44.695	10.933	0.867	3.832	2.313	– 6.188***	– 9.817***	15
Botswana	47.161	49.705	75.129	22.772	12.965	– 0.284	2.428	1.488	– 4.183	– 6.461***	55
Comoros	8.924	8.836	9.956	8.221	0.297	1.790	7.643	50.150***	– 3.409	– 14.636***	35
DRC	27.304	26.813	41.111	11.449	9.026	– 0.064	2.029	0.838	– 6.658***	– 8.432***	21
Lesotho	22.314	15.462	53.170	10.864	13.336	1.153	2.824	6.692**	– 4.549	– 10.595***	30
Madagascar	19.154	17.151	32.758	10.030	6.357	0.673	2.264	5.400*	– 5.521**	– 8.368***	55
Malawi	23.961	23.287	35.659	15.860	4.256	0.588	3.199	3.268	– 5.420**	– 10.176***	55
Mauritius	55.715	56.007	67.987	42.670	7.036	– 0.113	1.850	2.230	– 4.556	– 13.311***	39
Mozambique	17.171	12.006	33.426	2.524	10.638	0.351	1.472	4.121	– 4.029	– 6.830***	35
Namibia	46.815	45.442	70.388	38.714	6.074	1.872	7.637	51.816	– 3.771	– 7.264***	35
Seychelles	43.226	17.725	107.994	8.852	37.104	0.526	1.427	5.818*	– 7.051	– 8.557***	39
South Africa	97.016	26.885	135.622	20.703	3.554	0.195	2.545	0.823	– 3.799	– 6.801***	55
Tanzania	16.718	17.983	24.074	10.025	4.042	-0.230	2.059	1.142	– 7.120***	– 9.072***	25
Zambia	31.361	30.610	40.482	23.923	5.528	0.369	1.897	1.541	– 8.361***	– 7.694***	21
Zimbabwe	28.216	24.606	43.393	16.442	7.491	0.306	1.756	3.203	– 4.893*	– 9.268***	40

Source: Authors' calculations

JB denotes the empirical statistics of the Jarque–Bera test for normality. ZA is the empirical statistic of the Zivot and Andrews (1992) unit root test which is robust to structural breaks. *, **, and *** indicate rejection of the null hypotheses of normality and unit root at 10%, 5% and 1% statistical significance levels respectively.

1960 to 2020. For Angola, Comoros, DRC, Lesotho, Madagascar, Malawi, Mauritius, Seychelles, Tanzania, Zambia and Zimbabwe, CO_2 emissions follow the normal distribution while the opposite is the case for Botswana, Mozambique, Namibia and South Africa. Over the same period, trade openness has an average value of 97.016, 62.439, 55.715, 47.161 and 46.815 in South Africa, Angola, Mauritius, Botswana and Namibia respectively and reaches a peak of 135.622, 89.685, 67.987, 75.129 and 70.388 respectively. Table 1 further shows that both variables, after first differencing, become stationary using the Zivot and Andrews [113] unit root test which is robust to structural breaks.

3.3 Measuring trade openness

The measure of trade openness, which is used in this paper is called the composite trade intensity (CTI). The CTI-based proxy was originally introduced by Squalli and Wilson [92] to address the problems with the traditional trade intensity

Table 2 Critical values of the cointegration tests

Statistic	k = 1 (95%)		k = 2 (95%)	
	I(0)	I(1)	I(0)	I(1)
t_{BDM}	− 2.86	− 3.22	− 2.86	− 3.53
F_{PSS}	4.94	5.73	3.79	4.85
	k = 1 (90%)		k = 2 (90%)	
	I(0)	I(1)	I(0)	I(1)
t_{BDM}	− 2.57	− 2.91	− 2.57	− 3.21
F_{PSS}	4.04	4.78	3.17	4.14

Source: Pesaran, Shin and Smith (2001) tables.

k is the number of regressors entering the long-run relationship. In the symmetric ARDL model, k equals to 1, while in the asymmetric specification k varies between 1 and 2. The confidence intervals are presented in parentheses. The bounds critical values are taken from Pesaran, Shin, and Smith (2001) with unrestricted intercept and no trend (Case III).

(TI) which has been widely used in the previous literature. The CTI contains more crucial information that shows the contribution of a country to the world economy and its impact on the global economy. Intuitively, CTI represents TI adjusted by the share of a country's trade level in relation to average international trade. The novelty of using the CTI-based proxy is that it captures two dimensions of a country's ties with the rest of the world. The CTI is presented as:

$$CTI = \frac{(X+M)_i}{\frac{1}{n}\sum_{j=1}^{n}(X+M)_j}\frac{(X+M)_i}{GDP_i} \tag{7}$$

where: i denotes SADC in this case; j represents its trading partners; the first part of the Eq. (6) captures world trade intensity (WTI) while the second part represents SADC's trade intensity.

As highlighted by Squalli and Wilson [92], the CTI-based measure of trade openness is advantageous over traditional TI as follows: (i) CTI takes into consideration not only the trade share of a country's GDP but also the relative size of trade in relation to world trade in a given period; (ii) it is considered a better measure since it is more precise to capture the impact of trade openness on the environment; (iii) because it accounts for both TI and WTI, the adjustment is not always extreme; (iv) it considers two aspects of openness (i.e. TI and WTI) that capture the correct trade openness (the first dimension looks at the proportion of total income of SADC related to its international trade, whereas the second aspect highlights the comparative importance of SADC's contribution in world trade); (v) it considers real trade flows instead of potential trade flows as emphasized by lax or liberal trade policies as well as other important socioeconomic, geographic and demographic factors; (vi) it captures the gains derived from trading quite rigorously with the rest of the world; (vii) as established by Squalli and Wilson [92], using the TI-based proxies penalises bigger countries by seeing them as closed economies because their trade share of total economic activities are considerably small by world standards, therefore closed to trade benefits. However, using CTI, the world's largest trading economies such as China, Japan, USA, Germany, etc. are now seen to be open rather than closed economies. So, the proxy classifies more completely the degree of trade openness that countries enjoy.

4 Results and discussion

4.1 Asymmetric effects of trade openness on CO_2 emissions

Firstly, trade openness and CO2 emissions are tested for cointegration. The bounds of the critical values of t_{BDM} and F_{PSS} are reported in Table 2.

To analyse the asymmetric effects of trade openness on CO2 emissions, this study uses the NARDL approach. The general to specific approach is used to select the proper model specification associated with the appropriate equations capturing the symmetric ARDL and NARDL models. The approach involves starting with max p = max q = 12 and dropping all insignificant variables (i.e. stepwise regression). The Huber-White covariance methodology has been applied for the diminution of heteroscedasticity and the estimation of results for SADC member countries are individually reported and analysed below.

4.1.1 Angola

In the case of Angola (Table 3), the cointegration tests t_{BDM} and F_{PSS} in the restricted symmetric model are − 3.635 and 5.710, respectively. This evidence leads to rejection of the null hypothesis of no long-run relationship at the 10% significance level. However, at the 5% significance level, there is no solid inference to be drawn. Similarly, in the NARDL model with short-run asymmetry, the null hypothesis is rejected even at the 5% significance level. On the other hand, no evidence of cointegrating relationship between trade openness and CO2 emissions is detected when long-run asymmetries are examined.

Evidence from the Wald tests suggests absence of asymmetric behaviour for both short- and long-runs in the specific pair-wise relationship in both cases under review. Therefore, CO_2 emissions in Angola appear to respond similarly to trade openness increases and decreases. Given this evidence, the symmetric ARDL specification is thus investigated henceforth. The long-run coefficient L_{lnOpen} is negative (− 0.395) and highly statistically significant, suggesting that a 1% increase (decrease) in trade openness brings about improvement (deterioration) in the environmental quality by 0.395% in the long-run, holding other things constant. Our findings are in line with those of Pata et al. [72], who found that, between 1995 and 2018, trade openness improved environmental quality for countries in the Association of Southeast Asian Nations (ASEAN). Similar conclusions were reached by Mahmood [61], who noted that trade in Latin America had a net beneficial environmental impact between 1970 and 2019. Additionally, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period. The bottom part of Table 3 reports the results of diagnostic tests which show that all the models are well fitted having passed all the diagnostic tests. The tests show absence of misspecification in both symmetric ARDL and NARDL models, absence of serial correlation in all the models and residuals follow normal distribution based on the Jarque–Bera statistic.

4.1.2 Botswana

The estimation results of the four specifications for the relationship between trade openness and CO_2 emissions in Botswana are reported in Table 4.

The cointegration tests $t_{BDM} and F_{PSS}$ in the symmetric ARDL model are − 4.614 and 6.251 respectively. Since the $t_{BDM} and F_{PSS}$ cointegration tests are higher than the bounds critical values at both 5% and 10% significance levels, the null hypothesis of no cointegration is thus rejected. This evidence suggests presence of long-run relationship between trade openness and CO_2 emissions in Botswana. The last-mentioned is also applicable to the NARDL model with long-run asymmetry, whereas there is no evidence of cointegrating relationship between these two variables under review in the case of NARDL model with short-run asymmetry.

Evidence from the Wald tests shows that there is a strong asymmetric behaviour in the long-run responses of CO_2 emissions to trade openness variations. Nevertheless, in the short-run, CO_2 emissions in Botswana seem to respond similarly to trade openness increases and decreases. Therefore, the most suitable framework to analyse this is the NARDL model with long-run asymmetry. Given the fact that there is ample evidence of long-run relationship between the two variables under review, the long-run coefficients L_{lnOpen^+} and L_{lnOpen^-} being highly statistically significant are negative (− 0.299) and positive (0.426) respectively. The results therefore suggest that a 1% increase in trade openness leads to a fall in CO_2 emissions by 0.299%, whereas a 1% decrease in trade openness results in deterioration of the environmental condition by 0.426% in the long-run, *ceteris paribus*. Also, the particular NARDL model shows evidence of no general misspecification, absence of serial correlation and presence of normality in residuals. Our findings are in line with those made by Pata et al. [72], who found that, for the countries of the Association of Southeast Asian Nations (ASEAN), between 1995 and 2018, trade openness improves environmental quality. Similar conclusions were reached by Mahmood [61], who noted that from 1970 to 2019, commerce in Latin America had a net beneficial

Table 3 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Angola

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.149** (– 2.20)	InCO_{2t-1}	– 0.356*** (-4.65)	InCO_{2t-1}	– 0.173** (– 2.23)	InCO_{2t-1}	– 0.406*** (– 9.59)
InOpen_{t-1}	– 0.059*** (– 4.46)	$\mathrm{InOpen}^{+}_{t-1}$	– 0.044* (– 2.96)	$\mathrm{InOpen}^{+}_{t-1}$	– 0.261* (– 1.99)	InOpen_{t-1}	– 1.068*** (– 5.57)
$\Delta InCO_{2t-1}$	0.132** (4.24)	$\mathrm{InOpen}^{-}_{t-1}$	0.123*** (4.90)	$\mathrm{InOpen}^{-}_{t-1}$	0.835** (2.47)	$\Delta InCO_{2t-1}$	1.748* (1.99)
$\Delta InCO_{2t-3}$	0.233* (1.98)	$\Delta InCO_{2t-1}$	0.241*** (3.71)	$\Delta InCO_{2t-3}$	1.381** (2.07)	$\Delta InCO_{2t-2}$	0.630*** (7.93)
$\Delta InOpen$	– 0.161*** (– 2.13)	$\Delta InCO_{2t-3}$	0.454*** (4.50)	$\Delta InCO_{2t-5}$	1.305* (1.98)	$\Delta InCO_{2t-11}$	0.267*** (4.06)
$\Delta InOpen_{t-4}$	0.159** (2.03)	$\Delta InCO_{2t-4}$	0.215* (1.98)	$\Delta InCO_{2t-9}$	1.148* (2.00)	$\Delta InCO_{2t-12}$	0.821** (9.23)
$\Delta InOpen_{t-6}$	0.156* (1.99)	$\Delta InCO_{2t-5}$	0.215* (1.99)	$\Delta InCO_{2t-10}$	1.041* (2.00)	$\Delta InOpen^{+}$	1.087*** (4.27)
Const	0.379** (2.22)	$\Delta InOpen^{+}$	0.174** (2.42)	$\Delta InCO_{2t-11}$	0.841* (1.99)	$\Delta \mathrm{InOpen}^{+}_{t-1}$	-0.698* (-1.98)
L_{InOpen}	– 0.395*** (0.000)	$\Delta \mathrm{InOpen}^{+}_{t-1}$	0.124* (1.98)	$\Delta InOpen$	– 0.437** (– 2.54)	$\Delta \mathrm{InOpen}^{+}_{t-2}$	– 0.539** (– 2.15)
R^2	0.787	$\Delta \mathrm{InOpen}^{+}_{t-4}$	0.244*** (3.44)	$\Delta InOpen_{t-4}$	0.335** (2.07)	$\Delta \mathrm{InOpen}^{+}_{t-6}$	0.307* (1.99)
$Adj.R^2$	0.702	$\Delta \mathrm{InOpen}^{+}_{t-6}$	0.168** (2.41)	$\Delta InOpen_{t-5}$	0.378* (1.99)	$\Delta \mathrm{InOpen}^{+}_{t-8}$	0.494*** (6.22)
X^2_{SC}	7.131 (0.589)	$\Delta InOpen^{-}$	– 0.602*** (– 6.45)	$\Delta InOpen_{t-6}$	0.469 (2.42)	$\Delta \mathrm{InOpen}^{+}_{t-11}$	0.038*** (5.60)
X^2_{FF}	8.950 (0.102)	$\Delta \mathrm{InOpen}^{-}_{t-1}$	– 0.203* (– 1.99)	$\Delta InOpen_{t-11}$	0.435** (2.07)	$\Delta \mathrm{InOpen}^{+}_{t-12}$	– 0.184*** (– 7.93)
X^2_{NOR}	1.821 (0.161)	$\Delta \mathrm{InOpen}^{-}_{t-7}$	– 0.403*** (– 4.02)	Const	– 0.050** (– 2.58)	$\Delta InOpen^{-}$	– 0.944*** (– 5.61)
t_{BDM}	– 3.635 (0.001)	Const	0.29* (1.96)	$L_{InOpen^{+}}$	– 0.120** (0.016)	$\Delta \mathrm{InOpen}^{-}_{t-1}$	– 0.793*** (– 3.25)
F_{PSS}	5.710 (0.006)	$L_{InOpen^{+}}$	– 0.124*** (0.005)	$L_{InOpen^{-}}$	0.384*** (0.000)	$\Delta \mathrm{InOpen}^{-}_{t-2}$	– 1.728*** (– 3.03)
		$L_{InOpen^{-}}$	0.345*** (0.000)	R^2	0.764	$\Delta \mathrm{InOpen}^{-}_{t-4}$	– 2.111*** (-7.25)
		R^2	0.763	$Adj.R^2$	0.701	Const	1.93** (2.31)
		$Adj.R^2$	0.670	X^2_{SC}	7.931 (0.630)	L_{InOpen}	– 0.759*** (0.000)
		X^2_{SC}	7.642 (0.263)	X^2_{FF}	5.86 (0.121	R^2	0.712
		X^2_{FF}	7.250 (0.208)	X^2_{NOR}	1.321 (0.382)	$Adj.R^2$	0.692
		X^2_{NOR}	0.318 (0.436)	t_{BDM}	– 2.913 (0.005)	X^2_{SC}	6.382 (0.115)
		t_{BDM}	– 2.231 (0.001)	F_{PSS}	3.260 (0.012)	X^2_{FF}	4.22 (0.325)

Table 3 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		F_{PSS}	4.721 (0.000)	W_{LR}	0.052 (0.481)	X^2_{NOR}	0.914 (0.501)
		W_{LR}	0.431 (0.351)			t_{BDM}	− 3.718 (0.003)
		W_{SR}	0.392 (0.297)			F_{PSS}	6.413 (0.000)
						W_{SR}	0.090 (0.153)

Source: Authors' calculations

The general to specific approach is followed for the selection of the proper ARDL specification. The latter is selected by starting with max p = max q = 12 and dropping all insignificant variables (i.e., stepwise regression). The Huber-White covariance methodology has been applied for the diminution of heteroscedasticity. The long-run coefficients of the symmetric ARDL and NARDL asymmetric models are denoted as $L_{InOpen}, L_{InOpen^+} and L_{InOpen^-}$ respectively. *, ** and *** denote statistical significance at 10%, 5% and 1% levels respectively. T-ratios are in parentheses (). X^2_{SC} is the Lagrange multiplier statistic test for serial autocorrelation. X^2_{FF} is the Ramsey regression specification-error test for omitted variables. X^2_{NOR} is the test for normality. t_{BDM} stands for the BDM t-statistic, whilst F_{PSS} is the PSS F-statistic. The Wald tests for long- and short-run symmetry are denoted as WLR and WSR respectively.

environmental impact. Additionally, Ding et al. [114] showed that improved environmental quality benefits from higher economic openness among the G-7 nations. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.3 Comoros

In the case of Comoros (Table 5), there is a statistically robust long-run relationship between trade openness and CO_2 emissions, where the null hypothesis of no long-run relationship is rejected across all four specifications (symmetric, SR and LR asymmetry, LR asymmetry and SR asymmetry) at the 5% significance level. This evidence implies that the two variables share a historical cointegrating relationship.

The next step involves conducting a test to determine the possible short- or long-run asymmetries using the Wald test. The null of symmetry is rejected by both tests suggesting a different response of CO_2 emissions to trade openness deviations both in the short- and long-runs. Following this evidence, the right methodology for hypothesis testing is the NARDL model where both short- and long-term asymmetries are incorporated. The long-run coefficients L_{InOpen^+} and L_{InOpen^-} are statistically significant at 1% and affect CO_2 emissions in a negative and positive manner respectively. A 1% increase in trade openness results in a decrease in CO_2 emissions by 0.040%, while a corresponding drop gives rise to a 0.467% increase. Finally, the precise NARDL model shows evidence of no general misspecification, absence of serial correlation and presence of normality in residuals. Our findings support those of Pata et al. [72], who found that trade openness improves environmental quality for the Association of Southeast Asian Nations (ASEAN) countries between 1995 and 2018. Mahmood [61] reached a similar conclusion and noted that trade in Latin America had a net beneficial environmental impact between 1970 and 2019. Increased trade openness also improves the environmental quality of G-7 economies, as shown by Ding et al. in [114]. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

Table 4 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Botswana

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.235** (– 2.65)	InCO_{2t-1}	– 0.192*** (– 4.90)	InCO_{2t-1}	– 0.244** (– 2.38)	InCO_{2t-1}	– 1.080*** (– 4.37)
InOpen_{t-1}	– 0.143*** (– 2.48)	InOpen^{+}_{t-1}	– 0.018*** (– 3.08)	InOpen^{+}_{t-1}	– 0.073** (– 2.32)	InOpen_{t-1}	– 0.216** (– 2.44)
$\Delta InCO_{2t-1}$	– 0.184* (1.98)	InOpen^{-}_{t-1}	0.225*** (2.09)	InOpen^{-}_{t-1}	0.104** (2.70)	$\Delta InCO_{2t-1}$	0.323** (2.49)
$\Delta InCO_{2t-7}$	– 0.314** (– 2.25)	$\Delta InCO_{2t-2}$	0.565*** (4.51)	$\Delta InCO_{2t-1}$	-0.132*** (4.17)	$\Delta InCO_{2t-2}$	0.656** (2.42)
$\Delta InOpen$	1.073** (2.75)	$\Delta InCO_{2t-3}$	0.469*** (4.98)	$\Delta InCO_{2t-8}$	– 0.274* (– 1.99)	$\Delta InCO_{2t-3}$	0.789*** (3.97)
$\Delta InOpen_{t-8}$	0.894* (2.38)	$\Delta InOpen^{+}$	0.174** (2.42)	$\Delta InCO_{2t-9}$	– 0.171** (– 2.24)	$\Delta InCO_{2t-4}$	0.480** (2.34)
$\Delta InOpen_{t-10}$	– 0.871* (– 2.38)	$\Delta\text{InOpen}^{+}_{t-1}$	0.434*** (4.63)	$\Delta InCO_{2t-12}$	– 0.326** (– 2.50)	$\Delta InOpen^{+}$	3.349** (2.78)
$\Delta InOpen_{t-11}$	– 0.854*** (– 2.20)	$\Delta\text{InOpen}^{+}_{t-8}$	1.567*** (5.80)	$\Delta InOpen$	1.143*** (2.83)	$\Delta\text{InOpen}^{+}_{t-1}$	0.302*** (3.77)
$\Delta InOpen_{t-12}$	– 0.404* (– 3.11)	$\Delta\text{InOpen}^{+}_{t-9}$	0.283*** (3.17)	$\Delta InOpen_{t-2}$	– 0.961** (– 2.24)	$\Delta\text{InOpen}^{+}_{t-3}$	0.949** (2.47)
Const	3.138** (3.26)	$\Delta\text{InOpen}^{+}_{t-11}$	0.402** (2.82)	$\Delta InOpen_{t-4}$	-0.897** (-2.14)	$\Delta\text{InOpen}^{+}_{t-5}$	0.956* (2.02)
L_{InOpen}	– 0.608*** (0.000)	$\Delta\text{InOpen}^{+}_{t-12}$	0.769*** (3.23)	$\Delta InOpen_{t-10}$	– 0.988** (– 2.54)	$\Delta\text{InOpen}^{+}_{t-8}$	0.634** (2.23)
R^2	0.865	$\Delta InOpen^{-}$	1.572*** (3.63)	$\Delta InOpen_{t-11}$	– 1.015** (– 2.44)	$\Delta\text{InOpen}^{+}_{t-9}$	0.710* (2.08)
$Adj.R^2$	0.749	$\Delta\text{InOpen}^{-}_{t-5}$	1.516*** (3.45)	Const	0.974** (2.62)	$\Delta\text{InOpen}^{+}_{t-12}$	-0.241*** (-4.62)
X^2_{SC}	8.731 (0.135)	$\Delta\text{InOpen}^{-}_{t-6}$	1.241*** (3.33)	$L_{InOpen^{+}}$	– 0.299*** (0.000)	$\Delta InOpen^{-}$	– 0.813*** (-4.52)
X^2_{FF}	7.89 (0.281)	$\Delta\text{InOpen}^{-}_{t-7}$	-0.814* (-1.99)	$L_{InOpen^{-}}$	0.426*** (0.002)	$\Delta\text{InOpen}^{-}_{t-1}$	– 0.571*** (– 4.25)
X^2_{NOR}	0.714 (0.641)	$\Delta\text{InOpen}^{-}_{t-10}$	– 0.654* (– 1.99)	R^2	0.720	$\Delta\text{InOpen}^{-}_{t-2}$	– 1.634* (– 1.99)
t_{BDM}	– 4.614 (0.026)	$\Delta\text{InOpen}^{-}_{t-11}$	– 1.565*** (– 3.54)	$Adj.R^2$	0.682	$\Delta\text{InOpen}^{-}_{t-3}$	– 1.864* (– 2.26)
F_{PSS}	6.251 (0.004)	$\Delta\text{InOpen}^{-}_{t-12}$	– 1.126*** (-2.59)	X^2_{SC}	7.32 (0.168)	$\Delta\text{InOpen}^{-}_{t-9}$	– 1.655* (– 1.96)
		Const	0.982*** (3.44)	X^2_{FF}	4.67 (0.124)	$\Delta\text{InOpen}^{-}_{t-10}$	– 1.351* (– 2.17)
		$L_{InOpen^{+}}$	– 0.093*** (0.002)	X^2_{NOR}	2.416 (0.19)	$\Delta\text{InOpen}^{-}_{t-12}$	– 1.844** (– 2.50)
		$L_{InOpen^{-}}$	0.575** (0.025)	t_{BDM}	– 5.162 (0.013)	Const	– 4.740** (– 2.32)
		R^2	0.818	F_{PSS}	6.174 (0.002)	L_{InOpen}	– 0.199*** (0.001)
		$Adj.R^2$	0.776	W_{LR}	0.095 (0.004)	R^2	0.927
		X^2_{SC}	4.512 (0.337)			$Adj.R^2$	0.826
		X^2_{FF}	3.91 (0.142)			X^2_{SC}	7.720 (0.206)

Table 4 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		X^2_{NOR}	1.814 (0.328)			X^2_{FF}	1.42 (0.341)
		t_{BDM}	– 3.146 (0.019)			X^2_{NOR}	1.914 (0.142)
		F_{PSS}	4.011 (0.008)			t_{BDM}	– 2.820 (0.037)
		W_{LR}	0.503 (0.002)			F_{PSS}	3.379 (0.004)
		W_{SR}	0.431 (0.173)			W_{SR}	0.038 (0.150)

Similar to those in Table 3

4.1.4 Democratic Republic of Congo (DRC)

The results for the asymmetric effect of trade openness on CO_2 emissions in DRC are reported in Table 6. The cointegration statistics of the restricted model $t_{BDM} and F_{PSS}$ are equal to – 5.671 and 10.215, respectively. This evidence shows that the null hypothesis is rejected even at the 5% significance level, indicating a clear cointegrating relationship between the two variables. Similarly, when an asymmetric behaviour is examined, evidence of this long-run relationship is also found.

Evidence from the Wald tests suggests absence of asymmetric behaviour for both short- and long-runs in the specific pair-wise relationship in both cases under review. Therefore, CO_2 emissions in DRC appear to respond similarly to trade openness increases and decreases. Given this evidence, the symmetric ARDL specification is thus investigated henceforth. The long-run coefficient L_{InOpen} is negative (– 1.589) and highly statistically significant, suggesting that a 1% increase (decrease) in trade openness results in improvement (deterioration) in the environmental quality by 1.589% in the long run, ceteris paribus. Our findings are in line with those of Pata et al. [72], who found that, for the Association of Southeast Asian Nations (ASEAN) countries between 1995 and 2018, trade openness improves environmental quality. Mahmood [61] also reached the similar conclusions, indicating that from 1970 to 2019, trade in Latin America had a net beneficial environmental impact. Furthermore, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period. In relevance to the diagnostic tests of the symmetric specification, the model is well fitted since it passes all the diagnostic tests. The tests suggest that the model does not suffer either from serial correlation or from some form of general misspecification. The Jarque–Bera statistic suggests that the residuals follow normal distribution.

4.1.5 Lesotho

Table 7 reports the estimated results of the four models specified for the trade-CO_2 emissions relationship in Lesotho. The cointegration tests show evidence of long-run relationship between the two variables when the symmetric ARDL is examined. The null is rejected at 10% significance level, although there is no explicit conclusion to be drawn at 5%. By contrast, when asymmetries are considered, the null hypothesis of no cointegration fails to be rejected.

The Wald tests, when implemented, show that there is no evidence of asymmetric behaviour because both short- and long-run asymmetry cannot be observed, at least not a statistically significant one and, therefore, the symmetric ARDL is under review. The long-run coefficient L_{InOpen} is highly statistically significant and equal to 0.517, suggesting

Table 5 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Comoros

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	− 0.233** (− 3.43)	InCO_{2t-1}	− 0.366*** (− 4.79)	InCO_{2t-1}	− 0.274* (− 1.99)	InCO_{2t-1}	− 0.406*** (− 8.48)
$InOpen_{t-1}$	− 0.134*** (− 3.26)	$\mathrm{InOpen}^{+}_{t-1}$	− 0.015*** (− 3.90)	$\mathrm{InOpen}^{+}_{t-1}$	− 0.028*** (− 3.71)	InOpen_{t-1}	− 0.132*** (− 7.65)
$\Delta InCO_{2t-1}$	0.381** (2.72)	$\mathrm{InOpen}^{-}_{t-1}$	0.171*** (4.39)	$\mathrm{InOpen}^{-}_{t-1}$	0.175*** (3.41)	$\Delta InCO_{2t-1}$	− 0.795*** (− 3.39)
$\Delta InCO_{2t-4}$	0.518** (2.81)	$\Delta InCO_{2t-1}$	0.720* (1.99)	$\Delta InCO_{2t-1}$	− 1.208* (− 1.96)	$\Delta InCO_{2t-2}$	− 0.658** (− 2.30)
$\Delta InCO_{2t-9}$	− 0.555*** (− 2.97)	$\Delta InCO_{2t-3}$	0.084** (2.69)	$\Delta InCO_{2t-2}$	− 1.303** (− 2.34)	$\Delta InCO_{2t-4}$	0.987** (4.52)
$\Delta InCO_{2t-11}$	0.592*** (3.36)	$\Delta InOpen^{+}$	0.913*** (8.46)	$\Delta InCO_{2t-3}$	− 1.459** (− 2.44)	$\Delta InCO_{2t-9}$	− 0.034*** (− 6.06)
$\Delta InOpen$	0.538*** (5.76)	$\Delta\mathrm{InOpen}^{+}_{t-1}$	1.235*** (4.26)	$\Delta InCO_{2t-4}$	− 0.674** (− 2.37)	$\Delta InOpen^{+}$	0.861*** (5.64)
$\Delta InOpen_{t-2}$	− 0.509*** (− 4.58)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	0.440* (1.99)	$\Delta InCO_{2t-5}$	− 0.813** (− 2.14)	$\Delta\mathrm{InOpen}^{+}_{t-1}$	0.323*** (11.78)
$\Delta InOpen_{t-3}$	− 0.340*** (− 3.50)	$\Delta\mathrm{InOpen}^{+}_{t-3}$	0.639** (2.78)	$\Delta InCO_{2t-6}$	− 0.765* (− 1.99)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	0.575** (6.20)
$\Delta InOpen_{t-6}$	− 0.360*** (− 4.20)	$\Delta\mathrm{InOpen}^{+}_{t-9}$	0.942*** (5.48)	$\Delta InCO_{2t-9}$	− 0.674** (− 2.37)	$\Delta\mathrm{InOpen}^{+}_{t-5}$	1.116* (6.72)
$\Delta InOpen_{t-8}$	0.297*** (3.93)	$\Delta\mathrm{InOpen}^{+}_{t-12}$	1.518*** (4.81)	$\Delta InCO_{2t-12}$	− 0.293*** (− 3.95)	$\Delta\mathrm{InOpen}^{+}_{t-6}$	0.228** (2.36)
$\Delta InOpen_{t-10}$	− 0.246** (− 2.70)	$\Delta InOpen^{-}$	− 2.604*** (− 4.53)	$\Delta InOpen$	0.609*** (4.95)	$\Delta\mathrm{InOpen}^{+}_{t-7}$	0.012*** (5.25)
$\Delta InOpen_{t-11}$	− 0.264** (− 2.41)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	1.129*** (3.64)	$\Delta InOpen_{t-1}$	− 0.511** (− 2.79)	$\Delta\mathrm{InOpen}^{+}_{t-12}$	1.075*** (9.27)
Const.	0.647*** (3.64)	$\Delta\mathrm{InOpen}^{-}_{t-4}$	1.625*** (4.55)	$\Delta InOpen_{t-2}$	− 0.952*** (− 3.62)	$\Delta InOpen^{-}$	0.497** (2.54)
L_{InOpen}	− 0.575*** (0.000)	$\Delta\mathrm{InOpen}^{-}_{t-5}$	1.716*** (6.09)	$\Delta InOpen_{t-3}$	− 0.880*** (− 3.36)	$\Delta\mathrm{InOpen}^{-}_{t-1}$	1.656*** (5.20)
R^2	0.719	$\Delta\mathrm{InOpen}^{-}_{t-7}$	1.376*** (3.60)	$\Delta InOpen_{t-4}$	− 0.556** (− 2.89)	$\Delta\mathrm{InOpen}^{-}_{t-2}$	1.056** (2.83)
$Adj.R^2$	0.703	$\Delta\mathrm{InOpen}^{-}_{t-11}$	1.294*** (3.60)	$\Delta InOpen_{t-5}$	− 0.605** (− 2.99)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	1.119*** (5.54)
X^2_{SC}	2.718 (0.992)	$\Delta\mathrm{InOpen}^{-}_{t-12}$	− 1.038*** (− 4.72)	$\Delta InOpen_{t-6}$	− 0.866*** (− 3.45)	$\Delta\mathrm{InOpen}^{-}_{t-4}$	1.847*** (6.36)

Table 5 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X^2_{FF}	8.54 (0.167)	Const.	− 0.483*** (− 2.76)	$\Delta lnOpen_{t-7}$	− 0.543*** (− 3.45)	$\Delta \text{lnOpen}^-_{t-11}$	1.120*** (7.01)
X^2_{NOR}	2.914 (0.147)	L_{lnOpen^+}	− 0.040*** (0.000)	Const.	0. 388** (2.70)	$\Delta \text{lnOpen}^-_{t-12}$	− 0.457** (− 2.96)
t_{BDM}	− 4.518 (0.001)	L_{lnOpen^-}	0.467*** (0.000)	L_{lnOpen^+}	− 0.102*** (0.000)	Const.	− 1.037*** (− 5.16)
F_{PSS}	6.440 (0.005)	R^2	0.928	L_{lnOpen^-}	0.638*** (0.000)	L_{lnOpen}	− 0.325*** (0.001)
		$Adj.R^2$	0.707	R^2	0.715	R^2	0.997
		X^2_{SC}	2.239 (0.134)	$Adj.R^2$	0.658	$Adj.R^2$	0.978
		X^2_{FF}	6.08 (0.232)	X^2_{SC}	2.897 (0.887)	X^2_{SC}	7.016 (0.162)
		X^2_{NOR}	1.714 (0.593)	X^2_{FF}	9.24 (0.241)	X^2_{FF}	7.87 (0.254)
		t_{BDM}	− 4.514 (0.000)	X^2_{NOR}	2.915 (0.364)	X^2_{NOR}	1.745 (0.401)
		F_{PSS}	8.981 (0.003)	t_{BDM}	− 6. 428 (0.000)	t_{BDM}	− 4.013 (0.004)
		W_{LR}	0.148 (0.000)	F_{PSS}	5.316 (0.009)	F_{PSS}	9.831 (0.002)
		W_{SR}	0.024 (0.036)	W_{LR}	0.673 (0.004)	W_{SR}	0.130 (0.017)

Similar to those in Table 3

Table 6 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Democratic Republic of Congo

Dependent variable = InCO_{2t}

Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.056*** (– 4.39)	InCO_{2t-1}	– 0.483*** (– 5.97)	InCO_{2t-1}	– 0.131** (– 2.77)	InCO_{2t-1}	– 0.748*** (– 11.73)
$InOpen_{t-1}$	– 0.089*** (– 3.41)	$\mathrm{InOpen}^{+}_{t-1}$	– 0.200*** (– 4.48)	$\mathrm{InOpen}^{+}_{t-1}$	– 0.118*** (– 2.53)	InOpen_{t-1}	– 0.455*** (– 4.08)
$\Delta InCO_{2t-1}$	0.510** (2.60)	$\mathrm{InOpen}^{-}_{t-1}$	– 0.276*** (– 4.63)	$\mathrm{InOpen}^{-}_{t-1}$	– 0.126* (– 1.99)	$\Delta InCO_{2t-1}$	0.125*** (5.21)
$\Delta InCO_{2t-2}$	0.510** (2.75)	$\Delta InCO_{2t-1}$	1.161*** (4.29)	$\Delta InCO_{2t-1}$	– 1.351** (– 2.88)	$\Delta InCO_{2t-2}$	0.316*** (4.56)
$\Delta InCO_{2t-3}$	0.580*** (3.24)	$\Delta InCO_{2t-2}$	1.062*** (4.20)	$\Delta InCO_{2t-2}$	0.503* (1.99)	$\Delta InCO_{2t-3}$	0.715** (2.32)
$\Delta InCO_{2t-4}$	0.485** (2.39)	$\Delta InOpen^{+}$	– 0.128*** (– 6.01)	$\Delta InCO_{2t-3}$	0.573* (1.97)	$\Delta InCO_{2t-9}$	0.889*** (4.19)
$\Delta InCO_{2t-5}$	0.454** (2.33)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	0.168*** (3.50)	$\Delta InCO_{2t-5}$	0.465* (1.99)	$\Delta InOpen^{+}$	– 0.067*** (– 5.76)
$\Delta InCO_{2t-6}$	0.798*** (3.66)	$\Delta\mathrm{InOpen}^{+}_{t-3}$	0.083* (2.10)	$\Delta InCO_{2t-6}$	0.808*** (3.17)	$\Delta\mathrm{InOpen}^{+}_{t-1}$	2.402*** (10.83)
$\Delta InCO_{2t-7}$	0.570** (2.82)	$\Delta\mathrm{InOpen}^{+}_{t-4}$	0.154*** (3.06)	$\Delta InCO_{2t-7}$	0.617** (2.48)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	0.575** (6.20)
$\Delta InCO_{2t-8}$	0.557*** (3.38)	$\Delta\mathrm{InOpen}^{+}_{t-5}$	– 0.106*** (– 2.86)	$\Delta InCO_{2t-8}$	0.582*** (2.96)	$\Delta\mathrm{InOpen}^{+}_{t-4}$	2.330*** (11.35)
$\Delta InCO_{2t-9}$	0.526*** (3.12)	$\Delta\mathrm{InOpen}^{+}_{t-7}$	– 0.203*** (– 3.66)	$\Delta InCO_{2t-9}$	0.549** (2.80)	$\Delta\mathrm{InOpen}^{+}_{t-6}$	1.746** (2.24)
$\Delta InCO_{2t-10}$	0.540*** (2.88)	$\Delta InOpen^{-}$	– 1.931*** (– 6.81)	$\Delta InOpen$	– 0.034* (– 1.99)	$\Delta\mathrm{InOpen}^{+}_{t-9}$	0.851*** (8.87)
$\Delta InCO_{2t-11}$	0.348* (1.99)	$\Delta\mathrm{InOpen}^{-}_{t-1}$	0.392*** (4.13)	$\Delta InOpen_{t-1}$	0.107** (2.67)	$\Delta\mathrm{InOpen}^{+}_{t-12}$	– 0.854*** (– 10.10)
$\Delta InCO_{2t-12}$	0.409** (2.53)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	0.249*** (5.77)	$\Delta InOpen_{t-2}$	0.105** (2.35)	$\Delta InOpen^{-}$	– 0.804** (– 7.78)
$\Delta InOpen$	– 0.025* (1.96)	$\Delta\mathrm{InOpen}^{-}_{t-5}$	0.187*** (3.66)	$\Delta InOpen_{t-3}$	0.080* (1.96)	$\Delta\mathrm{InOpen}^{-}_{t-1}$	3.323*** (11.65)
$\Delta InOpen_{t-1}$	0.089*** (3.03)	$\Delta\mathrm{InOpen}^{-}_{t-9}$	0.157*** (3.49)	$\Delta InOpen_{t-12}$	0.037*** (4.89)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	2.909*** (10.60)
$\Delta InOpen_{t-2}$	0.080** (2.77)	$\Delta\mathrm{InOpen}^{-}_{t-10}$	0.138*** (3.10)	Const	– 2. 348** (– 3.06)	$\Delta\mathrm{InOpen}^{-}_{t-4}$	1.472*** (10.87)
$\Delta InOpen_{t-3}$	0.059* (2.03)	$\Delta\mathrm{InOpen}^{-}_{t-12}$	0.123*** (3.46)	$L_{InOpen^{+}}$	– 0.900 (0.025)	$\Delta\mathrm{InOpen}^{-}_{t-5}$	3.221*** (8.36)
Const	– 4.307*** (– 3.94)	Const	– 5.019*** (– 6.09)	$L_{InOpen^{-}}$	– 0.961*** (0.000)	$\Delta\mathrm{InOpen}^{-}_{t-11}$	0.261*** (7.06)
L_{InOpen}	– 1.589*** (0.000)	$L_{InOpen^{+}}$	– 0.414*** (0.000)	R^2	0.831	$\Delta\mathrm{InOpen}^{-}_{t-12}$	0.646** (2.41)
R^2	0.673	$L_{InOpen^{-}}$	– 0.571*** (0.000)	$Adj.R^2$	0.752	Const	– 1.224*** (– 11.33)
$Adj.R^2$	0.563	R^2	0.923	X^2_{SC}	4.858 (0.354)	L_{InOpen}	– 0.608*** (0.001)
X^2_{SC}	2.096 (0.147)	$Adj.R^2$	0.759	X^2_{FF}	7.66 (0.102)	R^2	0.997
X^2_{FF}	9.08 (0.207)	X^2_{SC}	2.579 (0.108)	X^2_{NOR}	0.042 (0.170)	$Adj.R^2$	0.971
X^2_{NOR}	0.831 (0.197)	X^2_{FF}	2.57 (0.112)	t_{BDM}	– 4. 721 (0.052)	X^2_{SC}	6.917 (0.217)

Table 6 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
t_{BDM}	− 5.671 (0.000)	X^2_{NOR}	1.815 (0.285)	F_{PSS}	5.56 (0.006)	X^2_{FF}	6.61 (0.254)
F_{PSS}	10.21 (0.008)	t_{BDM}	− 6.816 (0.008)	W_{LR}	0.218 (0.147)	X^2_{NOR}	0.614 (0.231)
		F_{PSS}	7.06 (0.000)			t_{BDM}	− 5.41 (0.000)
		W_{LR}	0.743 (0.315)			F_{PSS}	8.41 (0.002)
		W_{SR}	0.641 (0.109)			W_{SR}	0.801 (0.492)

Similar to those in Table 3

that a 1% increase (decrease) in trade openness makes CO_2 emissions rise (fall) by 0.517% in the long-run. Evidence from the diagnostic tests shows absence of serial correlation and the model does not suffer from some form of general misspecification, although there is non-normality in residuals. Our findings are in line with those of Pata et al. [72], who found that, for the Association of Southeast Asian Nations (ASEAN) countries between 1995 and 2018, trade openness improves environmental quality. Mahmood [61] also reached the similar conclusions, indicating that from 1970 to 2019, trade in Latin America had a net beneficial environmental impact. Furthermore, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.6 Madagascar

The estimated coefficients of the four specifications for the relationship between trade openness and CO_2 emissions in Madagascar are presented in Table 8.

The cointegration tests $t_{BDM} and F_{PSS}$ in the symmetric ARDL model are − 6.169 and 7.610 respectively. Since the $t_{BDM} and F_{PSS}$ cointegration tests are higher than the bounds critical values at both 5% and 10% significance levels, the null is rejected, suggesting presence of cointegrating relationship between trade openness and CO_2 emissions in Madagascar. When the three NARDL models are examined, the evidence shows that the null hypothesis is rejected even at the 5% significance level, indicating a clear cointegrating relationship between the two variables.

Evidence from the Wald tests reveals the presence of a strong asymmetric behaviour in the long-run responses of CO_2 emissions to trade openness variations. Nevertheless, in the short-run, CO_2 emissions in Madagascar appear to respond similarly to trade openness increases and decreases. Hence, the most suitable framework to analyse this is the NARDL model with long-run asymmetry. Given the fact that there is ample evidence of long-run relationship between the two variables under review, the long-run coefficients L_{InOpen^+} and L_{InOpen^-} being highly statistically significant are negative (-0.246) and positive (0.112) respectively. The results therefore suggest that a 1% increase in trade openness leads to a fall in CO_2 emissions by 0.246%, whereas a 1% decrease in trade openness results in deterioration of the environmental condition by 0.112% in the long-run, ceteris paribus. Also, the precise asymmetric specification passes all the tests for general misspecification and serial correlation. However, the residuals are not normally distributed. Our results are consistent with Pata et al. (2022), who discovered that, for the Association of Southeast Asian Nations (ASEAN) nations between 1995 and 2018, trade openness enhances environmental quality. Similarly, Mahmood (2022) came to the same findings, noting that from 1970 to 2019, trade in Latin America had a net positive environmental impact. Additionally, Ding et al. (2021) demonstrated that greater trade openness helps

Table 7 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Lesotho

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.114** (– 2.10)	InCO_{2t-1}	– 0.538*** (– 5.39)	InCO_{2t-1}	– 0.323*** (– 3.92)	InCO_{2t-1}	– 0.530*** (– 2.79)
$InOpen_{t-1}$	0.059** (2.61)	$\mathrm{InOpen}^{+}_{t-1}$	1.325*** (4.33)	$\mathrm{InOpen}^{+}_{t-1}$	– 0.206*** (– 4.80)	InOpen_{t-1}	– 0.426** (– 2.72)
$\Delta InCO_{2t-1}$	– 0.758*** (– 4.26)	$\mathrm{InOpen}^{-}_{t-1}$	0.426*** (3.68)	$\mathrm{InOpen}^{-}_{t-1}$	– 0.110*** (– 3.61)	$\Delta InCO_{2t-1}$	– 0.597*** (– 4.56)
$\Delta InCO_{2t-2}$	– 0.532** (– 2.62)	$\Delta InCO_{2t-3}$	0.476*** (2.03)	$\Delta InCO_{2t-1}$	– 0.550*** (– 3.17)	$\Delta InCO_{2t-3}$	0.429** (2.76)
$\Delta InCO_{2t-3}$	– 0.402** (– 2.45)	$\Delta InCO_{2t-7}$	– 0.145*** (– 3.21)	$\Delta InCO_{2t-2}$	– 0.484** (– 2.52)	$\Delta InCO_{2t-5}$	0.386** (2.72)
$\Delta InOpen$	– 0.162*** (4.81)	$\Delta InOpen^{+}$	– 0.084*** (– 3.07)	$\Delta InCO_{2t-3}$	– 0.355** (– 2.34)	$\Delta InCO_{2t-7}$	– 0.134* (– 2.13)
$\Delta InOpen_{t-1}$	– 0.182** (– 2.71)	$\Delta \mathrm{InOpen}^{+}_{t-1}$	– 1.428*** (– 4.63)	$\Delta InCO_{2t-4}$	0.161* (2.07)	$\Delta InOpen^{+}$	– 0.153*** (– 2.45)
$\Delta InOpen_{t-4}$	– 0.096*** (– 2.93)	$\Delta \mathrm{InOpen}^{+}_{t-2}$	– 1.348*** (– 4.38)	$\Delta InCO_{2t-5}$	0.150* (1.99)	$\Delta \mathrm{InOpen}^{+}_{t-2}$	0.227** (2.81)
$\Delta InOpen_{t-5}$	– 0.117*** (– 3.13)	$\Delta \mathrm{InOpen}^{+}_{t-3}$	– 1.423*** (– 4.70)	$\Delta InOpen$	0.141*** (5.24)	$\Delta \mathrm{InOpen}^{+}_{t-3}$	0.205* (2.09)
$\Delta InOpen_{t-6}$	– 0.074* (– 1.99)	$\Delta \mathrm{InOpen}^{+}_{t-11}$	– 1.491*** (– 5.19)	$\Delta InOpen_{t-1}$	0.191*** (4.43)	$\Delta \mathrm{InOpen}^{+}_{t-4}$	0.279** (2.40)
$\Delta InOpen_{t-7}$	– 0.188*** (– 4.72)	$\Delta \mathrm{InOpen}^{+}_{t-12}$	0.852*** (7.82)	$\Delta InOpen_{t-2}$	0.221*** (4.80)	$\Delta \mathrm{InOpen}^{+}_{t-5}$	0.304* (2.29)
$\Delta InOpen_{t-8}$	– 0.574*** (– 10.61)	$\Delta InOpen^{-}$	– 0.731*** (– 4.72)	$\Delta InOpen_{t-3}$	0.202* (4.72)	$\Delta \mathrm{InOpen}^{+}_{t-7}$	– 0.098* (– 1.99)
$\Delta InOpen_{t-9}$	– 0.473*** (– 4.41)	$\Delta \mathrm{InOpen}^{-}_{t-1}$	– 0.501*** (– 3.45)	$\Delta InOpen_{t-4}$	0.114** (2.48)	$\Delta \mathrm{InOpen}^{+}_{t-12}$	1.614*** (3.48)
$\Delta InOpen_{t-10}$	– 0.393*** (– 3.10)	$\Delta \mathrm{InOpen}^{-}_{t-2}$	– 0.388** (– 2.43)	$\Delta InOpen_{t-6}$	0.099** (2.42)	$\Delta InOpen^{-}$	0.298* (2.09)
$\Delta InOpen_{t-11}$	– 0.318*** (– 3.34)	$\Delta \mathrm{InOpen}^{-}_{t-3}$	– 0.626*** (– 4.11)	$\Delta InOpen_{t-8}$	– 0.378** (– 6.61)	$\Delta \mathrm{InOpen}^{-}_{t-1}$	0.589** (2.69)
Const.	0.678* (1.99)	$\Delta \mathrm{InOpen}^{-}_{t-4}$	– 0.922*** (– 6.34)	$\Delta InOpen_{t-9}$	– 0.412*** (– 3.96)	$\Delta \mathrm{InOpen}^{-}_{t-2}$	1.012*** (3.17)
L_{InOpen}	0.517** (0.010)	$\Delta \mathrm{InOpen}^{-}_{t-5}$	– 0.624*** (– 4.68)	$\Delta InOpen_{t-10}$	– 0.429*** (– 3.47)	$\Delta \mathrm{InOpen}^{-}_{t-4}$	– 1.077*** (– 3.56)
R^2	0.857	$\Delta \mathrm{InOpen}^{-}_{t-12}$	– 0.063* (– 2.07)	$\Delta InOpen_{t-11}$	– 0.351*** (– 3.76)	$\Delta \mathrm{InOpen}^{-}_{t-5}$	– 1.009*** (– 3.00)
$Adj.R^2$	0.784	Const.	– 1.290*** (– 4.29)	Const.	0.359** (2.58)	$\Delta \mathrm{InOpen}^{-}_{t-8}$	0.865* (2.02)
X^2_{SC}	4.786 (0.375)	$L_{InOpen^{+}}$	2.462*** (0.000)	$L_{InOpen^{+}}$	– 0.637 (0.000)	$\Delta \mathrm{InOpen}^{-}_{t-10}$	– 0.805** (– 2.80)
X^2_{FF}	8.54 (0.193)	$L_{InOpen^{-}}$	0.791*** (0.000)	$L_{InOpen^{-}}$	– 0.340*** (0.000)	Const.	– 5.836*** (– 2.75)
X^2_{NOR}	151.815 (0.000)	R^2	0.979	R^2	0.894	L_{InOpen}	– 0.803*** (0.000)
t_{BDM}	– 6.914 (0.000)	$Adj.R^2$	0.936	$Adj.R^2$	0.803	R^2	0.983
F_{PSS}	8.42 (0.047)	X^2_{SC}	5.827 (0.158)	X^2_{SC}	4.836 (0.360)	$Adj.R^2$	0.885
		X^2_{FF}	8.19 (0.148)	X^2_{FF}	8.68 (0.218)	X^2_{SC}	5.886 (0.169)

Table 7 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		X^2_{NOR}	150.152 (0.000)	X^2_{NOR}	126.198 (0.000)	X^2_{FF}	8.08 (0.120)
		t_{BDM}	– 5.163 (0.000)	t_{BDM}	– 6. 416 (0.000)	X^2_{NOR}	98.215 (0.000)
		F_{PSS}	12.57 (0.004)	F_{PSS}	9.73 (0.003)	t_{BDM}	– 4.93 (0.014)
		W_{LR}	0.657 (0.170)	W_{LR}	0.528 (0.613)	F_{PSS}	7.98 (0.079)
		W_{SR}	0.778 (0.263)			W_{SR}	0.841 (0.314)

Similar to those in Table 3

G-7 economies' environmental quality. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. (2022) found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.7 Malawi

In the case of Malawi (Table 9), the cointegration tests t_{BDM} and F_{PSS} in the restricted symmetric model are – 3.681 and 5.920, respectively. This evidence leads to rejection of the null hypothesis of no long-run relationship at both 5% and 10% significance levels. On the other hand, in all three NARDL models, there is no long-run relationship between trade openness and CO_2 emissions as shown when short-and long-run asymmetries are examined.

Evidence from the Wald tests suggests the absence of asymmetric behaviour for both short- and long-runs in the specific pair-wise relationship in both cases under review. Therefore, CO_2 emissions in Malawi appear to respond similarly to trade openness increases and decreases. Given this evidence, the symmetric ARDL specification is thus investigated henceforth. The long-run coefficient L_{InOpen} is positive (0.910) and highly statistically significant, suggesting that a 1% increase (decrease) in trade openness brings about deterioration (improvement) in the environmental quality by 0.910% in the long-run. The bottom part of Table 9 reports the results of diagnostic tests which show that the symmetric ARDL model is well fitted since it passes all the diagnostic tests. The tests suggest that the model does not suffer from the general misspecification and serial correlation. Also, the Jarque–Bera statistic shows evidence that the residuals follow normal distribution. Our results are consistent with Pata et al. [72], who discovered that, for the Association of Southeast Asian Nations (ASEAN) nations between 1995 and 2018, trade openness enhances environmental quality. Similarly, Mahmood [61] came to the same findings, noting that from 1970 to 2019, trade in Latin America had a net positive environmental impact. Additionally, Ding et al. [114] demonstrated that greater trade openness helps G-7 economies' environmental quality. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

Table 8 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Madagascar

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff	Var	Coeff	Var	Coeff
(1)	(2)	(3)	(4).	(5).	(6).	(7).	(8).
InCO_{2t-1}	– 0.616*** (– 4.45)	InCO_{2t-1}	– 0.806*** (– 4.62)	InCO_{2t-1}	– 0.784*** (– 4.19)	InCO_{2t-1}	– 0.874** (– 2.31)
$InOpen_{t-1}$	– 0.215*** (– 3.74)	InOpen^+_{t-1}	0.151*** (3.99)	InOpen^+_{t-1}	– 0.193*** (– 5.14)	InOpen_{t-1}	0.279** (2.68)
$\Delta InCO_{2t-9}$	– 0.326** (– 2.48)	InOpen^-_{t-1}	0.317** (2.42)	InOpen^-_{t-1}	0.088*** (3.92)	$\Delta InCO_{2t-1}$	– 0.720* (– 2.14)
$\Delta InCO_{2t-11}$	– 0.423*** (– 3.15)	$\Delta InCO_{2t-3}$	– 0.271* (– 2.00)	$\Delta InCO_{2t-1}$	1.079*** (2.94)	$\Delta InCO_{2t-2}$	– 1.048*** (– 3.37)
$\Delta InCO_{2t-12}$	– 0.182** (– 2.69)	$\Delta InCO_{2t-12}$	– 0.283*** (– 4.83)	$\Delta InCO_{2t-2}$	0.945** (2.73)	$\Delta InCO_{2t-3}$	– 0.913*** (– 3.23)
$\Delta InOpen$	– 0.142*** (– 3.41)	$\Delta InOpen^+$	– 0.173* (– 2.01)	$\Delta InCO_{2t-3}$	0.857** (2.72)	$\Delta InCO_{2t-5}$	– 0.832*** (– 3.09)
$\Delta InOpen_{t-3}$	– 0.142* (– 1.99)	$\Delta\text{InOpen}^+_{t-2}$	– 0.347** (– 2.10)	$\Delta InCO_{2t-4}$	0.710** (2.48)	$\Delta InOpen^+$	– 0.274*** (– 4.21)
$\Delta InOpen_{t-5}$	– 0.205** (– 2.68)	$\Delta\text{InOpen}^+_{t-3}$	– 0.392** (– 2.37)	$\Delta InCO_{2t-5}$	0.654** (2.56)	$\Delta\text{InOpen}^+_{t-1}$	– 1.270*** (– 7.08)
$\Delta InOpen_{t-9}$	0.204** (2.74)	$\Delta\text{InOpen}^+_{t-5}$	– 0.443*** (– 3.07)	$\Delta InCO_{2t-6}$	0.609** (2.89)	$\Delta\text{InOpen}^+_{t-4}$	0.445** (2.73)
$\Delta InOpen_{t-10}$	0.185** (2.17)	$\Delta\text{InOpen}^+_{t-6}$	– 0.408*** (– 2.88)	$\Delta InCO_{2t-7}$	0.558*** (2.89)	$\Delta\text{InOpen}^+_{t-5}$	– 0.497*** (– 3.42)
$\Delta InOpen_{t-11}$	0.621*** (3.89)	$\Delta\text{InOpen}^+_{t-7}$	– 0.408** (– 2.25)	$\Delta InCO_{2t-8}$	0.439** (2.39)	$\Delta\text{InOpen}^+_{t-6}$	– 0.843*** (– 5.31)
$\Delta InOpen_{t-12}$	0.121*** (4.82)	$\Delta InOpen^-$	– 0.301** (2.47)	$\Delta InCO_{2t-11}$	– 0.263* (2.01)	$\Delta\text{InOpen}^+_{t-7}$	– 0.957*** (– 6.44)
Const	– 0.890*** (– 4.34)	$\Delta\text{InOpen}^-_{t-3}$	0.329* (1.99)	$\Delta InCO_{2t-12}$	0.131** (2.48)	$\Delta\text{InOpen}^+_{t-11}$	0.545*** (3.30)
L_{InOpen}	– 0.349*** (0.000)	$\Delta\text{InOpen}^-_{t-5}$	0.425** (2.27)	$\Delta InOpen$	0.216*** (4.92)	$\Delta InOpen^-$	– 0.307** (– 2.70)
R^2	0.795	$\Delta\text{InOpen}^-_{t-7}$	0.424* (1.99)	$\Delta InOpen_{t-3}$	– 0.198* (– 2.06)	$\Delta\text{InOpen}^-_{t-1}$	– 0.384** (– 2.46)
$Adj.R^2$	0.746	$\Delta\text{InOpen}^-_{t-10}$	0.410** (2.15)	$\Delta InOpen_{t-5}$	– 0.320*** (– 3.19)	$\Delta\text{InOpen}^-_{t-2}$	– 0.377** (– 2.44)
X^2_{SC}	7.192 (0.952)	$\Delta\text{InOpen}^-_{t-11}$	0.289*** (3.17)	$\Delta InOpen_{t-7}$	– 0.223*** (– 2.45)	$\Delta\text{InOpen}^-_{t-3}$	– 0.959*** (– 6.36)
X^2_{FF}	1.73 (0.184)	$\Delta\text{InOpen}^-_{t-12}$	0.635*** (2.89)	$\Delta InOpen_{t-8}$	– 0.065** (– 2.51)	$\Delta\text{InOpen}^-_{t-4}$	– 0.615*** (– 3.77)
X^2_{NOR}	168.823 (0.000)	Const	– 0.912*** (– 3.50)	$\Delta InOpen_{t-12}$	0.063* (1.99)	$\Delta\text{InOpen}^-_{t-6}$	0.402*** (3.10)
t_{BDM}	– 6.169 (0.000)	L_{InOpen^+}	0.187* (0.043)	Const	– 3.081*** (– 4.27)	$\Delta\text{InOpen}^-_{t-12}$	0.916*** (4.64)
F_{PSS}	7.610 (0.002)	L_{InOpen^-}	0.393** (0.027)	L_{InOpen^+}	– 0.246*** (0.000)	Const	3.979* (1.99)
		R^2	0.841	L_{InOpen^-}	0.112*** (0.000)	L_{InOpen}	0.319** (0.036)
		$Adj.R^2$	0.692	R^2	0.803	R^2	0.983
		X^2_{SC}	0.126 (0.722)	$Adj.R^2$	0.718	$Adj.R^2$	0.866
		X^2_{FF}	2.43 (0.973)	X^2_{SC}	0.362 (0.547)	X^2_{SC}	3.482 (0.281)

Table 8 (continued)

Dependent variable = $InCO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff	Var	Coeff	Var	Coeff
(1)	(2)	(3)	(4).	(5).	(6).	(7).	(8).
		X^2_{NOR}	98.315 (0.000)	X^2_{FF}	1.03 (0.399)	X^2_{FF}	1.01 (0.532)
		t_{BDM}	– 6.261 (0.000)	X^2_{NOR}	151.031 (0.000)	X^2_{NOR}	125.903 (0.000)
		F_{PSS}	8.615 (0.000)	t_{BDM}	– 5. 648 (0.014)	t_{BDM}	– 5.815 (0.000)
		W_{LR}	0.310 (0.000)	F_{PSS}	7.410 (0.061)	F_{PSS}	7.581 (0.007)
		W_{SR}	0.137 (0.294)	W_{LR}	0.183 (0.029)	W_{SR}	0.105 (0.460)

Similar to those in Table 3

4.1.8 Mauritius

The results for the asymmetric effect of trade openness on CO_2 emissions in Mauritius are demonstrated in Table 10. The cointegration test results of the restricted model $t_{BDM} and F_{PSS}$ are equal to – 4.961 and 6.364, respectively. This evidence shows that the null hypothesis is rejected even at the 5% significance level, indicating a clear cointegrating relationship between the two variables. Similarly, when an asymmetric behaviour is examined, evidence of this long-run relationship is also detected.

The Wald tests for short- and long-run symmetry show that the asymmetric behaviour is not present in the particular pair-wise relationship in neither of the cases under review. Therefore, CO_2 emissions in Mauritius seem to respond similarly to trade openness increases and decreases. Given this evidence, the symmetric ARDL specification is thus investigated henceforth. The long-run coefficient L_{InOpen} is positive (0.691) and highly statistically significant, suggesting that a 1% increase (decrease) in trade openness brings about deterioration (improvement) in the environmental quality by 0.691% in the long run. In relevance to the diagnostic tests of the symmetric specification, the model is well fitted since it passes all the diagnostic tests. The tests suggest that the residuals follow normal distribution and the model suffers from neither some form of general misspecification nor serial correlation. Our findings are in line with those of Pata et al. [72], who found that, between 1995 and 2018, trade openness improved environmental quality for countries in the ASEAN. Similar conclusions were reached by Mahmood [61], who noted that trade in Latin America had a net beneficial environmental impact between 1970 and 2019. Additionally, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.9 Mozambique

The estimation results of the four specifications for the relationship between trade openness and CO_2 emissions in Mozambique are reported in Table 11.

The cointegration tests $t_{BDM} and F_{PSS}$ in the symmetric ARDL model are – 4.814 and 5.948 respectively. Since the $t_{BDM} and F_{PSS}$ cointegration tests are higher than the bounds critical values at both 5% and 10% significance levels, the null is rejected. This rejection suggests that there is ample evidence of long-run relationship between trade openness

Table 9 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Malawi

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.527*** (– 3.07)	InCO_{2t-1}	– 0.458*** (– 7.22)	InCO_{2t-1}	– 0.155*** (– 6.15)	InCO_{2t-1}	– 0.756*** (– 4.50)
$InOpen_{t-1}$	0.480*** (4.42)	InOpen^{+}_{t-1}	0.291*** (3.37)	InOpen^{+}_{t-1}	0.173*** (3.98)	InOpen_{t-1}	0.193* (1.96)
$\Delta InCO_{2t-1}$	– 0.543** (– 2.68)	InOpen^{-}_{t-1}	0.657*** (5.77)	InOpen^{-}_{t-1}	0.205*** (5.96)	$\Delta InCO_{2t-1}$	0.619** (2.63)
$\Delta InCO_{2t-2}$	– 0.402** (– 2.20)	$\Delta InCO_{2t-1}$	1.263*** (4.60)	$\Delta InCO_{2t-3}$	0.353** (2.49)	$\Delta InCO_{2t-3}$	0.992*** (4.66)
$\Delta InCO_{2t-5}$	0.515* (2.03)	$\Delta InCO_{2t-2}$	1.157*** (4.83)	$\Delta InCO_{2t-4}$	0.614*** (2.89)	$\Delta InCO_{2t-4}$	0.871*** (3.69)
$\Delta InCO_{2t-7}$	– 0.985*** (– 3.05)	$\Delta InOpen^{+}$	– 0.697*** (– 5.28)	$\Delta InCO_{2t-5}$	1.057*** (3.59)	$\Delta InCO_{2t-5}$	0.549* (2.02)
$\Delta InCO_{2t-8}$	– 0.709* (– 1.97)	$\Delta\text{InOpen}^{+}_{t-1}$	– 0.307** (– 2.39)	$\Delta InCO_{2t-11}$	– 0.112* (– 1.98)	$\Delta InOpen^{+}$	– 0.917*** (– 4.64)
$\Delta InCO_{2t-9}$	– 0.178** (– 2.31)	$\Delta\text{InOpen}^{+}_{t-3}$	– 0.879*** (– 6.04)	$\Delta InOpen$	– 0.231* (– 2.04)	$\Delta\text{InOpen}^{+}_{t-1}$	– 0.264* (– 1.99)
$\Delta InCO_{2t-10}$	– 0.201** (– 2.49)	$\Delta\text{InOpen}^{+}_{t-6}$	0.363** (2.74)	$\Delta InOpen_{t-1}$	– 0.605*** (– 5.08)	$\Delta\text{InOpen}^{+}_{t-2}$	– 0.424* (– 1.96)
$\Delta InCO_{2t-11}$	– 0.226** (– 2.86)	$\Delta\text{InOpen}^{+}_{t-10}$	0.547*** (3.20)	$\Delta InOpen_{t-2}$	– 0.336** (– 2.50)	$\Delta\text{InOpen}^{+}_{t-3}$	– 0.691** (– 2.63)
$\Delta InOpen$	– 0.162*** (– 2.78)	$\Delta\text{InOpen}^{+}_{t-11}$	0.332** (2.34)	$\Delta InOpen_{t-3}$	– 0.182* (– 1.99)	$\Delta\text{InOpen}^{+}_{t-4}$	1.020*** (3.06)
$\Delta InOpen_{t-1}$	– 0.707*** (– 5.35)	$\Delta InOpen^{-}$	0.399*** (3.01)	$\Delta InOpen_{t-5}$	0.456*** (4.15)	$\Delta\text{InOpen}^{+}_{t-6}$	0.760** (2.67)
$\Delta InOpen_{t-2}$	– 0.306** (– 2.50)	$\Delta\text{InOpen}^{-}_{t-1}$	– 1.994*** (– 10.46)	$\Delta InOpen_{t-6}$	0.567*** (3.65)	$\Delta\text{InOpen}^{+}_{t-7}$	0.667** (2.97)
$\Delta InOpen_{t-5}$	0.540*** (4.25)	$\Delta\text{InOpen}^{-}_{t-2}$	– 0.950*** (– 5.34)	$\Delta InOpen_{t-7}$	1.036*** (6.14)	$\Delta InOpen^{-}$	0.939*** (4.75)
$\Delta InOpen_{t-6}$	0.546*** (3.51)	$\Delta\text{InOpen}^{-}_{t-3}$	– 0.675*** (– 3.59)	$\Delta InOpen_{t-8}$	0.659*** (3.22)	$\Delta\text{InOpen}^{-}_{t-1}$	– 1.311*** (– 6.76)
$\Delta InOpen_{t-7}$	0.814*** (5.71)	$\Delta\text{InOpen}^{-}_{t-4}$	– 0.985*** (– 4.26)	$\Delta InOpen_{t-9}$	0.658*** (4.15)	$\Delta\text{InOpen}^{-}_{t-3}$	0.600* (2.20)
$\Delta InOpen_{t-8}$	0.421** (2.72)	$\Delta\text{InOpen}^{-}_{t-5}$	– 1.503*** (– 6.10)	$\Delta InOpen_{t-10}$	0.654*** (3.95)	$\Delta\text{InOpen}^{-}_{t-6}$	– 0.562** (– 2.37)
$\Delta InOpen_{t-10}$	0.319** (2.62)	$\Delta\text{InOpen}^{-}_{t-6}$	– 1.414*** (– 7.41)	$\Delta InOpen_{t-11}$	0.263* (1.99)	$\Delta\text{InOpen}^{-}_{t-7}$	1.213*** (5.76)
Const	9.884*** (4.25)	Const	9.477*** (7.17)	$\Delta InOpen_{t-12}$	0.167* (1.96)	$\Delta\text{InOpen}^{-}_{t-11}$	0.812*** (4.04)
L_{InOpen}	0.910*** (0.000)	$L_{InOpen^{+}}$	0.635** (0.043)	Const	4.908*** (6.13)	$\Delta\text{InOpen}^{-}_{t-12}$	1.367*** (4.64)
R^2	0.817	$L_{InOpen^{-}}$	1.434** (0.012)	$L_{InOpen^{+}}$	1.116*** (0.004)	Const	6.350** (2.72)
$Adj.R^2$	0.769	R^2	0.965	$L_{InOpen^{-}}$	1.322*** (0.000)	L_{InOpen}	0.255** (0.046)
X^2_{SC}	0.272 (0.602)	$Adj.R^2$	0.912	R^2	0.863	R^2	0.985
X^2_{FF}	5.05 (0.184)	X^2_{SC}	0.532 (0.465)	$Adj.R^2$	0.704	$Adj.R^2$	0.917
X^2_{NOR}	1.510 (0.274)	X^2_{FF}	4.82 (0.118)	X^2_{SC}	2.807 (0.939)	X^2_{SC}	3.215 (0.183)

Table 9 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
t_{BDM}	− 3.681 (0.000)	X^2_{NOR}	132.075 (0.000)	X^2_{FF}	0.18 (0.673)	X^2_{FF}	3.31 (0.139)
F_{PSS}	5.920 (0.000)	t_{BDM}	− 1.714 (0.008)	X^2_{NOR}	135.283 (0.000)	X^2_{NOR}	158.519 (0.000)
		F_{PSS}	2.329 (0.015)	t_{BDM}	− 2.731 (0.000)	t_{BDM}	− 2.612 (0.001)
		W_{LR}	0.172 (0.159)	F_{PSS}	3.018 (0.051)	F_{PSS}	3.158 (0.005)
		W_{SR}	0.382 (0.201)	W_{LR}	0.518 (0.316)	W_{SR}	0.164 (0.181)

Similar to those in Table 3

and CO_2 emissions in Mozambique. The last-mentioned applies to all versions of the NARDL model and, consequently, there is evidence of cointegrating relationship between these two variables under review.

Evidence from the Wald tests shows that there is a strong asymmetric behaviour in the long-run responses of CO_2 emissions to trade openness variations. Nevertheless, in the short-run, CO_2 emissions in Mozambique seem to respond similarly to trade openness increases and decreases. To this end, the appropriate specification for hypothesis testing is the NARDL model with long-run asymmetry. Given the fact that there is ample evidence of long-run relationship between the two variables under review, the long-run coefficients L_{InOpen^+} and L_{InOpen^-} being highly statistically significant at 1% are both positive 1.659 and 0.259 respectively. The results therefore suggest that a 1% increase in trade openness leads to a rise in CO_2 emissions by 1.659%, whilst a corresponding drop gives rise to a 0.259% decrease in the long-run, *ceteris paribus*. Moreover, the specific NARDL model passes all the tests. The tests suggest that the residuals follow normal distribution and the model suffers from neither some form of general misspecification nor serial correlation. Our findings concur with those of Suhrab et al. [93], who discovered that trade openness deteriorates Pakistan's environmental quality. In a similar vein, Omri and Saadaoui [71] found that trade openness significantly aggravated environmental degradation in France between 1980 and 2020. Similar to this, Ibrahim [43] found that trade openness greatly accelerated environmental degradation. Furthermore, Chhabra et al. [22] discovered that environmental degradation is worse in low middle-income nations than higher middle-income countries when trade openness is raised. Furthermore, Wenlong et al. [109] found that, between 1995 and 2018, the degradation of environmental quality in 10 Asian economies was considerably influenced by trade openness. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [66] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.10 Namibia

In the case of Namibia (Table 12), there is a statistically robust long-run relationship between trade openness and CO_2 emissions, where the null hypothesis of no long-run relationship is rejected across all four specifications (symmetric, SR and LR asymmetry, LR asymmetry and SR asymmetry) at the 5% significance level. This evidence implies that the two variables share a historical cointegrating relationship.

The next step involves conducting a test to determine the potential short- or long-run asymmetries using the Wald test. The null of symmetry is rejected by both tests suggesting a different response of CO_2 emissions to trade openness deviations, not only in the short-, but also in the long-run. Following this evidence, both short- and long-term asymmetries are properly accommodated by the suitable NARDL specification for hypothesis testing. The long-run coefficients L_{InOpen^+} and L_{InOpen^-} are both statistically significant at 1% and affect CO_2 emissions in a positive manner. A 1% increase in

Table 10 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Mauritius

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	− 0.149** (− 2.16)	InCO_{2t-1}	− 0.687** (− 2.29)	InCO_{2t-1}	− 0.418** (− 2.56)	InCO_{2t-1}	− 0.188*** (− 3.97)
$InOpen_{t-1}$	0.103** (2.56)	InOpen^{+}_{t-1}	1.220** (2.28)	InOpen^{+}_{t-1}	0.055** (2.53)	InOpen_{t-1}	0.057*** (6.13)
$\Delta InCO_{2t-1}$	− 0.631** (− 2.70)	InOpen^{-}_{t-1}	0.596* (2.04)	InOpen^{-}_{t-1}	0.222* (1.97)	$\Delta InCO_{2t-1}$	0.772* (2.05)
$\Delta InCO_{2t-2}$	− 0.184* (− 2.01)	$\Delta InCO_{2t-1}$	2.327* (2.04)	$\Delta InCO_{2t-1}$	− 0.818* (− 2.08)	$\Delta InCO_{2t-3}$	2.877** (2.36)
$\Delta InCO_{2t-5}$	− 0.328** (− 2.41)	$\Delta InCO_{2t-3}$	2.321** (2.23)	$\Delta InCO_{2t-2}$	− 0.977** (− 2.34)	$\Delta InCO_{2t-3}$	0.915*** (8.09)
$\Delta InCO_{2t-7}$	− 0.198** (− 2.61)	$\Delta InCO_{2t-4}$	1.664* (1.99)	$\Delta InCO_{2t-4}$	− 0.879** (− 2.22)	$\Delta InCO_{2t-12}$	0.423*** (6.37)
$\Delta InCO_{2t-8}$	− 0.142*** (− 4.01)	$\Delta InCO_{2t-5}$	1.774* (1.98)	$\Delta InCO_{2t-5}$	− 0.897** (− 2.76)	$\Delta InOpen^{+}$	1.649*** (7.27)
$\Delta InCO_{2t-9}$	− 0.521** (− 2.46)	$\Delta InOpen^{+}$	0.784** (2.89)	$\Delta InCO_{2t-6}$	− 0.668** (− 2.28)	$\Delta\text{InOpen}^{+}_{t-1}$	− 0.359*** (− 9.91)
$\Delta InCO_{2t-10}$	− 0.041** (− 2.47)	$\Delta\text{InOpen}^{+}_{t-1}$	− 1.232** (− 2.54)	$\Delta InCO_{2t-7}$	− 0.559* (− 1.99)	$\Delta\text{InOpen}^{+}_{t-2}$	− 1.378* (− 2.18)
$\Delta InCO_{2t-11}$	− 0.103* (− 1.96)	$\Delta\text{InOpen}^{+}_{t-3}$	− 1.025** (− 2.37)	$\Delta InCO_{2t-8}$	− 0.482* (− 1.99)	$\Delta\text{InOpen}^{+}_{t-3}$	− 0.682** (− 2.55)
$\Delta InOpen$	0.095*** (3.89)	$\Delta\text{InOpen}^{+}_{t-9}$	− 0.893* (− 1.97)	$\Delta InCO_{2t-9}$	− 0.511** (− 2.23)	$\Delta\text{InOpen}^{+}_{t-10}$	− 0.343*** (6.44)
$\Delta InOpen_{t-1}$	− 0.132* (− 2.02)	$\Delta InOpen^{-}$	0.731*** (3.62)	$\Delta InCO_{2t-12}$	− 0.347* (− 2.05)	$\Delta\text{InOpen}^{+}_{t-11}$	− 0.714** (− 2.30)
$\Delta InOpen_{t-2}$	− 0.831** (− 2.49)	$\Delta\text{InOpen}^{-}_{t-1}$	0.783* (1.99)	$\Delta InOpen$	0.260** (2.28)	$\Delta\text{InOpen}^{+}_{t-12}$	− 0.253* (− 1.97)
$\Delta InOpen_{t-5}$	0.418** (2.69)	$\Delta\text{InOpen}^{-}_{t-2}$	− 0.521*** (− 4.83)	$\Delta InOpen_{t-3}$	0.053* (1.96)	$\Delta InOpen^{-}$	− 0.859** (− 2.63)
$\Delta InOpen_{t-6}$	0.174*** (3.37)	$\Delta\text{InOpen}^{-}_{t-4}$	− 0.676** (− 2.57)	$\Delta InOpen_{t-4}$	0.076* (1.99)	$\Delta\text{InOpen}^{-}_{t-1}$	− 0.618*** (− 5.23)
$\Delta InOpen_{t-7}$	0.931*** (3.92)	$\Delta\text{InOpen}^{-}_{t-7}$	0.860* (2.02)	$\Delta InOpen_{t-6}$	0.183*** (3.82)	$\Delta\text{InOpen}^{-}_{t-3}$	− 0.437** (− 2.53)
$\Delta InOpen_{t-8}$	− 0.145* (− 1.97)	$\Delta\text{InOpen}^{-}_{t-11}$	1.339* (1.96)	$\Delta InOpen_{t-7}$	0.185* (2.01)	$\Delta\text{InOpen}^{-}_{t-4}$	− 0.485*** (− 3.04)
$\Delta InOpen_{t-10}$	0.792** (2.64)	$\Delta\text{InOpen}^{-}_{t-12}$	0.672*** (4.52)	$\Delta InOpen_{t-11}$	0.614** (2.02)	$\Delta\text{InOpen}^{-}_{t-5}$	− 0.594*** (− 6.57)
Const	0.515** (2.73)	Const	0.567* (2.13)	$\Delta InOpen_{t-12}$	0.803*** (3.84)	$\Delta\text{InOpen}^{-}_{t-11}$	− 0.184* (− 1.98)
L_{InOpen}	0.691* (0.069)	$L_{InOpen^{+}}$	1.775* (0.081)	Const	0.702** (2.80)	$\Delta\text{InOpen}^{-}_{t-12}$	− 0.647*** (6.37)
R^2	0.791	$L_{InOpen^{-}}$	0.867** (0.026)	$L_{InOpen^{+}}$	0.131** (0.016)	Const	3.409*** (6.15)
$Adj.R^2$	0.706	R^2	0.727	$L_{InOpen^{-}}$	0.531** (0.041)	L_{InOpen}	0.303*** (0.000)
X^2_{SC}	0.450 (0.502)	$Adj.R^2$	0.691	R^2	0.741	R^2	0.931
X^2_{FF}	6.22 (0.101)	X^2_{SC}	2.621 (0.105)	$Adj.R^2$	0.693	$Adj.R^2$	0.853
X^2_{NOR}	2.362 (0.184)	X^2_{FF}	13.41 (0.110)	X^2_{SC}	0.840 (0.359)	X^2_{SC}	5.410 (0.138)

Table 10 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
t_{BDM}	− 4.961 (0.000)	X^2_{NOR}	1.751 (0.302)	X^2_{FF}	3.66 (0.673)	X^2_{FF}	2.84 (0.160)
F_{PSS}	6.364 (0.004)	t_{BDM}	− 5.810 (0.000)	X^2_{NOR}	0.583 (0.274)	X^2_{NOR}	1.103 (0.371)
		F_{PSS}	8.815 (0.000)	t_{BDM}	− 6. 030 (0.070)	t_{BDM}	− 5.713 (0.023)
		W_{LR}	0.418 (0.371)	F_{PSS}	8.713 (0.051)	F_{PSS}	8.075 (0.017)
		W_{SR}	0.143 (0.382)	W_{LR}	0.937 (0.184)	W_{SR}	0.116 (0.370)

Similar to those in Table 3

trade openness results in a rise in CO_2 emissions by 0.943%, while a corresponding drop gives rise to a 0.345% decrease. In addition, the asymmetric model passes the tests for serial correlation and general misspecification, although the residuals do not follow the normal distribution. Our findings concur with those of Suhrab et al. [93], who discovered that increased trade openness in Pakistan leads to a decline in environmental quality. In a similar line, Omri and Saadaoui [71] found that, between 1980 and 2020, commercial openness significantly aggravated environmental degradation in France. Similar to this, Ibrahim [43] found that increased trade openness greatly accelerated environmental degradation. Furthermore, Chhabra et al. [22] discovered that lower middle-income nations experience more severe environmental degradation than higher middle-income countries when trade openness is raised. Furthermore, Wenlong et al. [109] found that between 1995 and 2018, environmental quality declined dramatically in 10 Asian nations. They attribute this reduction in part to trade openness. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [66] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

4.1.11 Seychelles

Table 13 reports the results of all four models specified for the trade openness-CO_2 emissions relationship in Seychelles. The two tests for cointegration display that there is a long-run relationship between the two variables when the symmetric ARDL is examined. The null is rejected at both 10% and 5% significance levels. Similarly, when asymmetries are considered, the null hypothesis of no cointegration is rejected even at 5% significance level.

The Wald tests, when implemented, indicates that there is no evidence of asymmetric behaviour since neither short-nor long-run asymmetry can be detected, at least not a statistically significant one and, hence, the symmetric ARDL is under review. The long-run coefficient L_{InOpen} is highly statistically significant and equal to 0.280, suggesting that a 1% increase (decrease) in trade openness makes CO_2 emissions rise (fall) by 0.280% in the long-run, *ceteris paribus*. The diagnostic tests show that the ARDL specification does not have problems of any general misspecification and serial correlation, although the residuals are not normally distributed. Our findings are in line with those of Pata et al. [72], who found that, between 1995 and 2018, trade openness improved environmental quality for countries in the ASEAN. Similar conclusions were reached by Mahmood [61], who noted that trade in Latin America had a net beneficial environmental impact between 1970 and 2019. Additionally, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries. In their study of the effects of economic growth (EG), capital formation (CF), and consumption of renewable and non-renewable energy (NRE) on CO_2 emissions and ecological footprint (EF) of 17 OECD countries spanning data from 1970 to 2016, Mujtaba et al. [65] found that economic growth and gross capital formation dampen environmental quality in the OECD region over the sampled period.

Table 11 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Mozambique

Dependent variable = $InCO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$InCO_{2t-1}$	− 0.214** (− 2.47)	$InCO_{2t-1}$	− 0.379*** (− 3.66)	$InCO_{2t-1}$	− 0.582** (− 2.32)	$InCO_{2t-1}$	− 0.190*** (− 4.89)
$InOpen_{t-1}$	0.211** (2.73)	$InOpen^{+}_{t-1}$	0.145** (2.77)	$InOpen^{+}_{t-1}$	0.966** (2.59)	$InOpen_{t-1}$	0.094*** (5.99)
$\Delta InCO_{2t-1}$	− 0.197** (− 2.82)	$InOpen^{-}_{t-1}$	0.756** (2.84)	$InOpen^{-}_{t-1}$	0.151** (2.66)	$\Delta InCO_{2t-1}$	0.103*** (8.08)
$\Delta InCO_{2t-2}$	− 0.138*** (− 3.73)	$\Delta InCO_{2t-1}$	0.923*** (3.10)	$\Delta InCO_{2t-1}$	0.634*** (4.95)	$\Delta InCO_{2t-2}$	0.156** (2.58)
$\Delta InCO_{2t-5}$	0.176** (2.62)	$\Delta InCO_{2t-2}$	0.960*** (3.47)	$\Delta InCO_{2t-2}$	− 0.853** (− 2.54)	$\Delta InCO_{2t-3}$	0.276*** (5.93)
$\Delta InCO_{2t-7}$	0.195** (2.73)	$\Delta InCO_{2t-3}$	0.795*** (3.97)	$\Delta InCO_{2t-4}$	0.384** (2.51)	$\Delta InCO_{2t-11}$	− 0.061*** (− 5.16)
$\Delta InCO_{2t-8}$	− 0.622*** (− 3.93)	$\Delta InCO_{2t-4}$	0.701*** (3.71)	$\Delta InCO_{2t-5}$	0.495** (2.76)	$\Delta InOpen^{+}$	0.727*** (7.63)
$\Delta InCO_{2t-9}$	− 0.464** (− 2.81)	$\Delta InOpen^{+}$	0.300*** (4.75)	$\Delta InCO_{2t-6}$	0.630** (2.59)	$\Delta InOpen^{+}_{t-1}$	0.207*** (3.06)
$\Delta InCO_{2t-10}$	− 0.152** (− 2.83)	$\Delta InOpen^{+}_{t-1}$	0.591** (2.26)	$\Delta InCO_{2t-7}$	0.479** (2.64)	$\Delta InOpen^{+}_{t-2}$	0.883** (2.89)
$\Delta InCO_{2t-11}$	− 0.133** (− 2.75)	$\Delta InOpen^{+}_{t-2}$	0.496*** (3.06)	$\Delta InCO_{2t-8}$	− 0.286* (− 2.05)	$\Delta InOpen^{+}_{t-3}$	0.960* (2.01)
$\Delta InOpen$	0.211** (2.67)	$\Delta InOpen^{+}_{t-5}$	0.559* (2.01)	$\Delta InCO_{2t-9}$	− 0.357** (− 2.58)	$\Delta InOpen^{+}_{t-4}$	0.635** (2.48)
$\Delta InOpen_{t-1}$	0.439** (2.64)	$\Delta InOpen^{-}$	1.951** (2.59)	$\Delta InCO_{2t-12}$	− 0.199** (− 2.75)	$\Delta InOpen^{+}_{t-5}$	0.498*** (6.71)
$\Delta InOpen_{t-2}$	0.401** (2.69)	$\Delta InOpen^{-}_{t-1}$	− 0.843*** (− 4.48)	$\Delta InOpen$	0.416*** (3.94)	$\Delta InOpen^{+}_{t-12}$	0.693** (2.89)
$\Delta InOpen_{t-5}$	0.123** (2.53)	$\Delta InOpen^{-}_{t-2}$	− 0.049* (− 2.05)	$\Delta InOpen_{t-1}$	− 0.290** (− 2.64)	$\Delta InOpen^{-}$	0.461*** (6.05)
$\Delta InOpen_{t-6}$	− 0.237* (− 1.96)	$\Delta InOpen^{-}_{t-5}$	− 0.559*** (− 3.19)	$\Delta InOpen_{t-4}$	− 0.599** (− 2.64)	$\Delta InOpen^{-}_{t-1}$	− 0.501*** (− 4.90)
$\Delta InOpen_{t-7}$	0.257** (2.76)	$\Delta InOpen^{-}_{t-6}$	− 0.623** (− 2.56)	$\Delta InOpen_{t-6}$	− 0.859* (− 1.96)	$\Delta InOpen^{-}_{t-2}$	− 0.659* (− 2.13)
$\Delta InOpen_{t-8}$	0.168** (2.84)	$\Delta InOpen^{-}_{t-7}$	− 0.153** (− 2.58)	$\Delta InOpen_{t-7}$	− 0.456* (− 2.11)	$\Delta InOpen^{-}_{t-3}$	− 0.258*** (− 3.87)
$\Delta InOpen_{t-10}$	0.323** (2.80)	$\Delta InOpen^{-}_{t-9}$	− 0.517*** (− 3.95)	$\Delta InOpen_{t-11}$	0.583*** (3.63)	$\Delta InOpen^{-}_{t-4}$	− 0.135*** (− 3.55)

Table 11 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Const	0.434** (2.73)	Const	− 1.365** (− 2.54)	$\Delta lnOpen_{t-12}$	0.123** (2.68)	$\Delta \ln Open^{-}_{t-11}$	− 0.508** (− 2.63)
L_{lnOpen}	0.985** (0.031)	$L_{lnOpen^{+}}$	0.382** (0.010)	Const	0.649** (2.07)	$\Delta \ln Open^{-}_{t-12}$	− 0.163*** (4.84)
R^2	0.892	$L_{lnOpen^{-}}$	1.994** (0.019)	$L_{lnOpen^{+}}$	1.659*** (0.000)	Const	2.738** (2.69)
$Adj.R^2$	0.810	R^2	0.858	$L_{lnOpen^{-}}$	0.259*** (0.000)	L_{lnOpen}	0.494* (0.064)
X^2_{SC}	0.294 (0.587)	$Adj.R^2$	0.703	R^2	0.815	R^2	0.916
X^2_{FF}	1.34 (0.300)	X^2_{SC}	5.815 (0.319)	$Adj.R^2$	0.786	$Adj.R^2$	0.895
X^2_{NOR}	0.173 (0.571)	X^2_{FF}	7.62 (0.317)	X^2_{SC}	0.303 (0.581)	X^2_{SC}	7.815 (0.261)
t_{BDM}	− 4.814 (0.006)	X^2_{NOR}	1.640 (0.151)	X^2_{FF}	2.09 (0.141)	X^2_{FF}	6.71 (0.160)
F_{PSS}	5.948 (0.051)	t_{BDM}	− 5.715 (0.000)	X^2_{NOR}	0.183 (0.203)	X^2_{NOR}	0.614 (0.193)
		F_{PSS}	7.520 (0.000)	t_{BDM}	− 4. 960 (0.000)	t_{BDM}	− 6.718 (0.000)
		W_{LR}	0.637 (0.001)	F_{PSS}	7.843 (0.000)	F_{PSS}	8.035 (0.000)
		W_{SR}	0.628 (0.105)	W_{LR}	0.621 (0.007)	W_{SR}	0.513 (0.316)

Similar to those in Table 3

Table 12 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Namibia

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	− 0.401*** (− 4.86)	InCO_{2t-1}	− 0.336** (− 2.85)	InCO_{2t-1}	− 0.208*** (− 3.32)	InCO_{2t-1}	− 0.338* (− 1.97)
$InOpen_{t-1}$	0.136*** (6.00)	$\mathrm{InOpen}^{+}_{t-1}$	0.317*** (3.64)	$\mathrm{InOpen}^{+}_{t-1}$	0.186*** (5.46)	InOpen_{t-1}	0.141*** (3.26)
$\Delta InCO_{2t-1}$	− 0.951*** (− 5.70)	$\mathrm{InOpen}^{-}_{t-1}$	0.116*** (5.20)	$\mathrm{InOpen}^{-}_{t-1}$	0.034*** (4.40)	$\Delta InCO_{2t-1}$	− 0.572*** (− 3.59)
$\Delta InCO_{2t-2}$	− 0.776*** (− 3.64)	$\Delta InCO_{2t-1}$	− 1.132*** (− 7.66)	$\Delta InCO_{2t-1}$	− 1.214** (− 2.89)	$\Delta InCO_{2t-2}$	− 0.372*** (− 6.98)
$\Delta InCO_{2t-3}$	− 0.345* (− 1.96)	$\Delta InCO_{2t-3}$	− 0.320*** (− 5.93)	$\Delta InCO_{2t-2}$	− 1.005** (− 2.52)	$\Delta InCO_{2t-4}$	0.303** (2.92)
$\Delta InCO_{2t-6}$	− 0.812*** (− 4.63)	$\Delta InCO_{2t-4}$	0.772*** (5.19)	$\Delta InCO_{2t-3}$	− 0.460* (− 1.99)	$\Delta InCO_{2t-6}$	− 1.057*** (− 5.60)
$\Delta InCO_{2t-7}$	− 0.681*** (− 3.54)	$\Delta InCO_{2t-6}$	− 0.829*** (− 7.54)	$\Delta InCO_{2t-6}$	− 1.025** (− 2.86)	$\Delta InOpen^{+}$	0.018** (2.76)
$\Delta InCO_{2t-10}$	− 0.379* (− 1.99)	$\Delta InOpen^{+}$	− 0.281* (− 2.04)	$\Delta InCO_{2t-7}$	− 0.937** (− 2.26)	$\Delta\mathrm{InOpen}^{+}_{t-1}$	− 0.323** (− 2.97)
$\Delta InCO_{2t-11}$	− 0.427* (− 1.97)	$\Delta\mathrm{InOpen}^{+}_{t-1}$	− 0.339** (− 3.86)	$\Delta InCO_{2t-10}$	− 0.398* (− 1.97)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	− 0.327*** (− 3.12)
$\Delta InCO_{2t-12}$	− 0.651*** (− 3.07)	$\Delta\mathrm{InOpen}^{+}_{t-2}$	− 0.316*** (− 3.71)	$\Delta InCO_{2t-11}$	− 0.566* (− 1.99)	$\Delta\mathrm{InOpen}^{+}_{t-3}$	− 0.306** (− 2.69)
$\Delta InOpen$	0.064** (2.74)	$\Delta\mathrm{InOpen}^{+}_{t-3}$	− 0.302* (− 3.52)	$\Delta InCO_{2t-12}$	− 0.750** (− 2.89)	$\Delta\mathrm{InOpen}^{+}_{t-4}$	− 0.367*** (− 5.29)
$\Delta InOpen_{t-1}$	− 0.696*** (− 5.88)	$\Delta InOpen^{-}$	0.073*** (3.19)	$\Delta InOpen$	0.066** (2.69)	$\Delta\mathrm{InOpen}^{+}_{t-5}$	− 0.320** (− 2.90)
$\Delta InOpen_{t-2}$	− 0.652*** (− 5.76)	$\Delta\mathrm{InOpen}^{-}_{t-1}$	− 0.416*** (− 5.71)	$\Delta InOpen_{t-1}$	− 0.743*** (− 2.64)	$\Delta\mathrm{InOpen}^{+}_{t-6}$	− 0.367*** (− 4.71)
$\Delta InOpen_{t-3}$	− 0.693*** (− 6.64)	$\Delta\mathrm{InOpen}^{-}_{t-2}$	− 1.367*** (− 4.15)	$\Delta InOpen_{t-2}$	− 0.696*** (− 5.28)	$\Delta InOpen^{-}$	0.091*** (4.95)
$\Delta InOpen_{t-4}$	− 0.750*** (− 5.62)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	− 0.903*** (− 4.57)	$\Delta InOpen_{t-3}$	− 0.738*** (− 5.91)	$\Delta\mathrm{InOpen}^{-}_{t-1}$	− 0.479*** (− 7.68)
$\Delta InOpen_{t-5}$	− 0.707*** (− 6.11)	$\Delta\mathrm{InOpen}^{-}_{t-4}$	− 1.679** (− 2.49)	$\Delta InOpen_{t-4}$	− 0.799* (− 5.21)	$\Delta\mathrm{InOpen}^{-}_{t-2}$	− 0.354** (− 2.55)
$\Delta InOpen_{t-6}$	− 0.693*** (− 5.98)	$\Delta\mathrm{InOpen}^{-}_{t-5}$	− 1.559*** (− 3.04)	$\Delta InOpen_{t-5}$	− 0.742*** (− 5.80)	$\Delta\mathrm{InOpen}^{-}_{t-3}$	− 0.578*** (− 8.90)
$\Delta InOpen_{t-7}$	− 0.685*** (− 5.27)	$\Delta\mathrm{InOpen}^{-}_{t-6}$	− 1.691*** (− 7.08)	$\Delta InOpen_{t-6}$	− 0.714*** (− 5.86)	$\Delta\mathrm{InOpen}^{-}_{t-4}$	− 0.603*** (− 3.13)
$\Delta InOpen_{t-8}$	− 0.652*** (− 5.55)	Const	− 0.339** (− 8.92)	$\Delta InOpen_{t-7}$	− 0.710*** (− 5.18)	$\Delta\mathrm{InOpen}^{-}_{t-5}$	− 0.564** (− 3.43)
$\Delta InOpen_{t-9}$	− 0.618*** (− 5.18)	$L_{InOpen^{+}}$	0.943*** (0.000)	Const	− 0.021** (− 2.83)	$\Delta\mathrm{InOpen}^{-}_{t-10}$	− 0.376*** (4.84)
$\Delta InOpen_{t-12}$	− 0.204** (− 2.13)	$L_{InOpen^{-}}$	0.345*** (0.000)	$L_{InOpen^{+}}$	0.894** (0.046)	Const	0.676*** (3.23)
Const	1.540*** (6.25)	R^2	0.984	$L_{InOpen^{-}}$	0.163** (0.036)	L_{InOpen}	0.417** (0.026)
L_{InOpen}	0.339* (0.062)	$Adj.R^2$	0.902	R^2	0.909	R^2	0.952
R^2	0.906	X^2_{SC}	6.214 (0.643)	$Adj.R^2$	0.841	$Adj.R^2$	0.936
$Adj.R^2$	0.861	X^2_{FF}	14.12 (0.710)	X^2_{SC}	0.010 (0.920)	X^2_{SC}	6.714 (0.193)

Table 12 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X^2_{SC}	6.183 (0.984)	X^2_{NOR}	151.415 (0.000)	X^2_{FF}	1.25 (0.336)	X^2_{FF}	8.81 (0.261)
X^2_{FF}	5.916 (0.468)	t_{BDM}	– 5.614 (0.027)	X^2_{NOR}	147.416 (0.000)	X^2_{NOR}	148.416 (0.000)
X^2_{NOR}	143.817 (0.000)	F_{PSS}	7.350 (0.000)	t_{BDM}	– 5. 814 (0.034)	t_{BDM}	– 4.637 (0.041)
t_{BDM}	– 6.489 (0.052)	W_{LR}	0.357 (0.000)	F_{PSS}	6.531 (0.057)	F_{PSS}	6.195 (0.032)
F_{PSS}	8.746 (0.000)	W_{SR}	0.410 (0.006)	W_{LR}	0.824 (0.003)	W_{SR}	0.461 (0.007)

Similar to those in Table 3

4.1.12 South Africa

In the case of South Africa (Table 14), there is a statistically robust long-run relationship between trade openness and CO_2 emissions, where the null hypothesis of no long-run relationship is rejected across all four specifications (symmetric, SR and LR asymmetry, LR asymmetry and SR asymmetry) at the 5% significance level. This evidence implies that the two variables share a historical cointegrating relationship.

The next step involves conducting a test to determine the potential short- or long-run asymmetries using the Wald test. In this light, the null of symmetry is rejected by both tests suggesting a different response of CO_2 emissions to trade openness deviations, not only in the short-, but also in the long-run. Following this evidence, the right methodology for hypothesis testing is the NARDL model where both short- and long-term asymmetries are incorporated. The long-run coefficients L_{InOpen^+} and L_{InOpen^-} are statistically significant at 1% and affect CO_2 emissions in a negative and positive manner respectively. A 1% increase in trade openness results in a decrease in CO_2 emissions by 0.532%, while a corresponding drop gives rise to a 0.244% increase. Moreover, the diagnostic tests show, while the residuals are normally distributed, the precise NARDL specification does not suffer from either general misspecification or serial correlation. Our findings are in line with those made by Pata et al. [72], who found that, for the countries of the ASEAN, between 1995 and 2018, trade openness improves environmental quality. Similar conclusions were reached by Mahmood [61], who noted that from 1970 to 2019, trade in Latin America had a net beneficial environmental impact. Additionally, Ding et al. [114] showed that improved environmental quality benefits from higher economic openness among the G-7 nations.

4.1.13 Tanzania

The estimation results of the four specifications for the relationship between trade openness and CO_2 emissions in Tanzania are reported in Table 15. The cointegration tests $t_{BDM} and F_{PSS}$ in the symmetric ARDL model are – 5.915 and 6.568 respectively. Since the $t_{BDM} and F_{PSS}$ cointegration tests are greater than the bounds critical values at both 5% and 10% significance levels, we reject the null hypothesis of no cointegration. This implies that there is ample evidence of long-run relationship between trade openness and CO_2 emissions in Tanzania. When the three versions of NARDL model are examined, the evidence shows that the null hypothesis is rejected even at the 5% significance level, indicating a clear cointegrating relationship between the two variables.

Evidence from the Wald tests shows that there is a strong asymmetric behaviour in the long-run responses of CO_2 emissions to trade openness variations. Nevertheless, in the short-run, CO_2 emissions in Tanzania seem to respond similarly to trade openness increases and decreases. Therefore, the most suitable framework to analyse this is the

Table 13 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in South Africa

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
InCO_{2t-1}	– 0.409*** (– 3.90)	InCO_{2t-1}	– 0.813*** (– 6.91)	InCO_{2t-1}	– 0.673*** (– 3.92)	InCO_{2t-1}	– 0.152*** (– 3.84)
$InOpen_{t-1}$	– 0.025* (– 1.96)	InOpen^+_{t-1}	– 0.433*** (– 7.75)	InOpen^+_{t-1}	– 0.247*** (– 3.12)	InOpen_{t-1}	– 0.039*** (– 3.76)
$\Delta InCO_{2t-1}$	0.418*** (4.83)	InOpen^-_{t-1}	0.199*** (7.17)	InOpen^-_{t-1}	0.125*** (3.08)	$\Delta InCO_{2t-1}$	– 1.995*** (– 3.75)
$\Delta InCO_{2t-2}$	0.272* (1.99)	$\Delta InCO_{2t-1}$	0.205* (1.99)	$\Delta InCO_{2t-1}$	0.518** (2.74)	$\Delta InCO_{2t-2}$	– 1.410*** (– 3.75)
$\Delta InCO_{2t-3}$	0.450** (2.67)	$\Delta InCO_{2t-2}$	– 0.221* (– 1.97)	$\Delta InCO_{2t-2}$	0.247* (1.99)	$\Delta InCO_{2t-3}$	– 1.502** (– 3.32)
$\Delta InCO_{2t-4}$	0.404** (2.41)	$\Delta InCO_{2t-7}$	0.270** (2.15)	$\Delta InCO_{2t-3}$	0.451** (2.22)	$\Delta InCO_{2t-12}$	– 1.223* (– 2.21)
$\Delta InCO_{2t-6}$	0.282* (2.01)	$\Delta InOpen^+$	0.126** (2.38)	$\Delta InCO_{2t-4}$	0.497** (2.33)	$\Delta InOpen^+$	– 0.711** (– 3.01)
$\Delta InCO_{2t-11}$	0.523*** (2.95)	$\Delta\text{InOpen}^+_{t-1}$	0.641*** (7.92)	$\Delta InCO_{2t-5}$	0.434* (2.01)	$\Delta\text{InOpen}^+_{t-1}$	– 0.712** (– 2.77)
$\Delta InCO_{2t-12}$	0.650*** (3.40)	$\Delta\text{InOpen}^+_{t-2}$	0.221*** (3.08)	$\Delta InCO_{2t-6}$	0.463** (2.14)	$\Delta\text{InOpen}^+_{t-4}$	– 0.858*** (– 4.50)
$\Delta InOpen$	0.083*** (5.82)	$\Delta\text{InOpen}^+_{t-3}$	0.354*** (4.49)	$\Delta InCO_{2t-10}$	0.304* (1.98)	$\Delta\text{InOpen}^+_{t-5}$	– 0.805*** (– 3.82)
$\Delta InOpen_{t-1}$	0.521** (2.57)	$\Delta InOpen^-$	– 0.223*** (– 5.43)	$\Delta InCO_{2t-12}$	0.289** (2.60)	$\Delta\text{InOpen}^+_{t-6}$	– 0.840*** (– 3.56)
$\Delta InOpen_{t-2}$	0.091** (2.73)	$\Delta\text{InOpen}^-_{t-1}$	0.085* (2.06)	$\Delta InOpen$	– 0.056** (– 2.89)	$\Delta\text{InOpen}^+_{t-7}$	– 1.743*** (– 4.33)
$\Delta InOpen_{t-7}$	0.071* (1.97)	$\Delta\text{InOpen}^-_{t-3}$	0.138*** (3.22)	$\Delta InOpen_{t-1}$	0.120** (2.18)	$\Delta\text{InOpen}^+_{t-8}$	– 1.606*** (– 3.28)
$\Delta InOpen_{t-12}$	– 0.097** (– 2.20)	$\Delta\text{InOpen}^-_{t-4}$	– 0.126*** (– 3.35)	$\Delta InOpen_{t-2}$	0.131** (2.68)	$\Delta InOpen^-$	– 0.345** (– 2.87)
Const	– 0.430* (– 1.97)	$\Delta\text{InOpen}^-_{t-12}$	0.279*** (4.92)	$\Delta InOpen_{t-3}$	0.105*** (2.00)	$\Delta\text{InOpen}^-_{t-2}$	– 0.385*** (– 3.37)
L_{InOpen}	– 0.061*** (0.009)	Const	– 0.207** (– 5.11)	$\Delta InOpen_{t-7}$	0.099* (2.07)	$\Delta\text{InOpen}^-_{t-3}$	– 0.690** (– 3.00)
R^2	0.841	L_{InOpen^+}	– 0.532* (0.083)	$\Delta InOpen_{t-10}$	0.095* (1.98)	$\Delta\text{InOpen}^-_{t-4}$	– 0.313** (– 2.33)
$Adj.R^2$	0.717	L_{InOpen^-}	0.244*** (0.000)	$\Delta InOpen_{t-11}$	0.042* (2.01)	$\Delta\text{InOpen}^-_{t-6}$	– 0.528** (– 2.81)
X^2_{SC}	0.129 (0.719)	R^2	0.882	$\Delta InOpen_{t-12}$	0.532** (2.85)	$\Delta\text{InOpen}^-_{t-7}$	0.255** (3.09)
X^2_{FF}	2.83 (0.581)	$Adj.R^2$	0.717	Const	– 0.014* (– 2.04)	$\Delta\text{InOpen}^-_{t-10}$	0.590*** (3.49)
X^2_{NOR}	1.031 (0.410)	X^2_{SC}	6.767 (0.643)	L_{InOpen^+}	– 0.367* (0.071)	Const	– 6.917*** (– 3.72)
t_{BDM}	– 5.842 (0.004)	X^2_{FF}	1.51 (0.254)	L_{InOpen^-}	0.185** (0.021)	L_{InOpen}	– 0.256** (0.005)
F_{PSS}	8.935 (0.001)	X^2_{NOR}	0.715 (0.162)	R^2	0.842	R^2	0.942
		t_{BDM}	– 6.053 (0.061)	$Adj.R^2$	0.761	$Adj.R^2$	0.883
		F_{PSS}	8.731 (0.058)	X^2_{SC}	1.280 (0.257)	X^2_{SC}	12.84 (0.305)

Table 13 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		W_{LR}	0.142 (0.001)	X^2_{FF}	0.86 (0.481)	X^2_{FF}	34.49 (0.124)
		W_{SR}	0.414 (0.006)	X^2_{NOR}	1.035 (0.418)	X^2_{NOR}	1.573 (0.103)
				t_{BDM}	– 5. 541 (0.008)	t_{BDM}	– 5.047 (0.082)
				F_{PSS}	7.491 (0.007)	F_{PSS}	8.791 (0.068)
				W_{LR}	0.618 (0.013)	W_{SR}	0.534 (0.000)

Similar to those in Table 3

NARDL model with long-run asymmetry. Given the fact that there is ample evidence of long-run relationship between the two variables under review, the long-run coefficients L_{InOpen^+} and L_{InOpen^-} are statistically significant at 1% and affect CO_2 emissions in a negative manner. The results therefore suggest that a 1% increase in trade openness leads to a fall in CO_2 emissions by 0.381%, whereas a 1% corresponding decrease in trade openness results in decrease in CO_2 emissions by 0.927% in the long-run, *ceteris paribus*. Additionally, the specific NARDL model passes all the tests for serial correlation and general misspecification, although the residuals do not follow the normal distribution. Our findings support those of Pata et al. [72], who found that trade openness improves environmental quality for the ASEAN countries between 1995 and 2018. Mahmood [61] reached a similar conclusion and noted that trade in Latin America had a net beneficial environmental impact between 1970 and 2019. More free trade also improves the environmental quality of G-7 economies, as shown by Ding et al. [114].

4.1.14 Zambia

Table 16 illustrates the estimated coefficients of all four specifications for the trade-CO_2 emissions relationship in Zambia. The two tests for cointegration display that there is a long-run relationship between the two variables when the symmetric ARDL is examined. The null is rejected at 10% significance level, although there is no explicit conclusion to be drawn at 5%. By contrast, when asymmetries are considered, the null hypothesis of no cointegration fails to be rejected.

The implementation of the Wald tests documents that there is no evidence of asymmetric behaviour since neither short- nor long-run asymmetry can be detected, at least not a statistically significant one and, hence, the symmetric ARDL is under review. The long-run coefficient L_{InOpen} is highly statistically significant and equal to – 0.559, suggesting that a 1% increase (decrease) in trade openness makes CO_2 emissions fall (rise) by 0.559% in the long-run. The diagnostic tests show that the residuals do not follow the normal distribution, while there is no evidence of serial correlation or any general misspecification**.** Our findings are in line with those of Pata et al. [72], who found that, for the ASEAN countries between 1995 and 2018, trade openness improves environmental quality. Mahmood [61] also reached the similar conclusions, indicating that from 1970 to 2019, trade in Latin America had a net beneficial environmental impact. Furthermore, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries.

4.1.15 Zimbabwe

In the case of Zimbabwe (Table 17), the cointegration tests t_{BDM} and F_{PSS} in the restricted symmetric model are – 4.813 and 6.754, respectively. This evidence leads to rejection of the null hypothesis of no long-run relationship at both 5%

Table 14 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Seychelles

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(4)	(5)	(7)	(8)	(10)	(11)
$\ln CO_{2t-1}$	– 0.189*** (– 3.54)	$\ln CO_{2t-1}$	– 0.378*** (– 4.71)	$\ln CO_{2t-1}$	– 0.248** (– 2.02)	$\ln CO_{2t-1}$	– 0.670*** (– 5.30)
$InOpen_{t-1}$	0.053*** (4.84)	$\ln Open^{+}_{t-1}$	0.170*** (9.48)	$\ln Open^{+}_{t-1}$	0.189** (2.45)	$\ln Open_{t-1}$	0.105*** (4.21)
$\Delta InCO_{2t-1}$	– 0.238* (– 1.98)	$\ln Open^{-}_{t-1}$	0.350*** (8.34)	$\ln Open^{-}_{t-1}$	0.118** (2.18)	$\Delta InCO_{2t-1}$	– 0.391** (– 2.51)
$\Delta InCO_{2t-2}$	0.249* (1.99)	$\Delta InCO_{2t-1}$	– 1.772*** (– 9.47)	$\Delta InCO_{2t-1}$	– 0.861** (– 2.32)	$\Delta InCO_{2t-2}$	– 0.412** (– 2.59)
$\Delta InCO_{2t-5}$	– 0.127* (– 2.01)	$\Delta InCO_{2t-2}$	– 1.496*** (– 7.80)	$\Delta InCO_{2t-3}$	– 0.574** (– 2.93)	$\Delta InCO_{2t-11}$	– 0.265*** (– 3.63)
$\Delta InCO_{2t-8}$	– 0.392*** (– 4.69)	$\Delta InCO_{2t-3}$	– 0.928* (– 2.00)	$\Delta InCO_{2t-4}$	– 0.480** (– 2.41)	$\Delta InCO_{2t-12}$	0.273*** (5.65)
$\Delta InCO_{2t-11}$	– 0.200*** (– 3.20)	$\Delta InCO_{2t-7}$	– 0.525*** (– 9.06)	$\Delta InCO_{2t-5}$	– 0.500** (– 2.71)	$\Delta InOpen^{+}$	0.125** (4.37)
$\Delta InOpen$	– 0.032* (– 1.99)	$\Delta InOpen^{+}$	– 0.032* (– 1.98)	$\Delta InCO_{2t-7}$	– 0.446** (– 2.77)	$\Delta \ln Open^{+}_{t-1}$	0.274*** (8.07)
$\Delta InOpen_{t-3}$	0.033* (1.98)	$\Delta \ln Open^{+}_{t-1}$	0.650*** (5.46)	$\Delta InCO_{2t-8}$	– 0.680*** (– 4.31)	$\Delta \ln Open^{+}_{t-3}$	0.101*** (3.75)
$\Delta InOpen_{t-9}$	0.049** (2.48)	$\Delta \ln Open^{+}_{t-2}$	0.353*** (7.19)	$\Delta InOpen$	– 0.053*** (– 4.85)	$\Delta \ln Open^{+}_{t-4}$	0.129** (4.32)
$\Delta InOpen_{t-10}$	0.024* (1.98)	$\Delta \ln Open^{+}_{t-12}$	0.106*** (8.39)	$\Delta InOpen_{t-1}$	0.185** (2.99)	$\Delta \ln Open^{+}_{t-5}$	0.123*** (4.06)
$\Delta InOpen_{t-11}$	0.025* (2.01)	$\Delta InOpen^{-}$	– 0.232*** (– 8.36)	$\Delta InOpen_{t-2}$	0.161** (2.28)	$\Delta \ln Open^{+}_{t-10}$	0.109*** (5.40)
Const	0.717*** (3.88)	$\Delta \ln Open^{-}_{t-1}$	0.223*** (7.19)	$\Delta InOpen_{t-3}$	0.172** (2.68)	$\Delta \ln Open^{+}_{t-11}$	0.056** (2.59)
L_{InOpen}	0.280* (0.017)	$\Delta \ln Open^{-}_{t-2}$	0.102*** (3.58)	$\Delta InOpen_{t-4}$	0.111* (1.98)	$\Delta InOpen^{-}$	– 0.249*** (– 6.55)
R^2	0.785	$\Delta \ln Open^{-}_{t-3}$	0.364*** (6.55)	$\Delta InOpen_{t-5}$	0.108** (2.22)	$\Delta \ln Open^{-}_{t-1}$	– 0.037* (– 2.02)
$Adj.R^2$	0.707	$\Delta \ln Open^{-}_{t-4}$	– 0.099** (– 2.30)	$\Delta InOpen_{t-6}$	0.146** (2.30)	$\Delta \ln Open^{-}_{t-2}$	– 0.085** (– 2.84)
X^2_{SC}	9.494 (0.482)	$\Delta \ln Open^{-}_{t-6}$	– 0.416*** (– 4.32)	$\Delta InOpen_{t-7}$	0.095** (2.30)	$\Delta \ln Open^{-}_{t-3}$	0.461*** (4.68)
X^2_{FF}	1.09 (0.373)	$\Delta \ln Open^{-}_{t-11}$	– 0.220** (– 2.68)	$\Delta InOpen_{t-10}$	0.080** (2.22)	$\Delta \ln Open^{-}_{t-4}$	0.265*** (3.20)
X^2_{NOR}	150.025 (0.000)	Const	– 2.661*** (– 4.02)	$\Delta InOpen_{t-11}$	0.073** (2.35)	$\Delta \ln Open^{-}_{t-5}$	0.336*** (4.54)
t_{BDM}	– 4.731 (0.017)	$L_{InOpen^{+}}$	0.449* (0.067)	Const	0.260* (2.01)	$\Delta \ln Open^{-}_{t-6}$	0.154** (2.88)
F_{PSS}	6.520 (0.064)	$L_{InOpen^{-}}$	0.925* (0.096)	$L_{InOpen^{+}}$	0.762*** (0.000)	Const	0.102* (1.99)
		R^2	0.942	$L_{InOpen^{-}}$	0.475*** (0.000)	L_{InOpen}	0.156*** (0.000)
		$Adj.R^2$	0.891	R^2	0.882	R^2	0.941
		X^2_{SC}	3.147 (0.701)	$Adj.R^2$	0.783	$Adj.R^2$	0.901
		X^2_{FF}	7.13 (0.933)	X^2_{SC}	9.347 (0.142)	X^2_{SC}	4.816 (0.282)

Table 14 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(4)	(5)	(7)	(8)	(10)	(11)
		X^2_{NOR}	125.814 (0.000)	X^2_{FF}	7.23 (0.871)	X^2_{FF}	9.77 (0.230)
		t_{BDM}	– 5.152 (0.008)	X^2_{NOR}	157.915 (0.000)	X^2_{NOR}	151.831 (0.000)
		F_{PSS}	7.882 (0.004)	t_{BDM}	– 5.152 (0.006)	t_{BDM}	– 4.815 (0.004)
		W_{LR}	0.317 (0.360)	F_{PSS}	6.934 (0.032)	F_{PSS}	7.110 (0.015)
		W_{SR}	0.019 (0.171)	W_{LR}	0.637 (0.208)	W_{SR}	0.048 (0.471)

Similar to those in Table 3

and 10% significance levels. On the other hand, in all three versions of the NARDL model, no evidence of cointegrating relationship between trade openness and CO_2 emissions is detected when short-and long-run asymmetries are examined.

The Wald tests for short- and long-run symmetry show that the asymmetric behaviour is not present in the particular pair-wise relationship in neither of the cases under review. Therefore, CO_2 emissions in Zimbabwe seem to respond similarly to trade openness increases and decreases. Given this evidence, the symmetric ARDL specification is thus investigated henceforth. The long-run coefficient L_{InOpen} is negative (– 0.381) and highly statistically significant, suggesting that a 1% increase (decrease) in trade openness brings about improvement (deterioration) in the environmental quality by 0.381% in the long-run. The bottom part of Table 17 reports the results of diagnostic tests which show that the symmetric ARDL model is well fitted since it passes all the diagnostic tests. The tests suggest that the model does not suffer from the general misspecification and serial correlation. Also, the Jarque–Bera statistic shows evidence that the residuals are normally distributed. Our findings are in line with those of Pata et al. [72], who found that, between 1995 and 2018, trade openness improved environmental quality for countries in ASEAN. Similar conclusions were reached by Mahmood [61], who noted that commerce in Latin America had a net beneficial environmental impact between 1970 and 2019. Additionally, Ding et al. [114] showed that improved trade openness benefits the environmental quality of G-7 countries.

4.2 Robustness check

We implemented a testing technique that can account for two structural breaks in the model because the traditional unit root tests were unable to detect the presence of structural breaks in the variables. Following Mujtaba and Jena [64], Jena et al. [48] and Mujtaba et al. [65], the study employs the Clemente-Montanes-Reyes (1998) detrended unit root test, and the findings are shown in Table 18 (see Appendix). The variables exhibit two structural breaks in distinct years, as seen in Table 18. Consequently, for robustness check, two dummy variables (D1993 and D2008) are created for the break years of 1993 and 2008 respectively to account for the possibility of structural breaks in the variables. While the 1993 break year was a result of structural economic changes in the region, the 2008 break year was a result of the 2008 global financial crisis, which had a substantial effect on the region. The results, which are shown in Table 19 and are available in the Appendix, imply that structural breaks are not statistically significant. This finding thus suggests that the structural breaks in our model have no impact.

4.3 Implication for sustainability

The Sustainable Development Goals (SDGs) of the United Nations provide a suitable framework for addressing developmental challenges in order to realize a sustainable future free from social, economic, and environmental inequalities and thereby guarantee a greener and healthier planet for future generations. The region's impressive performance across

Table 15 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Tanzania

Dependent variable = $InCO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$InCO_{2t-1}$	− 0.528*** (− 5.18)	$InCO_{2t-1}$	− 0.483*** (− 5.42)	$InCO_{2t-1}$	− 0.288*** (− 5.13)	$InCO_{2t-1}$	− 0.591** (− 2.67)
$InOpen_{t-1}$	− 0.139*** (− 6.14)	$InOpen^{+}_{t-1}$	− 0.241** (− 2.72)	$InOpen^{+}_{t-1}$	− 0.110*** (− 4.32)	$InOpen_{t-1}$	− 0.250*** (− 3.16)
$\Delta InCO_{2t-1}$	− 1.185*** (− 6.45)	$InOpen^{-}_{t-1}$	− 0.183*** (− 5.99)	$InOpen^{-}_{t-1}$	− 0.267** (− 2.73)	$\Delta InCO_{2t-1}$	− 0.754** (− 2.57)
$\Delta InCO_{2t-2}$	0.422** (2.74)	$\Delta InCO_{2t-1}$	0.163* (1.98)	$\Delta InCO_{2t-1}$	0.909*** (8.31)	$\Delta InCO_{2t-2}$	− 0.980*** (− 3.93)
$\Delta InCO_{2t-3}$	− 0.123* (− 1.98)	$\Delta InCO_{2t-3}$	− 0.527*** (− 4.90)	$\Delta InCO_{2t-2}$	0.430*** (4.58)	$\Delta InCO_{2t-4}$	− 0.610** (− 2.31)
$\Delta InCO_{2t-4}$	− 0.339* (− 1.97)	$\Delta InCO_{2t-4}$	− 0.560*** (− 6.58)	$\Delta InCO_{2t-3}$	0.261*** (8.60)	$\Delta InCO_{2t-7}$	− 0.584* (− 2.05)
$\Delta InCO_{2t-5}$	0.396*** (7.08)	$\Delta InCO_{2t-5}$	0.790*** (6.85)	$\Delta InCO_{2t-4}$	0.097*** (3.85)	$\Delta InOpen^{+}$	− 0.261** (2.64)
$\Delta InCO_{2t-6}$	0.450*** (4.32)	$\Delta InOpen^{+}$	− 0.123* (− 2.01)	$\Delta InCO_{2t-5}$	0.583** (4.62)	$\Delta InOpen^{+}_{t-1}$	− 0.351* (− 1.97)
$\Delta InCO_{2t-8}$	− 0.342*** (− 3.78)	$\Delta InOpen^{+}_{t-1}$	0.325*** (5.77)	$\Delta InCO_{2t-6}$	0.819*** (6.51)	$\Delta InOpen^{+}_{t-2}$	0.250** (2.20)
$\Delta InCO_{2t-9}$	− 0.130* (− 1.96)	$\Delta InOpen^{+}_{t-3}$	− 0.311*** (− 5.16)	$\Delta InOpen$	− 0.813*** (− 3.59)	$\Delta InOpen^{+}_{t-5}$	0.851*** (3.18)
$\Delta InCO_{2t-10}$	0.647*** (8.80)	$\Delta InOpen^{+}_{t-4}$	0.627*** (6.71)	$\Delta InOpen_{t-1}$	− 0.835** (− 5.07)	$\Delta InOpen^{+}_{t-7}$	0.981* (1.97)
$\Delta InCO_{2t-11}$	− 0.281*** (− 4.21)	$\Delta InOpen^{+}_{t-5}$	0.587*** (6.37)	$\Delta InOpen_{t-2}$	− 0.613*** (− 5.39)	$\Delta InOpen^{+}_{t-8}$	− 0.277** (− 2.60)
$\Delta InCO_{2t-12}$	− 0.610*** (− 8.33)	$\Delta InOpen^{+}_{t-6}$	− 0.542*** (− 7.18)	$\Delta InOpen_{t-3}$	− 0.349*** (− 3.53)	$\Delta InOpen^{+}_{t-12}$	− 0.223* (− 2.03)
$\Delta InOpen$	− 0.830*** (− 4.94)	$\Delta InOpen^{-}$	− 0.863*** (− 4.48)	$\Delta InOpen_{t-5}$	− 0.185** (− 2.93)	$\Delta InOpen^{-}$	− 0.814*** (− 4.64)
$\Delta InOpen_{t-2}$	0.186** (2.34)	$\Delta InOpen^{-}_{t-1}$	− 0.168*** (− 3.16)	$\Delta InOpen_{t-6}$	0.353*** (6.40)	$\Delta InOpen^{-}_{t-1}$	− 0.421** (− 2.63)
$\Delta InOpen_{t-7}$	− 0.323*** (− 5.35)	$\Delta InOpen^{-}_{t-4}$	− 0.454*** (− 5.25)	$\Delta InOpen_{t-7}$	− 0.348*** (− 5.54)	$\Delta InOpen^{-}_{t-4}$	0.486* (2.04)
$\Delta InOpen_{t-8}$	− 0.503*** (− 4.30)	$\Delta InOpen^{-}_{t-6}$	0.486*** (5.76)	$\Delta InOpen_{t-9}$	− 0.265*** (− 3.26)	$\Delta InOpen^{-}_{t-5}$	0.380** (2.73)
$\Delta InOpen_{t-10}$	0.499*** (5.36)	$\Delta InOpen^{-}_{t-7}$	0.420** (2.81)	$\Delta InOpen_{t-10}$	0.762*** (5.51)	$\Delta InOpen^{-}_{t-7}$	0.635* (1.98)
$\Delta InOpen_{t-11}$	0.170*** (5.33)	Const	− 0.165*** (− 6.35)	$\Delta InOpen_{t-12}$	0.604*** (3.24)	$\Delta InOpen^{-}_{t-9}$	0.318*** (3.83)
$\Delta InOpen_{t-12}$	0.391*** (8.33)	$L_{InOpen^{+}}$	− 0.498** (0.015)	Const	− 0.412*** (− 7.20)	$\Delta InOpen^{-}_{t-12}$	0.631*** (3.62)
Const	− 1.297*** (− 5.82)	$L_{InOpen^{-}}$	− 0.378*** (0.000)	$L_{InOpen^{+}}$	− 0.381** (0.035)	Const	− 1.488*** (− 3.34)
L_{InOpen}	− 0.263*** (0.000)	R^2	0.905	$L_{InOpen^{-}}$	− 0.927* (0.084)	L_{InOpen}	− 0.423** (0.036)
R^2	0.975	$Adj.R^2$	0.873	R^2	0.913	R^2	0.915
$Adj.R^2$	0.947	X^2_{SC}	4.326 (0.375)	$Adj.R^2$	0.841	$Adj.R^2$	0.862
X^2_{SC}	10.701 (0.115)	X^2_{FF}	12.17 (0.184)	X^2_{SC}	8.914 (0.105)	X^2_{SC}	8.416 (0.173)

Table 15 (continued)

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X^2_{FF}	17.27 (0.158)	X^2_{NOR}	114.026 (0.000)	X^2_{FF}	18.05 (0.142)	X^2_{FF}	5.21 (0.117)
X^2_{NOR}	126.742 (0.000)	t_{BDM}	− 4.628 (0.037)	X^2_{NOR}	114.518 (0.000)	X^2_{NOR}	135.607 (0.000)
t_{BDM}	− 5.915 (0.005)	F_{PSS}	5.928 (0.004)	t_{BDM}	− 5.614 (0.041)	t_{BDM}	− 5.831 (0.000)
F_{PSS}	6.568 (0.001)	W_{LR}	0.941 (0.041)	F_{PSS}	7.411 (0.071)	F_{PSS}	6.330 (0.057)
		W_{SR}	0.635 (0.182)	W_{LR}	0.816 (0.095)	W_{SR}	0.821 (0.316)

Similar to those in Table 3

all five goals—Clean Water and Sanitation, Affordable and Clean Energy, Industry, Innovation and Infrastructure, Life on Land and Peace, Justice and Social Institutions, and Climate Action—is substantially responsible for the target's forward movement. The results of this study strongly relate to the thirteenth goal of the United Nations (Climate Action); in order to realize this goal, the results implore the policymakers and stakeholders of the sampled region to promote the growth of international trade in order to lessen trade protectionism, particularly in terms of technology and the effective use of renewable and non-renewable energy sources. Additionally, it is important to promote the interchange of environmental products and services since they can aid in the fight against climate change. When attempting to better its environment and encourage environmental sustainability, the SADC region should successfully boost its trade policies. Due to the various beneficial effects of international trade on the region's economy, the long-term harmful effects of trade openness on the environment do not warrant serious measures to close the borders. Instead, appropriate action must be taken to guarantee that global trade makes a constructive contribution to reducing the rising level of emissions and achieving regional environmental sustainability. To ensure efficiency in the industrial processes, regional officials should step up their use of eco-friendly technology to transition away from non-renewable energy sources and toward renewable or less carbon-intensive ones. Meanwhile, switching from non-renewable energy sources to alternatives like solar power will significantly lower CO_2 emissions in the area. Additionally, in order to address the growing transboundary environmental deterioration and other associated spillover effects, global cooperation to reduce carbon emissions is very essential. To guarantee strong ties with the rest of the world to exchange technologies that might reduce pollution, the SADC region should work toward this goal. To enable a transition to cleaner sectors and a low-carbon economy, governments should, more crucially, include thorough environmental chapters in their trade agreement rules. This will encourage the creation of green goods and services. Additionally, trade policy might be complemented by additional measures to encourage long-term GHG emission reductions and continuously assist the development of innovative technologies that enhance regional environmental conditions and protect the environment globally.

5 Conclusions and policy implications

5.1 Conclusion

Using the Squalli and Wilson (SQ) measure of trade openness, this study examined the asymmetric impact of trade openness on CO_2 emissions among Southern African Development Community (SADC) member nations within a NARDL framework. The SQ proxy takes into consideration a country's trade share of its GDP as well as the proportion of its trade volume to the average global trade volume during a certain time period. The research tested for short- and long-run

Table 16 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Zambia

Dependent variable = $\ln CO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\ln CO_{2t-1}$	− 0.363** (− 2.82)	$\ln CO_{2t-1}$	− 0.908*** (− 6.97)	$\ln CO_{2t-1}$	− 0.586*** (− 7.25)	$\ln CO_{2t-1}$	− 0.512*** (− 4.01)
$InOpen_{t-1}$	− 0.203*** (− 3.22)	$\ln Open^{+}_{t-1}$	− 0.530*** (− 5.85)	$\ln Open^{+}_{t-1}$	0.073*** (3.85)	$\ln Open_{t-1}$	− 0.498*** (− 7.50)
$\Delta InCO_{2t-1}$	− 0.810* (− 1.98)	$\ln Open^{-}_{t-1}$	0.798*** (5.10)	$\ln Open^{-}_{t-1}$	0.116*** (7.26)	$\Delta InCO_{2t-1}$	− 0.152** (− 2.76)
$\Delta InCO_{2t-2}$	− 1.276*** (− 3.08)	$\Delta InCO_{2t-1}$	0.536*** (5.61)	$\Delta InCO_{2t-1}$	0.977*** (6.74)	$\Delta InCO_{2t-2}$	− 1.117*** (− 3.75)
$\Delta InCO_{2t-3}$	− 0.985* (− 1.99)	$\Delta InCO_{2t-2}$	0.733*** (5.71)	$\Delta InCO_{2t-2}$	0.706*** (3.78)	$\Delta InCO_{2t-4}$	− 0.841*** (− 4.14)
$\Delta InCO_{2t-4}$	− 1.309** (− 2.64)	$\Delta InCO_{2t-3}$	0.750*** (5.91)	$\Delta InCO_{2t-3}$	0.576*** (3.35)	$\Delta InCO_{2t-5}$	− 1.886*** (− 6.52)
$\Delta InCO_{2t-5}$	− 1.573*** (− 2.72)	$\Delta InCO_{2t-4}$	0.969*** (5.90)	$\Delta InCO_{2t-5}$	− 0.438*** (− 2.31)	$\Delta InOpen^{+}$	0.098** (2.57)
$\Delta InCO_{2t-6}$	− 0.069*** (− 2.99)	$\Delta InOpen^{+}$	0.374*** (4.73)	$\Delta InCO_{2t-6}$	− 1.058*** (− 5.05)	$\Delta \ln Open^{+}_{t-1}$	0.502*** (6.65)
$\Delta InCO_{2t-7}$	− 0.804*** (− 3.26)	$\Delta \ln Open^{+}_{t-1}$	0.510*** (5.52)	$\Delta InCO_{2t-7}$	− 1.945*** (− 5.93)	$\Delta \ln Open^{+}_{t-2}$	0.384*** (6.78)
$\Delta InCO_{2t-9}$	0.154** (2.30)	$\Delta \ln Open^{+}_{t-2}$	0.381*** (4.76)	$\Delta InOpen$	− 0.152*** (− 3.62)	$\Delta \ln Open^{+}_{t-3}$	0.305*** (5.86)
$\Delta InOpen$	0.215*** (3.72)	$\Delta \ln Open^{+}_{t-3}$	0.374*** (5.66)	$\Delta InOpen_{t-1}$	− 0.073** (− 2.37)	$\Delta \ln Open^{+}_{t-4}$	0.494** (2.60)
$\Delta InOpen_{t-1}$	0.188*** (3.03)	$\Delta \ln Open^{+}_{t-4}$	0.521*** (7.51)	$\Delta InOpen_{t-2}$	− 0.067** (− 2.11)	$\Delta \ln Open^{+}_{t-5}$	0.464*** (9.87)
$\Delta InOpen_{t-2}$	0.179** (2.66)	$\Delta \ln Open^{+}_{t-5}$	0.607*** (7.54)	$\Delta InOpen_{t-3}$	− 0.045* (− 1.98)	$\Delta \ln Open^{+}_{t-6}$	0.311*** (6.85)
$\Delta InOpen_{t-3}$	0.154** (2.42)	$\Delta InOpen^{-}$	− 0.299* (− 2.03)	$\Delta InOpen_{t-4}$	0.123*** (3.91)	$\Delta InOpen^{-}$	− 0.145*** (− 8.80)
$\Delta InOpen_{t-4}$	0.246*** (3.60)	$\Delta \ln Open^{-}_{t-1}$	− 0.585*** (− 3.88)	$\Delta InOpen_{t-5}$	0.165*** (4.21)	$\Delta \ln Open^{-}_{t-1}$	0.661** (2.57)
$\Delta InOpen_{t-5}$	0.230*** (3.08)	$\Delta \ln Open^{-}_{t-2}$	− 0.830*** (− 4.39)	$\Delta InOpen_{t-6}$	0.126*** (3.05)	$\Delta \ln Open^{-}_{t-2}$	− 0.351* (− 2.07)
$\Delta InOpen_{t-6}$	0.152** (2.14)	$\Delta \ln Open^{-}_{t-8}$	− 0.737*** (− 3.92)	$\Delta InOpen_{t-7}$	0.169*** (4.40)	$\Delta \ln Open^{-}_{t-3}$	0.494** (2.86)
$\Delta InOpen_{t-7}$	0.221*** (3.37)	$\Delta \ln Open^{-}_{t-12}$	− 0.826*** (4.29)	$\Delta InOpen_{t-10}$	0.095** (2.71)	$\Delta \ln Open^{-}_{t-5}$	− 0.549*** (− 5.07)
$\Delta InOpen_{t-9}$	0.129** (2.37)	Const	0.408*** (6.69)	$\Delta InOpen_{t-12}$	0.033* (1.98)	$\Delta \ln Open^{-}_{t-6}$	− 0.282*** (− 3.58)
$\Delta InOpen_{t-10}$	0.209*** (3.37)	$L_{InOpen^{+}}$	− 0.583*** (0.004)	Const	0.256*** (7.23)	$\Delta \ln Open^{-}_{t-11}$	0.274* (2.04)
$\Delta InOpen_{t-11}$	0.145** (2.11)	$L_{InOpen^{-}}$	− 0.878* (0.063)	$L_{InOpen^{+}}$	0.124*** (0.000)	Const	− 4.799*** (− 8.22)
Const	− 6.484*** (− 4.08)	R^2	0.893	$L_{InOpen^{-}}$	0.197** (0.026)	L_{InOpen}	− 0.972** (0.010)
L_{InOpen}	− 0.559*** (0.000)	$Adj.R^2$	0.764	R^2	0.842	R^2	0.864
R^2	0.851	X^2_{SC}	7.012 (0.912)	$Adj.R^2$	0.796	$Adj.R^2$	0.807
$Adj.R^2$	0.783	X^2_{FF}	3.32 (0.865)	X^2_{SC}	1.491 (0.220)	X^2_{SC}	5.031 (0.241)

Table 16 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X^2_{SC}	4.748 (0.293)	X^2_{NOR}	98.501 (0.000)	X^2_{FF}	10.62 (0.271)	X^2_{FF}	8.58 (0.258)
X^2_{FF}	10.18 (0.217)	t_{BDM}	− 1.815 (0.035)	X^2_{NOR}	143.842 (0.000)	X^2_{NOR}	116.014 (0.000)
X^2_{NOR}	103.514 (0.000)	F_{PSS}	2.150 (0.069)	t_{BDM}	− 1.284 (0.076)	t_{BDM}	− 2.014 (0.083)
t_{BDM}	− 3.112 (0.005)	W_{LR}	0.830 (0.392)	F_{PSS}	3.087 (0.055)	F_{PSS}	3.013 (0.021)
F_{PSS}	5.137 (0.009)	W_{SR}	0.607 (0.218)	W_{LR}	0.143 (0.115)	W_{SR}	0.046 (0.103)

Similar to those in Table 3

asymmetries and evaluated the impact of negative and positive trade openness on CO_2 emissions during the period of 1960–2020 using this approach to gauge trade openness.

The results were different for each country. More specifically, there was evidence of short- and long-run symmetry in Angola, the Democratic Republic of Congo (DRC), Lesotho, Malawi, Mauritius, Seychelles, Zambia and Zimbabwe. This result is in accordance with those reached by Twerefou et al. [94] and Ling et al. [59]. In contrast, long-run asymmetry was present in Botswana, Madagascar, Mozambique and Tanzania, while strong evidence of short- and long-run asymmetry was found in Comoros, Namibia and South Africa, supporting the results reached by Mahmood et al. [62] for the case of Tunisia, Munir and Riaz [67] for Australia, China and USA and Rahmana et al. [78] for Pakistan.

5.2 Policy implications

These findings have important policy ramifications since they suggest that SADC members with both short- and long-term asymmetric connections should work to enhance and change their trade policies in order to cut back on carbon emissions. In this approach, environmental policies that can encourage the manufacturing and trading of eco-friendly items should be strengthened and modified by policymakers [95, 97, 98]. A "tax or subsidy" policy, for instance, might be used to penalize the trade in ecologically hazardous goods while encouraging the trade in eco-friendly ones. Along with offsetting the damaging effects of trade on the environment, adoption of this strategy can speed up the transfer of green technology to SADC member nations.

Furthermore, the area should develop stronger policies to guarantee that trade openness helps to improve their environmental quality because there are many advantages to being open to international goods markets [68, 69]. Therefore, governments should step up their efforts to encourage foreign investors to use modern, environmentally friendly, and cleaner technology. In the end, this will make it possible for the area to switch from non-renewable energy sources to renewable or less carbon-intensive ones, all while maintaining industrial process excellence. The environmental condition of the area will also be significantly improved by substituting solar electricity for non-renewable energy sources.

Additionally, it is crucial to work together globally to reduce the expanding transboundary environmental deterioration as well as numerous spillover consequences. Considering this, regional leaders and governments should work effectively to share technologies that can lower carbon emissions with the rest of the globe [69, 98]. In order to make the transition to cleaner sectors and a low-carbon economy simpler, the SADC member nations should incorporate comprehensive environmental chapters into their trade agreement regulations. In the end, this will support the creation of eco-friendly products and services. Last but not least, other developmental policies could be implemented in conjunction with trade policy reforms in order to promote long-term value for reducing GHG emissions and continuously support the development of new technologies that enhance regional environmental quality and safeguard the environment globally.

Table 17 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in Zimbabwe

Dependent variable = $InCO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$InCO_{2t-1}$	− 0.299** (− 2.38)	$InCO_{2t-1}$	− 0.733*** (− 4.25)	$InCO_{2t-1}$	− 0.262** (− 2.58)	$InCO_{2t-1}$	− 0.359** (− 2.43)
$InOpen_{t-1}$	− 0.114** (− 2.43)	$InOpen^{+}_{t-1}$	− 0.195*** (− 3.88)	$InOpen^{+}_{t-1}$	− 0.088** (− 2.71)	$InOpen_{t-1}$	− 0.292*** (− 3.62)
$\Delta InCO_{2t-1}$	− 0.532** (− 2.46)	$InOpen^{-}_{t-1}$	− 0.474*** (− 4.07)	$InOpen^{-}_{t-1}$	− 0.070*** (− 6.77)	$\Delta InCO_{2t-1}$	− 1.362** (− 3.27)
$\Delta InCO_{2t-2}$	− 0.457** (− 2.48)	$\Delta InCO_{2t-1}$	0.709** (2.64)	$\Delta InCO_{2t-1}$	− 0.595** (− 2.48)	$\Delta InCO_{2t-2}$	− 1.402** (− 2.70)
$\Delta InCO_{2t-4}$	− 0.707*** (− 4.26)	$\Delta InCO_{2t-3}$	− 0.523* (− 2.05)	$\Delta InCO_{2t-2}$	− 0.495** (− 2.54)	$\Delta InCO_{2t-3}$	− 1.568*** (− 2.60)
$\Delta InCO_{2t-5}$	− 0.350* (− 2.01)	$\Delta InCO_{2t-4}$	− 1.387*** (− 5.49)	$\Delta InCO_{2t-4}$	− 0.688*** (− 3.79)	$\Delta InCO_{2t-4}$	− 2.177*** (− 3.45)
$\Delta InCO_{2t-6}$	− 0.527** (− 2.48)	$\Delta InCO_{2t-5}$	− 0.905*** (− 3.46)	$\Delta InCO_{2t-5}$	− 0.413* (− 1.98)	$\Delta InOpen^{+}$	0.162*** (4.98)
$\Delta InCO_{2t-7}$	− 0.378* (− 2.03)	$\Delta InOpen^{+}$	− 0.153** (− 2.81)	$\Delta InCO_{2t-6}$	− 0.533** (− 2.37)	$\Delta InOpen^{+}_{t-1}$	0.793** (2.78)
$\Delta InCO_{2t-9}$	− 0.258** (− 2.43)	$\Delta InOpen^{+}_{t-1}$	− 0.717*** (− 3.64)	$\Delta InCO_{2t-7}$	− 0.376* (− 1.99)	$\Delta InOpen^{+}_{t-4}$	− 0.208*** (− 2.13)
$\Delta InCO_{2t-10}$	− 0.347*** (− 3.27)	$\Delta InOpen^{+}_{t-2}$	− 0.542*** (− 3.43)	$\Delta InOpen$	0.080** (2.47)	$\Delta InOpen^{+}_{t-6}$	− 0.490** (− 2.93)
$\Delta InOpen$	− 0.104*** (− 4.81)	$\Delta InOpen^{+}_{t-3}$	− 0.503*** (− 3.89)	$\Delta InOpen_{t-2}$	− 0.090* (− 2.01)	$\Delta InOpen^{+}_{t-7}$	− 0.321** (− 2.59)
$\Delta InOpen_{t-1}$	− 0.162* (− 2.06)	$\Delta InOpen^{+}_{t-4}$	− 0.226** (− 2.93)	$\Delta InOpen_{t-3}$	− 0.141* (− 1.98)	$\Delta InOpen^{+}_{t-8}$	− 0.508* (− 1.98)
$\Delta InOpen_{t-2}$	− 0.098** (2.66)	$\Delta InOpen^{+}_{t-5}$	− 0.203** (− 2.37)	$\Delta InOpen_{t-4}$	− 0.218*** (− 3.12)	$\Delta InOpen^{+}_{t-9}$	− 0.210*** (− 1.98)
$\Delta InOpen_{t-3}$	− 0.140* (− 1.98)	$\Delta InOpen^{-}$	− 0.163** (− 2.85)	$\Delta InOpen_{t-5}$	− 0.180** (− 2.31)	$\Delta InOpen^{-}$	− 0.202* (− 2.01)
$\Delta InOpen_{t-4}$	− 0.215*** (− 3.21)	$\Delta InOpen^{-}_{t-1}$	− 1.040*** (− 3.38)	$\Delta InOpen_{t-6}$	− 0.254*** (− 3.65)	$\Delta InOpen^{-}_{t-1}$	0.717*** (3.79)
$\Delta InOpen_{t-5}$	− 0.158*** (− 2.25)	$\Delta InOpen^{-}_{t-2}$	− 0.867*** (− 3.86)	$\Delta InOpen_{t-7}$	− 0.181** (− 2.51)	$\Delta InOpen^{-}_{t-2}$	0.849*** (3.84)
$\Delta InOpen_{t-6}$	− 0.244*** (− 3.71)	$\Delta InOpen^{-}_{t-8}$	− 1.229*** (− 3.76)	$\Delta InOpen_{t-9}$	− 0.152** (− 2.46)	$\Delta InOpen^{-}_{t-3}$	0.806*** (3.22)
$\Delta InOpen_{t-7}$	− 0.161** (− 2.46)	$\Delta InOpen^{-}_{t-10}$	− 1.476*** (− 4.32)	$\Delta InOpen_{t-10}$	− 0.206** (− 2.76)	$\Delta InOpen^{-}_{t-4}$	0.928** (2.42)
$\Delta InOpen_{t-9}$	− 0.151** (− 2.63)	Const	6.712*** (4.06)	$\Delta InOpen_{t-11}$	− 0.131* (− 2.03)	$\Delta InOpen^{-}_{t-7}$	− 0.795*** (− 2.62)
$\Delta InOpen_{t-10}$	− 0.201*** (− 2.84)	$L_{InOpen^{+}}$	− 0.266** (0.038)	Const	− 0.323** (2.61)	$\Delta InOpen^{-}_{t-12}$	− 0.392* (− 1.97)
$\Delta InOpen_{t-11}$	− 0.151** (− 2.85)	$L_{InOpen^{-}}$	− 0.646** (0.019)	$L_{InOpen^{+}}$	− 0.335* (0.064)	Const	− 8.406*** (− 3.50)
Const	− 3.117*** (− 3.31)	R^2	0.915	$L_{InOpen^{-}}$	− 0.267** (0.035)	L_{InOpen}	− 0.813** (0.000)
L_{InOpen}	− 0.381*** (0.000)	$Adj.R^2$	0.852	R^2	0.746	R^2	0.925
R^2	0.884	X^2_{SC}	2.457 (0.117)	$Adj.R^2$	0.653	$Adj.R^2$	0.882
$Adj.R^2$	0.810	X^2_{FF}	6.43 (0.740)	X^2_{SC}	5.126 (0.722)	X^2_{SC}	2.235 (0.134)

Table 17 (continued)

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
X^2_{SC}	10.507 (0.943)	X^2_{NOR}	1.413 (0.120)	X^2_{FF}	3.74 (0.463)	X^2_{FF}	4.52 (0.684)
X^2_{FF}	3.16 (0.501)	t_{BDM}	− 1.010 (0.016)	X^2_{NOR}	2.790 (0.361)	X^2_{NOR}	1.314 (0.280)
X^2_{NOR}	1.091 (0.281)	F_{PSS}	2.095 (0.009)	t_{BDM}	− 2.418 (0.071)	t_{BDM}	− 1.042 (0.083)
t_{BDM}	− 4.813 (0.000)	W_{LR}	0.104 (0.308)	F_{PSS}	3.030 (0.025)	F_{PSS}	2.081 (0.015)
F_{PSS}	6.754 (0.004)	W_{SR}	0.831 (0.172)	W_{LR}	0.628 (0.210)	W_{SR}	0.735 (0.201)

Similar to those in Table 3

5.3 Limitations and potential future study directions

In the instance of the SADC area, the current analysis produced strong empirical results, although it has a number of shortcomings that might be taken into account in further research. The limited availability of the data outside of the sample period, which limits the breadth of the time series analysis used, is one of the investigation's major limitations. Future research utilizing other econometric methods or micro-disaggregated pertinent data may focus on other emerging economies. Additional growth-related elements that were not taken into account in this study, such as institutional quality and natural resources, can be examined in future research. However, CO_2 emissions were utilized in this study as an indicator of the state of the environment. Additional research is required to determine whether consumption-based carbon emissions are a reliable indicator of ecological harm, or whether other metrics of carbon footprints, such as ground-level gaseous pollutants, sulfur compounds, volatile organic compounds, hydrocarbons, and unburned hydrocarbons, are more appropriate. The current study uses CO_2 emissions as a reflection of environmental deterioration even though they are not the primary cause of ecological pollution. Future research for the SADC area should investigate this connection by taking into account additional ecological contamination factors, such as water pollution and hazardous contaminants. By combining time series data with panel estimate techniques, further research may compare country-specific results to generic panel outputs using far more complicated methodology. This can assist illuminate the existing evidence by providing a comparison analysis with the findings of this inquiry. Last but not least, the investigation's partial consideration of one area is a grave shortcoming. Therefore, for a more comprehensive view, future research should concentrate on examining the moderating influence of trade openness on environmental quality through economic growth, energy consumption, and foreign direct investment in the African panel setting and other regions of the world.

Author contributions Maxwell Chukwudi Udeagha and Marthinus Christoffel Breitenbach conceptualized the study idea, drafted the paper, collected data, analyzed data, wrote the introduction section, organized the literature review, drafted the methodology section, interpreted the results, and provided the discussions, concluded the study with policy implications and organized the reference list.

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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 that they have no competing financial and/ or non-financial interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Appendix

See Tables 18, 19.

Table 18 Clemente-Montanes-Reyes detrended unit root test

Innovative outliers				Additive outlier		
	T-statistic	TB1	TB2	T-statistic	TB1	TB2
Panel A: CO_2 individual information						
Angola	– 4.371	1978	1993	– 1.208	1977	1992
Botswana	– 5.715*	1993	2008	– 2.584	1973	1984
Comoros	– 3.270	1978	1994	– 1.693	1992	2008
DRC	– 2.792	1973	1995	– 3.841	1977	1995
Lesotho	– 3.830	1988	1999	– 1.300	1987	2002
Madagascar	– 4.387	1965	1992	– 2.792	1973	1995
Malawi	– 5.538*	1993	2008	– 3.860	1978	2008
Mauritius	– 4.883	1987	1997	– 4.113	1986	2008
Mozambique	– 7.640*	1993	2008	– 1.625	1977	1995
Namibia	– 2.543	1991	2006	– 1.514	1992	1996
Seychelles	– 3.408	1968	1983	– 3.324	1980	1998
South Africa	– 4.443	1980	1999	– 3.414	1980	1999
Tanzania	– 4.534	1986	2002	– 3.373	1985	2008
Zambia	– 2.350	1979	1997	– 3.583	1981	2008
Zimbabwe	– 4.240	1984	1993	– 4.065	1966	1996
Panel B: Trade openness individual information						
Angola	– 3.578	1998	2006	– 2.716	1997	2005
Botswana	– 3.479	1973	1986	– 3.753	1973	1985
Comoros	– 4.899	1978	2008	– 6.713	1977	2008
DRC	– 3.530	1992	2005	– 5.864*	1991	2008
Lesotho	– 9.504*	1993	2008	– 6.076*	1992	2004
Madagascar	– 5.503*	1992	2008	– 1.172	1990	1996
Malawi	– 3.837	1992	2000	– 1.451	1991	2008
Mauritius	– 5.503*	1993	2008	– 1.945	1984	2008
Mozambique	– 5.824*	1979	2008	– 2.510	1978	1991
Namibia	– 6.445*	1978	1988	– 3.077	1977	1989
Seychelles	– 5.937*	1993	1994	– 2.092	1973	1997
South Africa	– 3.899	1987	2008	– 3.188	1990	1997
Tanzania	– 6.183*	1992	2008	– 2.547	1989	2008
Zambia	– 3.407	1992	2002	– 0.216	1991	2003
Zimbabwe	– 3.792	1973	1990	– 4.025	1972	1988

Authors' calculations

(i)* denotes statistical significance at 5% level. (ii) Critical value is – 5.490 at 5% level of significance.

Table 19 Full-information estimates of both symmetric ARDL and nonlinear ARDL (NARDL) models in SADC region while controlling for structural breakS

Dependent variable = InCO_{2t}							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
D1993	– 0.015 (0.98)	D1993	– 0.021 (1.28)	D1993	– 0.014 (0.73)	D1993	– 0.062 (1.42)
D2008	– 0.058 (1.05)	D2008	– 0.075 (0.68)	D2008	– 0.093 (1.23)	D2008	– 0.064 (0.94)
InCO_{2t-1}	– 0.390** (– 2.81)	InCO_{2t-1}	– 0.908*** (– 6.97)	InCO_{2t-1}	– 0.552*** (– 7.10)	InCO_{2t-1}	– 0.546*** (– 4.63)
$InOpen_{t-1}$	– 0.285*** (– 3.01)	InOpen^{+}_{t-1}	– 0.530*** (– 5.85)	InOpen^{+}_{t-1}	0.071*** (3.03)	InOpen_{t-1}	– 0.405*** (– 7.03)
$\Delta InCO_{2t-1}$	– 0.853* (– 1.99)	InOpen^{-}_{t-1}	0.798*** (5.10)	InOpen^{-}_{t-1}	0.179*** (7.03)	$\Delta InCO_{2t-1}$	– 0.117** (– 2.83)
$\Delta InCO_{2t-2}$	– 1.276*** (– 3.08)	$\Delta InCO_{2t-1}$	0.536*** (5.61)	$\Delta InCO_{2t-1}$	0.915*** (6.63)	$\Delta InCO_{2t-2}$	– 1.195*** (– 3.93)
$\Delta InCO_{2t-3}$	– 0.985* (– 1.99)	$\Delta InCO_{2t-2}$	0.733*** (5.71)	$\Delta InCO_{2t-2}$	0.783*** (3.05)	$\Delta InCO_{2t-4}$	– 0.832*** (– 4.03)
$\Delta InCO_{2t-4}$	– 1.309** (– 2.64)	$\Delta InCO_{2t-3}$	0.750*** (5.91)	$\Delta InCO_{2t-3}$	0.504*** (3.70)	$\Delta InCO_{2t-5}$	– 1.873*** (– 6.02)
$\Delta InCO_{2t-5}$	– 1.573*** (– 2.72)	$\Delta InCO_{2t-4}$	0.969*** (5.90)	$\Delta InCO_{2t-5}$	– 0.438*** (– 2.31)	$\Delta InOpen^{+}$	0.091** (2.57)
$\Delta InCO_{2t-6}$	– 0.069*** (– 2.99)	$\Delta InOpen^{+}$	0.374*** (4.73)	$\Delta InCO_{2t-6}$	– 1.058*** (– 5.05)	$\Delta\text{InOpen}^{+}_{t-1}$	0.502*** (6.65)
$\Delta InCO_{2t-7}$	– 0.804*** (– 3.26)	$\Delta\text{InOpen}^{+}_{t-1}$	0.510*** (5.52)	$\Delta InCO_{2t-7}$	– 1.945*** (– 5.93)	$\Delta\text{InOpen}^{+}_{t-2}$	0.384*** (6.78)
$\Delta InCO_{2t-9}$	0.154** (2.30)	$\Delta\text{InOpen}^{+}_{t-2}$	0.381*** (4.76)	$\Delta InOpen$	– 0.152*** (– 3.62)	$\Delta\text{InOpen}^{+}_{t-3}$	0.305*** (5.86)
$\Delta InOpen$	0.215*** (3.72)	$\Delta\text{InOpen}^{+}_{t-3}$	0.374*** (5.66)	$\Delta InOpen_{t-1}$	– 0.073** (– 2.37)	$\Delta\text{InOpen}^{+}_{t-4}$	0.494** (2.60)
$\Delta InOpen_{t-1}$	0.188*** (3.03)	$\Delta\text{InOpen}^{+}_{t-4}$	0.521*** (7.51)	$\Delta InOpen_{t-2}$	– 0.067** (– 2.11)	$\Delta\text{InOpen}^{+}_{t-5}$	0.464*** (9.87)
$\Delta InOpen_{t-2}$	0.179** (2.66)	$\Delta\text{InOpen}^{+}_{t-5}$	0.607*** (7.54)	$\Delta InOpen_{t-3}$	– 0.045* (– 1.98)	$\Delta\text{InOpen}^{+}_{t-6}$	0.311*** (6.85)
$\Delta InOpen_{t-3}$	0.154** (2.42)	$\Delta InOpen^{-}$	– 0.299* (– 2.03)	$\Delta InOpen_{t-4}$	0.123*** (3.91)	$\Delta InOpen^{-}$	– 0.145*** (– 8.80)
$\Delta InOpen_{t-4}$	0.246*** (3.60)	$\Delta\text{InOpen}^{-}_{t-1}$	– 0.585*** (– 3.88)	$\Delta InOpen_{t-5}$	0.165*** (4.21)	$\Delta\text{InOpen}^{-}_{t-1}$	0.661** (2.57)
$\Delta InOpen_{t-5}$	0.230*** (3.08)	$\Delta\text{InOpen}^{-}_{t-2}$	– 0.830*** (– 4.39)	$\Delta InOpen_{t-6}$	0.126*** (3.05)	$\Delta\text{InOpen}^{-}_{t-2}$	– 0.351* (– 2.07)
$\Delta InOpen_{t-6}$	0.152** (2.14)	$\Delta\text{InOpen}^{-}_{t-8}$	– 0.737*** (– 3.92)	$\Delta InOpen_{t-7}$	0.169*** (4.40)	$\Delta\text{InOpen}^{-}_{t-3}$	0.494** (2.86)
$\Delta InOpen_{t-7}$	0.221*** (3.37)	$\Delta\text{InOpen}^{-}_{t-12}$	– 0.826*** (4.29)	$\Delta InOpen_{t-10}$	0.095** (2.71)	$\Delta\text{InOpen}^{-}_{t-5}$	– 0.549*** (– 5.07)
$\Delta InOpen_{t-9}$	0.129** (2.37)	Const	0.408*** (6.69)	$\Delta InOpen_{t-12}$	0.033* (1.98)	$\Delta\text{InOpen}^{-}_{t-6}$	– 0.282*** (– 3.58)
$\Delta InOpen_{t-10}$	0.209*** (3.37)	$L_{InOpen^{+}}$	– 0.583*** (0.004)	Const	0.256*** (7.23)	$\Delta\text{InOpen}^{-}_{t-11}$	0.274* (2.04)
$\Delta InOpen_{t-11}$	0.145** (2.11)	$L_{InOpen^{-}}$	– 0.878* (0.063)	$L_{InOpen^{+}}$	0.124*** (0.000)	Const	– 4.799*** (– 8.22)
Const	– 6.484*** (– 4.08)	R^2	0.893	$L_{InOpen^{-}}$	0.197** (0.026)	L_{InOpen}	– 0.972** (0.010)

Table 19 (continued)

Dependent variable = $InCO_{2t}$							
Model 1		Model 2		Model 3		Model 4	
Symmetric ARDL		NARDL with SR and LR asymmetry		NARDL with LR asymmetry		NARDL with SR asymmetry	
Var.	Coeff.	Var.	Coeff.	Var.	Coeff.	Var.	Coeff.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L_{InOpen}	− 0.559*** (0.000)	$Adj.R^2$	0.764	R^2	0.842	R^2	0.864
R^2	0.851	X^2_{SC}	7.012 (0.912)	$Adj.R^2$	0.796	$Adj.R^2$	0.807
$Adj.R^2$	0.783	X^2_{FF}	3.32 (0.865)	X^2_{SC}	1.491 (0.220)	X^2_{SC}	5.031 (0.241)
X^2_{SC}	4.748 (0.293)	X^2_{NOR}	98.501 (0.000)	X^2_{FF}	10.62 (0.271)	X^2_{FF}	8.58 (0.258)
X^2_{FF}	10.18 (0.217)	t_{BDM}	− 1.815 (0.035)	X^2_{NOR}	143.842 (0.000)	X^2_{NOR}	116.014 (0.000)
X^2_{NOR}	103.514 (0.000)	F_{PSS}	2.150 (0.069)	t_{BDM}	− 1.284 (0.076)	t_{BDM}	− 2.014 (0.083)
t_{BDM}	− 3.112 (0.005)	W_{LR}	0.830 (0.392)	F_{PSS}	3.087 (0.055)	F_{PSS}	3.013 (0.021)
F_{PSS}	5.137 (0.009)	W_{SR}	0.607 (0.218)	W_{LR}	0.143 (0.115)	W_{SR}	0.046 (0.103)

Similar to those in Table 3

References

1. Abbas S, Gui P, Chen A, Ali N. The effect of renewable energy development, market regulation, and environmental innovation on CO2 emissions in BRICS countries. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-20013-7.
2. Adebayo TS, Rjoub H, Akinsola GD, Oladipupo SD. The asymmetric effects of renewable energy consumption and trade openness on carbon emissions in Sweden: new evidence from quantile-on-quantile regression approach. Environ Sci Pollut Res. 2022;29(2):1875–86.
3. Aichele R, Felbermayr G. The effect of the kyoto protocol on carbon emissions. J Policy Anal Manage. 2013;32(4):731–57.
4. Ali N, Phoungthong K, Techato K, Ali W, Abbas S, Dhanraj JA, Khan A. FDI, green innovation and environmental quality nexus: new insights from BRICS economies. Sustainability. 2022;14(4):2181.
5. Ang JB. CO2 emissions, energy consumption, and output in France. Energy Policy. 2007;35(10):4772–8.
6. Antweiler W, Copeland BR, Taylor MS. Is free trade good for the environment? American Economic Review. 2001;91(4):877–908.
7. Awokuse TO, Christopoulos DK. Nonlinear dynamics and the exports–output growth nexus. Econom Modell. 2009;26(1):184–90.
8. Bahmani-Oskooe M, Durmaz N. Exchange rate volatility and Turkish commodity trade with the rest of the world. Econ Change Restruct. 2016;49(1):1–21.
9. Bahmani-Oskooe M, Halicioglu F, Mohammadian A. On the asymmetric effects of exchange rates on changes in domestic production in Turkey. Econ Change Restruct. 2018;51(2):97–112.
10. Bahmani-Oskooe M, Hegerty SW, Hosny A. The effects of exchange-rate volatility on industrial trade between the US and Egypt. Econ Change Restruct. 2015;48(2):93–117.
11. Bahmani-Oskooe M, Iqbal J, Khan S. Impact of exchange rate volatility on the commodity trade between Pakistan and the US. Econ Change Restruct. 2017;50(2):161–87.
12. Bahmani-Oskooe M, Saha S. On the relation between stock prices and exchange rates: a review article. J Econ Stud. 2015;42(4):707–32.
13. Bahmani-Oskooe M, Saha S. Do exchange rates have symmetric or asymmetric effects on stock prices? Glob Financ J. 2016;31:57–72.
14. Bahmani-Oskooe M, Saha S. On the relation between exchange rates and stock prices: a nonlinear ARDL approach and asymmetry analysis. J Econ Financ. 2018;42(1):112–37.
15. Bahmani-Oskooe M, Zhang R. The J-curve effect in the commodity trade between Korea and the rest of the world. Econ Change Restruct. 2014;47(3):227–50.

16. Balin BE, Akan HDM, Altayligil YB. Trade Liberalization and Environmental Degradation: a time series analysis for Turkey. Int. J. Econ. Commer. Manag. 2018;6(5):1–15.
17. Balke NS, Fomby TB. Threshold cointegration. Int. Econ Rev. 1997;38:627–45.
18. Banerjee A, Dolado J, Mestre R. Error correction mechanism tests for cointegration in a single-equation framework. J Time Ser Anal. 1998;19(3):267–83.
19. Beghin J, Roland-Holst D, Van der Mensbrugghe D. A survey of the trade and environment nexus: global dimensions. OECD Econ Stud. 1994;23:167–92.
20. Beeson M. The coming of environmental authoritarianism. Environmental Politics. 2010;19(2):276–94.
21. Cherniwchan J. Trade liberalization and the environment: Evidence from NAFTA and US manufacturing. J Int Econ. 2017;105:130–49.
22. Chhabra M, Giri AK, Kumar A. Do technological innovations and trade openness reduce CO2 emissions? Evidence from selected middle-income countries. Environ Sci Pollut Res. 2022;29:65723. https://doi.org/10.1007/s11356-022-20434-4.
23. Copeland BR, Taylor MS. Trade, growth, and the environment. J Econ Lit. 2004;42(1):7–71.
24. Copeland BR, Taylor MS. North-south trade and the environment. Q J Econ. 1994;109(3):755–87.
25. Cuestas J, Tang B. Asymmetric exchange rate exposure of stock returns: empirical evidence from Chinese industries. Stud Nonlinear Dyn Econom. 2017;21(4):1–21.
26. Destek MA, Balli E, Manga M. The relationship between CO2 emission, energy consumption, urbanization and trade openness for selected CEECs. Research in World Economy. 2016;7(1):52.
27. Dinda, S. (2006) Globalization and Environment: Can pollution haven hypothesis alone explain the impact of globalization on environment? Munich Personal RePEc Archive (MPRA) S. R. Fatepuria College, Beldanga, Murshidabad, WB, India, ERU, Indian Statistical Institute, Kolkata, India, MPRA Paper 50590. 2006. p.1–21. https://mpra.ub.uni-muenchen.de/50590/. Accessed 25 May 2022.
28. Dogan E, Seker F, F. Determinants of CO2 emissions in the European union: the role of renewable and non-renewable energy. Renew Energy. 2016;94:429–39.
29. Dogan E, Turkekul B. CO 2 emissions, real output, energy consumption, trade, urbanization and financial development: testing the EKC hypothesis for the USA. Environ Sci Pollut Res. 2016;23(2):1203–13.
30. Engle RF, Granger CW. Co-integration and error correction: representation, estimation, and testing. Econometrica. 1987;55(2):251–276
31. Ertugrul HM, Cetin M, Seker F, Dogan E. The impact of trade openness on global carbon dioxide emissions: evidence from the top ten emitters among developing countries. Ecol Ind. 2016;67:543–55.
32. Fernández-Amador O, Francois JF, Oberdabernig DA, Tomberger P. Carbon dioxide emissions and economic growth: an assessment based on production and consumption emission inventories. Ecol Econ. 2017;135:269–79.
33. Frankel JA, Rose AK. Is trade good or bad for the environment? Sorting out the causality. Rev Econ Stat. 2005;87(1):85–91.
34. Gale LR, Mendez JA. The empirical relationship between trade, growth and the environment. Int Rev Econ Financ. 1998;7(1):53–61.
35. Grether JM, De Melo J. Globalization and dirty industries: Do pollution havens matter? In: Baldwin, R.-E. & Winters, L.-A. Challenges to Globalization: Analyzing the Economics. Chicago: University of Chicago Press, 2004. p. 167–205. https://doi.org/10.3386/w9776.
36. Grossman G, Krueger A. Economic growth and the environment? Q J Econ. 1995;110(2):353–77.
37. Grossman GM, Krueger AB. Environmental Impacts of a North American Free Trade Agreement. In: Barber P, editor. The US-Mexico free trade agreement. Cambridge: MIT Press; 1993.
38. Grossman GM, Krueger AB. Environmental impacts of a north American free trade agreement (No. w3914). National Bureau of Economic Research 1050 Massachusetts Avenue Cambridge, MA 02138 (No. w3914). 1991. p. 1–57. https://doi.org/10.3386/w3914.
39. Grossman GM, Krueger AB. The inverted-U: what does it mean? Environ Dev Econ. 1996;1(01):119–22.
40. Hasson A, Masih M. Energy consumption, trade openness, economic growth, carbon dioxide emissions and electricity consumption: evidence from South Africa based on ARDL. Munich Personal RePEc Archive (MPRA) INCEIF, Malaysia, MPRA Paper No. 79424. 2017. p. 1–23. https://mpra.ub.uni-muenchen.de/79424/. Accessed 17 May 2022.
41. Hu X, Ali N, Malik M, Hussain J, Fengyi J, Nilofar M. Impact of economic openness and innovations on the environment: a new look into ASEAN countries. Polish J Environ Stud. 2021;30:3601–13.
42. Hussain J, Zhou K, Muhammad F, Khan D, Khan A, Ali N, Akhtar R. Renewable energy investment and governance in countries along the belt & road initiative: does trade openness matter? Renewable Energy. 2021;180:1278–89.
43. Ibrahim RL. Post-COP26: can energy consumption, resource dependence, and trade openness promote carbon neutrality? homogeneous and heterogeneous analyses for G20 countries. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-21855-x.
44. Inglesi-Lotz R. Decomposing the South African CO2 emissions within a BRICS countries context: signalling potential energy rebound effects. Energy. 2018;147:648–54.
45. Iyke BN, Ho SY. Trade openness and carbon emissions: Evidence from Central and Eastern Europe. In: MPRA Paper 80399. University Library of Munich, Germany, 2017. p. 1-20. https://mpra.ub.uni-muenchen.de/80399/. Accessed 25 July 2022.
46. Jabeen A. Is trade liberalization, economic growth, energy consumption good for the environment? Rom J Fisc Policy. 2015;6(2):1–13.
47. Jamel L, Maktouf S. The nexus between economic growth, financial development, trade openness, and CO2 emissions in European countries. Cogent Econom Financ. 2017;5(1):1341456.
48. Jena PK, Mujtaba A, Joshi DPP, Satrovic E, Adeleye BN. Exploring the nature of EKC hypothesis in Asia's top emitters: role of human capital, renewable and non-renewable energy consumption. Environ Sci Pollut Res. 2022;29:88557–76.
49. Kahneman D, Tversky A. Prospect theory: an analysis of decisions under risk. Econometrica. 1979;47:263–91.
50. Kahuthu A. Economic growth and environmental degradation in a global context. Environ Dev Sustain. 2006;8(1):55–68.
51. Kapetanios G, Shin Y, Snell A. Testing for cointegration in nonlinear smooth transition error correction models. Econom Theory. 2006;22:279–303.
52. Kearsley A, Riddel M. A further inquiry into the pollution haven hypothesis and the environmental Kuznets curve. Ecol Econ. 2010;69(4):905–19.
53. Kebede S. Modeling Energy Consumption, CO2 Emissions and economic growth nexus in Ethiopia: evidence from ARDL approach to cointegration and causality analysis. Munich Personal RePEc Archive (MPRA) Jigjiga University, paper No. 83000. 2017. p.1-23. https://mpra.ub.uni-muenchen.de/83000/. Accessed 25 July 2022.

54. Keynes JM. The general theory of employment, interest and money. London: Macmillan; 1936.
55. Kwakwa PA, Alhassan H, Adu G. Effect of natural resources extraction on energy consumption and carbon dioxide emission in Ghana. Int J Energy Sect Manag. 2020;14(1):20–39. https://doi.org/10.1108/IJESM-09-2018-0003.
56. Le TH, Chang Y, Park D. Trade openness and environmental quality: International evidence. Energy Policy. 2016;92:45–55.
57. Li Z, Xu N, Yuan J. New evidence on trade-environment linkage via air visibility. Econ Lett. 2015;128:72–4.
58. Lin F. Trade openness and air pollution: city-level empirical evidence from China. China Econ Rev. 2017;45:78–88.
59. Ling CH, Ahmed K, Muhamad RB, Shahbaz M. Decomposing the trade-environment nexus for Malaysia: what do the technique, scale, composition, and comparative advantage effect indicate? Environ Sci Pollut Res. 2015;22(24):20131–42.
60. Lopez R. The environment as a factor of production: the effects of economic growth and trade liberalization. J Environ Econ Manag. 1994;27(2):163–84.
61. Mahmood H. Trade, FDI, and CO2 emissions nexus in Latin America: the spatial analysis in testing the pollution haven and the EKC hypotheses. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-23154-x.
62. Mahmood H, Maalel N, Zarrad O. Trade openness and CO2 emissions: evidence from Tunisia. Sustainability. 2019;11(12):3295.
63. Mapapu B, Phiri A. Carbon emissions and economic growth in South Africa: a quantile regression analysis. Int J Energy Econom Policy. 2018;8(1):195–202.
64. Mujtaba A, Jena PK. Analyzing asymmetric impact of economic growth, energy use, FDI inflows, and oil prices on CO2 emissions through NARDL approach. Environ Sci Pollut Res. 2021;28(24):30873–86.
65. Mujtaba A, Jena PK, Bekun FV, Sahu PK. Symmetric and asymmetric impact of economic growth, capital formation, renewable and non-renewable energy consumption on environment in OECD countries. Renew Sustain Energy Rev. 2022;160: 112300.
66. Mujtaba A, Pawar S, Joshi DP, Gopinathan R. Examining asymmetric impact of climatic factors on crop yields in India. Appl Econ Lett. 2022. https://doi.org/10.1080/13504851.2022.2064416.
67. Munir K, Riaz N. Asymmetric impact of energy consumption on environmental degradation: evidence from Australia, China, and USA. Environ Sci Pollut Res. 2020;27:11749–59.
68. Ngepah N, Udeagha MC. African regional trade agreements and intra-African trade. J Econ Integr. 2018;33(1):1176–99.
69. Ngepah N, Udeagha MC. Supplementary trade benefits of multi-memberships in African regional trade agreements. J Afr Bus. 2019;20(4):505–24.
70. Oh KY, Bhuyan MI. Trade openness and CO 2 emissions: evidence of Bangladesh. Asian J Atmospheric Environ. 2018;12(1):30.
71. Omri E, Saadaoui H. An empirical investigation of the relationships between nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions in France: fresh evidence using asymmetric cointegration. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-22958-1.
72. Pata UK, Dam MM, Kaya F. How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO2 emissions? An EKC analysis for ASEAN countries. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-23160-z.
73. Pesaran MH, Shin Y, Smith RJ. Bounds testing approaches to the analysis of level relationships. J Appl Econ. 2001;16(3):289–326.
74. Pesaran MH, Shin Y, Smith RP. Pooled mean group estimation of dynamic heterogeneous panels. J Am Stat Assoc. 1999;94(446):621–34.
75. Psaradakis Z, Sola M, Spagnolo F. On Markov error-correction models with an application to stock prices and dividends. J Appl Econom. 2004;19:69–88.
76. Raggad B. Economic development, energy consumption, financial development, and carbon dioxide emissions in Saudi Arabia: new evidence from a nonlinear and asymmetric analysis. Environ Sci Poll Res. 2020. https://doi.org/10.1007/s11356-020-08390-3.
77. Rahman ZU, Ahmad M. Modeling the relationship between gross capital formation and CO 2 (a) symmetrically in the case of Pakistan: an empirical analysis through NARDL approach. Environ Sci Pollut Res. 2019;26(8):8111–24.
78. Rahmana ZU, Chongboa W, Ahmad M. An (a)symmetric analysis of the pollution haven hypothesis in the context of Pakistan: a non-linear approach. CARBON MANAGEMENT. 2019;10(3):227–39.
79. Raza SA, Shah N. Impact of financial development, economic growth and energy consumption on environmental degradation: evidence from Pakistan. In: MPRA Paper 87095. University Library of Munich, Germany, 2018. p.1–26. https://mpra.ub.uni-muenchen.de/87095/. Accessed 17 May 2022.
80. Roy J. On the environmental consequences of intra-industry trade. J Environ Econ Manag. 2017;83:50–67.
81. Saikkonen P. Stability of regime switching error correction models under linear cointegration. Econom Theory. 2008;24:294–318.
82. Selden TM, Song D. Environmental quality and development: is there a Kuznets curve for air pollution emissions? J Environ Econ Manag. 1994;27(2):147–62.
83. Shafik N. Economic development and environmental quality an econometric analysis. Oxford Econom Papers. 1994;46:757–73.
84. Shafik N, Bandyopadhyay S. Economic growth and environmental quality: time-series and cross-country evidence. Washington: World Bank Publications; 1992.
85. Shahbaz M, Nasreen S, Ahmed K, Hammoudeh S. Trade openness–carbon emissions nexus: the importance of turning points of trade openness for country panels. Energy Economics. 2017;61:221–32.
86. Shahbaz M, Tiwari AK, Nasir M. The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa. Energy Policy. 2013;61:1452–9.
87. Shiller RJ. Macro markets: creating institutions for managing society's largest economic risks. Oxford: Clarendon Press; 1993.
88. Shiller RJ. Irrational exuberance. 2nd ed. Princeton: Princeton University Press; 2005.
89. Shin Y, Yu B, Greenwood-Nimmo M. Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. In: Sickels R, Horrace W, editors. Festschrift in honor of peter schmidt: econometric methods and applications. New York: Springer; 2014. p. 281–314.
90. Solarin SA, Al-Mulali U, Musah I, Ozturk I. Investigating the pollution haven hypothesis in Ghana: an empirical investigation. Energy. 2017;124:706–19.
91. Soytas U, Sari R, Ewing BT. Energy consumption, income, and carbon emissions in the United States. Ecol Econ. 2007;62(3):482–9.
92. Squalli J, Wilson K. A new measure of trade openness. World Economy. 2011;34(10):1745–70.

93. Suhrab M, Soomro JA, Ullah S, Chavara J. The effect of gross domestic product, urbanization, trade openness, financial development, and renewable energy on CO2 emission. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-23761-8.
94. Twerefou DK, Appiah-Konadu P, Anaman KA. Impact of international trade on the quality of the natural environment: a case study of Ghana from 1970 to 2010. Ghana Soc Sci J. 2015;12(1):1–21.
95. Udeagha MC, Breitenbach MC. Estimating the trade-environmental quality relationship in SADC with a dynamic heterogeneous panel model. African Rev Econom Financ. 2021;13(1):113–65.
96. Udeagha MC, Muchapondwa E. Investigating the moderating role of economic policy uncertainty in environmental Kuznets curve for South Africa: evidence from the novel dynamic ARDL simulations approach. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-21107-y.
97. Udeagha MC, Ngepah N. Revisiting trade and environment nexus in South Africa: fresh evidence from new measure. Environ Sci Pollut Res. 2019;26:29283–306.
98. Udeagha MC, Ngepah N. Trade liberalization and the geography of industries in South Africa: fresh evidence from a new measure. Int J Urban Sci. 2020;24(3):354–96.
99. Udeagha MC, Ngepah N. The asymmetric effect of trade openness on economic growth in South Africa: a nonlinear ARDL approach. Econ Chang Restruct. 2021;54(2):491–540.
100. Udeagha MC, Ngepah N. Dynamic ARDL simulations effects of fiscal decentralization green technological innovation, trade openness, and institutional quality on environmental sustainability. Evid South Africa Sustain. 2022;14:10268. https://doi.org/10.3390/su141610268.
101. Udeagha MC, Ngepah N. Disaggregating the environmental effects of renewable and non-renewable energy consumption in South Africa: fresh evidence from the novel dynamic ARDL simulations approach. Econ Chang Restruct. 2022;55:1767–814.
102. Udeagha MC, Ngepah N. Does trade openness mitigate the environmental degradation in South Africa? Environ Sci Pollut Res. 2022;29(13):19352–77.
103. Udeagha MC, Ngepah N. The asymmetric effect of technological innovation on CO2 emissions in South Africa: new evidence from the QARDL approach. Front Environ Sci. 2022;10: 985719. https://doi.org/10.3389/fenvs.2022.985719.
104. Udeagha MC, Ngepah N. Striving towards environmental sustainability in the BRICS economies: the combined influence of fiscal decentralization and environmental innovation. Int J Sust Dev World. 2022. https://doi.org/10.1080/13504509.2022.2123411.
105. Udeagha MC, Ngepah NN. A step towards environmental mitigation In South Africa: Does trade liberalisation really matter fresh evidence from a novel Dynamic ARDL simulations approach. Research square. 2021. https://doi.org/10.2203/rs.3.rs-419113/v1.
106. Udeagha MC, Breitenbach MC. Exploring the moderating role of financial development in environmental Kuznets curve for South Africa: Fresh evidence from the novel dynamic ARDL simulations approach. Financ Innov. 2022. https://doi.org/10.1186/s40854-022-00396-9.
107. Wan R, Nakada M, Takarada Y. Trade liberalization in environmental goods. Resour Energy Econom. 2018;51:44–66.
108. Wen J, Ali W, Hussain J, Khan NA, Hussain H, Ali N, Akhtar R. Dynamics between green innovation and environmental quality: new insights into South Asian economies. Economia Politica. 2022;39(2):543–65.
109. Wenlong Z, Tien NH, Sibghatullah A, Asih D, Soelton M, Ramli Y. Impact of energy efficiency, technology innovation, institutional quality, and trade openness on greenhouse gas emissions in ten Asian economies. Environ Sci Pollut Res. 2022. https://doi.org/10.1007/s11356-022-20079-3.
110. World Development Report. development and the environment world development report world development indicators. Washington: World Bank Group; 1992.
111. Zerbo E. CO2 emissions, growth, energy consumption and foreign trade in Sub-Sahara African countries. In: Working papers hal-01110769. HAL; 2015.
112. Zerbo E. Income-environment relationship in Sub-Saharan African countries: further evidence with trade openness. Environ Sci Pollut Res. 2017;24(19):16488–502.
113. Zivot E, Andrews D. Further evidence of great crash, the oil price shock and unit root hypothesis. J Bus Econ Stat. 1992;10:251–70.
114. Ding Q, Khattak SI, Ahmad M. Towards sustainable production and consumption: assessing the impact of energy productivity and eco-innovation on consumption-based carbon dioxide emissions (CCO2) in G-7 nations. Sustain Product Consum. 2021;27:254–68.
115. Ibrahim RL, Ajide KB. Disaggregated environmental impacts of non-renewable energy and trade openness in selected G-20 countries: the conditioning role of technological innovation. Environ Sci Pollut Res. 2021;28(47):67496–510.
116. Ibrahim RL, Ajide KB. Trade facilitation and environmental quality: empirical evidence from some selected African countries. Environ Dev Sustain. 2022;24(1):1282–312.
117. Khan Z, Ali S, Umar M, Kirikkaleli D, Jiao Z. Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy. Sci Total Environ. 2020;730: 138945.
118. Khan MA, Walmsley T, Mukhopadhyay K. Trade liberalization and income inequality: The case for Pakistan. J Asian Econ. 2021;74: 101310.
119. Ibrahim RL, Ajide KB. Nonrenewable and renewable energy consumption, trade openness, and environmental quality in G-7 countries: the conditional role of technological progress. Environ Sci Pollut Res. 2021;28(33):45212–29.
120. Van Tran N. The environmental effects of trade openness in developing countries: conflict or cooperation? Environ Sci Pollut Res. 2020;27(16):19783–97.
121. Khan M, Ozturk I. Examining the direct and indirect effects of financial development on CO2 emissions for 88 developing countries. J Environ Manage. 2021;293: 112812.
122. Ali S, Yusop Z, Kaliappan SR, Chin L. Dynamic common correlated effects of trade openness, FDI, and institutional performance on environmental quality: evidence from OIC countries. Environ Sci Pollut Res. 2020;27(11):11671–82.
123. Aydin M, Turan YE. The influence of financial openness, trade openness, and energy intensity on ecological footprint: revisiting the environmental Kuznets curve hypothesis for BRICS countries. Environ Sci Pollut Res. 2020;27(34):43233–45.