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Asymmetric effect of environmental tax on CO_2 emissions embodied in domestic final demand in developing economies: A panel NARDL approach

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Abstract
This paper employs the panel nonlinear autoregressive distributed lag model to investigate the asymmetric effects of environmental taxes on CO_2 emissions embodied in domestic final demand (CDFD) in 23 developing economies. The results indicate that a reduction in environmental tax has a more adverse effect on CDFD than an increase in tax, implying that environmental taxes alone may not be sufficient to reduce CO_2 emissions, especially in the context of rapid economic growth. Additionally, the study finds that fluctuations in GDP and population growth are associated with changes in CDFD. The findings further reveal that environmental tax has a positive association with CDFD, which suggests that to achieve emission reduction targets, policymakers need to consider other measures such as incentives for clean technology and regulations on high-emission industries. Furthermore, the robustness test results suggest that technological innovation is significantly linked to a decrease in CO_2 emissions embodied in domestic final demand and greenhouse gas (GHG) emissions, while trade openness is positively associated with CDFD but negatively correlated with GHG emissions. This research provides crucial implications for policymakers on the effectiveness of environmental taxes and the need for supplementary measures to decrease CO_2 emissions in developing economies.

Keywords Environmental tax · CO_2 emissions · Asymmetric effect · Developing economies

1 Introduction

Environmental tax and CO_2 emissions embodied in domestic final demand are interconnected, with both economic and environmental factors playing a role. Sustainable environmental policy can take many forms and can be used to influence the behaviour of firms and households in ways that reduce CO_2 emissions (Harding et al., 2014; Xie et al., 2018).

Environmental tax refers to a tax that is levied on goods and services that have a negative impact on the environment. It is a broader term that encompasses various types of taxes, such as taxes on pollution, waste, and energy consumption (Wolde-Rufael &

Extended author information available on the last page of the article

Mulat-Weldemeske, 2021). Environmental tax can also be applied to products that are environmentally friendly, as a way to encourage their consumption and production. Carbon taxes, in particular, target carbon dioxide (CO_2) emissions, the primary contributor to climate change (Telatar & Birinci, 2022), by imposing a tax on the carbon content of fossil fuels such as coal, oil, and natural gas (Parry, 2019).

In the context of this study, CO_2 emissions embodied in domestic final demand refer to the total amount of carbon dioxide emissions associated with the production, distribution, and consumption of goods and services within a particular country. It includes emissions generated during the extraction and processing of raw materials, manufacturing of products, transportation and distribution, use and disposal of goods and services by consumers (Meinrenken et al., 2020; Sizirici et al., 2021; Yamano & Guilhoto, 2020), and encompasses the entire life-cycle of a product. Understanding CO_2 emissions embodied in domestic final demand is important because it helps to determine the extent to which a country is responsible for its emissions, including those associated with the consumption of goods and services produced in other countries (Mózner, 2013; Wu et al., 2022). This information can inform policies and strategies aimed at reducing CO_2 emissions and transitioning to a more sustainable economy.

Against this backdrop, this study delves into a critical issue that affects our planet's sustainability and the well-being of future generations. The relentless increase in CO_2 emissions has prompted governments and policymakers to search for effective strategies to tackle this problem. While environmental taxes have been proposed as a potential solution, there is a dearth of empirical evidence on their effectiveness in developing economies. As our world becomes increasingly interconnected, understanding the concept of asymmetry in the relationship between environmental tax and CO_2 emissions embodied in domestic final demand is crucial. Surprisingly, this concept has received little attention in the case of developing economies. Our study aims to fill this gap by using a panel nonlinear autoregressive distributed lag (NARDL) approach to investigate this relationship and determine whether changes in environmental tax have a greater impact on CO_2 emissions embodied in domestic final demand when taxes are decreased, as opposed to increased. In other words, this study specifically aim to examine the extent to which minor and major positive and negative shocks to environmental tax influence CO2 emissions embodied in domestic final demand in developing economies. Furthermore, from a symmetric standpoint, the study aim to explore the contingency influence of GDP growth rate and population growth rate on the effectiveness of environmental tax on CO_2 emissions embodied in domestic final demand.

The motivation for this study is to provide insights into how environmental tax policies can be designed and implemented to effectively reduce CO_2 emissions. We believe that the concept of asymmetry is fundamental to understanding how environmental tax policies can be optimally designed and implemented. In this regard, our study will shed light on how the impact of a decrease in environmental tax on CO_2 emissions embodied in domestic final demand may be more significant than the impact of an increase in environmental tax, and vice versa.

The implications of this study are far-reaching and will provide valuable insights for policymakers in designing and implementing sustainable environmental policies. This is particularly relevant in the context of developing economies, a country heavily impacted by the effects of climate change, with a high level of carbon emissions per capita, and a significant increase in greenhouse gas emissions in recent years. Our findings will contribute to informing policies and strategies aimed at reducing CO_2 emissions and transitioning to a more sustainable economy in developing economies and other developing economies facing similar challenges.

The remaining sections of the paper are structured as follows: Sect. 2 provides a review of relevant literature, while Sect. 3 outlines our empirical methodology and data. Section 4 presents the results and corresponding discussions. Finally, Sect. 5 elucidates the policy implications drawn from the findings.

2 Literature review

The unrestrained expansion of carbon emissions due to industrial energy utilization not only intensifies the destructive impacts of global warming but also significantly undermines the potential for sustainable growth of our economy and society. It is imperative that we take decisive action to curb this trend and pave the way for a more sustainable and prosperous future (Yu et al., 2023). Such possible actions are in the form of environmental regulation and policy. Previous studies that examined the relationship between environmental regulation and various outcomes, such as pollution reduction and carbon emissions has produced mixed results. Our review builds on the existing literature by synthesizing the findings of a number of studies that specifically examine the relationship between environmental regulation and energy conservation and efficiency as shown in Table 1.

The studies in Table 1 utilized different methodologies and revealed that environmental taxes generally have a negative impact on carbon emissions, with a few exceptions where taxes were found to be ineffective. Some studies indicated that environmental taxes are effective in reducing CO_2 emissions while maintaining a certain level of GDP growth, with the effectiveness of the tax depending on its level. Additionally, other studies suggest that economic growth has a negative effect on CO_2 emissions in the low growth regime, and environmental policy stringency can be effective in reducing CO_2 emissions in emerging economies.

The current research on the asymmetric effect of environmental taxes on CO2 emissions embodied in domestic final demand in developing economies is insufficient. Despite studies that have explored the nonlinear effects of various environmental sustainability determinants, such as Jiang et al. (2022), Ali and Kirikkaleli (2022), and Abdul-Mumuni et al. (2022), there is still a significant knowledge gap to be filled. Albulescu et al. (2022) is among the few studies that specifically focus on the nonlinear connection between environmental policy and carbon emissions, but it employed panel threshold analysis to determine the point at which the effectiveness of environmental regulation reverses. In contrast, this study aims to determine the extent to which minor and major positive and negative changes in environmental tax influence CO_2 emissions embodied in domestic production and demand from both symmetric and contingency analysis of interaction terms in developing economies.

Furthermore, while recent literature has placed major emphasis on other forms of environmental sustainability, such as ecological footprint and greenhouse emissions, the context of CO_2 emissions embodied in domestic production and demand has been largely overlooked. This broader measurement of emissions accounts for the total amount of CO_2 emissions associated with the production of goods and services consumed within a country, including imports. The importance of this measure lies in its ability to inform policies that aim to reduce emissions by altering consumption patterns while achieving emission reduction targets and promoting sustainable growth.

Table 1 Summary of empirical literature

Author	Country	Purpose	Methodology	Summary of findings
Bashir et al. (2020)	OECD economies	Nexus between environmental tax and carbon	System-GMM and quantile regression	Environmental tax negatively affects carbon emissions
Aydin and Esen (2018)	15 EU member countries	Nonlinear relationship between environmental taxes and CO_2 emissions	Dynamic panel threshold regression model	Environmentally related taxes on CO_2 emissions change from insignificantly positive to significantly negative after exceeding threshold level in 15 EU member countries between 1995 and 2013
Silajdzic and Mehic (2018)	Ten Central and Eastern European countries	The impact of environmental taxes on CO_2 emissions	Fully modified least squares (FMOLS)	Environmental taxes do not seem to be effective in modifying the behavior of economic agents and in protecting the environment
Renner et al., (2017)	Mexico	Effects of environmental taxes on welfare and carbon emissions	Regression estimate	Short-run emission reductions at the household level can be substantial. This effectiveness combined with moderate and manageable adverse distributional impacts renders the carbon tax a preferred mitigation instrument
Aye and Edoja (2017)	31 developing countries	Effect of economic growth on CO_2 emission	Dynamic panel threshold framework	Economic growth has negative effect on CO_2 emission in the low growth regime
Shrestha et al., (1998)	Developing country	Interfuel/technological substitution and electricity demand effects of carbon tax on electric utility planning and CO 2 emissions	Regression Estimate	Low carbon tax may not be effective to reduce CO_2 emissions through interfuel and technological substitution in power generation regardless of technological restrictions

Table 1 (continued)

Author	Country	Purpose	Methodology	Summary of findings
Mardones and Muñoz (2018)	Chile	Effect of Environmental taxation in reducing greenhouse gases emissions	Environmental extension of the Leontief price model	A lower tax of US $30 per ton of CO_2 and other GHGs applied to all sectors of the economy could reduce CO_2 and other GHGs emissions by up to 25.7%
Dogan et al., (2022)	Selected countries	Role of green growth and environmental taxes in reducing emissions	Quantile regressions	A scheme of taxes levied on the emission of six pollutants, including the greenhouse gases CO_2 and methane, drives emission reduction measures
Safi et al., (2021)	G7 economies	Importance of environmental taxes and R&D in achieving the goal of carbon neutrality	Panel analysis and Dumitrescu and Hurlin Granger causality test	Environmental taxes, environmental R&D, and exports significantly reduce carbon emissions for G-7 countries over a period of 1990–2019
Wei et al., (2022)	China	Effects of energy efficiency and climate change policy alternatives in the post-COVID-19 period	Computable general equilibrium (CGE)	A 5 RMB per ton carbon tax will reduce emissions by 4.1% and GDP by 0.27%
Liu et al., (2017)	Various countries, including China	Effect of carbon tax on carbon emission abatement and GDP	Multi-objective optimization approach	A carbon tax is an effective means to reduce CO_2 emissions while maintaining a certain level of GDP growth
Alper (2018)	18 selected European countries	Analysis of Carbon Tax on Selected European Countries	Panel data analysis	A 1% increase in environmental taxes reduces carbon dioxide emissions by 0.9%
Lu et al., (2010)	China	Impact of carbon tax on Chinese economy	Dynamic recursive general equilibrium model	Carbon tax is an effective policy tool in reducing carbon emissions with a little negative impact on economic growth

Table 1 (continued)

Author	Country	Purpose	Methodology	Summary of findings
Wolde-Rufael and Mulat-Weldemeskel (2021)	7 emerging economies	Effect of environmental taxes and environmental stringency policies in reducing CO_2 emissions	Augmented Mean Group (AMG)	Environmental policy stringency can be effective in mitigating CO_2 emissions in emerging economies

2.1 Theoretical underpinning

The theoretical framework for the relationship between environmental taxes and CO_2 emissions embodied in domestic final demand is rooted in the concept of market failure and the need for government intervention. The Coase theorem posits that when property rights are clearly defined and transaction costs are low, the market will efficiently allocate resources and externalities will be internalized. However, in reality, transaction costs are often high and property rights are not always clearly defined, leading to market failure and the need for government intervention (Madema & Steven, 2020).

The issue of CO_2 emissions and its impact on the environment and climate change is a prime example of market failure. The burning of fossil fuels and deforestation, among other human activities, are causing significant harm to the environment and contributing to climate change. The scientific consensus is that these activities are increasing the concentrations of greenhouse gases, such as CO_2, in the atmosphere, which are trapping more heat and causing global temperatures to rise. This warming is leading to a range of negative impacts, including sea level rise, more extreme weather events, and changes in precipitation patterns.

To address these issues, governments around the world have implemented a variety of regulatory measures aimed at reducing emissions of greenhouse gases, including CO_2. These measures include things like carbon taxes, cap-and-trade systems, and regulations on specific industries, such as power plants and transportation. The underlying principle behind these regulations is the "polluter pays" principle, which holds that those who generate pollution should bear the cost of mitigating it. This principle is based on the idea that polluters have an obligation to society to minimize the harm they are causing and that it is more efficient to make them pay for the damage they cause than to make society pay for it. However, Autor (2010) contend that the most effective approach to addressing issues related to pollution is not to completely regulate it out of existence, but rather to promote negotiation in order for the parties affected by the regulation to arrive at a solution that is economically efficient.

GDP growth and population growth are also important variables in this context because they can affect the effectiveness of environmental taxes in reducing CO_2 emissions. GDP growth can drive increased consumption and production, leading to higher emissions, while population growth can lead to an increase in the number of consumers and producers, also resulting in higher emissions. However, the specific relationship between them will depend on a range of factors, including the specifics of the environmental tax and the overall economic and demographic context of the country in question.

3 Data and methodology

3.1 Data

This study essentially examines historical events and consequently relies absolutely on secondary data obtained from the World Development Indicators. Data on 23 developing economies were obtained for the period 1995–2021. The choice of the selected countries and the base year for the study is informed by data availability on the variables of interest. Data on CO_2 emissions embodied in domestic final demand (i.e. explained variable) and environmental tax (i.e. main independent variable) were obtained from the IMF climate database, while data on the control variables, gross domestic product (GDP) growth rate and population growth were collated from the World Bank Database.

GDP is used as a control variable in the analysis to capture the overall economic conditions and its potential impact on CO_2 emissions. A country with a high GDP is likely to have a higher level of domestic final demand, which in turn may lead to higher CO_2 emissions. By controlling for GDP, researchers can estimate the effect of environmental policies on CO_2 emissions while controlling for the overall economic conditions. Moreover, population enters the model as a control variable to account for the number of people living in a country, which can affect the level of domestic final demand and potentially CO_2 emissions. A country with a high population is likely to have a higher level of domestic final demand, which in turn may lead to higher CO_2 emissions. By controlling for population, researchers can estimate the effect of environmental policies on CO_2 emissions while controlling for the number of people living in a country. The model variables are further described in Table 2.

3.2 Empirical framework

To investigate the impact of sustainable environmental policy on CO_2 emissions embodied in domestic final demand, this study employs both panel Autoregressive Distributed Lag (ARDL) and panel nonlinear autoregressive distributed lag (NARDL) models. The panel ARDL model is used to examine the symmetric relationship between the variables of interest, while the panel NARDL model is used to explore the potential asymmetric effects. These econometric models are commonly used in research to analyse the dynamic relationship between economic variables and are well-suited for studying the impact of environmental policies on CO_2 emissions.

3.2.1 Symmetric panel ARDL

The ARDL model is a method for estimating the long-run and short-run relationship between variables in a cointegrated system, as well as the consideration of possible endogeneity issues. It is a generalization of the traditional Engle-Granger two-step cointegration method and allows for estimation of both short-run and long-run elasticities simultaneously. This makes it an appropriate choice for studying the impact of environmental policies on CO_2 emissions, as it allows for analysis of both the immediate and long-term effects of policy changes.

The dependent variable in this study is CDFD, which measures the amount of carbon dioxide emissions associated with the production and consumption of goods and services within a country. The independent variable is environmental tax (ENVT), which represents the policy measure implemented to reduce emissions. Control variables include GDP growth rate (GDPG), which captures the overall economic performance of the country, and population growth rate (POPG), which reflects changes in the number of individuals in the population. Based on the time series data for the relevant variables, we estimated three models: the first model is a basic ARDL model, the second model is an ARDL model with interaction terms, and the third model is a nonlinear specification of the ARDL model.

We begin our analyses by assuming a symmetric response of CO_2 emissions embodied in domestic final demand to changes in environmental tax, and thereafter we relax this

Table 2 Description of model variables

Variable	Description	Measure	Designation
CDFD	CO_2 emissions embodied in domestic final demand: refer to the amount of carbon dioxide emissions that are associated with the production and consumption of goods and services within a country. This includes emissions that occur during the extraction, production, transportation, and disposal of goods and services consumed by households, businesses, and government within the country. It is a measure of the carbon footprint of a country's domestic consumption	% of GDP	Dependent variable
ENVT	Environmental tax: is a fee imposed on a specific physical unit of a product or activity that harms the environment. Examples of this include a gallon of gasoline/petrol, passenger flight, or a metric ton of waste being sent to a landfill	% of GDP	Independent Variable
GDPG	Gross domestic product growth rate: is a measure of the increase in the value of all goods and services produced within a country over a period of time, typically a quarter or a year	Annual %	Control Variable
POPG	Population growth: refers to the change in the number of individuals in a population over a specific period of time	Annual %	Control Variable

assumption in order to allow for positive and negative changes in environmental tax. Consequently, the symmetric version of the panel ARDL is given as:

$$\begin{aligned}\Delta\gamma_{it} =& \beta_{0i} + \beta_{1i}\gamma_{i,t-1} + \beta_{2i}\delta_{t-1} + \sum_{j=1}^{N1}\lambda_{ij}\Delta\gamma_{i,t-j} + \sum_{j=0}^{N2}\varphi_{ij}\Delta\delta_{t-j} + \mu_i + \varepsilon_{it} \\ & i = 1,2,\ldots,N; t = 1,2,\ldots,T.\end{aligned} \tag{1}$$

where γ_{it} is the natural logarithm of CO_2 emissions embodied in domestic final demand for each unit i over a period of time t; δ_t denotes the vector of explanatory variables at period t; μ_i is the group-specific effect. For each cross-section, the long-run slope (elasticity) coefficient is computed as $-\frac{\beta_{2i}}{\beta_{1i}}$ since in the long run, it is assumed that $\Delta\gamma_{i,t-j} = 0$ and $\Delta\delta_{t-j} = 0$. Therefore, the short-run estimate for the explanatory variables is obtained as φ_{ij}. Equation (4) can be re-specified to include an error correction term as follows:

$$\Delta\gamma_{it} = \rho_i\tau_{i,t-1} + \sum_{j=1}^{N1}\lambda_{ij}\Delta\gamma_{i,t-j} + \sum_{j=0}^{N2}\varphi_{ij}\Delta\delta_{t-j} + \mu_i + \varepsilon_{it} \tag{2}$$

where $\tau_{i,t-1} = \gamma_{i,t-j} - \theta_{01} - \theta_{1i}\delta_{t-1}$ is the linear error correction term for each unit; the parameter ρ_i is the error-correcting speed of adjustment term for each unit which is also equivalent toβ_{1i}. The parameters θ_{01} and θ_{1i} are computed as $-\frac{\beta_{0i}}{\beta_{1i}}$ and $-\frac{\beta_{2i}}{\beta_{1i}}$, respectively. It can be observed that in both Eqs. (5) and (6), there are no decompositions of the explanatory variable into positive and negative changes; hence, the assumption of symmetric impact of environmental tax on CO_2 emissions embodied in domestic final demand under this scenario.

The panel ARDL model is based on the above scenario has been modified to fully incorporate the selected indicators. As a result, the dynamic models are presented as follows:

$$\begin{aligned}\Delta\mathrm{CDFD}_{i,t} =& \sum_{j=1}^{p-1}\lambda_j\Delta\mathrm{CDFD}_{i,t-j} + \sum_{j=0}^{q-1}\delta_j\Delta\mathrm{ENV}T_{i,t-j} + \sum_{j=0}^{q-1}\delta_j\Delta\mathrm{GDPG}_{i,t-j} + \sum_{j=0}^{q-1}\delta_j\Delta\mathrm{POPG}_{i,t-j} \\ & + \varphi_i'\left[\mathrm{CDFD}_{i,t-i} - \left\{\beta_0 + \beta_1\mathrm{ENVT}_{i,t-1} + \beta_2\mathrm{GDPG}_{i,t-1} + \beta_3\mathrm{POPG}_{i,t-1}\right\}\right] + \varepsilon_{i,t}\end{aligned} \tag{3}$$

where i and t denote country and time period, respectively, and CDFD = CO_2 emissions embodied in domestic final demand (% of GDP), ENVT = environmental tax (% of GDP), GDPG = GDP growth rate, and POPG = population growth rate. Therefore, taking its log form of CO_2 emissions embodied in domestic final demand would stabilize the variance of the time series and bring it to same base with other variables, and ε = error term. λ and δ_j denote the short-run coefficients of lagged dependent and explanatory variables, respectively. Δ represents differencing operator. β_1–β_3 are the long-run parameters, and β_0 is the constant term. φ is the parameter of speed of adjustment towards long-run equilibrium.

In addition to the baseline model in Eq. (2), we specify an ARDL model with interaction terms, which allows for the analysis of potential interactions between the independent variables and the control variable. The model is specified as follows:

$$\Delta \mathrm{CDFD}_{i,t} = \sum_{j=1}^{p-1} \lambda_j \Delta \mathrm{CDFD}_{i,t-j} + \sum_{j=0}^{q-1} \delta_j \Delta \mathrm{ENVT}_{i,t-j} + \sum_{j=0}^{q-1} \delta_j \Delta \mathrm{GDPG}_{i,t-j} + \sum_{j=0}^{q-1} \delta_j \Delta \mathrm{POPG}_{i,t-j} + \varphi_i' \left[\mathrm{CDFD}_{i,t-i} - \left\{ \begin{array}{l} \beta_0 + \beta_1 \mathrm{ENVT}_{i,t-1} + \beta_2 \mathrm{ENVT} * \mathrm{GDPG}_{i,t-1} \\ + \beta_3 \mathrm{ENVT} * \mathrm{POPG}_{i,t-1} + \beta_4 \mathrm{GDPG}_{i,t-1} + \beta_5 \mathrm{POPG}_{i,t-1} \end{array} \right\} \right] + \varepsilon_{i,t} \tag{4}$$

where:β_2 and β_3 are the coefficients for the interaction terms between ENVT and GDPG, and ENVT and POPG, respectively.

The inclusion of interaction terms in this model is important because it allows for a more comprehensive analysis of the relationship between environmental tax, GDP growth rate, and population growth on CO_2 emissions embodied in domestic final demand. Without interaction terms, the model assumes that the effects of environmental tax, GDP growth rate, and population growth on the dependent variable are independent of each other. However, in reality, the impact of environmental tax on CO_2 emissions embodied in domestic final demand may depend on the level of GDP growth rate and population growth. By including interaction terms, the model is able to capture any potential interactions between the independent variables and the dependent variable.

Furthermore, the inclusion of interaction terms allows for a more detailed understanding of the underlying mechanisms that drive the relationship between environmental tax and CO_2 emissions embodied in domestic final demand. For example, the coefficient of the interaction term between environmental tax and GDP growth rate (β_2) measures the additional effect of environmental tax on CO_2 emissions embodied in domestic final demand given a certain level of GDP growth rate. Similarly, the coefficient of the interaction term between environmental tax and population growth (β_3) measures the additional effect of environmental tax on CO_2 emissions embodied in domestic final demand given a certain level of population growth.

3.2.2 Asymmetric panel ARDL

The NARDL model, on the other hand, is an extension of the ARDL model that takes into account the possibility of asymmetric relationships between variables over time. This is important in the context of environmental policy, as the effects of policy changes on CO_2 emissions may not be symmetric across different time periods. The NARDL model allows for examination of the impact of policy changes on CO_2 emissions in both the short run and long run, while also allowing for the possibility of asymmetric relationships between the policy variables and emissions. The asymmetric assumption in the relationship between variables refers to the idea that the effect of a change in one variable on another variable may be different depending on the direction of the change. For example, a 1% increase in a policy variable may have a different effect on CO_2 emissions than a 1% decrease in the same policy variable. Therefore, environmental policies may have different effects on CO_2 emissions depending on the specific policy measures implemented, the economic conditions at the time the policy is implemented, and the overall level of emissions at the time the policy is implemented. Additionally, the effects of policy changes on CO_2 emissions may not be immediate and may take time to fully materialize. Furthermore, the asymmetric assumption is also supported by previous research in this area. Studies have shown that environmental policies have heterogeneous effects on CO_2 emissions and that the direction of policy change is an important factor in determining the size and direction of the effect on emissions (Tang & Dou, 2021).

We implement the Shin and Greenwood-Nimmo (2014) nonlinear ARDL model in panel form, which is a suitable representation of dynamic heterogeneous panel data models for large T panels. This approach is adopted for three key reasons. Firstly, it enables us to capture asymmetries in a nonlinear way. Secondly, it accounts for inherent heterogeneity effects that are present in the data. Thirdly, this approach is more appropriate when there is a unit root or mixed order of integration of not more than I(1). In contrast to traditional large N, small T dynamic panels, the asymptotics of large N, large T dynamic panels differ significantly, as highlighted by Blackburne and Frank (2007). Small T panel estimation typically relies on fixed- or random-effects estimators, or a combination of fixed-effects estimators and instrumental-variable estimators, such as the Arellano and Bond (1991) generalized method-of-moments estimator (Blackburne and Frank, 2007). However, it is often inappropriate to assume homogeneity of slope parameters in large N, large T dynamic panels. As a result, we employ the dynamic heterogeneous panel data model in our study since we are dealing with large T panels. The asymmetric long-run regression is expressed as:

$$\Delta\gamma_{it} = \beta_{0i} + \beta_{1i}\gamma_{i,t-1} + \beta_{2i}^{+}\delta_{t-1}^{+} + \beta_{2i}^{-}\delta_{t-1}^{-} + \sum_{j=1}^{N1}\lambda_{ij}\Delta\gamma_{i,t-j} + \sum_{j=0}^{N2}\left(\varphi_{ij}^{+}\Delta\delta_{t-j}^{+} + \varphi_{ij}^{-}\Delta\delta_{t-j}^{-}\right) + \mu_i + \varepsilon_{it}. \tag{5}$$

where δ_t^+ and δ_t^- denote the positive and negative shocks in the explanatory variables, respectively. The long-run (elasticity) coefficients for δ_t^+ and δ_t^- are calculated as $-\frac{\beta_{2i}^{+}}{\beta_{1i}}$ and $-\frac{\beta_{2i}^{-}}{\beta_{1i}}$. The partial sum decompositions of changes in the explanatory variables are used to isolate the impact of the shocks on the response variable, while holding other factors constant. This allows us to better understand the relationship between the explanatory and response variables and to analyze the impact of shocks on the model. By calculating the long-run coefficients for positive and negative shocks, we can determine the direction and magnitude of the impact of these shocks on the response variable in the long run. This information can be useful in predicting future trends and making informed decisions based on the model's predictions. The positive and negative shocks of changes in the explanatory variables as defined below:

$$\delta_t^+ = \sum_{k=1}^{t}\Delta\delta_{ik}^{+} = \sum_{k=1}^{t}\max\left(\Delta\delta_{ik}, 0\right) \tag{6}$$

$$\delta_t^- = \sum_{k=1}^{t}\Delta\delta_{ik}^{-} = \sum_{k=1}^{t}\min\left(\Delta\delta_{ik}, 0\right) \tag{7}$$

The error correction version of Eq. (5) can be expressed as follows:

$$\Delta\gamma_{it} = \rho_i\xi_{i,t-1} + \sum_{j=1}^{N1}\lambda_{ij}\Delta\gamma_{i,t-j} + \sum_{j=0}^{N2}\left(\varphi_{ij}^{+}\Delta\delta_{t-j}^{+} + \varphi_{ij}^{-}\Delta\delta_{t-j}^{-}\right) + \mu_i + \varepsilon_{it} \tag{8}$$

The error correction term and speed of adjustment $\xi_{i,t-1}$ captures the long-run equilibrium in the asymmetric panel ARDL specified in Eq. (8), while its associated parameter ρ_i is the speed of adjustment term that measures how long it takes the system to converge to its long-run equilibrium in the presence of a shock.

4 Results and discussion

4.1 Descriptive statistics

The descriptive statistics results in Table 3 provide important insights into the distribution and central tendency of the variables as well as the Variance Inflation Factors (VIF) test for multicollinearity.

The first panel of Table 3 presents the descriptive statistics. Starting with CDFD, The wide range of values for the natural logarithm of CO_2 emissions suggests that there are significant differences in CO_2 emissions across countries in developing Africa. This information is crucial for designing effective policies that can reduce CO_2 emissions and mitigate the impact of climate change. The mean, maximum, and minimum values for the environmental tax (% of GDP) indicate that this variable has a moderate dispersion of values around the mean and a negative minimum, which is concerning. The negative minimum value suggests that some countries in developing Africa provide subsidies or tax breaks for environmentally harmful activities. This finding highlights the need for more effective environmental policies that incentivize sustainable practices and discourage environmentally harmful activities. The wide range of values for the GDP growth rate indicates significant variation in economic growth across countries in developing Africa. This finding is important for policymakers as they need to understand the relationship between economic growth and environmental sustainability. Balancing economic growth with environmental sustainability requires a careful assessment of policies that can promote economic growth without undermining environmental goals. Finally, the moderate dispersion of values around the mean and the negative minimum for the population growth rate suggest that some countries in developing Africa have a declining population.

The second panel presents the result of the variance inflation factor (VIF) test for multicollinearity in a panel data analysis. The Variance Inflation Factor (VIF) is a crucial measure for assessing multicollinearity in a regression model, as it helps to identify the degree of correlation between the independent variables. High VIF values indicate a strong correlation

Table 3 Descriptive statistics and variance inflation factors results

Variable	Mean	Max	Min	Std. Dev	Obs
CDFD	130.4994	559.899	2.563	123.0523	552
ENVT	1.682181	5.3	−1.53	1.078707	555
GDPG	3.982537	19.04728	−14.1154	4.031215	620
POPG	0.917574	2.760033	−2.1707	0.816561	621

Variance inflation factors: test for multicollinearity

	Coefficient	Uncentered	Centered
Variable	Variance	VIF	VIF
ENVT	29.03651	3.940714	1.167638
GDPG	2.204596	2.332799	1.012911
POPG	50.22623	2.528397	1.181429

between two or more independent variables, which can lead to problems such as unreliable coefficient estimates and unstable predictions. In this study, we examined multicollinearity in all nine models by calculating the VIF values, which are presented in Table 3. A VIF exceeding 5 or 10 indicates high multicollinearity between independent variables and other variables. However, our results showed that all explanatory variables had VIF values less than 5, suggesting that our models are free from any multicollinearity issues.

4.2 Cross cross-sectional dependence test

The assessment of cross-sectional dependence (CSD) in panel data is an important step in ensuring the validity of the statistical models used in the analysis. The results presented in Table 4 provide insight into the extent to which the data may be correlated across the different sections of the panel. The CSD test results suggest that there is no significant cross-sectional dependence in the data, which indicates that the statistical models used in the analysis are valid. The lack of significant cross-sectional dependence implies that each country in the panel data can be considered an independent unit for analysis. The results also suggest that any shocks or disturbances that occur in one country are not transmitted to other countries in the panel data, indicating that the panel can be treated as a set of independent observations. It is important to note, however, that the absence of cross-sectional dependence does not imply that there is no correlation between the variables within each country. It only suggests that any correlation that exists is limited to within-country relationships and not between countries in the panel data.

4.3 Panel unit root test

Table 5 shows the results of the first generation of tests conducted, taking into consideration the cross-sectional independence confirmed by the cross-sectional dependence test result in Table 3.

The results of the panel unit root test are presented in Table 4, indicating that the variables under investigation do not have unit roots and attain stationarity at I(0) and I(1), but not at I(2). This finding is significant as it fulfills the necessary condition for estimating panel autoregressive distributed-lag (ARDL) models using various estimators. This is particularly relevant for our research, which involves a large number of individuals (N) and time periods (T), as highlighted by Pesaran and Shin (1996, 1999). Thus, the panel ARDL model is the appropriate method for estimation.

4.4 Presentation and discussion of regression results

The study employs two different estimators, MG and PMG, to estimate all the equations, followed by a Hausman test to determine the efficient estimator. The null hypothesis is

Table 4 Cross-sectional dependence test results

Variables	LM [Prob]	CDLM [Prob]	CD [Prob]	LMadj [Prob]
CDFD	69.57898 [0.164]	17.56604 [0.241]	7.604484 [0.135]	17.47542 [0.216]
ENVT	110.834 [0.299]	29.44551 [0.037]	9.843175 [0.199]	29.3257 [0.17]
GDPG	99.02753 [0.634]	26.05632 [0.151]	9.296017 [0.157]	25.96292 [0.043]
POPG	13.00577 [0.106]	17.60726 [0.147]	2.94647 [0.171]	9.897019 [0.106]

Table 5 Panel unit root test

Variable	Methods & statistic					Order of integration
	[a]Levin, Lin & Chu t	[a]Breitung t-stat	[b]Im, Pesaran and Shin W-stat	[b]ADF—Fisher Chi-square	[b]PP—Fisher Chi-square	
CDFD	−4.51705***	−4.80211**	−14.5797**	315.937***	1990.59**	I(1)
ENVT	−1.69272***	−3.35601***	−1.88489**	75.0678***	96.7741***	I(0)
GDPG	−4.07173**	−3.21738***	−3.98347***	108.656***	253.495***	I(0)
POPG	−8.67584***	−6.62077**	−12.5722***	272.841***	1238.36***	I(1)

**Significant at 5%

***Significant at 1%

[a]Null: Unit root (assumes common unit root process),

[b]Null: Unit root (assumes individual unit root process)

that the PMG estimator is more efficient, while the alternative hypothesis is that the MG estimator is more efficient. The results of the Hausman test strongly support the adoption of the PMG estimator as the efficient estimator for modeling the linkages between environmental tax and CO_2 emissions embodied in domestic final demand. Tables 6 and 7 illustrate that the PMG estimator is consistently chosen as the efficient estimator for all the models, whether the specification is linear (symmetric) or nonlinear (asymmetric). Consequently, only the results obtained from the preferred estimator (PMG) are discussed in this study.

4.4.1 Symmetric panel ARDL analysis with interaction terms

The panel autoregressive distributed lag (ARDL) model with interaction terms is an advanced econometric model that seeks to estimate the relationship between a dependent variable and one or more independent variables. It considers the potential moderating effects of the independent variables on the dependent variable. In the present study, we use this model to investigate the relationship between CO_2 emissions embodied in domestic final demand (CDFD) and environmental tax (ENVT), with GDP growth rate (GDPG) and population growth rate (POPG) as control variables.

Our analysis focuses on the long-run estimates generated by the pooled mean group (PMG) method, which is the preferred model in line with the Hausman test results. This method is preferred for its ability to overcome the limitations of the mean group (MG), such as the unbalanced panel data, serial correlation, and heteroscedasticity. By using the PMG approach, we can obtain more reliable and robust results. In addition to the long-run estimates, we also present the short-run results, which reveal the dynamics of the relationship between the variables in the short term. However, for the purpose of our analysis, we primarily rely on the PMG long-run estimates. These estimates are crucial for understanding the sustained and stable effects of environmental tax on CO_2 emissions embodied in domestic final demand, after accounting for the influence of GDP growth rate and population growth rate.

The findings presented in Table 6 demonstrate a significant and positive association between environmental tax (ENVT) and CO_2 emissions embodied in domestic final demand (CDFD). The parameter estimate indicates that a 1% increase in ENVT

Table 6 Baseline ARDL results with interaction terms

Response variable: CO_2 emissions embodied in domestic final demand (CDFD)				
Selected model: ARDL(1, 1, 1, 1)				
Model selection method: Akaike info criterion (AIC)				
Sample (unadjusted): 1995–2021				
	Pooled mean group (PMG)		Mean Group (MG)	
	Coefficient	*t*-statistic	Coefficient	t-Statistic
Long-run coef.				
ENVT	0.493**	5.534	−0.055*	−1.442
ENVT*GDPG	−0.122*	−1.856	0.232**	4.121
ENVT*POPG	−0.085**	−2.718	−0.427**	−3.084
GDPG	0.146**	3.225	0.063**	2.609
POPG	0.764**	4.131	−0.110*	−0.881
Short-run coef.				
D(ENVT)	0.472*	1.454	0.151**	3.103
D(ENVT*GDPG)	−0.164	−1.138	−0.094*	−1.244
D(ENVT*POPG)	−0.505**	−4.63	0.016*	0.886
D(GDPG)	0.778	0.575	−0.180**	−4.032
D(POPG)	0.569**	5.509	0.132**	2.117
Adj. speed	−0.811**	−3.473	−0.528**	2.973
Intercept	1.895**	2.531	1.333*	1.775
Log likelihood	709.002			
Hausman	0.817			
No. of groups	24			
No. Obs	575			

corresponds to a 0.49% increase in CDFD. This positive coefficient for ENVT is counterintuitive as environmental tax is usually implemented as a policy tool to reduce CO_2 emissions. This is in line with Bashir et al. (2020) and Silajdzic and Mehic (2018) among other studies that argue that environmental tax has not been effective in reducing CO_2 emissions. Moreover, some body of literature contend that environmental tax correlates with reduction in CO_2 emissions (see Wei et al., 2022; Safi et al., 2021; Mardones & Muñoz, 2018). However, these results contradict the findings of Sundar et al. (2016), which suggests that as the rate of environmental tax increases, the concentration of carbon dioxide decreases. In the same vein, Mardones and Flores (2018) found that environmental taxes, when set at either excessively low or excessively high levels, prove effective in generating revenue but fail to effectively curb emissions.

There are several possible explanations for this unexpected result. Firstly, an increase in environmental tax may decrease the cost of production for firms, which could increase economic activity and subsequently lead to an increase in CO_2 emissions. Secondly, a reduction in environmental tax may reduce the incentive for firms to invest in clean technologies and practices, thereby increasing the level of CO_2 emissions. In the light of these findings, policymakers should exercise caution when considering increasing

Table 7 Panel NARDL Estimation Results

Response variable: CO_2 emissions embodied in domestic final demand (CDFD)				
Selected model: ARDL(1, 1, 1, 1)				
Model selection method: Akaike info criterion (AIC)				
Sample (unadjusted): 1995–2021				
	Pooled mean group (PMG)		Mean group (MG)	
	Coefficient	*t*-statistic	Coefficient	*t*-statistic
Long-run coef.				
$ENVT^+$	−0.104**	−2.318	−0.009*	−0.820
$ENVT^-$	−0.311**	−5.564	−0.015**	−3.054
$GDPG^+$	0.013**	−2.730	−0.011**	−2.671
$GDPG^-$	−0.007**	6.367	0.008**	4.822
$POPG^+$	0.034**	3.426	−0.052*	−1.745
$POPG^-$	0.023**	4.206	0.016*	1.193
Short-run coef.				
$D(ENVT)^+$	0.181*	1.362	0.013**	2.844
$D(ENVT)^-$	0.065*	1.664	−0.069*	−0.881
$D(GDPG)^+$	0.011**	4.139	0.003*	1.257
$D(GDPG)^-$	−0.023**	−8.693	−0.014**	−3.508
$D(POPG)^+$	−0.019*	−0.677	0.033**	3.071
$D(POPG)^-$	−0.047**	−4.394	−0.088**	−5.987
Adj. speed	−0.733**	−4.199	−0.811**	−3.249
Intercept	1.654	1.470	1.892	1.629
Log likelihood	685.447			
Hausman	0.649			
No. of groups	24			
Periods included	27			
No. obs	820			

environmental tax as a strategy to reduce CO_2 emissions. Instead, they should consider other measures such as regulations, subsidies for clean energy, and incentives for the development of clean technologies.

The model includes an interaction term between environmental tax (ENVT) and GDP growth rate (GDPG) to assess how the joint effect of these two variables affects CO_2 emissions. The result shows that the coefficient of the interaction term is negative (−0.12). This implies that as the GDP growth rate increases, the effectiveness of environmental tax in reducing CO_2 emissions embodied in domestic final demand decreases. This result suggests that economic growth may offset the emission reduction benefits of environmental taxes. Moreover, the estimated coefficient of −0.12 suggests that for every 1% increase in GDP growth rate, the impact of environmental tax in reducing CO_2 emissions embodied in domestic final demand declines by 0.12%. This indicates that the impact of environmental tax on emissions reduction becomes less effective as the economy grows. These results have important implications for policymakers as they suggest that environmental taxes alone may not be sufficient to reduce CO_2 emissions in the context of rapid economic growth. Additional measures such as incentives for clean technology, renewable energy, and energy efficiency, as well as regulations on high-emission industries, may be necessary to achieve emissions reduction targets while promoting sustainable growth.

Further, the coefficient of the interaction term ENVT*POPG is −0.09, indicating a negative and statistically significant relationship between environmental tax and population growth rate on CO_2 emissions embodied in domestic final demand. This suggests that as population growth rate increases by 1%, the effectiveness of environmental tax in reducing CO_2 emissions decreases by 0.09%. This finding is particularly relevant for policymakers who seek to design and implement sustainable environmental policies. Furthermore, the coefficient of population growth as a control variable, without any interaction with environmental tax, is also found to be positive and statistically significant. This implies that as population grows, the demand for goods and services increases, leading to an increase in economic activity, and consequently an increase in CO_2 emissions. Additionally, as population grows, the demand for housing, transportation, and energy also increases, which may further contribute to an increase in CO_2 emissions.

The result also revealed a positive relationship between GDP growth rate and CO_2 emissions embodied in domestic final demand. As the GDP growth rate increases by 1%, the CO_2 emissions embodied in domestic final demand also increase by 0.15%. The findings of this study align with the research conducted by Aye and Edoja (2017), who suggest a correlation between GDP growth and a rise in CO_2 emissions during periods of low growth. Similarly, Usman et al. (2023) discovered a feedback causal effect between economic growth and greenhouse gas emissions in the Mercosur countries, further supporting the notion that our economic and environmental well-being are inextricably linked. Nevertheless, the discovery contradicts the claim made by Aye and Edoja (2017) that in the low growth regime, economic growth is negatively associated with CO_2 emissions. In the context of developing economies, this finding suggests that economic growth and environmental protection may not always be mutually exclusive. In other words, achieving economic growth while simultaneously reducing emissions requires policies that promote sustainable growth and reduce emissions. Similarly, the result also indicates a positive relationship between population growth and CO_2 emissions embodied in domestic final demand. As the population grows, the CO_2 emissions embodied in domestic final demand also increase by 0.74%. This implies that as the population increases, so does the demand for goods and services, which in turn leads to an increase in CO_2 emissions. However, policies can be put in place to mitigate the negative impact of population growth on the environment, such as implementing more energy-efficient practices, promoting renewable energy sources, and encouraging sustainable consumption patterns. Additionally, policymakers could implement policies that limit the environmental impact of population growth, such as investing in public transportation and encouraging low-impact housing developments. Such policies could mitigate the negative impact of population growth on the environment while promoting sustainable economic development.

4.4.2 Asymmetric panel ARDL analysis with interaction terms

The discussion of the results presented in Table 7 suggests that there is an asymmetric relationship between environmental tax and CO_2 emissions embodied in domestic final demand in developing economies. The panel NARDL model estimation shows that a negative change in environmental tax has a more significant adverse effect on CO_2 emissions embodied in domestic final demand than a positive change. This means that when environmental taxes are decreased, there is a stronger impact on CO_2 emissions than when they are increased. The coefficients on the positive and negative changes in environmental tax provide evidence for this finding. The coefficient on the positive change in environmental tax (*ENVT*+) is -0.10, which suggests that a 1% increase in environmental tax is associated with a 0.10% decrease in CO_2 emissions embodied in domestic final demand. On the other hand, the coefficient on the negative change in environmental tax (*ENVT*−) is approximately −0.31, which is about three times larger than the coefficient on the positive change. This implies that a 1% decrease in environmental tax is associated with a 0.31% increase in CO_2 emissions embodied in domestic final demand. This is consistent with Shrestha et al. (1998) that argued that lowering carbon tax has detrimental effect on CO_2 emission. On the contrary, Mardones and Muñoz (2018) argue that a reduced carbon tax can yield positive outcomes in curbing CO_2 emissions. Similarly, Aydin and Esen (2018) contend that when environmentally related taxes on CO_2 emissions surpass a threshold level in 15 EU member countries, their impact shifts from being insignificantly positive to significantly negative. This finding has significant implications for policymakers who are considering changes in environmental tax as a strategy to reduce CO_2 emissions. The result suggests that an increase in environmental tax is associated with a decrease in CO_2 emissions embodied in domestic final demand, while a decrease in environmental tax is strongly related to an increase in CO_2 emissions embodied in domestic final demand. Therefore, policymakers should exercise caution when considering changes in environmental tax and should carefully consider the potentially adverse impact of a reduction in environmental tax on CO_2 emissions.

Furthermore, the findings suggest that there is a correlation between shocks to GDP growth and changes in CO_2 emissions embodied in domestic final demand (CDFD) in developing economies. Both positive and negative shocks to GDP growth are found to be associated with an increase in CDFD. However, the model suggests that negative shocks to GDP growth have a less severe impact on CDFD than positive shocks. This finding may be attributed to the fact that negative shocks to GDP growth may lead to a decrease in economic activity and, therefore, a reduction in energy consumption and subsequent CO_2 emissions.

The result suggests that population growth is a crucial factor to consider when developing policies aimed at reducing CO_2 emissions. The finding that positive shocks to population growth are associated with an increase in CDFD indicates that as the population grows, the demand for goods and services increases, leading to an increase in CO_2 emissions embodied in domestic final demand. Similarly, negative shocks to population growth are correlated with a decrease in CDFD, indicating that a decrease in the population size may lead to a reduction in CO_2 emissions embodied in domestic final demand. Therefore, the study highlights the importance of taking population dynamics into account when developing policies aimed at reducing CO_2 emissions in developing economies.

4.4.3 Robustness check and analysis of baseline estimation with additional control variables and a response variable

Table 8 presents the results of a robustness test conducted to confirm the stability of the findings obtained from the baseline estimations, using Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) techniques. The FMOLS and DOLS techniques account for

Table 8 Results of FMOLS and DOLS tests

Variable	DOLS (1) [Coeff.] (*p*-value)	DOLS (2) [Coeff.] (*p*-value)	FMOLS (1) [Coeff.] (*p*-value)	FMOLS (2) [Coeff.] (*p*-value)
Response variable: CO_2 emissions embodied in domestic final demand				
ENVT	[0.0191]		[0.0250]	
	(0.0304)		(0.0119)	
GDPG	[0.0988]		[0.1562]	
	(0.0071)		(0.0262)	
POPG	[0.0310]		[0.0369]	
	(0.0440)		(0.0238)	
TOPN	[0.0012]		[0.0167]	
	(0.0119)		(0.1346)	
TINOV	[-0.0179]		[−0.0645]	
	(0.0083)		(0.0572)	
Response variable: greenhouse gas (GHG) emission				
ENVT		[0.0071]		[0.0262]
		(0.0016)		(0.0166)
GDPG		[−0.219]		[−0.1531]
		(0.0679)		(0.0238)
POPG		[−0.3229]		[0.1071]
		(0.0000)		(0.0700)
TOPN		[0.0015]		[0.0012]
		(0.0024)		(0.0600)
TINOV		[−0.1107] (0.0019)		[−0.1321] (0.0000)
R^2	0.765	0.772	0.856	0.815
Adjusted R^2	0.711	0.729	0.818	0.784
	Kao residual cointegration test		Kao residual cointegration test	
t-statistic	−4.554		−3.903	
Prob	0.000		0.000	
Residual variance	44.292		51.351	
HAC variance	17.875		21.116	

nuisance parameters, autocorrelation, heteroscedasticity, and endogeneity issues that may arise from explanatory variables that are correlated with the error term, and are superior to the OLS estimator. The results of the FMOLS and DOLS techniques confirm and extend the previous long-run findings from panel ARDL estimations. The Kao cointegration tests reveal that there is a long-run relationship in both models, rejecting the null hypothesis of no such relationship. In the robustness test, two models are presented: DOLS (1) and FMOLS (1) analyse the influence of environmental tax, GDPG and POPG, along with new control variables, TOPN and TINOV, on CDFD, while DOLS (2) and FMOLS (2) estimate the effect of environmental tax, along with the control variables, on GHG emissions.

The results from DOLS (1) and FMOLS (1) confirm that environmental tax is positively associated with CO_2 emissions embodied in domestic final demand in developing economies. Although the direction of the relationship remains consistent across models, the magnitude of the effect varies. In contrast, DOLS (2) and FMOLS

(2) reveal that environmental tax is associated with a decrease in GHG emissions in developing countries. The results also show that technological innovation is significantly associated with a decrease in CDFD and GHG emission, consistent with Jahanger et al. (2022). On the contrary, the study conducted by Shmelev and Speck in 2018 revealed that the implementation of a CO_2 tax in Sweden did not lead to a substantial reduction in CO_2 emissions. Likewise, according to a study by Țibulcă (2021), it was discovered that Environmental taxes have proven to be ineffective in mitigating air pollution within the European Union. However, while trade openness is found to be positively related to CDFD, it was negatively correlated with GHG emission. In general, the impact of TOPN and TINOV on the baseline PMG estimations varied in terms of magnitude, but not in direction. Consequently, the robustness test affirms that the results obtained from the model are stable.

5 Concluding practical policy implications

Based on the results of the study, there are several practical implications and policy recommendations that can be made. Firstly, the finding that there is an asymmetric relationship between environmental tax and CO_2 emissions embodied in domestic final demand in developing economies implies that policymakers should carefully consider the effects of changes in environmental taxes. Specifically, decreasing environmental taxes should be avoided as much as possible, as the negative impact on CO_2 emissions is much stronger than the positive impact of increasing taxes. Therefore, it is recommended that policymakers focus on increasing environmental taxes, as this can lead to a significant reduction in CO_2 emissions embodied in domestic final demand. Secondly, the study also found that positive and negative shocks to GDP growth are associated with an increase in CO_2 emissions embodied in domestic final demand. This implies that policies that promote sustainable economic growth should be implemented, such as investment in renewable energy, energy efficiency, and sustainable transportation. These policies can help to reduce the negative impact of GDP growth on CO_2 emissions embodied in domestic final demand.

The findings of this study suggest that environmental taxes alone may not be sufficient in reducing CO_2 emissions in developing economies. The contingency analysis and interaction term reveal a positive association between ENVT and CO_2 emissions embodied in domestic final demand, indicating that environmental taxes may not be as effective in reducing emissions as previously thought. This finding is crucial as it highlights the need for policymakers to take a more comprehensive approach to reducing CO_2 emissions. Policymakers must look beyond environmental taxes as the only means to reduce emissions and consider alternative measures that may be more effective. Moreover, the observed negative coefficient for the interaction term between ENVT and GDP growth rate is particularly concerning. It suggests that economic growth may offset the emission reduction benefits of environmental taxes, rendering them less effective in reducing CO_2 emissions. As developing economies strive for growth, this finding is essential for policymakers to take into account when developing policies aimed at reducing emissions. Policymakers must consider additional measures to reduce emissions and promote sustainable growth. One potential solution could be to provide incentives for clean technology, renewable energy, and energy efficiency. These incentives can encourage businesses and individuals to invest in clean technologies that reduce emissions and contribute to sustainable growth. For example, governments could offer tax credits or grants for businesses that invest in clean technologies or install renewable energy sources such as solar panels. Policymakers can also consider regulations on high-emission industries to encourage them to adopt cleaner technologies and reduce their carbon footprint. For instance, governments can enforce emissions standards and impose penalties for non-compliance.

The results of the robustness test suggest that technological innovation is a key factor in reducing CO_2 emissions embodied in domestic final demand and greenhouse gas (GHG) emission. This finding has important practical implications for policymakers and stakeholders in addressing climate change and mitigating the negative impact of global warming. Firstly, policymakers should prioritize investments in research and development to promote the adoption of environmentally friendly technologies, particularly in industries that emit significant amounts of GHG. Additionally, the government can incentivize firms to adopt green technology by providing tax credits or subsidies. This policy approach can create a win–win scenario where businesses can improve their bottom line while reducing their environmental footprint. Secondly, the negative correlation between trade openness and GHG emissions highlights the importance of trade policies that encourage sustainable production and consumption patterns. Policymakers can leverage trade agreements to promote green production practices by establishing common standards for environmental protection and reducing trade barriers for environmentally friendly products. Moreover, policymakers should consider imposing carbon tariffs on imported goods produced in countries with weaker environmental regulations to incentivize sustainable practices and create a level playing field for domestic producers.

Although the study on the asymmetric effects of environmental taxes on CO_2 emissions embodied in domestic final demand provides valuable information, there are still some limitations that need to be addressed in future research. The study's sample size was limited to 23 developing economies, which may restrict the generalizability of the findings to other regions or countries. Additionally, the study focused solely on the impact of environmental taxes on CDFD, disregarding the potential impact of other environmental policies such as cap-and-trade systems and subsidies. In future research, expanding the scope of analysis to a wider range of countries, investigating the impact of other environmental policies, and exploring the potential interactions between policies could provide more comprehensive guidance to policymakers on effective strategies for reducing CO_2 emissions while promoting sustainable economic growth in developing economies.

Data availability The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors of this article declare that they have not received any funding from any individual, organization, or corporation for the research or writing of this article, and has no conflict of interest.

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