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ORIGINAL RESEARCH PAPER

Comparative Effects of Financial Depth and Economic Openness on Environmental Pollution Indicators in Developing and Developed Countries with Emphasis on Global Warming Potential

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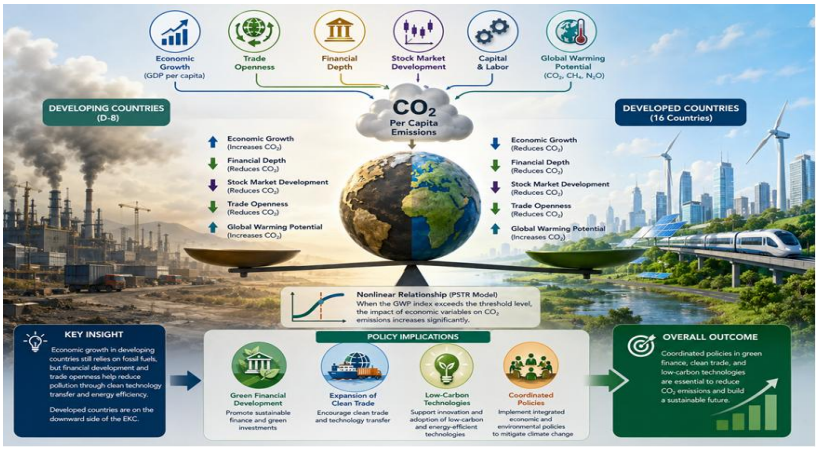
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A B S T R A C T

This study examines the comparative effects of financial depth and economic openness on environmental pollution, with particular emphasis on global warming potential (GWP), in selected developing and developed countries during 2000–2024. The sample includes the D-8 member states as developing countries and sixteen developed economies. Per capita carbon dioxide (CO_2) emissions are used as the indicator of environmental pollution. The explanatory variables include per capita GDP, trade openness, stock market development, financial depth, capital, labor force, and GWP, measured by converting CO_2, CH_4, and N_2O emissions into carbon dioxide equivalents. The Panel Smooth Transition Regression (PSTR) model is employed to capture nonlinear relationships after confirming stationarity and cointegration through the IPS unit root and Kao cointegration tests. The findings show that in developing countries, per capita GDP and GWP increase CO_2 emissions, whereas financial development, stock market development, and trade openness significantly reduce environmental pollution. In developed countries, per capita GDP has a negative effect on emissions, supporting the Environmental Kuznets Curve hypothesis, while financial development, stock market development, and trade openness also contribute to environmental improvement. GWP exerts a positive and significant effect on pollution in both groups. Overall, the results suggest that exceeding the GWP threshold intensifies the environmental impacts of economic activities, highlighting the importance of promoting green finance, clean trade, and low-carbon technologies..



1. Introduction

Financial depth reflects the extent of development of financial markets and their ability to mobilize and allocate financial resources to different sectors of the economy. The more developed a country's financial system is, the greater and more diversified the access of firms and households to credit resources will be. This can facilitate investment in infrastructure, industries, and new technologies. In developed countries, financial depth is usually associated with higher efficiency of the banking system, the existence of advanced capital markets, and broad access to financial instruments. Such conditions make it possible to finance environmental projects, develop renewable energies, and promote low-carbon technologies [1]. In contrast, in many developing countries, financial development has not yet reached a level at which it can play an effective role in financing clean technologies. In these countries, financial resources are often directed toward sectors with higher short-term returns, such

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as extractive industries, energy-intensive manufacturing, and activities dependent on fossil fuels. Under such conditions, increased access to credit may lead to the expansion of polluting industrial activities and, consequently, an increase in greenhouse gas emissions. Therefore, the effect of financial depth on the global warming potential index in developing countries may be positive in the short run, although this relationship may change in the long run with improvements in institutional structures and increased investment in clean technologies [2]. Another important economic factor affecting environmental pollution is the degree of economic openness. Economic openness indicates the extent to which an economy is integrated into global trade and is usually measured by the ratio of exports and imports to gross domestic product. Increased foreign trade can affect greenhouse gas emissions through several channels. One of these channels is the scale effect, which refers to the increase in production and consumption resulting from trade expansion. When international trade increases, the level of economic production also rises, and as a result, energy consumption and pollutant emissions may increase [4]. In developing countries, the situation is somewhat different. In some cases, increased economic openness has led to the attraction of foreign investment in manufacturing and extractive industries, which often have high energy consumption. If environmental regulations are weak, this can result in increased greenhouse gas emissions. This phenomenon is known in economic literature as the pollution haven hypothesis. According to this hypothesis, multinational corporations may transfer their polluting activities to countries with more lenient environmental law [3]. Nevertheless, the impact of foreign trade on the environment is not necessarily negative. If countries are able to use trade opportunities to import clean technologies and develop high-value-added industries, economic openness can help reduce greenhouse gas emissions. In recent years, many developing countries have attempted to reform their industrial and trade policies in order to shift their production structures toward lower-carbon activities. Under such conditions, foreign trade can play an important role in improving environmental performance [5]. A comparison of the effects of financial depth and economic openness shows that these two factors influence the global warming potential index through different channels. Financial depth mainly operates through the financing of investments and the direction of economic resource allocation. In contrast, economic openness affects greenhouse gas emissions primarily through changes in production structure, technology transfer, and increased international competition. The interaction between these two factors can also play a decisive role in shaping environmental outcomes [6]. For example, in an economy that has a developed financial system as well as a high level of foreign trade, firms can access the financial resources needed to import clean technologies. Such a combination can lead to a reduction in greenhouse gas emission intensity and an improvement in the global warming potential index. Conversely, if financial development occurs without appropriate environmental regulations and financial resources are mainly allocated to polluting industries, greenhouse gas emissions may increase even under conditions of economic openness.In developed countries, the combination of financial development, advanced technology, and strict environmental policies has usually caused economic growth to be accompanied by a gradual reduction in greenhouse gas emission intensity. Many of these countries have made extensive investments in renewable energy, energy efficiency, and the development of low-carbon technologies. The advanced financial systems of these countries have played an important role in financing such projects, which has helped financial depth contribute to the improvement of environmental indicators [7]. In contrast, developing countries face different challenges. These countries need to expand productive and industrial activities in order to achieve economic growth and reduce poverty. In many cases, this process is accompanied by increased energy consumption and greenhouse gas emissions. In addition, financial and technological constraints may prevent extensive investment in clean technologies. For this reason, the effects of financial depth and economic openness on the global warming potential index in these countries may differ from those in developed countries.However, global trends indicate that many developing countries are also gradually moving toward low-carbon development patterns. Increased international cooperation, the transfer of green technologies, and the creation of new financial mechanisms to support environmental projects can play an important role in this process. In this regard, the development of the financial system and the expansion of foreign trade, if accompanied by appropriate environmental policies, can become tools for reducing greenhouse gas emissions [8]. The comparative effects of financial depth and economic openness on environmental pollution indicators, especially the global warming potential index, depend on numerous factors. The level of economic development, industrial structure, quality of economic institutions, and strictness of environmental regulations are among the factors that can determine the direction and intensity of this relationship. While in developed countries financial development and foreign trade have often been associated with improved environmental performance, in developing countries this relationship is more complex and depends on economic management and environmental policies.From a policy-making perspective, coordination among financial, trade, and environmental policies is highly important. The development of the financial system should be guided in such a way that more financial resources are allocated to environmentally compatible projects and low-carbon technologies. Trade policies can also contribute to reducing greenhouse gas emissions by lowering barriers to the import of clean equipment and supporting the transfer of green technologies. Such an approach can pave the way for achieving sustainable economic growth and reducing the negative impacts of human activities on the global climate [9].

In recent decades, the relationship between economic development and the environment has become one of the most important research topics in economics. Although economic growth leads to improved welfare, increased production, and expanded investment opportunities, it is often accompanied by greater pressure on natural resources and rising environmental pollution. In this context, macroeconomic variables such as financial depth and the degree of economic openness play significant roles in shaping production patterns, energy consumption, and ultimately the level of environmental pollutants. Examining the comparative effects of these two factors can contribute to a better understanding of the economic mechanisms affecting the environment and provide a basis for designing environmentally sustainable development policies [10,11]. Financial depth refers to the level of development and efficiency of the financial system within an economy and is commonly measured using indicators such as the ratio of credit allocated to the private sector to gross domestic product, liquidity relative to GDP, and the development of capital markets. Increased financial depth generally implies greater access of firms and households to financial resources, increased investment, and improved resource allocation. On the one hand, this process can expand productive and industrial activities, thereby increasing energy consumption and pollutant emissions. On the other hand, financial development can facilitate investment in clean technologies, improve energy efficiency, and support the development of low-carbon industries. Therefore, the ultimate effect of financial depth on environmental pollution may be dual and dependent on the economic structure and environmental policies of each country [12]. In economies with more advanced financial systems, firms usually have access to cheaper and more diversified financial resources. This can increase investment in new equipment, more efficient technologies, and less energy-intensive production processes. Such developments may reduce energy intensity and pollutant emissions in the long run. However, in the early stages of financial development, increased access to credit may encourage the expansion of energy-intensive industrial activities and increase pollution levels in the short run. Accordingly, some studies suggest that the relationship between financial depth and environmental pollution may be nonlinear [13]. Alongside financial development, the degree of economic openness is also considered an important factor influencing the environment. Economic openness is generally measured by the ratio of total exports and imports to gross domestic product and reflects the extent of an economy's interaction with the global economy. Increased international trade can affect the environment through several channels. One of these channels is the scale effect, meaning that greater trade may increase economic production and consequently lead to higher energy consumption and pollutant emissions [14]. In contrast, the composition effect is another important mechanism through which foreign trade affects the environment. Economic openness can alter the structure of production and direct countries toward producing goods in which they hold a comparative advantag [15]. If a country's comparative advantage lies in polluting and energy-intensive industries, increased trade may result in greater pollution. However, if the country has a comparative advantage in technology-based or low-carbon industries, economic openness can help reduce pollution. Therefore, the compositional effect of trade on the environment largely depends on the production structure and the level of economic developmen [16]. The technology effect is another important channel through which trade influences the environment. International trade can facilitate the transfer of advanced and efficient technologies. Imports of modern machinery and clean technologies can improve energy efficiency and reduce pollutant emissions. In addition, competition arising from foreign trade may force firms to adopt more efficient and environmentally friendly technologies [17].

However, some perspectives argue that international trade may lead to the relocation of polluting industries from developed countries to developing countries. This view, known as the "Pollution Haven Hypothesis," suggests that multinational corporations may transfer their polluting activities to countries with weaker environmental regulations in order to reduce environmental compliance cost [18]. A comparison of the effects of financial depth and economic openness on environmental pollution indicators shows that both factors can affect the environment through different mechanisms. Financial development mainly operates through the provision of investment resources and changes in firms' financing patterns, whereas economic openness primarily influences the environment through changes in production structures, technology transfer, and increased international competitio [19]. For example, in an economy with a developed financial system and a high level of foreign trade, firms' access to financial resources can facilitate the import of clean technologies. This may reduce energy intensity and pollutant emissions. Conversely, if a developed financial system mainly allocates financial resources to polluting industries, the combination of financial development and economic openness may intensify negative environmental effects [20]. Another important dimension of this issue is the role of government policies and institutional frameworks. Appropriate environmental regulations can direct investments toward clean technologies. Under such conditions, financial development can become a tool for financing green projects and expanding renewable energy. Likewise, suitable trade policies can facilitate the import of energy-efficient equipment and clean technologie [21].

Empirical studies conducted in different countries have produced varying results regarding the relationship between financial depth, economic openness, and environmental pollution. In some countries, financial development has been associated with increased carbon dioxide emissions, whereas in others, financial system development has contributed to reducing pollution. These differences are generally related to the level of economic development, industrial structure, institutional quality, and environmental policies [22]. In developing economies that are highly dependent on energy-intensive industries, increased access to financial resources may initially expand industrial activities and energy consumption in the short run. However, in the long run, if financial development is accompanied by supportive policies for clean technologies, it can contribute to reducing pollution. Similarly, economic openness can have varying environmental effects depending on a country's economic structure [23]. From a policy perspective, understanding the comparative effects of financial depth and economic openness on environmental pollution indicators can help in designing sustainable development policies. If financial development occurs without considering environmental consequences, it may lead to increased pollution. Therefore, financial and banking policies should be designed in ways that encourage investment in green projects and low-carbon technologies [24]. In the field of foreign trade, adopting policies that facilitate the transfer of clean technologies is highly important. Reducing import tariffs on environmental equipment, supporting foreign investment in renewable energy, and strengthening environmental standards can reinforce the positive environmental effects of economic openness. In addition, international cooperation in technology transfer and financing environmental projects can play an important role in pollution reduction [25]. In conclusion, the relationship between financial depth, economic openness, and environmental pollution is complex and multidimensional. Each of these factors can generate both positive and negative environmental effects, and the final outcome depends on economic management, production structures, and institutional frameworks. Therefore, achieving sustainable development requires coordinated financial and trade policies that ensure economic growth alongside environmental protection.

1.1. Channels Through Which Financial Depth Affects Environmental Pollution Indicators

Pollution-reducing effect

- Firms can invest in clean technologies more easily.
- Financing for renewable energy and equipment modernization increases.
- Inefficient and polluting firms may become more efficient due to pressure from financial markets.

The effect of financial depth is usually nonlinear:

- At low levels of financial development, it may lead to increased pollution.
- At higher levels, and when accompanied by appropriate regulations, it can reduce pollution.

1.2. Channels Through Which Economic Openness Affects Environmental Pollution Indicators

Economic openness refers to the extent of a country's participation in global trade, imports, exports, and foreign investment.

- The import of advanced machinery and technologies can bring clean technologies into the country.
- Global competition may encourage firms to improve productivity and reduce energy consumption.
- Access to global markets may sometimes compel countries to comply with environmental standards.

In many empirical studies, these relationships are observed as follows:

- U-shaped or inverted U-shaped relationships
- Threshold effects
- Dependence on per capita income, governance quality, and energy mix

Financial depth and the degree of economic openness have significant and often nonlinear effects on environmental pollution indicators. In the absence of strong environmental institutions, they may increase pollution; however, in the presence of clean technologies, effective supervision, and an advanced economic structure, they can contribute to reducing pollution.

1.3. Previous Studies

1.3.1. Foreign Studies

Kim et al. (2025) , in a study entitled "The relationship between economic growth, energy intensity, environmental taxes, trade openness, and environmental quality: Evidence from selected European OECD countries," examined the effects of economic and energy-related factors on environmental quality. The study employed both first- and second-generation panel econometric methods, taking into account heterogeneity and cross-sectional dependence among countries. The results showed that economic growth and energy intensity, particularly in traditional industries, have a negative impact on environmental quality. In contrast, environmental taxes were found to have a positive effect on the Load Capacity Factor (LCF), indicating the effectiveness of this policy instrument in countries with lower environmental quality. The findings also suggest that trade openness may have potentially positive implications for improving environmental quality, although further research is needed to determine the extent of its statistical significance. Overall, the results indicate that policymakers should balance economic growth and environmental protection by using instruments such as environmental taxes and managing energy intensity. Pizzol et al. (2026), in a study entitled "AI-driven development of a set of indicators for assessing the environmental, social, economic, and technological performance impacts of materials and chemicals," investigated how to operationalize the Safe and Sustainable by Design (SSbD) framework proposed by the Joint Research Centre of the European Commission. This study used an AI-based knowledge extraction process to identify and compile indicators related to sustainability assessment. The research resulted in the identification of 986 indicators across 103 categories in the environmental, social, economic, and functional performance domains. However, the findings showed that the AI-generated categorization requires refinement and review by experts. The study also proposed a method for statistical analysis and prioritization of indicators so that, in simplified sustainability assessments, the most important indicators can be examined first. The findings of this research can help companies identify the information needed for sustainability assessment during the early stages of product development and reduce research and development costs. Chen et al. (2025) examined the role of artificial intelligence, the circular economy, and financial development in achieving the Sustainable Development Goals (SDGs) in G20 countries. The study confirmed that artificial intelligence, circular economy principles, and levels of financial development synergistically contribute to sustainable economic growth, inequality reduction, and improvements in quality of life in G20 countries. Furthermore, artificial intelligence and the circular economy play key roles in reducing carbon emissions and improving environmental indicators, thereby facilitating the achievement of sustainable development goals.

Kim et al. (2025) analyzed the combined effects of decarbonization technologies, green investment, and innovative financial development policies on economic and environmental resilience in selected emerging economies. The results indicated that decarbonization technologies, innovative green investment instruments, and financial development policies significantly enhance the economic and environmental resilience of emerging economies. These factors reduce vulnerability to climate and economic shocks and pave the way for more sustainable development.

Wang et al. (2023) investigated the role of trade openness, human capital, renewable energy, and natural resource income within the framework of the Environmental Kuznets Curve hypothesis. The findings showed that trade openness and human capital positively contribute to environmental quality improvement, while investment in renewable energy and effective natural resource management significantly reduce environmental pollutants.

Sui et al. (2023) examined the multiple effects of investment in information and communication technology (ICT) on carbon emissions in China. The findings revealed that the impact of ICT on pollutant emissions is complex and multidimensional, as it can both reduce and increase carbon emissions depending on governance policies and investments in green infrastructure.

Yang and Wang (2023) analyzed the effects of clean energy policies and carbon emission markets on reducing carbon dioxide emissions in China. Their results demonstrated that these policies play an effective role in reducing greenhouse gases and improving air quality and can serve as important strategies for combating environmental pollution in developing countries.

Yamgo et al. (2021), in a study on economic globalization, institutions, and environmental quality in Sub-Saharan African countries during the period 2002–2017, found that institutional quality positively affects environmental degradation, whereas economic globalization and corruption control negatively affect environmental degradation in Sub-Saharan African countries.

1.3.2. Domestic Studies

Golkhandan et al. (2025) , in a study entitled "The Impact of Dependence on Natural Resources and Economic Globalization on Environmental Sustainability in Iran within the Framework of the N-Shaped Environmental Kuznets Curve," examined the effects of natural resource dependence, economic globalization, and economic growth on environmental degradation indicators in Iran. Using time-series data from 1990 to 2021, the study analyzed variables such as per capita GDP, its square and cube, the share of natural resource rents in GDP, the KOF economic globalization index, and two environmental indicators including carbon dioxide emissions and ecological footprint. Johansen–Juselius cointegration tests and the Vector Error Correction Model (VECM) were employed to examine long-run and short-run relationships. The results showed that the relationship between economic growth and environmental degradation in Iran follows an N-shaped Environmental Kuznets Curve. Economic growth initially increases environmental degradation, then reduces it at intermediate levels, and eventually increases it again at higher stages of development. The findings also indicated that dependence on natural resources has a positive and significant effect on pollutant emissions and ecological footprint, whereas economic globalization has a negative and significant effect on environmental degradation indicators, thereby reducing environmental pollution. The study emphasized the importance of developing clean energy, improving natural

resource management, and moving toward an open economy to enhance environmental quality in Iran. Esfandiari et al. (2025), in a study titled "International Trade and the Environment," examined the relationship between the expansion of international trade and environmental quality. Using a descriptive-analytical approach, the study aimed to analyze the effects of trade liberalization on environmental indicators in selected countries. The results indicated that the environmental effects of international trade differ across countries depending on factors such as the level of economic development, institutional structure, and environmental policies. The findings showed that in countries with advanced technologies and efficient environmental policies, trade expansion can facilitate the transfer of clean technologies and improve environmental quality. In contrast, in many developing countries with weaker environmental standards, trade liberalization may increase production, resource consumption, and ultimately environmental pollution. The study concluded that coordination between trade and environmental policies at both national and international levels is essential for achieving sustainable development under economic globalization.

Hajipour Aporovari et al. (2025) , in a study entitled "The Impact of Intra-Regional and Extra-Regional Trade in Information and Communication Technology Goods on Environmental Quality," examined the environmental effects of ICT goods trade between developed and developing countries. The study used panel data from 33 developed and 78 developing countries during the period 2000–2023. In addition to ICT trade, variables such as energy consumption, foreign direct investment, GDP, and population density were analyzed as determinants of environmental quality. The findings revealed that imports of ICT goods from both northern and southern countries increase carbon dioxide emissions in developed countries, with imports from developed countries having a stronger effect. In developing countries, ICT imports from northern countries increased CO2 emissions and environmental degradation, whereas imports from southern countries improved environmental quality, highlighting the benefits of South–South regional trade in reducing environmental pollution. The results also confirmed a U-shaped Environmental Kuznets Curve in developed countries and an inverted U-shaped curve in developing countries. Moreover, the Pollution Haven Hypothesis was confirmed in developing countries but rejected in developed economies. Energy consumption was found to increase environmental degradation in both groups of countries, while foreign direct investment improved environmental quality in developed countries but intensified pollution in developing countries. Gholizadeh et al. (2025), in a study titled "The Relationship between Environmental, Social, and Corporate Governance Performance and Trade Credit Financing with the Mediating Role of Product Market Competition," investigated the impact of ESG performance on firms' financing methods. This applied research adopted a causal-correlational (ex post facto) methodology. The statistical population consisted of companies listed on the Tehran Stock Exchange, from which 151 firms were selected using systematic elimination during the period 2017–2023. Data were collected from corporate financial statements and the Codal system and analyzed using Stata software. The results showed a positive and significant relationship between ESG performance and trade credit financing, indicating that firms with stronger environmental, social, and governance performance have greater access to trade credit. The findings also demonstrated a positive relationship between ESG performance and product market competition, suggesting that socially and environmentally responsible firms enjoy stronger competitive positions in the market. Additionally, a positive and significant relationship was found between product market competition and trade credit financing. The final results indicated that product market competition plays a mediating role in the relationship between ESG performance and trade credit financing. These findings suggest that firms' attention to ESG dimensions can strengthen both their competitive position and access to financial resources.

Khorsand Vakilzadeh et al. (2024) , in a study entitled "Examining the Environmental Kuznets Curve Hypothesis Using Environmental Performance and Green Growth Indicators," investigated the relationship between economic growth and environmental degradation. The main objective was to identify strategies for reducing environmental degradation while increasing production and economic growth. Using panel data from 134 countries during 1980–2018, the study tested the Environmental Kuznets Curve hypothesis through fixed effects models and Data Envelopment Analysis (DEA), with all analyses conducted using R software. The results confirmed the Environmental Kuznets Curve hypothesis using both environmental performance and green growth indicators. The study further examined the effects of variables such as trade, foreign direct investment, education, and research and development on three environmental indicators: the Environmental Kuznets Curve, environmental performance, and green growth. The findings showed that trade significantly affects both the Environmental Kuznets Curve and environmental performance indicators. Specifically, within the Kuznets Curve framework, trade increases carbon dioxide emissions while simultaneously improving countries' environmental performance. Foreign direct investment significantly affected only the Environmental Kuznets Curve by increasing carbon emissions. In addition, higher levels of education positively influenced environmental performance, whereas research and development had no significant impact on any of the examined indicators. The study recommended that policymakers pay greater attention to measuring and analyzing various environmental indicators in order to facilitate sustainable development through identifying influential factors such as trade and education.

Ahmadi et al. (2025) examined the role of artificial intelligence and venture capital investment in the development of innovative technologies and sustainable employment generation in Iran's private sector. The study showed that the use of artificial intelligence in production and service processes, together with increased venture capital investment in technology-based startups, significantly contributes to innovation growth and sustainable job creation in the private sector. Moreover, financial development through these instruments strengthens the effectiveness of government support policies within the entrepreneurial ecosystem.

Mohammadi et al. (2025) analyzed the impact of renewable energy development and environmental incentive policies on reducing air pollution and improving human development indicators in Iranian metropolitan areas. The results indicated that increasing the share of renewable energy in the country's energy mix, alongside the effective implementation of environmental incentive policies, has significantly reduced air pollution in major cities. This has consequently improved human development indicators such as public health and quality of life, representing an important step toward sustainable urban development.

Barzegar et al. (2024), in a comprehensive study, investigated the relationship between research and development expenditures and environmental quality across different provinces of Iran. The findings demonstrated that increased investment in research and development improves environmental quality and reduces environmental pollutants. These results highlight the important role of research and development activities in reducing environmental pollution in the country. Tayyari et al. (2023) [23], in a study examining the impact of research and development expenditures on environmental degradation in developing countries, concluded that investment in research and development can reduce environmental pollutants. However, the effectiveness of this relationship varies across countries depending on factors such as the type of technologies and environmental policies adopted.

2. Method

2.1. Methodology

Following the studies of Zhang et al. (2022) [29], Ali Nasir et al. (2021) [19], and Othman et al. (2021), the present study investigates the comparative effects of financial depth and the degree of economic openness on environmental pollution indicators in developing and developed countries, with particular emphasis on Global Warming Potential (GWP), over the period 2000–2024. The research regression models are specified as follows:

$$\begin{aligned} co2_{i,t} = \alpha_0 &+ \beta_1 GDP_{i,t} + \beta_2 COE_{i,t} + \beta_3 TRADE_{i,t} + \beta_4 INDEX_{i,t} + \beta_5 FD_{i,t} \\ &+ \beta_{i,t} K_t + \beta_7 L_{i,t}(\theta_1 GDP_{i,t} + \theta_2 COE_{i,t} \\ &+ \theta_3 TRADE_{i,t} + \theta_4 INDEX_{i,t} + \theta_5 FD_{i,t} + \theta_{i,t} K_t \\ &+ \theta_7 L_{i,t}) F(S_t, \gamma, c) + u_t \end{aligned} \quad (1)$$

Where the transition function FFF is defined as follows:

$$F(\gamma, s_t, c) = (1 + COE\{-\gamma(s_t - c)\})^{-1}, \quad \gamma > 0 \quad (2)$$

2.2. Dependent Variable:

Carbon dioxide emissions (metric tons per capita), which serve as an indicator of environmental pollution.

2.3. Explanatory Variables:

(COE): Global Warming Potential (GWP), according to Lee et al. (2020) [26], is calculated as follows: the amounts of the three greenhouse gases, namely CO2, CH4, and N2O, are estimated based on the product of energy consumption and the emission coefficients of each gas, respectively equal to 1, 21, and 310 per joule of energy consumed from each source. Considering the different capacities of CH4 and N2O in causing global warming, the total greenhouse gas emissions are converted into CO2-equivalent units. Each kilogram of CH4 and N2O has greenhouse effects equivalent to 21 and 310 kilograms of CO2, respectively.

After calculating the total Global Warming Potential (GWP), the GWP values are expressed per unit area (kg CO2 equivalent per hectare), per unit weight (kg CO2 equivalent per ton), per unit of input energy (kg CO2 equivalent per gigajoule), and per unit of output energy (kg CO2 equivalent per gigajoule).

$$CO_{E_{it}} = CO_2 + 21 * CH_4 + 310 * N_2O \quad (3)$$

After calculating Equation as the Global Warming Potential (GWP) index, it is incorporated into the regression model.

GDP: Gross Domestic Product per capita measured in constant 2010 U.S. dollars.

Trade: Degree of economic openness, measured as the ratio of total trade volume to GDP.

INDEX: Total value of traded stocks, used as an indicator of stock market development.

FD: Financial depth, used as an indicator of financial development.

K: Gros s fixed capital formation per capita in dollars (measured as a percentage growth rate).

L: Labor force participation rate as a percentage of the total population.

The study period covers 2000–2024, and the data are collected from the World Bank database for selected developing and developed countries.

In this study, the developing countries consist of the D-8 countries, an economic group comprising eight developing Islamic countries: Iran, Turkey, Pakistan, Bangladesh, Indonesia, Malaysia, Egypt, and Nigeria. The selected developed countries include Belgium, Canada, Denmark, Finland, Germany, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United States, the United Kingdom, Luxembourg, and France.

The D-8 group, due to its shared characteristics in economic transition and dependence on fossil fuels, provides an ideal case for analyzing the relationship between financial depth, economic openness, and environmental pollution indicators in emerging developing economies. The diversity in levels of economic openness among D-8 countries offers a unique opportunity to examine the asymmetric effects of trade on pollution indicators. Given the strategic role of D-8 countries in the growth of global energy demand, identifying the factors affecting pollutant emissions in this bloc is essential for formulating regional climate policies.

3. Results and Discussion

3.1.Stationarity Tests (Unit Root Tests)

One of the important issues that must be examined before estimating the model is the stationarity of the variables. Therefore, the stationarity of the variables was initially tested using the Im, Pesaran, and Shin (IPS) unit root test. The results of the stationarity test indicate that some of the variables are not stationary at the level form. Hence, the existence of a unit root among the variables cannot be rejected. Consequently, the stationarity of the variables was re-examined after taking the first difference, and the results indicate that all variables become stationary after first differencing.

Table 1. Unit Root Test for Variables

	Developed Countries			Developing Countries		
	Im, Pesaran and Shin W-stat			Im, Pesaran and Shin W-stat		
	Probability Level	Calculated Statistic	Level of Stationarity	Probability Level	Calculated Statistic	Level of Stationarity
Global Warming Potential	-5.886	0.000	I(0)	-3.446	0.000	I(0)
Carbon Dioxide Emissions	-10.929	0.000	I(0)	-1.693	0.045	I(0)
Stock Market Development Index	-3.862	0.000	I(0)	-5.896	0.000	I(0)
Financial Development	-4.6903	0.000	I(0)	-2.525	0.005	I(0)
Degree of Economic Openness	-7.3950	0.000	I(0)	-2.583	0.004	I(0)
Gross Domestic Product per Capita	-2.8357	0.002	I(0)	-5.037	0.000	I(0)
Labor Force	-3.9946	0.000	I(0)	-2.837	0.002	I(0)
Capital	-2.8727	0.002	I(0)	-5.937	0.002	I(0)

Source: Research Finding

3.2. Investigation of the Presence of Long-Run Relationships

Since the variables in the model do not have the same order of integration, the Kao test is used to examine the presence or absence of a cointegration relationship among the variables. This test was conducted for the research model, and the results are presented in Table 2.

Table 2. Results of the Panel Cointegration Test

Test Statistic	Kao Test	
	Value of the Test Statistic	Significance Level
Developing Countries	0.0165	-2.131263
Developed Countries	0.0000	-4.952662

Source: research Finding

According to the results presented in Table 2, for the selected countries and at the 95% confidence level, the null hypothesis of no cointegration relationship among the variables is rejected, while the alternative hypothesis indicating the existence of convergence among the variables is accepted. Therefore, the existence of a long-run relationship between the variables is confirmed.

3.3. Results of Estimating the Model Using the PSTR Method

Environmental Pollution Model in Developing Countries

Initially, the linearity test of the model is examined.Linearity Test, Selection of Transition Variable, and Model TypeTo investigate whether the relationship among the model variables is linear or nonlinear, it must be determined whether mmm (the number of regime parameters) is equal to one or not. It should be noted that in the following tests, the null hypothesis assumes a linear model, while the alternative hypothesis considers either a logistic PSTR model (m=1)(m=1)(m=1) or an exponential PSTR model (m=2)(m=2)(m=2).The diagnostic test results reported in Table (3) indicate that the linearity assumption of the model (null hypothesis) is rejected. Therefore, a nonlinear relationship exists between financial depth, the degree of economic openness, and the environmental pollution index in developing countries, with emphasis on Global Warming Potential. Accordingly, the PSTR approach is required for estimating the model parameters.

Table 3. Results of the Model Linearity Hypothesis Test (BBC Test)

Null Hypothesis	F-statistic	Significance Level (p-value)
Wald Test	236.5	0.000
Fisher Test	598.4	0.000
LRT Test (Likelihood Ratio Test)	789.4	0.000

Source: Research Finding

As can also be observed from the test results reported in Table (3), the hypothesis of a linear relationship among the variables is rejected; therefore, the possibility of a linear relationship between the variables is ruled out.It should also be noted that the proposed PSTR model, based on the selected transition variable, is chosen as the optimal model for estimating the relationship in the selected developing countries. For this purpose, following González et al. (2005) and Colletaz and Hurlin (2006), the null hypothesis of a PSTR model with one transition function is tested against the alternative hypothesis of a PSTR model with at least two transition functions. The results are presented in Table (4).The findings indicate that the null hypothesis regarding the adequacy of a single transition function is not rejected in either the one-threshold or two-threshold cases. Therefore, one transition function is sufficient to characterize the nonlinear behavior between financial depth, economic openness, and the environmental pollution index in developing countries, with emphasis on Global Warming Potential.

Table 4. Test for the Presence of Remaining Nonlinear Relationship

Case of Two Thresholds M=2			Case of one Thresholds M=1		
LR	**LMf**	**LMw**	**LR**	**LMf**	**LMw**
1.425	1/239	1.258	1.236	1.116	1.012
(0.489)	(0.532)	(0.521)	(0.542)	(0.612)	(0.687)
H0: r=1, H1: r=2					

Source: Research Finding

After confirming the existence of a nonlinear relationship among the variables and the adequacy of a single transition function to characterize nonlinear behavior, the next step is to determine the optimal specification between a transition function with one threshold and one with two thresholds. For this purpose, the PSTR model corresponding to each specification is estimated, and based on the criteria of the residual sum of squares, Schwarz criterion, and Akaike criterion, the PSTR model with a single threshold is identified as the optimal model. Therefore, a PSTR model with one transition function and one threshold is selected to examine the nonlinear behavior among the variables under study.Using a PSTR model in which Global Warming Potential serves as the transition variable, the environmental pollution function (CO2 emissions) and the effects of financial depth and economic openness on the environmental pollution index are modeled. Given the confirmation of the nonlinear specification, the analysis proceeds with the nonlinear component of the model.According to the estimation results of the CO2 model in the nonlinear section, the coefficient of gross domestic product is positive and statistically significant at the 95% confidence level, indicating that economic growth increases environmental pollution in the selected countries. The effect of financial development on environmental pollution is negative and significant at the 5% significance level. Likewise, the degree of economic openness has a negative and statistically significant effect on environmental pollution, consistent with theoretical expectations. Furthermore, the Global Warming Potential variable has a positive and statistically significant impact on environmental pollutants at the 95% confidence level.

Table 5. Estimation of the Model Using the PSTR Model

Selected Developing Countries Estimation of the Linear Part of the Model				
Variable	**Coefficient**	**Standard Error**	**t-Statistic**	**Probability**

CONSTANT	0.521556	0.300193	1.737401	0.0823
GDP	0.139694	0.048299	2.892296	0.0038
COE	0.038076	0.004899	7.771932	0.0000
TRADE	-0.237879	0.061631	-3.859691	0.0001
INDEX	-0.047188	0.007428	-6.352493	0.0000
FD	-0.035862	0.014372	-2.495362	0.0129
K	0.164212	0.061974	2.649681	0.0092
L	0.134509	0.025286	5.319560	0.0000
Estimation of the Nonlinear Part of the Model				
CONSTANT	0.454951	0.260162	1.748721	0.0937
GDP	0.077482	0.009537	8.124038	0.0000
COE	-0.007565	0.001745	-4.335478	0.0000
TRADE	-0.265979	0.021786	-12.208750	0.0000
INDEX	-0.092975	0.015336	-6.062719	0.0000
FD	0.144602	0.008895	16.257300	0.0000
K	0.177326	0.070478	2.516070	0.0126
L	0.964102	0.158623	6.077495	0.0000
Threshold value(C)	6.675325	2.934622	2.274678	0.0284
Slope parameter(γ)	0.077482	0.009537	8.124038	0.0000
Adjusted R-squared = 0.88				

Source: Research Finding

The comparison of coefficients in the two different regimes is based on the transition variable and its values, where the value of the transition variable can determine the transition function and consequently the prevailing regime. In the above estimation, the transition variable is the Global Warming Potential (GWP) index, with the estimated threshold value for this variable equal to 0.964102. Depending on the distance of the Global Warming Potential from this threshold value, the model follows two distinct extreme regimes. By comparing the coefficients of the model in these two regimes, it is observed that when the Global Warming Potential surpasses the threshold (0.964102) (transition from the linear to the nonlinear part), the response of environmental pollution to changes in this variable increases significantly. This indicates that energy sector policymakers have attempted to control environmental pollution more effectively through appropriate reactions, thereby preventing its increase.

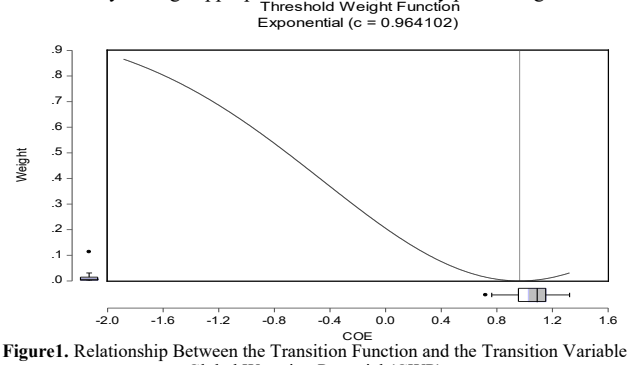


Figure1. Relationship Between the Transition Function and the Transition Variable Global Warming Potential (GWP)

Source: Research finding

3.4. Diagnostic Tests

In the present study, the Durbin-Watson test is used to examine autocorrelation.

Table 6. Results of the Autocorrelation Test

F-statistic (F-value)	Probability (p-value)	Durbin-Watson
1.458	0.48	2.398

Source: Research Finding

As shown in the above table, the results of the Durbin-Watson autocorrelation test indicate that there is no autocorrelation among the disturbance terms. Therefore, the third classical standard assumption of no autocorrelation between error terms is not violated. Consequently, the estimators possess the necessary properties (minimum variance and efficiency). [27]Another classical standard assumption is homoscedasticity. In the present study, the Breusch-Pagan-Godfrey test is used to examine this assumption.

Table 7. Results of the Heteroscedasticity Test

F-statistic (F-value)	Prob	Breusch-Pagan-Godfrey
0.698	0.812	1.139

Source: Research Finding

As observed in the table, the test results indicate the absence of heteroscedasticity.

3.5. Test for Coefficient Stability Between Two Regimes

Another appropriate measure for evaluating the quality of the estimated model is examining the stability of coefficients between the two regimes. If the estimated model is reliable, it is expected that the coefficients remain stable and unchanged across regime shifts.

Table 8. Results of the Smooth Transition Parameter Stability Test

Null Hypothesis	F	Prob
b1=b2=b3=b4=0	1.236	0.653
b1=b2=b3=0	1.320	0.574
b1=b2=0	1.348	0.512
b1=0	1.487	0.456

Source: Research Finding

As is also evident from the table, the test for coefficient stability between the two regimes shows that the coefficients do not change due to the regime shift.[28]

3.6. Environmental Pollution Model in Developed Countries

To examine whether there is a linear or nonlinear relationship between the model variables, it should be tested whether m m m (the number of regime parameters) equals one or not. It is worth mentioning that in the following tests, the null hypothesis assumes a linear model, while the alternative hypothesis corresponds to the logistic PSTR model (m=1 m=1 m=1) or the exponential PSTR model (m=2 m=2 m=2).The diagnostic test results in Table (9) indicate that the linearity of the model (null hypothesis) is rejected. Therefore, a nonlinear relationship exists between financial depth and the degree of economic openness on the environmental pollution index in developed countries, with an emphasis on the Global Warming Potential. Accordingly, the estimation of the model parameters requires the use of the PSTR method.

Table 9. Results of the Model Linearity Hypothesis Test (BBC Test)

Null Hypothesis	(F-value)	(p-value)
Null Hypothesis	3.005	0.0000
Wald Test	3.912	0.0000
Likelihood Ratio Test (LRT)	3.281	0.0000

Source: Research Finding

As is evident from the test results presented in Table (9), the hypothesis of linearity in the relationship between the variables is rejected; therefore, the possibility of a linear relationship between the variables is ruled out.It is also worth mentioning that the PSTR model proposed by the selected transition variable is chosen as the optimal model for estimating the model in developed countries.To this end, following González et al. (2005) and Kohlitz and Harulin (2006), the null hypothesis of the existence of a PSTR model with a single transition function versus the alternative hypothesis of a PSTR model with at least two transition functions is tested. The results of this test are presented in Table (10).The results indicate that the null hypothesis, which states that considering one transition function is sufficient in both cases of one and two threshold parameters, is not rejected. Therefore, one transition function is capable of capturing the nonlinear behavior between financial depth and the degree of economic openness on the environmental pollution index in developed countries, with an emphasis on the Global Warming Potential. [29]

Table 10 Test for the Presence of Remaining Nonlinear Relationship

Case of Two Thresholds (M = 2)			Case of One Threshold (M = 1)		
LR	LMF	LMW	LR	LMF	LMW
1.305 (0.401)	1.417 (0.352)	1.104 (0.501)	1.852 (0.369)	1.953 (0.447)	1.004 (0.537)

Source: Research Finding

With confirmation of the existence of a nonlinear relationship among the variables and the sufficiency of a single transition function to capture the nonlinear behavior, the next step is to select the optimal form between a transition function with one or two thresholds. For this purpose, the PSTR model corresponding to each case will be estimated, and based on the criteria of the sum of squared residuals, Schwarz Information Criterion (SIC), and Akaike Information Criterion (AIC), the PSTR model with one threshold is identified as the optimal model. Therefore, a PSTR model with one transition function and one threshold is chosen to examine the nonlinear behavior among the variables under study.Using a PSTR model where the transition variable is the Global Warming Potential (GWP) index, environmental pollution and the effects of financial depth and economic openness on the environmental pollution index in developed countries are modeled with emphasis on the Global Warming Potential.Given the confirmation of the nonlinear model, the analysis now turns to the results of the nonlinear part of the model.According to the estimation results of the environmental pollution model for the selected developed countries, in the nonlinear part, the coefficient of the per capita gross domestic product (GDP) variable on environmental pollution is negative and significant at the 95% confidence level. This indicates that the selected developed countries are located on the right side of the Kuznets curve, where, contrary to developing countries, industrial production in this group of countries leads to a decrease in environmental pollution. This outcome aligns with the goals of the Paris Agreement.Furthermore, financial development can also reduce environmental pollution.Additionally, the Global Warming Potential variable has a positive and significant impact on environmental pollution in this group of countries.

Table 11. Model Estimation Using the PSTR Model

Selected Developing Countries Estimation of the Linear Part of the Model				
Variable	Coefficient	Standard Error	t-Statistic	Probability (p-value)
CONSTANT	0.196692	0.095788	2.053411	0.0549
GDP	-0.123968	0.028846	-4.297628	0.0004
COE	0.474573	0.124633	3.807772	0.0066
TRADE	-0.112346	0.033569	-3.346760	0.0036
INDEX	-0.116226	0.039950	-2.909323	0.0094
FD	-0.203325	0.054194	-3.751771	0.0045
K	-0.521203	0.272529	-1.912466	0.0974

L	-0.593920	0.289288	-2.053044	0.0703
Estimation of the Nonlinear Part of the Model				
CONSTANT	0.102195	0.043170	2.367280	0.0267
GDP	-0.228524	0.054462	-4.196024	0.0005
COE	0.242560	0.040182	6.036585	0.0000
TRADE	-0.137959	0.041832	-3.297954	0.0040
INDEX	-0.513400	0.157400	-3.262762	0.0098
FD	-0.014838	0.006607	-2.245690	0.0378
K	-0.120704	0.060604	-1.991677	0.0487
L	-0.433451	0.159418	-2.718959	0.0218
Threshold value(C)	0.139098	0.031256	4.450281	0.0000
Slope parameter(γ)	0.723252	0.050810	14.23457	0.0000
Adjusted R-squared = 0.82				

Source: Research Finding

transition variable and its values, where the value of the transition variable determines the transition function and consequently the prevailing regime. In the above estimation, the transition variable is the Global Warming Potential (GWP), for which the estimated threshold value is 0.13.Depending on the distance of the Global Warming Potential from this threshold value, the model follows two distinct extreme regimes. By comparing the coefficients of the model in these two regimes, it is observed that when the Global Warming Potential surpasses the threshold (0.13) (i.e., the transition from the linear to the nonlinear part), the response of environmental pollution to changes in this variable increases significantly.

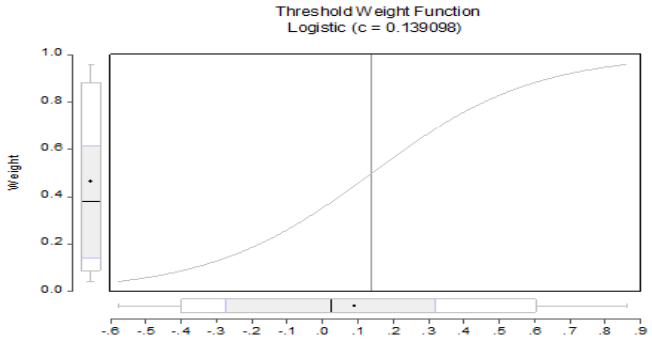


Figure2. Relationship Between the Transition Function and the Transition Variable Global Warming Potential

Source: Research Finding

3.7. Threshold Effects of Global Warming Potential on Environmental Pollution Indicators

In this study, the threshold effects of Global Warming Potential (GWP) on environmental pollution indicators are examined at four main levels:

3.7.1.Direct Effect: Intensification of Pollution Through Climate Feedbacks

When global warming potential increases, the Earth's temperature rises. This temperature increase can itself lead to the production or release of new pollutants:

- **Increase in secondary pollutants:** Higher temperatures accelerate chemical reactions in the atmosphere.
- **Methane emissions from natural sources:** Global warming causes the thawing of polar frozen layers, or **permafrost**, and the warming of wetlands, which leads to the release of large amounts of methane gas with very high GWP. This represents a positive feedback loop that worsens the situation.
- **Widespread wildfires:** Rising temperatures and drought increase the risk of forest fires.

3.7.2. Changes in the Distribution and Persistence of Pollutants

Climate change caused by global warming potential alters meteorological patterns:

- **Changes in wind and precipitation patterns:** Reduced rainfall in some regions causes pollutants to remain suspended in the air for longer periods and prevents them from being washed out.
- **Temperature inversion:** Atmospheric changes may cause temperature inversion in large cities, preventing the dispersion of pollutants and increasing their concentration near the ground surface.

3.7.3. Effects on Human Health: The Link Between GWP and Pollution

As GWP increases, the effects of other pollutants are also intensified:

- **Pollutant mixture syndrome:** Warmer air and higher concentrations of greenhouse gases, combined with industrial pollutants, intensify toxic effects on the human respiratory and cardiovascular systems.
- **Changes in allergic sensitivities:** Rising temperatures and higher CO_2 concentrations promote the growth of allergenic plants and increase pollen production. When combined with chemical pollutants, this worsens public health conditions.

3.7.4. Distinction Between Short-Lived Climate Pollutants (SLCPs)

Many environmental pollutants themselves have global warming potential. These are known as **short-lived climate pollutants (SLCPs)**:

- **Black carbon:** These particulate matters, in addition to causing severe damage to the lungs, directly absorb sunlight and contribute to global warming.
- **Hydrofluorocarbons (HFCs):** Used in cooling systems, these substances have very high global warming potential.

In conclusion, Global Warming Potential (GWP) can be said to act as an **"environmental catalyst."** This means that:

1. High GWP in individual pollutants directly intensifies the greenhouse effect.
2. The consequences of warming, including changes in temperature and climate, alter atmospheric chemical processes and cause ordinary pollutants, such as particulate matter or nitrogen oxides, to become more toxic or more persistent.

3.7.5. Diagnostic Tests

In the present study, the Durbin-Watson test was used to check for autocorrelation.

Table 12. Results of the Autocorrelation Test

F-statistic	Prob	Durbin-Watson
1.315	0.57	1.958

Source: Research Finding

As shown in the above table, the results of the Durbin-Watson autocorrelation test indicate that there is no autocorrelation among the disturbance components. Therefore, the third classical standard assumption of no autocorrelation in the error terms is not violated. Consequently, the estimators possess the necessary properties (minimum variance and efficiency).Another classical standard assumption is homoscedasticity (constant variance). In the present study, the Breusch-Pagan-Godfrey test was used to examine this assumption

Table 13. Results of the Heteroskedasticity Test

F = F-statistic	Prob	Breusch-Pagan-Godfrey
0.748	0.882	1.325

Source: Research Finding

As observed in the table, the test results indicate the absence of heteroscedasticity.

3.7.6. Coefficient Stability Test Between Two Regimes

Another appropriate measure for evaluating the quality of the estimated model is examining the stability of coefficients between the two regimes. If the estimated model is suitable, it is expected that the coefficients remain stable and unchanged across regime shifts.

Table 14. Results of the Smooth Transition Parameter Stability Test

Null Hypothesis	F-statistic	Prob
b1=b2=b3=b4=0	1.205	0.492
b1=b2=b3=0	1.228	0.558
b1=b2=0	1.958	0.401

Source: Research Finding

As is also evident in the table, the coefficient stability test between the two regimes shows that the coefficients do not change with the regime shift.

4. Conclusions

Considering the existing theoretical and empirical foundations in previous studies, this research was conducted to examine the comparative effects of financial depth and the degree of economic openness on the environmental pollution index in developing and developed countries, with emphasis on Global Warming Potential (GWP), during the period 2000–2024. Following the approaches of reputable studies such as Zhang et al. (2022) [30], Ali Nasir et al. (2021), and Usman et al. (2021) within the research methodology framework enabled us to analyze the complex and nonlinear relationships among variables using the Panel Smooth Transition Regression (PSTR) model. In this model, the "Global Warming Potential index" acts as the transition variable determining the different prevailing regimes in the relationships.The estimation results for developing countries confirm the nonlinear model and the existence of significant threshold effects of global warming potential. The findings indicate that per capita GDP has a positive and significant effect on environmental pollutants, which is logical and expected because increased energy consumption associated with higher production—especially through fossil fuels—leads to greenhouse gas emissions and consequently higher global warming potential. These results may also suggest that with trade expansion, technological innovation in industry, and improved stock market performance (which may facilitate capital attraction for cleaner and more efficient technologies), the possibility of reducing harmful environmental effects

becomes stronger. This finding is consistent with economic literature, indicating that increases in economic activities and energy consumption directly contribute to higher pollution levels.The impact of financial development on environmental pollution was found to be negative and statistically significant at the 5% significance level, once again emphasizing the moderating role of financial development in reducing negative environmental effects. Similarly, trade volume, as expected, had a negative and significant impact on environmental pollution. This may indicate the transfer of cleaner technologies and higher environmental standards through trade. Nevertheless, some findings were noteworthy and may reflect further complexities in the relationship between industry and pollution, or perhaps offsetting effects arising from improvements in efficiency and technology within the industrial sector that are not directly observable in the model.The estimation results for environmental pollutants also showed a negative effect of per capita GDP on this variable, while financial development likewise had a negative and significant effect on environmental pollutants. This highlights the importance of financial development as a policy instrument for achieving sustainable development and environmental preservation. Overall, the findings of this study demonstrate that financial development, beyond being a simple factor, exerts threshold effects on environmental pollution, and these effects become stronger and more efficient in reducing environmental damage as the level of financial development improves.These findings provide a valuable basis for economic and environmental policymakers in both developing and developed countries to formulate more effective strategies for achieving sustainable development goals. By clarifying the moderating and threshold role of financial development, this study contributes to a deeper understanding of the relationships among economic growth, trade, energy consumption, and environmental consequences. The results emphasize the necessity of focusing on policies that simultaneously promote financial development and environmental protection. Furthermore, differences in the intensity of effects and threshold levels among the examined variables highlight the importance of considering the specific conditions of each country and region when designing policies. Therefore, it is recommended that policymakers incorporate these threshold effects into their planning in order to fully utilize the potential of financial development in addressing environmental challenges.

4.1. Recommendations

Given the positive effect of global warming potential on pollutant emissions in both groups of countries, policymakers should focus emission-reduction programs on greenhouse gases with high warming effects, such as methane and nitrous oxide. Controlling methane leakage in the energy sector, improving waste management, optimizing the use of chemical fertilizers, and increasing efficiency in the agricultural sector can play an important role in reducing the intensity of environmental pollution. Since financial development and financial depth have shown a reducing effect on carbon dioxide emissions in both groups of countries, it is recommended that banking and financial systems be directed toward green financing. Providing low-interest loans for renewable energy projects, energy-efficient buildings, clean transportation systems, and low-carbon industrial technologies can strengthen the positive role of financial development in reducing environmental pollution.Considering the negative

impact of stock market development on pollutant emissions, capital markets should expand green financial instruments. The issuance of green bonds, the establishment of environmental investment funds, and requiring listed companies to disclose carbon emission information can redirect capital from polluting activities toward cleaner and more sustainable investments. Since economic openness has had a reducing effect on pollutant emissions in both developing and developed countries, trade policies should encourage the import of clean technologies, energy-efficient equipment, and low-consumption machinery. At the same time, measures should be taken to prevent international trade from becoming a channel for the entry of polluting industries and outdated technologies. Given that in developing countries gross domestic product and capital formation have an increasing effect on pollutant emissions, economic growth in these countries should gradually move away from fossil-fuel-based development patterns. New investments should be conditioned on compliance with environmental standards, the use of renewable energy sources, and improvements in energy efficiency in the industrial, transportation, and building sectors. In developed countries, the negative impact of GDP on carbon dioxide emissions indicates that economic growth accompanied by clean technologies and strict environmental policies can lead to lower pollution levels. Therefore, developing countries can benefit from the experiences of developed countries in implementing carbon taxes, energy consumption standards, support for green innovation, and the development of clean public transportation infrastructure. Considering the existence of a threshold level for global warming potential, it is necessary to design environmental monitoring and early-warning systems so that control policies can be activated before warming indicators exceed critical levels. Such a system could include continuous monitoring of greenhouse gas emissions, setting allowable emission caps for economic sectors, imposing penalties on highly polluting industries, and providing incentives for low-carbon production units

Author Contributions

All authors contributed equally to the conception, preparation, and writing of this manuscript.

Conflict of Interest

The authors, while observing publication ethics in the referencing, declare the absence of interest of conflict.

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AI-Assisted

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