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Exploring the N-Curve of CO_2 Emissions: The Interactive Roles of Trade, Manufacturing, Financial Development, and Fiscal Policy across Income Groups

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ABSTRACT

This study analyses the relationship between trade openness, the manufacturing industry, financial development, and fiscal policy on CO_2 emissions using the *System-GMM* approach in 119 countries from 2008 to 2023, grouped by income level. The results demonstrate a nonlinear relationship, consistent with the EKC hypothesis, characterized by variations in the shape of the curve. Trade openness is significant in low-income countries, characterized by an inverted N-curve pattern, whereas manufacturing and financial development influence high-income groups, exhibiting an N-curve pattern. Fiscal policy is substantial in the upper-middle group, characterized by an inverted N-curve, and forms a U-curve in the combined group of all countries. The interaction between variables reveals differences: Financial development, combined with trade openness, reduces emissions in the overall group, whereas manufacturing actually increases emissions in the low-income group. Effective fiscal policy, on the other hand, reduces emissions in the lower-middle and combined groups. These findings underscore the importance of considering income context and implementing integrated policies to reduce emissions.

Keywords: CO_2 Emissions, Trade Openness, Financial Development, Manufacturing Industry Output, Fiscal Policy
JEL Classification: Q56, F18, O44, O14, G20

1. INTRODUCTION

Climate change is defined as a shift in the Earth's temperature, characterized by rising temperatures in the atmosphere, oceans, and land. In addition to affecting the Earth's temperature, climate change also has an impact on current social conditions. According to World Bank Development Data (2025), CO_2 emissions have continued to increase over the past 16 years, mainly due to global warming. In 2008, CO_2 emissions reached 32.43 thousand metric tons, and rapid growth continued until they surpassed 36.22 thousand metric tons in 2014. The graph shows a decline in 2020 due to the COVID-19 pandemic, which reduced people's mobility outside their homes, thereby reducing CO_2 emissions. However, after the pandemic ended, CO_2 emissions increased again in 2022, reaching 38.25 thousand metric tons, and in 2023, reaching 39.02 thousand metric tons.

Climate change and economic globalization pose significant challenges, one of which is marked by an increase in international trade activities. In this context, every country needs to establish good economic relations with other countries, a concept known as economic openness. An open economy refers to a country's economic activity that engages in trade with other countries, including the export and import of goods, as well as participation in capital market activities with other countries (Mankiw et al., 2007). If a country engages in trade, its economy will likely experience growth, thereby laying the foundation for the country's economic development. Findings by Raghutla (2020) suggest that trade openness plays a crucial role in driving economic growth and promoting economic development in developing market economies.

Financial development, on the other hand, is one of the efforts to achieve a high-quality and sustainable environment. If these credit services are allocated to more environmentally friendly sectors, the impact will be more positive and help reduce CO_2 emissions. Supported by findings Yuniasih et al. (2020), which conclude that financial development, as measured by credit services, can reduce CO_2 emissions in the private sector in Asia when using a dynamic panel model, aligning with the sustainable development goals. Conclusions related to the relationship between financial development and the environment have an uncertain influence, as they depend on policy and implementation.

Government policies play a crucial role in mitigating CO_2 emissions by implementing fiscal policies that promote resilient environmental development. The main tools in fiscal policy are government spending and tax rates. On the expenditure side, the government can allocate budgets to invest in green infrastructure, such as solar-powered public transportation or renewable energy efficiency. In controlling spending, fiscal policy will direct economic and business activities that are environmentally friendly (Halkos and Paizanos, 2016). From a budgetary perspective, *a carbon tax* is imposed on companies or individuals according to the amount of carbon emissions they produce. This tax will provide incentives for industries to adopt more environmentally friendly technologies (Taşdemir, 2022). Fiscal policy instruments are taxes and government expenditures that are directly linked to GDP growth, production levels, energy use, and environmental quality. In this regard, previous studies concur that fiscal spending is a crucial tool in controlling ecological pollution (İşletme et al., 2023).

The Environmental Kuznets Curve supports most studies on the relationship between the economy and environmental quality. According to the environmental Kuznets curve hypothesis, environmental damage tends to increase during the early stages of economic development. When a country reaches a high income level, environmental damage begins to decrease. This is due to the country's increased attention to environmental sustainability, supported by financial capabilities and technology that are considered adequate in reducing environmental damage (Grossman and Krueger, 1991). Several studies have found that economic development increases CO_2 emissions, in line with the inverted U-shaped environmental Kuznets curve hypothesis (Kamal et al., 2021; Le and Ozturk, 2020; Salam and Xu, 2022; Voumik et al., 2022). Previous researchers have also found a standard U-shaped environmental Kuznets curve that does not fit the environmental Kuznets curve hypothesis (Abokyi et al., 2021; Dogan and Turkekul, 2016; Mar'I et al., 2023; Saidi and Mbarek, 2017). In the development of the environmental Kuznets curve hypothesis, there are also N-shaped curve results, indicating that environmental degradation will begin to increase again beyond a certain income level (Ali et al., 2017; Awan and Azam, 2022; Gyamfi et al., 2021).

This study is interested in using income groups of countries. *The World Bank* has categorized countries into several income groups, including low-income, lower-middle-income, middle-income, upper-middle-income, and high-income. These groups are updated annually on July 1 based on the Gross National Income (GNI) per capita of the previous calendar year. The primary reasons for selecting these income groups are their distinct income standards and economic disparities, as well as variations in industrial structure, technology, and environmental regulations. For example, middle- and lower-income countries aspire to undergo structural transformation for economic growth through increased productivity in goods and services. Industrialisation in middle- and low-income countries is entering the early stages of industrialisation, which necessitates technological improvements and efforts to catch up economically (Panayotou, 1997). Additionally, the ability to adopt pollution-reducing technologies also needs time to adapt in middle- and low-income countries.

To date, no research has been conducted on the interaction between financial development, trade openness, the manufacturing industry, and fiscal policy. This study is novel and contributes to the existing literature on the relationship between economic activity and environmental degradation, particularly in the context of CO_2 emissions. This study also enriches the empirical understanding by differentiating the analysis results based on country groups according to income level, namely high-income, upper-middle-income, lower-middle-income, and low-income. Therefore, this study not only fills a gap in cross-country studies on economic and environmental dynamics but is also expected to provide strategic policy recommendations for countries with similar economic characteristics to achieve sustainable development, as well as a deeper insight into the dynamics of the relationship between these variables and CO_2 emissions at various income levels.

2. THEORETICAL BASIS AND DEVELOPMENT OF HYPOTHESIS

The Environmental Kuznets Curve concept was first introduced by the World Bank in the World Development Report (1992) (World Bank, 1992), which explained that economic development initially tends to worsen environmental quality. Still, at a certain income level, the damage begins to decrease (Singh and Yadav, 2021). This relationship exhibits an inverted U-shaped pattern, where resource-based growth and industrialisation initially lead to increased pollution. However, at a later stage, increased income encourages the adoption of clean technology and stricter environmental policies, thereby reducing degradation (Chen et al., 2022; Htike et al., 2022). Thus, the turning point becomes a critical phase when the economy transitions from an industrial to a post-industrial orientation, focusing on services and more environmentally friendly innovations (Bibi and Jamil, 2021). Some studies are uncertain about finding an inverted U pattern, but rather an N curve (Torras and Boyce, 1998; Xu et al., 2022), especially when scale effects dominate over composition and technique effects (Gyamfi et al., 2021; Khan and Ozturk, 2021; Kurniawan et al., 2024; Ochi and Saidi, 2024).

2.1. The Effect of Trade Openness on CO_2 Emissions

Grossman and Krueger (1991) explain that three main mechanisms describe the relationship between economic growth and environmental quality, namely scale effects, composition effects, and technical effects (Htike et al., 2022a). The scale effect occurs when economic expansion increases energy consumption and resource exploitation, thereby driving pollution, particularly in countries with limited technological capabilities (Khan et al., 2022). Furthermore, the composition effect reflects changes in economic structure, whereby developed countries shift from heavy industry to cleaner service and technology sectors, thereby reducing carbon emissions (Ochi and Saidi, 2024). At a more advanced stage of development, the technical effect becomes dominant as technological advances, environmentally friendly production innovations, and improvements in global trade efficiency drive enhancements in environmental quality (Handoyo et al., 2022; Javed et al., 2023; Kurniawan et al., 2024; Tachie et al., 2020).

2.2. The Impact of Manufacturing Industry Output on CO_2 Emissions

Industrial development in line with technological advances has significant environmental consequences because production activities consistently generate waste in various forms, including liquids, solids, and gases, which have the potential to disrupt ecosystems and human health (Soeder, 2021). The manufacturing sector, especially those that rely on fossil fuels, is a major contributor to carbon emissions and causes negative externalities (Javed et al., 2023; Kurniawan et al., 2024). Numerous empirical studies support this view. Li et al. (2022) found that manufacturing activities worsen environmental quality, while Uddin (2020) showed an inverse U-shaped relationship in accordance with the EKC. Other studies confirm sectoral mechanisms and decompositional effects (Htike et al., 2022a; Khan et al., 2022).

2.3. The Impact of Financial Development on CO_2 Emissions

Industrial development in line with technological advances has significant environmental consequences because production activities consistently generate waste in various forms, including liquids, solids, and gases, which can disrupt ecosystems and harm human health (Wu et al., 2024). The manufacturing sector, especially those that rely on fossil fuels, is a major contributor to carbon emissions and causes negative externalities to environmental quality (Tao et al., 2023; Xu et al., 2022). Other literature mentions that the role of green finance and financing is considered to mediate this impact. Acheampong et al. (2020) argue that financial development influences emissions through energy consumption, while Qin et al. (2021) highlight the connection between economic growth and renewable energy utilization. Tao et al. (2023) found a nonlinear relationship between financial development and carbon intensity. Mirza et al. (2025) reported that the development of green finance, when combined with technological innovation, increases the efficiency of emission control.

2.4. The Effect of Fiscal Policy on CO_2 Emissions

Fiscal policy plays a crucial role in influencing both economic growth and environmental quality. According to Bashir et al. (2024), budgetary instruments such as environmental taxes can boost GDP growth while also affecting the energy sector, as energy demand tends to be inelastic. The effect of fiscal policy on the environment can vary depending on its source: if it is through the production side, government spending can improve environmental quality, while if it is through consumption, increased fiscal spending will increase people's purchasing power and energy consumption, so the direction of the policy determines the extent of its contribution to controlling emissions and environmental degradation (Zeraibi et al., 2024). Recent literature shows diverse findings: Wang et al. (2023), found that green fiscal policy reduces emissions, (Gugler et al., 2024) emphasized the combination of carbon pricing and R&D subsidies, Arcila and Baker (2022) showed that effectiveness depends on policy design, and Zeng and Zhao (2023) found that fiscal decentralization modifies the effectiveness of carbon taxes.

2.5. Variable Interaction on CO_2 Emissions

Variable interactions in economic research are understood as a form of moderation or synergy, specifically when the influence of independent variables on dependent variables is affected by the presence of other variables (Bui, 2020). In environmental economics, interaction analysis explains the complexity of development, energy, and sustainability. Several empirical studies by Khan and Eggoh (2021) found that direct financial development reduces CO_2 emissions, but its interaction with income increases emissions. Sheraz et al. (2021) reported that economic and human capital development reduce emissions, while the GDP-energy interaction exacerbates pollution. Chen et al. (2019) showed that financial moderation alters the validity of the EKC. Other literature also shows strong evidence of moderation, such as Aldieri et al. (2023) finding that financial development moderates the effect of renewable energy on CO_2, Ehigiamusoe et al. (2020) showing that energy consumption moderates the income-CO_2 nexus, Htike et al. (2022) describe sectoral scale/composition/technique effects, and Kurniawan et al. (2024) report that industrial value added increases the ecological footprint.

3. RESEARCH METHODS

This empirical study aims to examine the effects of trade openness, manufacturing output, financial development, and fiscal policy on CO_2 emissions across income groups, using the *generalised method of moments* (GMM) to estimate data from 2008 to 2023. The author collected data from 119 countries, grouped by income level, namely high-income, upper-middle-income, lower-middle-income, and low-income countries, to provide varied results with more robust estimates. Different income levels in each country will show various effects on environmental quality. This study employs independent variables, including trade openness, manufacturing output, financial development, and fiscal policy, while the dependent variable is carbon dioxide (CO_2) emissions. The operational definitions, which serve as the basis for using these variables, are shown in Table 1.

Table 1: Operational definitions

Variable	Symbol	Unit	Source
Dependent variable			
CO_2 emissions	CO_2	Metric Tons	World Development Indicator (WDI)
Independent variable			
Trade openness	TO	Percent	World Development Indicator (WDI)
Manufacturing	M	Percent	World Development Indicator (WDI)
Financial development	FD	Percent	World Development Indicator (WDI)
Fiscal policy	FP	Percent	World Development Indicator (WDI)
Control variables			
Human capital	HC	Percentage	World Development Indicator (WDI)
Institutional quality	IQ	Scale index	World Government Indicator (WGI)
Research and development expenditure	RD	Percent	World Development Indicator (WDI)

The following are models for high income, upper middle income, lower middle income, and low income:

$$lnCO2it = \beta 0 + lnCO2i(t-1) + \beta 1\ lnTOit + \beta 2lnTOit\ 2 + \beta 3lnTOit\ 3 + \beta 4lnHCit + \beta 5IQit + \beta 6lnRDit + \varepsilon it \quad (1)$$

$$lnCO2it = \beta 0 + lnCO2i(t-1) + \beta 1lnMit + \beta 2lnMit\ 2 + \beta 3lnMit\ 3 + \beta 4lnHCit + \beta 5IQit + \beta 6lnRDit + \varepsilon it \quad (2)$$

$$lnCO2it = \beta 0 + lnCO2i(t-1) + \beta 1lnFDit + \beta 2lnFDit\ 2 + \beta 3lnFDit\ 3 + \beta 4lnHCit + \beta 5IQit + \beta 6lnRDit + \varepsilon it \quad (3)$$

$$lnCO2it = \beta 0 + lnCO2i(t-1) + \beta 1lnFPit + \beta 2lnFPit\ 2 + \beta 3lnFPit\ 3 + \beta 4lnHCit + \beta 5IQit + \beta 6lnRDit + \varepsilon it \quad (4)$$

$$lnCO2it = \beta 0 + lnCO2i(t-1) + \beta 1lnTOit + \beta 2lnMit + \beta 3lnFDit + \beta 4lnFPit + \beta 5lnHCit + \beta 6IQit + \beta 7lnRDit + \beta 8ln(TO*FD)it + \beta 9ln(M*FD)it + \beta 10ln(FD*FP)it + \varepsilon it \quad (5)$$

4. RESULTS AND DISCUSSIONS

Table 2 presents several variables categorized by different country classifications, including high-income, upper-middle-income, and lower-middle-income countries. These classifications are accompanied by the number of observations, mean, median, standard deviation, minimum, and maximum values.

Standard deviation, minimum, and maximum values.

4.1. Testing the Environmental Kuznets Curve (EKC)

Based on Tables 3-7, the results of this study reveal a nonlinear relationship pattern, characterized by an N curve or inverted N curve, between economic variables and CO_2 emissions across different income groups. Significant trade openness in low-income countries forms an inverted U-curve, while in high-income countries, manufacturing and financial development exhibit a U-shaped pattern. Fiscal policy has a substantial effect on the upper-middle group with an inverted N pattern and forms an N pattern in high-income and combined groups. These findings expand on the classic EKC hypothesis, which emphasizes only the inverted U curve, by showing that the interaction of economic variables can produce two turning points, as indicated by the N curve. These results are in line with studies (Duong and Duong, 2025; Khan and Eggoh, 2021), which confirm that trade openness, manufacturing industry output, financial development, and fiscal policy play essential roles in carbon emission dynamics, and support evidence of a more complex nonlinear relationship between economic growth and the environment.

4.2. Discussion

The results of the Sys-GMM model estimates presented in Tables 3-7 indicate that trade openness has a nonlinear effect on CO_2 emissions, with significant variations across income groups (Barkat et al., 2025; Dou et al., 2023; Kitila, 2024). The most notable and significant results are observed in the low-income group, indicating an inverted N-shaped curve. These findings align with the results of a recent study (Qayoom and Altaf, 2025) that identified an inverted N-shaped curve between trade openness and CO_2 emissions in India. The relationship between trade openness and CO_2 emissions confirms that in the early stages of economic growth and trade integration, emissions tend to increase before efficiency improvements occur, then rise again in the higher openness phase (Suleman et al., 2024). The results for the other four groups — namely, the all-income group, high-income group, upper-middle-income group, and lower-middle-income group — were not statistically significant. Thus, the hypothesis that there is a nonlinear N-curve relationship in trade openness is only accepted for the low-income group, while the other groups reject the hypothesis.

The N-curve in the manufacturing industry is only accepted for high-income groups. The N-curve illustrates the nonlinear relationship between manufacturing value added, which increases during the early stages of industrialisation until it peaks, then declines as the economy shifts to the service sector. This pattern is influenced by technological advances, global competition, and structural changes, making it relevant for understanding the dynamics of industrialisation in economic growth (Karahasan, 2023; Mazhar and Rehman, 2020). In line with Htike et al. (2022), it was found that CO_2 emissions in the manufacturing and construction sectors tend to decrease monotonically as income increases. High-income countries are encouraged to adopt industrial policies that focus on the application of environmentally friendly technologies and promote the development of low-carbon intensity sectors. This strategy is considered effective in controlling potential emission spikes that arise in line with the N-shaped EKC pattern (Taşdemir, 2022). The hypothesis was rejected for the combined income groups of upper-middle, lower-middle, and low income.

Table 2: Descriptive statistics

Panel	Variable	Obs	Mean	Standard deviation	Min	Max
Low income	CO_2	144	2.8429	2.1678	0.3951	10.0282
	TO	144	62.0055	20.1057	30.4205	135.5604
	TO_2	144	4246.11	3027.414	925.4074	18,376.62
	TO_3	144	322,633.4	380,907.7	28,151.37	2,491.142
	M	144	8.4001	4,204	1.5079	19,487
	M2	144	88.1119	86,338	2.2736	379.7447
	M3	144	1,084.972	1,628.872	3.4283	7,400.101
	FD	144	14.1237	8.7918	0.0032	32.0531
	FD2	144	276.2379	274.2755	0.0000	1027.403
	FD3	144	6192.354	8105.363	0.0000	32,931.49
	FP	144	13.7621	4.9931	4.5678	26.0848
	FP2	144	214.1545	142.2646	20.8646	680.4158
	FP3	144	3637.846	3,478.603	95.3051	17,748.49
	HC	144	7.2248	3.0151	1.021	11.384
	IQ	144	−0.86137	0.4518	−1.7555	0.38836
	RD	144	0.5238	0.6743	0.0109	3.35
Lower middle income	CO_2	192	257.9406	613.9473	0.4415	2955.182
	TO	192	84.2211	41.7219	24.7016	186.6758
	TO_2	192	8824.839	7795.862	610.168	34,847.86
	TO_3	192	1059839	1,274.995	15,072.12	6505251
	M	192	15.5245	3,628	7.3633	24.5796
	M2	192	254.1038	115.1107	54.2182	604.1553
	M3	192	4354.876	2,945.951	399.2249	14,849.88
	FD	192	42.7941	26.4093	10.0238	125.912
	FD2	192	2,525.152	3,013.094	100,476.4	15,853.83
	FD3	192	184,018.8	329,000	1007.154	1996188
	FP	192	15,341	7,737.4	5.6251	43.4823
	FP2	192	294.9029	371.0721	31.6416	1890.712
	FP3	192	7322.068	15,340.07	177.9865	82,212.55
	HC	192	8.0218	2.1301	4.3	11.961
	IQ	192	−0.37637	0.4136	−1.18245	0.47511
	RD	192	0.3644	0.2797	0.0126	1.0197
Upper middle income	CO_2	320	732.3305	2,356.521	3.4372	13,259.64
	TO	320	75.7022	34.8377	22.106	176.6683
	TO_2	320	6,940.693	5,999.505	488.6742	31,211.7
	TO_3	320	729,333.4	894,475.8	10,802.62	5,514.118
	M	320	15.5422	6.8633	1.7224	32.1194
	M2	320	288,519	235,381	2.9668	1,031.656
	M3	320	6,045.416	7,113.172	5.1102	33,136.2
	FD	320	58.3584	42.5273	2.6822	194.674
	FD2	320	5,208.618	7,136.421	7,1943	37,897.96
	FD3	320	595,684.4	1,134.385	19.2967	7,377.749
	FP	320	15.3949	3.4321	7.4301	23.7639
	FP2	320	248.7458	106.4695	55.2059	564.7215
	FP3	320	4190.533	2,615.688	410.1835	13,419.97
	HC	320	10.0135	2.5487	6,304	15.087
	IQ	320	−0.20714	0.5761	−1.38961	1.11504
	RD	320	8.0534	94.8564	0.0184	1227
High income	CO_2	608	290.6546	826.7957	0.2754	5689.7
	TO	608	126.355	87.1447	23.1048	442.62
	TO_2	608	23547.3	36,196.37	533.8295	19,591.25
	TO_3	608	6017955	13,900.000	12334	86,700.000
	M	608	12.9256	6.0457	0.9127	37.9948
	M2	608	203.5618	189.7203	0.833	1443.608
	M3	608	3,720.272	5,709.293	0.7602	54,849.65
	FD	608	101.4828	49.2222	25.9534	264.4298
	FD2	608	12717.59	12,405.38	673.5805	69,923.12
	FD3	608	1880386	2831017	17,481.72	18,500.000
	FP	608	19.5441	4.0358	8.6687	28.0706
	FP2	608	398.2307	151.3744	75.1464	787.958
	FP3	608	8,386.406	4,524.231	651,422	22,118.45
	HC	608	11.9682	1.3419	7,782	14,256
	IQ	608	1.25084	0.49089	−0.15516	2.46966
	RD	608	1.7883	1.1441	0.001	5.7056

(*Contd...*)

Table 2: (*Continued*)

Panel	Variable	Obs	Mean	Standard deviation	Min	Max
All Income	CO_2	1264	364.7134	1,357.081	0.2754	13,259.64
	TO	1264	99.8266	70.355	22,106	442.62
	TO_2	1264	14,911.25	26,823.91	488.6742	195912.5
	TO_3	1264	3277427	10,000.000	10,802.62	86,700.000
	M	1264	13.4626	6.1852	0.9127	37.9948
	M2	1264	219.4692	193.9702	0.833	1443.608
	M3	1264	4,102.455	5,669.04	0.7602	54,849.65
	FD	1264	74.5093	76.8981	0.0032	1234.571
	FD2	1264	11,460.28	74,520.01	0.0000	1524165
	FD3	1264	5545295	91,500.000	0.0000	188,000.000
	FP	1264	17.21	5.2974	4.5678	43.4823
	FP2	1264	324.2246	206.5288	20.8646	1890.712
	FP3	1264	6,636.277	7,258.068	95,305.1	82,212.55
	HC	1264	10.3335	2.7291	1.021	15.087
	IQ	1264	0.39326	0.98138	−1.75555	2.46966
	RD	1264	3.0724	47.7712	0.001	1227

Source: Processed data, 2025

Table 3: Sys-GMM analysis results in the combined income group (All Income)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)
l.lnCO_2	0.997 *** (0.007)	0.9961 *** (0.009)	0.998 *** (0.008)	0.996 *** (0.004)	0.992*** (0.007)
lnTO	−1.3888 (2.755)	....	....	....	0.1276*** (0.04)
lnTO_2	0.30481 (0.6075)	....	....	....	....
lnTO_3	−0.0219 (0.0439)	....	....	....	....
lnMan	....	−0.382 (0.380)	....	....	0.003 (0.015)
lnMan2	....	0.2018 (0.2057)	....	....	....
lnMan3	....	−0.0317 (0.033)	....	....	....
lnFD	....	....	−0.0436*** (0.0160)	....	0.1566*** (0.055)
lnFD2	....	....	−0.0050** (0.0020)	....	....
lnFD3	....	....	0.0012*** (0.0004)	....	....
lnFP	....	....	....	1.4112* (0.7811)	0.0156 (0.024)
lnFP2	....	....	....	−0.5197* (0.2804)	....
lnFP3	....	....	....	0.0618* (0.0330)	....
lnHC	−0.033 *** (0.011)	−0.0331*** (0.0102)	−0.0165 (0.0179)	−0.0265*** (0.0101)	−0.0361*** (0.0123)
lnIQ	−0.0087 (0.005)	−0.0088 (0.0061)	0.0055 (0.0083)	−0.0090* (0.0049)	−0.0021 (0.0094)
lnRD	−0.005 (0.004)	−0.0042 (0.0053)	−0.0143** (0.0060)	−0.0025 (0.0037)	−0.0014 (0.0050)
lnTO*FD	....	....	....	....	−0.0283*** (0.0108)
lnMan*FD	....	....	....	....	−0.0017 (0.0034)
lnFP*FD	....	....	....	....	−0.0163*** (0.0059)
Constant	2.169 (4.117)	0.2945 (0.2060)	0.1563*** (0.0482)	−1.1457 (0.7064)	−0.4408** (0.1950)
AR (2)	0.415	0.403	0.409	0.410	0.461
Hansen	0.628	0.066	0.631	1.000	1.000
Lag	1 2	1 1	2 1	1 2	1 2
Obs	1185	1185	1185	1185	1185

Source: processed data, 2025. ***P<0.01, **P<0.05, *P<0.1

The proposed hypothesis is that financial development has a nonlinear relationship and confirms the environmental Kuznets curve for CO_2 emissions. It was found that the N-shaped curve in the income group was only accepted in the high-income group (Wang et al., 2023). The emergence of an N-shaped curve pattern in high-income countries is reflected in the finding that financial development initially reduced environmental damage but later had the potential to increase emissions due to high consumption and production activities (Naqvi et al., 2021). This supports the argument (Samreen and Social, 2020) that the financial sector in developed countries can promote environmental efficiency but still risks creating a rebound effect or a resurgence in CO_2 emissions. In high-income countries, economic systems are generally more mature, diversified, and supported by strict environmental regulations, so financing tends to flow to productive sectors, including green technology and renewable energy (Rezagholizadeh and Abdi, 2022; Ruza and Caro-Carretero, 2022; Uddin, 2020).

The estimation results indicate that fiscal policy has a significant impact on CO_2 emissions across three groups of countries: all income countries, high-income countries, and upper-middle-income countries. This pattern reflects that in developed countries, fiscal policy has a complex and nonlinear impact on emissions, depending on the phase of the policy implemented. A study (Tong et al., 2024)

Table 4: Sys-GMM analysis results in the high income group

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)
l.lnCO_2	0.9999 *** (0.015)	0.9973*** (0.0074)	0.9538 *** (0.0195)	0.9999*** (0.0025)	0.9923 (0.0218)
lnTO	−4.141 (4.915)	....	....	....	−0.0620 (0.3091)
lnTO_2	0.901 (1.066)	....	....	....	....
lnTO_3	−0.064 (0.07)	....	....	....	....
lnMan	....	0.1969*** (0.0699)	....	....	−0.2812 (0.3147)
lnMan2	....	−0.1335*** (0.0475)	....	....	....
lnMan3	....	0.0247*** (0.008)	....	....	....
lnFD	....	....	22.979** (10.504)	....	−0.1256 (0.6975)
lmFD2	....	....	−5.2235** (2.3870)	....	....
lnFD3	....	....	0.3918** (0.1789)	....	....
lnFP	....	....	....	8.0882*** (2.3985)	0.0423 (0.6841)
lnFP2	....	....	....	−2.9253*** (0.880)	....
lnFP3	....	....	....	0.35119*** (0.1066)	....
lnHC	−0.1099 (0.1083)	−0.1407 (0.0988)	−0.4487** (0.1989)	−0.0343*** (0.0099)	−0.1232 (0.1926)
lnIQ	0.0184 (0.0216)	0.0015 (0.0092)	−0.0102 (0.0286)	0.0100** (0.0004)	0.0160 (0.0191)
lnRD	−0.0110 (0.0233)	−0.0024 (0.0133)	0.0789* (0.0450)	−0.006* (0.003)	0.0075 (0.0320)
lnTO*FD	....	....	....	....	0.0086 (0.0642)
lnMan*FD	....	....	....	....	0.0572 (0.0647)
lnFP*FD	....	....	....	....	−0.0296 (0.1476)
Constant	6.40815 (7.6185)	0.2925 (0.2745)	−32.070** (14.8037)	−7/123*** (2.165)	1.3075 (2.90311)
AR (2)	0.089	0.089	0.122	0.084	0.065
Hansen	0.937	1.000	0.353	0.066	1.000
Obs	570	570	570	570	570

Source: Processed data, 2025. ***P<0.01, **P<0.05, *P<0.1

Table 5: Sys-GMM analysis results in the upper middle income group (upper middle income)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)
l.lnCO_2	0.9957*** (0.0286)	0.9842*** (0.0274)	0.944*** (0.030)	0.959*** (0.020)	0.991 *** (0.024)
lnTO	7.404 (13.984)	....	....	....	−0.330 (0.429)
lnTO_2	−1.772 (3.4117)	....	....	....	....
lnTO_3	0.1401 (0.2750)	....	....	....	
lnMan	....	−1.20 (4.3689)	....	....	−0.276 (0.426)
lnMan2	....	0.553 (2.1519)	....	....	....
lnMan3	....	−0.07 (0.3246)	....	....	....
lnFD	....	....	0.643 (0.561)	....	−0.797 (1.363)
lmFD2	....	....	−0.21 (0.176)	....	....
lnFD3	....	....	0.023 (0.018)		....
lnFP	....	....	....	−12.900 ** (5.607)	−0.589 (1.184)
lnFP2	....	....	....	5.062 ** (2.181)	....
lnFP3	....	....	....	−0.661 ** (0.281)	....
lnHC	−0.0216 (0.1416)	−0.04 (0.0852)	−0.27 (0.141)	−0.244 ** (0.099)	0.035 (0.147)
lnIQ	0.0059 (0.0263)	0.0146 (0.0207)	0.015 (0.025)	0.014 (0.022)	−0.02 (0.016)
lnRD	−0.001 (0.0132)	0.0048 (0.0260)	0.012 (0.015)	0.014 (0.014)	0.009 (0.018)
lnTO*FD	....	....	....	....	0.073 (0.093)
lnMan*FD	....	....	....	....	0.068 (0.118)
lnFP*FD	....	....	....	....	0.124 (0.295)
Constant	−10.11 (19.1383)	0.9826 (2.6987)	0.324 (0.327)	11.746 ** (5.022)	3.576 (5.325)
AR (2)	0.648	0.520	0.530	0.820	0.658
Hansen	0.063	0.085	0.126	0.167	0.308
Obs	300	300	300	300	300

Source: processed data, 2025. ***P < 0.01, **P < 0.05, *P < 0.1

confirms that the effectiveness of fiscal policy in reducing pollution depends on reaching a certain threshold, while (Zeraibi et al., 2024) finds that fiscal expansion through increased government spending actually drives an increase in CO_2 emissions in China, both in the short and long term. These findings also support the existence of an N-curve pattern, confirming the N-shaped EKC hypothesis. However, the effectiveness of fiscal policy is significantly influenced by external factors, including governance, public debt levels, and global economic conditions (Nguyen, 2022). Therefore, a balance is needed between short-term stabilisation goals and long-term fiscal sustainability (Mata et al., 2024). In contrast, upper-middle-income countries exhibit the opposite pattern, forming an inverted N-curve

Table 6: Sys-GMM estimation results in the lower middle income group (lower middle income)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)
l.lnCO_2	0.993 *** (0.047)	0.972 *** (0.045)	0.952*** (0.077)	0.979*** (0.087)	0.987 *** (0.029)
lnTO	2.827 (11.359)	……	……	……	0.018 (0.164)
lnTO_2	−0.854 (2.789)	……	……	……	……
lnTO_3	0.082 (0.226)	……	……	……	……
lnMan	……	11.35 (27.100)	……	……	−0.367 (0.312)
lnMan2	……	−4.61 (10.380)	……	……	……
lnMan3	……	0.609 (1.320)		……	……
lnFD	……	……	−0.72 (1.821)	……	−0.110 (0.204)
lmFD2	……	……	0.175 (0.534)	……	……
lnFD3	……	……	−0.01 (0.051)	……	……
lnFP	……	……	……	3.140 (2.637)	0.163 (0.120)
lnFP2	……	……	……	−1.19 (0.997)	.
lnFP3	……	……	……	0.145 (0.113)	.
lnHC	0.029 (0.098)	−0.042 (0.109)	−0.10 (0.131)	−0.01 (0.171)	−0.024 (0.069)
lnIQ	0.018 (0.081)	0.090 (0.070)	0.07 (0.102)	0.040 (0.124)	0.038 (0.031)
lnRD	0.010 (0.038)	0.013 (0.054)	0.04 (0.073)	0.00 (0.037)	0.009 (0.016)
lnTO*FD	……	……	……	……	−0.002 (0.049)
lnMan*FD	……	……	……	……	0.097 (0.098)
lnFP*FD	……	……	……	……	−0.063 ** (0.026)
Constant	−2.901 (15.048)	−8.764 (23.089)	1.478 (1.992)	−2.448 (1.595)	0.718 (0.661)
AR (2)	0.429	0.356	0.381	0.368	0.348
Hansen	0.663	0.655	0.945	0.344	0.587
Obs	180	180	180	180	180

Source: Processed data, 2025. ***P<0.01, **P<0.05, *P<0.1

Table 7: Sys-GMM analysis results in the low income group (low income)

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)	Coefficient (standard error)
l.lnCO_2	0.8949*** (0.0628)	0.941*** (0.0506)	0.8491*** (0.1728)	0.9316*** (0.2001)	0.7757*** (0.0638)
lnTO	−15.7044* (8.4370)	……	……	……	0.335** (0.1346)
lnTO_2	3.860* (2.0501)	……	……	……	……
lnTO_3	−0.3092* (0.1641)	……	……	……	……
lnMan	……	−0.6236 (0.4978)	……	……	0.0119 (0.0188)
lnMan2	……	0.5255 (0.3810)	……	……	……
lnMan3	……	−0.1151 (0.0788)		……	……
lnFD	……	……	0.0250 (0.0842)	……	0.0401 (0.1579)
lmFD2	……	……	0.0198 (0.0215)	……	……
lnFD3	……	……	0.003* (0.0016)	……	……
lnFP	……	……	……	−4.6453 (3.6680)	0.2314*** (0.0479)
lnFP2	……	……	……	1.9112 (1.6125)	.
lnFP3	……	……	……	−0.2486 (0.2119)	.
lnHC	−0.0196 (0.0265)	−0.0093 (0.0132)	0.0228 (0.0327)	−0.012* (0.0053)	−0.0137 (0.0169)
lnIQ	0.0129 (0.0393)	−0.0837 (0.0706)	−0.1938 (0.2397)	−0.0851 (0.2550)	−0.1815** (0.0547)
lnRD	0.0014 (0.0131)	0.0201 (0.0147)	0.0250 (0.0330)	0.0127 (0.0315)	0.0352** (0.0129)
lnTO*FD	……	……	……	……	−0.0260 (0.0317)
lnMan*FD	……	……	……	……	0.0149** (0.0048)
lnFP*FD	……	……	……	……	0.0241 (0.0256)
Constant	21.0059 (11.5070)	0.1707 (0.1247)	−0.2556 (0.4466)	3.6007 (2.3631)	−1.9123*** (0.5585)
AR (2)	0.470	0.816	0.880	0.863	0.589
Hansen	0.988	0.395	0.459	0.207	1.000
Obs	135	135	135	135	135

Source: Processed data, 2025. ***P<0.01, **P<0.05, *P<0

(negative-positive-negative) (Setyari and Kusuma, 2021). The apparent lack of a clear N-curve pattern in upper-middle-income countries may be influenced by several factors, including the level of economic development, characteristics of energy consumption, and the effectiveness of environmental policy implementation (Almeida et al., 2024; Alzgool et al., 2020; Mazina et al., 2022).

Based on Tables 3-7, Human capital control variables have been shown to significantly reduce CO_2 emissions in several groups, confirming their role in increasing awareness of environmental compliance (Dehghan Shabani, 2024; Kim and Go, 2020; Kuziboev et al., 2023). Conversely, institutional quality is generally insignificant except in specific models, consistent with the view that institutional effects are more long-term. R&D contributes to emission reductions in the combined group, but actually increases emissions in high- and low-income countries because innovation outcomes are not yet fully oriented towards green technology (Chang et al., 2023).

4.3. Interaction Variable

In general, the results of variable interactions show that the interaction between financial development and trade openness is only significantly negative in the all-income group, supporting the findings (Udeagha and Breitenbach, 2023; Xia et al., 2024) that a mature financial system can control the environmental impact of economic openness. Meanwhile, the interaction between financial development and the manufacturing industry is significantly positive only in the low-income group, in line with Onanuga et al. (2021), who assert that developing countries tend to rely on cheap energy, thereby accelerating emissions, coupled with weak environmental regulations, so that financial development has not been directed towards green investment. The manufacturing sector, which still relies on outdated technology and fossil fuels, tends to be supported by financial development, thereby exacerbating CO_2 emissions (Al-Kubati et al., 2022; Dallali et al., 2024; Elatroush, 2023). The interaction between financial development and fiscal policy has proven effective in reducing CO_2 emissions in the lower-middle-income and all income groups, as both can encourage sustainable investment and support environmentally friendly production technologies (Bilgili et al., 2025; Nguyen et al., 2024; Sakilu and Chen, 2024; Yeboah et al., 2024).

5. CONCLUSION

The study's results reveal variations in the impact of key variables on CO_2 emissions across different income groups. Trade openness proved to be significant for low-income groups, forming an inverted U-shaped curve. At the same time, manufacturing and financial development had a substantial effect in high-income countries, exhibiting an N-curve pattern. Fiscal policy had a significant effect on the upper-middle group with an inverted N pattern, while in the high-income and combined groups, it formed an N pattern. On the other hand, the interaction of financial development with the main variables produces diverse patterns: the combination with trade openness reduces emissions in the combined group, and the interaction with the manufacturing industry increases emissions in the low group. In contrast, the interaction with fiscal policy weakens the impact of emissions in the combined and lower-middle groups. These findings confirm that the relationship between economic growth, policy instruments, and environmental quality is complex and varies across income levels.

This study has limitations in terms of variables and proxies, including the exclusion of renewable energy consumption and environmentally friendly technologies. Therefore, future studies are recommended to add these variables to obtain a more comprehensive picture of CO_2 emissions. In addition, the methodological approach can be expanded by using heterogeneous dynamic panels (PMG) or integrating international and regional spatial analysis, as a country's emissions may also be influenced by the conditions of neighbouring countries in the era of globalisation.

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