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Research Article

The Role of Financial Development in Environmental Pollution and Climate Change

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Abstract
Climate change constitutes one of the pressing challenges confronting contemporary. Financial development possesses the potential to significantly contribute to the alleviation of environmental pollution and the mitigation of climate change by fostering economic growth predicated on sustainable energy sources. Nevertheless, a definitive consensus regarding the impact of financial development on environmental pollution remains elusive, and a small number of empirical investigations have scrutinized its direct repercussions on climate change. Consequently, the current study elucidates the impact of financial development on environmental pollution and climate change by employing a more comprehensive definition of financial development that incorporates four distinct indicators across two dimensions (banking and stock market) and two levels (flow and stock). It seems that, for the first time, the impact of pollution on mean temperature has been scrutinized through disaggregation of De Martonne's six climatic zones. Data were gathered from 106 countries categorized as developed, developing, and least-developed over the period 1990–2021. Subsequently, the pollution and climate change models were estimated employing a dynamic panel method. The findings revealed that the advancement of the banking sector exerts a positive effect on environmental pollution and mean temperature. This sector, through the reduction of financing costs, the proliferation of polluting industries, and the wealth effect, has precipitated environmental deterioration. Furthermore, the positive effect of stock market maturation on pollution and mean temperature suggests that companies persist in investing in environmentally detrimental projects or in utilizing antiquated and polluting technologies, without concern for reputational harm or potential depreciation in market value. These empirical results underscore the critical necessity of instituting and reforming financial sector regulations, instruments, and institutions to align with the optimal distribution of financial resources towards socially responsible industries, green (low-carbon) production enterprises, and environmentally sustainable initiatives.

Keywords Pollution . Climate change . Financial development . Panel data

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Introduction

Currently, climate change is pervasive, intense, accelerating, and certain aspects of it are irreversible, affecting all regions of the Earth. Article 1 of the United Nations Framework Convention on Climate Change (UNFCCC) defines climate change and global warming as externalities resulting from human activities (Stern, 2006). Over the past century, due to the greenhouse gases, the Earth's temperature has increased by 0.3 to 0.6 degrees Celsius (°C), and by the year 2100, the temperature is projected to rise by 1 to 3.5 °C. Since the Industrial Revolution, anthropogenic activities have engendered an anomalous increase in the concentration of greenhouse gases within the atmosphere through excessive consumption of fossil fuels. Carbon Dioxide (CO_2), which accounts for about 60% of the greenhouse effect, has played a major role in environmental pollution, global warming, and climate change. Today, the atmospheric concentration of CO_2 is about 50% higher than it was in 1750. Climate change not only creates serious problems for the environment but also leads to economic and financial crises (Intergovernmental Panel on Climate Change (IPCC), 2007; International Energy Agency (IEA), 2008; Environmental Protection Agency (EPA), 2016).

Given the close connection between human well-being and health, and environmental health and sustainability, global frameworks and agreements such as the UNFCCC (1992), the Kyoto Protocol (1997), and the Paris Agreement (2015) have established three general categories of climate action, namely, the mitigation of greenhouse gas emissions, the adaptation to the effects of climate change, and the provision of sufficient financial resources for climate initiatives, to avert the most severe consequences of climate change and to achieve net-zero carbon emissions. According to the Paris Agreement, countries must commit to reducing greenhouse gas emissions by half by 2030 and to zero by 2050, in order to limit the temperature increase to below 2 °C this century and reduce it to 1.5 °C above pre-industrial levels in the future. Accordingly, achieving sustainable economic performance without compromising the quality of environmental systems has been established as a global objective (IPCC, 2007).

Financial Development (FD), as a prerequisite for economic growth and development, affects environmental pollution and climate change. However, research results indicate that there are two fundamentally opposing views regarding the relationship between FD, energy consumption, and carbon emissions. One view argues that FD, by increasing energy consumption in both the production and consumption sectors, leads to higher greenhouse gas emissions and, consequently, has a detrimental impact on the environment (Farhani et al., 2014; Ito, 2017; Katircioglu & Taspinar, 2017). The other view maintains that FD, through various channels such as improving efficiency, financing renewable energy projects, and advancing clean and environmentally friendly technologies, contributes to reducing pollution and global warming (Zaidi et al., 2019; Mesagan & Olunkwa, 2022).

Financial development has both wealth and scale effects. On the one hand, a strong financial system facilitates easy access to capital, thereby raising living standards and, consequently, increasing the consumption of fossil fuels and greenhouse gas emissions. On the other hand, FD leads to new production lines and the large-scale acquisition of advanced equipment, which is more energy-efficient. Financial development also has technological and structural effects on the environment (Du et al., 2012).

Climate change is occurring, and in the absence of immediate and decisive measures today, adapting to its forthcoming ramifications will increasingly become more challenging and financially burdensome. The important role that FD has been theoretically proven, but the findings are inconclusive. Therefore, this paper examines the role of different dimensions of financial development (including the banking sector and the stock market, and at both flow and stock levels) in environmental pollution and climate change in a large set of developed and developing countries. Accordingly, it aims to answer three main questions: (1) What is the role of FD in environmental pollution? (2) What is the role of FD and environmental pollution in climate change? and (3) What is the role of FD through environmental pollution in climate change?

The remaining sections are organized as follows: Section 2 presents the theoretical framework, Section 3 describes the research methodology and data, Section 4 reports and analyzes the findings, and Section 5 concludes the paper.

Theoretical Framework

Dual Role of Financial Development

The development of financial sectors (banks and stock markets) enhances the financial efficiency of the economy (Sadorsky, 2011). A well-developed financial sector can play an important role in trade transactions, savings, monitoring resources, and mobilizing them for economic growth and development (Nasreen et al., 2017). According to World Bank studies, countries with more developed financial sectors experience faster economic growth. Also, there is a bidirectional causal relationship between financial development and economic growth. Hence, financial development, by accelerating economic growth based on the consumption of non-renewable or renewable energy can have a positive or negative impact on pollution and global warming.

On the one hand, financial development, by encouraging economic growth through industrial activities dependent on fossil fuels leads to increased environmental pollution (Chang, 2015; Ziaei, 2015; Nasreen et al., 2017; Assi et al., 2021). Furthermore, from a consumption perspective, an efficient financial structure allows consumers to obtain more credit or loans, that increases their demand for carbon-emitting durable goods such as automobiles, washing machines, air conditioners, and refrigerators (Mishra et al., 2009; Jalil & Feridun, 2011; Kayani et al., 2020).

When stock market develops, companies can obtain financing at lower rates and allocate it for purchasing machinery or development projects, that ultimately increase CO_2 emissions. Financial development enables some heavy industries to invest more, install new facilities, and expand their production capacity, which can increase emissions of environmental pollutants (Dasgupta et al., 2001; Sadorsky, 2010; Tamazian & Rao, 2010; Zhang, 2011). Also, higher foreign direct investment lead to increased consumption of non-renewable energy and CO_2 emissions (Frankel & Romer, 1999; Ntow-Gyamfi et al., 2020).

On the other hand, a well-developed financial sector can play a key role in reducing industrial pollution. The economic growth necessarily harm the environment and climate (Adedoyin et al., 2020). When industrial activities that rely on renewable energy lead to economic growth, the demand for renewable energy increases, and pollution decreases (Assi et al., 2021). A developed financial sector can be beneficial by effectively screening investment proposals and allocating funds to environmentally friendly projects (Zaidi et al., 2019; Mesagan & Olunkwa, 2022). Moreover, FD can enhance energy efficiency and reduce carbon emissions by encouraging businesses and manufacturing to implement, adopt, and invest in advanced clean technologies (Birdsall & Wheeler, 1993; King & Levine, 1993; Frankel & Rose, 2002; Tamazian et al., 2009; Shahzad et al., 2014; Pata, 2018; Shahbaz et al., 2020).

According to the Environmental Kuznets Curve (EKC), development is the most effective remedy for environmental problems. The adoption of renewable energy consumption faces serious obstacles due to high and diverse costs, such as the development of new infrastructure, operational expenses, and start-up costs. A stable financial system is essential to support, finance, and manage the risks associated with the transition from non-renewable to renewable energy sectors. In addition, technological innovations are essential for improving energy efficiency and reducing energy prices in a way that encourages producers to shift from fossil fuels to renewable energy sources (Wurgler, 2000; Zhou et al., 2010; Eren et al., 2019; Alam & Murad, 2020). FD can facilitate the transfer of environmentally friendly technologies and Research and Development (R&D) projects through free trade and the foreign direct investment. As a result, environmental pollution is reduced by increasing economic growth based on the use of renewable energy and improving energy efficiency (Grossman & Krueger, 1993; Hsueh et al., 2013; Pazienza, 2015; Assi et al., 2021; Birdsall & Wheeler, 1993; Frankel & Rose, 2002).

Financial development can increase investment in new low-carbon technologies, enabling greater use of renewable energy and a reduction in fossil fuel consumption. The reduction of borrowing expenses, the enhancement of trust and savings among lenders and borrowers, the reallocation of credit towards research in renewable energy, and the financial support for R&D initiatives in clean energy serve to incentivize institutions and individuals to foster innovations and secure patents for novel renewable energy sources (Assi et al., 2021). FD can facilitate the transition to a "low-carbon economy" by providing credit to low-carbon companies and projects in order to ensure sufficient funding for carbon-free technological innovations (Wang et al., 2012). Empirical findings indicate that in advanced economies, pollutant emissions per unit of production have diminished due to the implementation of environmentally sustainable technological advancements and stringent ecological (Stern, 2018).

Ultimately, the dichotomous perspectives regarding the function of financial development in relation to environmental degradation and climate alteration can be encapsulated through the inverted U-shaped Kuznets curve. Grossman & Krueger (1995) and Selden & Song (1994) provided empirical evidence that in the early stages of economic development, economic growth with greater consumption of non-renewable fossil fuels leads to gradual environmental degradation and contributes to global warming. But, after reaching a certain level of per capita income and increasing demand for renewable resources, society will move towards environmental sustainability. Therefore, not all forms of economic growth necessarily harm the environment and climate (Raymond, 2004; Adedoyin et al., 2020). The relationship between financial development and pollution is also likely to be nonlinear. In the early stages of financial development, environmental degradation increases. However, financial development gradually reduces degradation as financial resources become available to firms that adopt cleaner production techniques (Khan et al., 2022).

Literature Review

This section reviews several studies related to the impact of financial development on environmental pollution and climate change (Table 1). Most of these studies have used variables such as CO_2 emissions and domestic credit to the private sector by banks as proxy for financial development. However, few studies have considered various dimensions of financial development. Most of these studies have been conducted in a single country or among a group of countries with similar levels of development. Some have also focused on distinguishing between developed and developing countries. However, no study has been conducted on a large set of both developed and developing countries. The findings of these studies classified into three distinct categories: (1) positive effect, (2) negative effect, and (3) inconclusive. Therefore, there is no clear consensus on the role of financial development in environmental pollution and climate change, because the mechanism of financial development's impact is complex. Moreover, few studies directly investigate the effect of financial development on climate change.

Accordingly, the present study examines the role of financial development in environmental pollution and climate change, with the following distinctions: (1) By embracing a more comprehensive conceptualization of the financial development index, which encompasses the banking sector and capital markets at both flow and stock levels, it helps to clarify the direct impact of financial development on pollution and climate change; (2) Different specifications are estimated across a large sample of developed and developing countries over the period 1990–2021 to improve the statistical reliability; (3) It seems that, for the first time, the De Martonne aridity index has been employed to analyze the impact of pollution on global warming, differentiated by climatic regions.

Table 1. Summary of recent empirical studies.

Authors (Year)	Methodology	Country (Period)	Main Findings
Jalil & Feridun (2011)	ARDL	China (1953–2006)	Negative impact of FD on environmental pollution and confirmation of the EKC
Dafermos et al. (2018)	DEFINE model Panel data	A group of countries (2016–2120, Simulated)	Negative impact of climate-induced financial instability on credit expansion and the intensification of the negative impact of climate change on economic activities
Guo et al. (2019)	STIRPAT model Panel data	China (1997–2015)	Positive impact of efficiency and stock trading volume on CO_2, in contrast to the negative impact of scale and market value of listed companies
Kayani et al. (2020)	Panel VECM PFMOLS	Top 10 carbon emitters (1990–2016)	Positive impact of FD on CO_2 in long run
Saud et al. (2020)	Dumitrescu–Hurlin (DH) panel causality	Belt & Road Initiative (BRI) (1990–2014)	Positive impact of FD on ecological footprint, carbon footprint, and CO_2
Sethi et al. (2020)	ARDL Granger causality	India (1980–2015)	Negative and positive impacts of FD on CO_2 in the short and long run, respectively
Sun et al. (2020)	Panel data	China (1995–2017)	Positive or negative impacts of various climate change risks on the financial performance of mining companies
Umar et al. (2020)	Panel data	China (1971–2018)	Negative impact of FD and innovation on CO_2; one-way causality from FD to CO_2
Assi et al. (2021)	P-ARDL, DH	ASEAN (1998–2018)	Lack of a significant relationship between FD and renewable energy
Chenet et al. (2021)	–	–	Analyzing preventive actions and steering financial markets clearly towards a net-zero carbon future
Khan et al. (2021)	GMM	BRI (2000–2014)	Positive impact of FD on renewable energy consumption and CO_2 reduction
Onyimadu & Uche (2021)	Budget analysis	Nigeria (2013–2020)	Priority given to flood control, erosion control, and irrigation projects, in contrast, a low share of industry-related programs
Sahoo et al. (2021)	ARDL	India (1990–2018)	Negative impact of FD and information & communication technology, and the positive impact of electricity consumption on CO_2
Saliya & Wickrama (2021)	CFA models in SEM	Fiji	Identification of political leadership, administrative direction, international standards, and supervisory mechanisms as dimensions of financial risk preparedness for climate change
Zhao et al. (2021)	Spatial regression	China (1999–2017)	Negative impact of financial depth and positive impact of improved financial efficiency on SO_2 and industrial solid waste
Baur & Oll (2022)	Mean–variance analysis	(2011–2021)	Improved risk-return profile and reduced carbon emissions by adding Bitcoin to a diversified equity portfolio
Ehigiamusoe et al. (2022)	Panel data	31 African nations (1990–2019)	Inverted U-shaped relationship between FD and CO_2; confirmation of the EKC
Guan et al. (2022)	CRS-SBM-DEA	China (2011–2015)	Positive impact of FD and trade on pollution control, environmental quality, and resource use efficiency
Khan et al. (2022)	GMM, FGLS Granger causality	Asia Pacific (1990–2016)	Positive impact of FD on ecological footprint in linear function, and negative impact in non-linear function

Authors (Year)	Methodology	Country (Period)	Main Findings
Mesagan & Olunkwa (2022)	Panel data	18 African nations (1996–2017)	Positive and negative impacts of FD on CO_2 in the short and long run, respectively
Agyeman et al. (2023)	FMOLS DOLS PMG	27 African economies (2000–2020)	Positive impact of FD and energy consumption, and negative impact of innovation on CO_2, confirmation of the EKC
Liao et al. (2023)	NARDL	China (1970–2021)	Negative impact of FD, technological innovation, and renewable energy on pollution
Aytun et al. (2024)	CS-ARDL	19 middle-income (1980–2016)	Positive impact of FD on environmental quality
Chen et al. (2024)	Panel data FMOLS, VECM	26 OECD & 18 non-OECD (1996–2019)	Negative impact of financial development and renewable energy investment on climate change in the long run
Ozkan et al. (2024)	Wavelet quantile-based techniques	Turkey (2000–2019)	Negative impact of FD and energy vulnerability on environmental quality
Wijethunga et al. (2024)	ARDL	Australia (1980–2021)	Confirmation of the EKC and the Financial Environmental Kuznets Curve
Fatima et al. (2025)	DOLS, FMOLS CCR, MMQR	Sub-Saharan African (1990–2020)	Positive relationships of FD, green technological innovation, energy transition, and environmental policy stringency with environmental sustainability

Model and Data

The aim is to estimate the impact of FD on environmental pollution and climate change using a dynamic panel data approach in developed and developing countries over the period 1990–2021. Based on the theoretical framework and previous studies, including Alizadeh (2015), Guo et al. (2019), Sethi et al. (2020), Sun et al. (2020), Khan et al. (2021a, 2021b), and Mesagan & Olunkwa (2022), the regression equations of pollution (1) and climate change (2) were defined as follows:

$$LCO_2T_{it} = \beta_0 + \beta_1 LCO_2T_{it-1} + \beta_2 FD_{it} + \beta_3 LGDP_{it} + \beta_4 REC_{it} + \beta_5 IS_{it} + \beta_6 TR_{it} + \beta_7 UR_{it} + \beta_8 FDI_{it} + u_{it} \quad (1)$$

$$LMT_{it} = \theta + \gamma_1 LMT_{it-1} + \gamma_2 LCO_{2,it} + \gamma_3 D_1 \times LCO_{2,it} + \gamma_4 D_2 \times LCO_{2,it} + \gamma_5 D_3 \times LCO_{2,it} + \gamma_6 D_4 \times LCO_{2,it} + \gamma_7 D_5 \times LCO_{2,it} + \gamma_8 FD_{it} + \gamma_9 NRD_{it} + \varepsilon_{it} \quad (2)$$

In the pollution model (1), the dependent variable is the natural logarithm of CO_2 emissions per capita in metric tons (LCO_2T). The independent variables include the financial development index (FD), domestic credit to the private sector by banks (BS, flow) and broad money (M_3, stock) as indicators of banking sector development, and the total value of stocks traded (ST, flow) and the market capitalization of listed domestic companies (MC, stock) as indicators of stock market development. Natural logarithm of gross domestic product per capita in constant 2015 US dollars (LGDP); renewable energy consumption as a percentage of total final energy consumption (REC); industrial sector value added to GDP ratio as an industrialization index (IS); total value of exports and imports to GDP ratio as an index of trade openness (TR); share of urban population in total population as an index of urbanization (UR); and net inflows of foreign direct investment as a percentage of GDP (FDI).

In the climate change model (2), the dependent variable is the natural logarithm of the average annual temperature in degrees Celsius (LMT). The explanatory variables include the following: the natural logarithm of total CO_2 emissions in kilotons as a total pollution index (LCO_2); defining dummy variables (D_1 to D_5) based on the De Martonne climate classification index; natural resources depletion (the sum of net depletion of forests, energy, and minerals) as a percentage of Gross National Income (NRD); and the financial development index. All data was extracted from the World Bank. The explanations are summarized in Table 2.

Table 2. Variables list

Variable	Symbol	Definition
Dependent variables		
Environmental pollution	CO_2T	CO_2 emissions per capita (metric tons)
Climate change	MT	Mean temperature (annual, °C)
Independent variables		
Environmental pollution	CO_2	Total CO_2 emissions (kt)
Financial development	FD	Financial development index:
1) Bank-based financial development index		
Flow	BS	Domestic credit to the private sector by banks (% of GDP)
Stock	M_3	Broad money (% of GDP)
2) Stock market-based financial development index		
Flow	ST	Stocks traded, total value (% of GDP)
Stock	MC	Market capitalization of listed domestic companies (% of GDP)
Economic growth	GDP	Gross Domestic Product (GDP) per capita (constant 2015 US$)
Renewable energy	REC	Renewable energy consumption (% of total final energy consumption)
Industrialization	IS	Industry (including construction), value added (% of GDP)
Trade openness	TR	Total trade (exports + imports), (% of GDP)
Urbanization	UR	Urban population (% of total population)
Foreign direct investment	FDI	Net inflows of foreign direct investment (% of GDP)
Natural resources depletion	NRD	Adjusted savings: natural resources depletion (% of GNI)

This study utilizes panel data from a large set of developed and developing countries, including 106 countries in the pollution model and 99 countries in the climate change model over the period from 1990 to 2021. The variables, countries, and period were selected based on data availability. Outliers were removed, and missing data were interpolated using geometric mean and exponential methods.

In order to more accurately assess the impact of the total pollution index on climate change, the sample countries are classified according to climate type. Climate classification means dividing countries into regions with similar climate characteristics in the long term. In this study, the De Martonne climate classification method is employed. The De Martonne aridity coefficient index is calculated as follows:

$$I = \frac{PR}{(MT + 10)} \quad (3)$$

Which is the division of the average annual precipitation in millimeters by the sum of ten and the average annual temperature in degrees Celsius (De Martonne, 1926; Alizadeh, 2015; Khalili et al., 2022). The calculations revealed that most countries experienced climate change during this 32-year period. The results also indicate that the sample countries exhibit substantial climatic diversity. A summary of the climate classification results of the countries and the definition of dummy variables is provided in Table 3.

The model estimates using the Generalized Method of Moments (GMM) that consists of five steps: (1) Investigating the stationarity of variables using unit root tests, including Levin, Lin & Chu (LLC) with common unit root, and Im, Pesaran & Shin (IPS), Augmented Dickey–Fuller–Fisher (ADF–F), and Phillips–Perron–Fisher (PP–F) with individual unit root. (2) Individual and time effects are test by F, Breusch–Pagan, and Honda statistics. (3) If effects is confirmed, the type of effects (fixed or random) is identified using the Hausman test. (4) Then, the final model is estimated dynamically. (5) Finally, to ensure the validity of the instrumental variables, the Sargan test and the Arellano–Bond test were performed to examine the order of autocorrelation in the error terms (Baltagi, 2008).

Table 3. Climatic classification of countries based on the De Martonne index (Alizadeh (2015) and Research findings)

Climate type	De Martonne index values	Dummy variable	Country
Arid	$I < 10$	D_1	11
Semi-arid	$10 \leq I < 20$	D_2	10
Moderately arid (Mediterranean)	$20 \leq I < 24$	D_3	1
Semi-humid	$24 \leq I < 28$	D_4	5
Humid	$28 \leq I < 35$	D_5	17
Very humid	$I \geq 35$	Basis	55

Empirical Results

Descriptive Evidence

In this section, scatter plots are drawn to better understand the relationship between the main research variables. Figure 1 shows the scatter plots of various dimensions of financial development and the environmental pollution index. The vertical axis represents CO_2 emissions in metric tons per capita (CO_2T), and the horizontal axis displays the flow (BS) and stock (M_3) indicators of banking, and the flow (ST) and stock (MC) indicators of the stock market, respectively, from left to right in graphs A, B, C, and D. According to this figure, the highest density of CO_2T observations is within the range of 0 to 10, whereas the highest density of FD indicators lies below 90 percent of GDP.

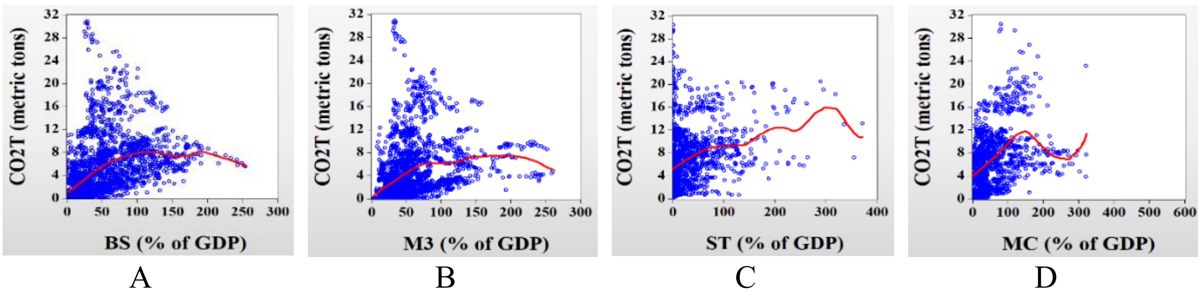
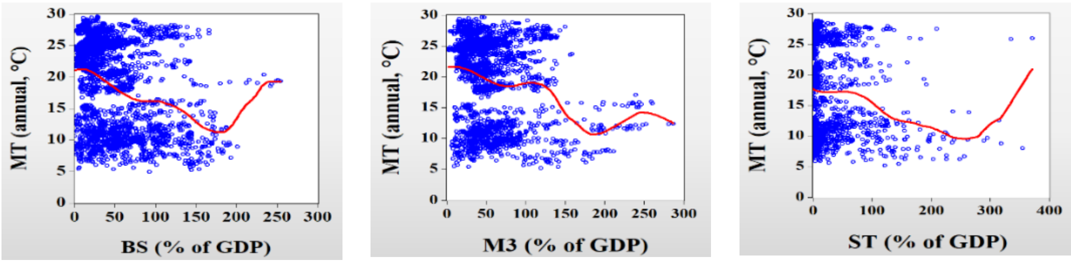


Figure 1. Scatter plots of financial development and environmental pollution

Based on the fitted line for different levels of the FD index, its type of relationship with the pollution index is obvious. For example, in graph D, there is a direct relationship for levels between 0–150. With a decrease in the density of observations at levels between 150–270, this relationship is reversed, and finally becomes direct again for levels above 270. Overall, it is speculated that a direct relationship exists between MC and CO_2T. In general, all graphs suggest a direct relationship between financial development and environmental pollution. Figure 2 shows scatter plots of different dimensions of financial development and the climate change index. Overall, based on the fitted line, an inverse relationship between FD and average temperature is observed.



A B C

Figure 2. Scatter plots of financial development and mean temperature.

Unit Root Tests

The results of the unit root tests for the research variables are reported in Table 4. The optimal lag length was selected automatically, and then the tests were performed at the variable level, considering two specifications: “with constant only” and “with both constant and trend”. The findings indicate that all the research variables are stationary at level.

Table 4. Panel unit root tests

Variable	LLC		IPS		ADF–F		PP–F	
	C	T	C	T	C	T	C	T
LCO_2	-8.00***	-3.43***	-1.54*	-2.48***	311.35***	298.25***	373.25***	275.44***
LCO_2T	-4.62***	-3.88***	-0.87	-2.81***	309.99***	303.45***	338.91***	265.03***
LMT	-24.87***	-34.16***	-21.55***	-35.19***	878.73***	1364.88***	905.97***	1985.70***
LPR	-42.84***	-39.67***	-40.42***	-38.13***	1750.14***	1516.40***	1915.20***	3270.01***
LI	-42.44***	-38.50***	-40.53***	-37.35***	1760.81***	1485.54***	1965.27***	2995.70***
BS	-1.12	1.11	1.53	-0.53	220.92	263.15***	186.34	684.90***
M_3	4.67	-5.74***	7.70	-4.21***	144.41	436.29***	158.45	360.79***
ST	-5.36***	0.38	-6.22***	-3.36***	273.58***	214.97***	254.72***	212.34***
MC	-10.42***	-5.52***	-8.40***	-6.15***	292.32***	248.72***	271.25***	247.22***
LGDP	-2.39***	-2.74***	4.98	-2.50***	188.77	347.03***	214.62	559.22***
REC	1.75	-4.11***	4.38	-0.74	260.38**	330.22***	253.05**	492.64***
IS	-7.46***	-2.19**	-4.63***	-1.28*	333.77***	274.30***	368.05***	270.80***
TR	-6.57***	-10.70***	-4.44***	-8.70***	346.84***	574.70***	318.68***	353.93***
UR	-6.29***	0.58	5.50	-0.62	311.63***	512.72***	639.78***	705.51***
FDI	-15.22***	-15.70***	-17.47***	-15.00***	740.77***	637.46***	758.69***	647.38***
NRD	-12.30***	-5.73***	-10.66***	-6.21***	496.88***	376.65***	482.07***	382.82***

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. C = constant, T = constant & trend.
Source: Research findings

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At first, the pollution model was estimated using panel data for 106 countries. Then, the Breusch–Pagan, Honda, F, and Hausman tests were conducted to detect effects (Table 5). The results indicate that the model with banking development indicators has fixed individual effects, while strong evidence supporting the presence of time effects has not been found. In the model with stock market and financial sector development indicators, fixed individual effects were confirmed, and time effects were supported by the Breusch–Pagan and F tests. However, the estimation results did not show significant differences between using only fixed individual effects or both individual and time effects.

Table 5. Effect tests for pollution models

Test	Banking index		Stock market index		Financial sector index	
	Flow	Stock	Flow	Stock	Flow	Stock
Breusch–Pagan						
Cross-section	25447.50***	23073.93***	15713.64***	13893.34***	13813.76***	9875.77***
Period	2.72*	3.49*	6.12**	4.31**	5.99**	5.76**
Honda						
Cross-section	159.52***	151.90***	125.35***	117.87***	117.53***	99.38***
Period	-1.65	-1.87	-2.47	-2.08	-2.45	-2.40
Analysis of variance F						
Cross-section	183.90***	179.79***	374.15***	413.38***	347.79***	429.39***
Period	0.74	0.94	2.07***	2.16***	2.49***	2.04***
Hausman (random, fixed)						
Cross-section	38.07***	41.01***	32.89***	28.94***	35.80***	24.94***
Period	–	–	9.13	11.88	9.24	9.74

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Furthermore, the Sargan test results confirmed the validity of the instrumental variables, and the Arellano–Bond tests confirmed the presence of first-order autocorrelation and the absence of second-order autocorrelation in the error terms (Table 6).

In all models, the lagged value of pollution had a significant and positive effect on current pollution levels. GDP per capita had a significant and positive impact on environmental pollution. Higher economic growth can lead to increased emissions of greenhouse gases such as CO_2 and, as a result, more environmental pollution by expanding industrial activities, increasing the depletion of natural resources, and more consumption of non-renewable energy. This result is consistent with the research of Ozkan et al. (2024), Ehigiamusoe et al. (2022), Khan et al. (2021a, 2021b), and Saud et al. (2020).

The impact of renewable energy consumption (REC) on environmental pollution is significant and negative. Renewable energy is clean, accessible, abundant, sustainable, and economically viable. The renewable energy (such as solar, wind, and geothermal energy) reduces CO_2 emissions and pollution. This finding underscores the importance of R&D in the clean energy sector, and is consistent with the findings of Liao et al. (2023), Khan et al. (2021a, 2021b), and Kayani et al. (2020).

The impact of industrialization rate (IS) has been found to be significant and positive. Industrialization exacerbates environmental degradation through the proliferation of manufacturing establishments, the augmentation of production activities, the acceleration of economic development, and the heightened consumption of fossil fuels. Moreover, industrial growth is associated with increasing labor demand and improving income levels. Therefore, rising labor incomes and growing demand for durable consumer goods lead to greater energy consumption and environmental pollution (Mishra et al., 2009; Jalil & Feridun, 2011; Kayani et al., 2020).

The trade openness (TR) has a significant and positive effect on environmental pollution. Based on the study by Grossman & Krueger (1993), this can be explained through comparative advantage. In a country with a comparative advantage in the production of pollution-intensive goods, the scale effect (increasing the volume of production activities) and the composition effect (changing the production composition towards polluting goods) have dominated the effect of technology (changing the production technology towards clean technology). Or in a country with a comparative advantage in the production of clean goods, the scale effect has dominated the effects of composition and technology. As a result, trade has led to an increase in environmental pollution, which is consistent with Agyeman et al. (2023), Sethi et al. (2020), and Jalil & Feridun (2011), but contradicts the results of Saud et al. (2020).

The impact of urbanization rate (UR) on environmental pollution is significant and positive in models with stock market development indicators and financial sector flows. The escalation of urbanization propels the proliferation of economic endeavors, the inefficient utilization of natural resources, the heightened consumption of non-renewable energy, particularly within the domestic and transportation sectors, and a concomitant rise in CO_2 emissions. These findings are consistent with those of Ehigiamusoe et al. (2022), Kayani et al. (2020), and Guo et al. (2019), but contradict the results of Agyeman et al. (2023). Nonetheless, reforming the structure of the economic sector, more efficient use of energy and urban infrastructure, and investing in renewable energy can help reduce the threat of environmental problems in cities (Mol & Spaargaren, 2000).

Table 6. Pollution model estimation results

Variable	Banking index		Stock market index		Financial sector index	
	Flow	Stock	Flow	Stock	Flow	Stock
Constant	-0.22518** (0.08983)	-0.22549* (0.12210)	-0.06745 (0.09962)	-0.15466 (0.12612)	-0.10333 (0.09711)	-0.53210* (0.28989)
$LCO_2T\ (-1)$	0.61767*** (0.01705)	0.64760*** (0.01793)	0.34129*** (0.02509)	0.39786*** (0.01995)	0.31066*** (0.01807)	0.42231*** (0.03581)
BS	0.00020** (0.00009)	–	–	–	0.00007** (0.00003)	–
M_3	–	-0.00007 (0.00013)	–	–	–	-0.00013 (0.00013)
ST	–	–	0.00008*** (0.00001)	–	0.00006*** (0.00002)	–
MC	–	–	–	0.00012*** (0.00001)	–	0.00007** (0.00003)
LGDP	0.11623*** (0.01826)	0.10285*** (0.02075)	0.11623*** (0.02077)	0.11180*** (0.02678)	0.11692*** (0.01259)	0.16644** (0.06896)
REC	-0.01483*** (0.00059)	-0.01284*** (0.00055)	-0.02265*** (0.00099)	-0.01981*** (0.00061)	-0.02231*** (0.00030)	-0.01729*** (0.00106)
IS	0.00247*** (0.00028)	0.00271*** (0.00022)	0.00303*** (0.00026)	0.00407*** (0.00043)	0.00317*** (0.00034)	0.00322*** (0.00042)
TR	0.00023*** (0.00004)	0.00013** (0.00006)	0.00030*** (0.00004)	0.00029*** (0.00005)	0.00025*** (0.00005)	0.00029*** (0.00008)
UR	-0.00178 (0.00119)	-0.00109 (0.00088)	0.00359*** (0.00135)	0.00327* (0.00197)	0.00442*** (0.00106)	0.00025 (0.00532)
FDI	0.00005*** (0.00001)	0.00059*** (0.00009)	0.00003** (0.00001)	0.00007*** (0.00001)	0.00005*** (0.00002)	0.00022*** (0.00008)
Observations	2465	2210	1402	1265	1290	952
Sargan test	88.70731	79.80812	55.40145	51.44572	55.86959	32.53167
Arellano–Bond test:						
AR (1)	-3.46900***	-3.32240***	-5.11880***	-5.55200***	-4.89800***	-4.45310***
AR (2)	-0.71065	-0.51340	-0.30530	-0.28137	-0.38772	-0.56586

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Parentheses display the standard errors.

Foreign direct investment (FDI) has had a significant and positive impact on environmental pollution. According to the Rybczynski theory, FDI can influence environmental quality by changing the composition of production. According to this theory, the accumulation of physical capital has led to the expansion of pollution-intensive industries, economic growth based on the consumption of fossil fuels, and heightened environmental pollution. This result is confirmed in Khan et al. (2021a) and Sethi et al. (2020), but no in Saud et al. (2020). However, in later stages, as per capita income grows and economies transition from the industrial to the service sector, economic growth is driven by the accumulation of human capital, resulting in a reduction in environmental pollution (Grossman & Krueger, 1995).

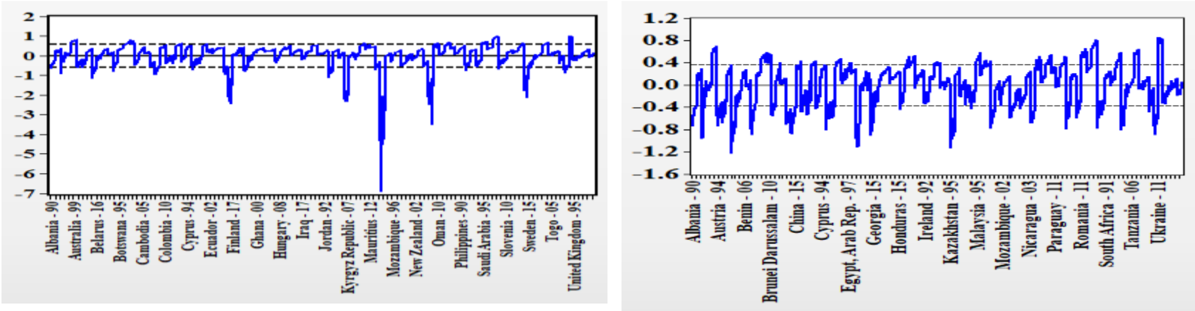
To answer the first research question, the coefficients of various dimensions of financial development are analyzed. In models with the flow indicator of banking development (BS), as well as the flow (ST) and stock (MC) indicators of stock market development, the positive effect of FD on pollution is confirmed at the 5% and 1% significance levels, respectively. In contrast, in all models, the effect of the banking development stock indicator (M_3) on pollution is not statistically significant. Models with financial sector development indicators that simultaneously include flow (stock) indicators more strongly confirm these results. The positive effect of banking sector development aligns with Ehigiamusoe et al. (2022) and Sethi et al. (2020), but contradicts those of Liao et al. (2023) and Guo et al. (2019). As for stock market development, the positive effects of the flow and stock indicators are respectively consistent and inconsistent with the results of Guo et al. (2019).

The positive effect of the banking development flow indicator on pollution demonstrates that advancements in the banking sector have facilitated investments in new projects that lack environmental sustainability. The development of the banking sector enables heavy and pollution-intensive industries to expand their production capacities. As a result, emissions of environmental pollutants increase (Dasgupta et al., 2001; Sadorsky, 2010; Tamazian & Rao, 2010). Furthermore, banking sector development provides consumers with greater access to credit, which leads to higher demand for durable goods, such as automobiles and air conditioners, thereby increasing carbon emissions (Mishra et al., 2009; Jalil & Feridun, 2011; Kayani et al., 2020).

The positive impact of stock market development on pollution can be interpreted from the perspective that high stock trading volume indicates strong liquidity and increased stock market trading. As the dynamics of stock market operations escalate, emblematic of economic expansion and progress, the generation of goods and services increases, resulting in heightened greenhouse gas emissions, particularly CO_2 (Paramati et al., 2018). In addition, stock market development has failed to encourage listed companies to invest in environmentally friendly technologies (renewable energy), improve energy efficiency, and reduce pollutant emissions. The stock market has also fallen short in responding appropriately to the disclosure of firms' environmental performance (Lanoie et al., 1998; Dasgupta et al., 2006; Tamazian et al., 2009).

The Impact of Financial Development on Climate Change

Benchmark model climate model (excluding financial development) was estimated using data from 106 developed and developing countries, and the residual graph is plotted in Figure 3–A. Countries with high residuals, most of which were countries with negative average temperatures, were identified as outliers and removed (Canada, Finland, Kyrgyzstan, Mongolia, Norway, Russia, and Sweden). So the number of countries was reduced from 106 to 99, and re-estimation indicated that the residuals are satisfactory (Figure 3B).



A B

Figure 3. Residual graphs of the benchmark model before (A) and after (B) removing outliers

Then, effect tests were performed (Table 7). The results indicate that the benchmark model has individual effects according to Breusch–Pagan and Honda, and the Hausman test supports the fixed effects. The F-test confirms the presence of both effects. Nevertheless, the estimations show minimal differences between the individual fixed effect and both fixed effects.

Table 7. Effect tests for climate change models

Test	Benchmark	Banking index		Stock market index		Financial sector index	
		Flow	Stock	Flow	Stock	Flow	Stock
Breusch–Pagan							
Individual	34699.13***	29379.34***	28224.15***	17657.53***	14855.72***	14341.62***	10431.60***
Time	1.09	0.97	0.17	2.23	1.98	2.34	1.31
Honda							
Individual	186.28***	171.40***	168.00***	132.88***	121.88***	119.76***	102.14***
Time	-1.05	-0.99	-0.41	-1.49	-1.41	-1.53	-1.15
Analysis of variance F							
Individual	3384.45***	3282.81***	3702.13***	3164.33***	3088.33***	3087.73***	3641.73***
Time	40.82***	29.05***	22.12***	24.91***	24.03***	16.41***	10.64***
Hausman (random, fixed)							
Individual	39.47***	46.45***	33.62***	18.15**	13.83*	20.25**	11.94
Time	14.48**	14.48*	23.03***	16.96**	17.20**	13.57	21.44**

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8. Estimation results of the benchmark climate change model

Variable	Coefficient	Variable	Coefficient
Constant	1.86119*** (0.00550)	$D_5 \times LCO_2$	0.00267*** (0.00003)
LMT (-1)	0.29412*** (0.00062)	NRD	-0.00094*** (0.00004)
LCO_2	0.01125*** (0.00048)	Observations	2674
$D_1 \times LCO_2$	0.00754*** (0.00009)	Sargan test	98.38559
$D_2 \times LCO_2$	0.00633*** (0.00009)	Arellano–Bond test:	
$D_3 \times LCO_2$	0.00482*** (0.00003)	AR (1)	-4.75930***
$D_4 \times LCO_2$	0.00433*** (0.00004)	AR (2)	1.29620

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Parentheses display the standard errors. A very humid climate is considered as the base climate.

The Sargan test results confirmed the validity of the instrumental variables, and the Arellano–Bond tests indicated the presence of first-order autocorrelation and the absence of second-order autocorrelation in the error terms (Table 8). The lagged average temperature had a significant and positive effect on the current average temperature. At the 1% significance level, the effect of the total pollution index, and its differentiated impact across the five distinct De Martonne climate zones, on average temperature was significant and positive. This implies that an increase in atmospheric greenhouse gases, intensifies the greenhouse effect, thereby raising the average temperature. According to the findings, pollution (both generally and separately in arid, semi-arid, Mediterranean, semi-humid, and humid climates) increases average temperature and negatively affects climate change, in line with the results of Usman et al. (2022). The effect of natural resource depletion (NRD) on average temperature is significant and negative, contrary to expectations. It was expected that an increase in the net depletion of natural resources such as forests, energy, and minerals would lead to increased pollution and higher average temperature.

Now it is employed to incorporate financial development indicators. As previously noted, preliminary tests for effect specification are undertaken (Table 7). The results indicate the presence of fixed individual effects. According to the Hausman test, fixed effects are identified for the flow model, whereas random effects are detected for the stock model.

Table 9. Estimation results of climate change models

Variable	Banking index		Stock market index		Financial sector index	
	Flow	Stock	Flow	Stock	Flow	Stock
Constant	1.76015*** (0.00942)	2.16251*** (0.02335)	1.62322*** (0.05210)	2.04646*** (0.03094)	1.88602*** (0.05601)	2.84668*** (0.10955)
$LMT(-1)$	0.28024*** (0.00166)	0.21262*** (0.00416)	0.22149*** (0.00862)	0.16207*** (0.00418)	0.22187*** (0.00652)	0.12186*** (0.01073)
LCO_2	0.02627*** (0.00072)	0.00658*** (0.00162)	0.04382*** (0.00325)	0.02052*** (0.00310)	0.02322*** (0.00295)	-0.03931*** (0.00815)
$D_1 \times LCO_2$	0.00713*** (0.00020)	0.00647*** (0.00020)	0.00434*** (0.00018)	0.00605*** (0.00076)	0.00511*** (0.00027)	0.00764*** (0.00061)
$D_2 \times LCO_2$	0.00575*** (0.00015)	0.00504*** (0.00020)	0.00312*** (0.00020)	0.00482*** (0.00067)	0.00408*** (0.00024)	0.00582*** (0.00030)
$D_3 \times LCO_2$	0.00408*** (0.00005)	0.00330*** (0.00013)	0.00251*** (0.00008)	0.00281*** (0.00040)	0.00294*** (0.00013)	0.00407*** (0.00022)
$D_4 \times LCO_2$	0.00357*** (0.00006)	0.00274*** (0.00014)	0.00156*** (0.00013)	0.00206*** (0.00035)	0.00197*** (0.00010)	0.00303*** (0.00025)
$D_5 \times LCO_2$	0.00276*** (0.00005)	0.00222*** (0.00007)	0.00213*** (0.00008)	0.00184*** (0.00013)	0.00247*** (0.00007)	0.00229*** (0.00020)
BS	0.00013*** (0.00001)	–	–	–	0.00025*** (0.00003)	–
M_3	–	0.00081*** (0.00003)	–	–	–	0.00142*** (0.00014)
ST	–	–	0.00022*** (0.00001)	–	0.00014*** (0.00001)	–
MC	–	–	–	0.00023*** (0.00002)	–	0.00022*** (0.00001)
NRD	-0.00092*** (0.00007)	-0.00089*** (0.00008)	-0.00524*** (0.00053)	-0.00324*** (0.00026)	-0.00421*** (0.00042)	-0.00005 (0.00051)
Observations	2491	2235	1442	1299	1310	967
Sargan test	97.02866	81.85563	58.59742	51.42172	55.96615	32.22690
Arellano–Bond test:						
AR (1)	-4.34830***	-3.59450***	-4.50840***	-4.40520***	-4.19220***	-3.15880***
AR (2)	0.78044	0.71760	-0.82261	-1.26750	-1.38180	-0.75270

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Parentheses display the standard errors. A very humid climate is considered as the base climate.

Estimations of the final models are reported in Table 9. The Sargan test confirms the validity of the instrumental variables, and the Arellano–Bond tests indicates the presence of first-order autocorrelation and the absence of second-order autocorrelation in the error terms. The lagged average temperature has a significant and positive effect on the current period's average temperature. At the 1% significance level, the effect of the total pollution index on the average temperature was significant and positive, except in the model with the financial sector development stock indicators, where the effect was significant and negative, contrary to expectations. In all models, at the 1% significance level, increased pollution leads to higher average temperatures across arid, semi-arid, Mediterranean, semi-humid, and humid climates, and negatively affects climate change, consistent with Usman et al. (2022). The effect of natural resource depletion on the average temperature was significant and negative, contrary to expectations, except in the model with the financial sector stock indicators, where this effect was not statistically significant.

Therefore, the results indicate a positive effect of various dimensions of financial development, including the flow and stock indicators of the banking sector, the stock market, and the financial sector on average temperature. These findings are consistent with the study by Chen et al. (2024) and contradict Usman et al. (2022), who found that financial development has improved environmental and climate quality. In the previous section, since the analyses confirmed the positive effect of pollution on average temperature, the results can be implicitly compared with research on the effect of banking sector development on environmental pollution. The findings are consistent with the studies by Ehigiamusoe et al. (2022) and Sethi et al. (2020), but contradict the findings of Liao et al. (2023) and Guo et al. (2019). The results can also be implicitly related to studies on the impact of stock market development on pollution. The positive effect of the flow and stock indicators of stock market development is consistent and inconsistent with the findings of Guo et al. (2019), respectively.

Conclusions and Policy Implications

This study aims to investigate the impact of financial development on environmental pollution and climate change. Sample countries of developed, developing, and least-developed, were selected for the period 1990–2021, and the pollution and climate change models were estimated separately employing four distinct financial development indicators and GMM.

The results are summarized in Figure 4. Economic growth, industrialization, trade openness, urbanization, and foreign direct investment positively affect environmental pollution emissions by increasing the consumption of non-renewable fossil fuels, while renewable energy negatively affects environmental pollution by improving energy efficiency. The estimates also confirmed the positive effect of pollution, both overall and separately for the De Martonne climatic regions, on average temperature. More importantly, the development indicators of the banking sector and the stock market have a positive effect on environmental pollution and average temperature. Financial development has contributed to environmental degradation by reducing financing costs, funding polluting development projects, reinforcing the polluting industrial structure, or through the wealth effect on the economy. The estimations confirm the first view that financial development has a negative role in environmental sustainability by increasing pollution through greater consumption of fossil fuels in both production and consumption sectors.

Accordingly, the answers to the research questions are clarified. The answer to question (1) is that the effect of financial development on environmental pollution is positive. For question (2), the findings indicate that both financial development and environmental pollution positively affect average temperature. These results are supported by the studies of Chen et al. (2024), Ozkan et al. (2024), Agyeman et al. (2023), Saud et al. (2020), and Sethi et al. (2020), while they are contradicted by Fatima et al. (2025), Aytun et al. (2024), Usman et al. (2022), and Khan et al. (2021a). Based on the findings of questions (1) and (2), the answer to question (3) is that financial development has a positive effect on average temperature through its impact on environmental pollution.

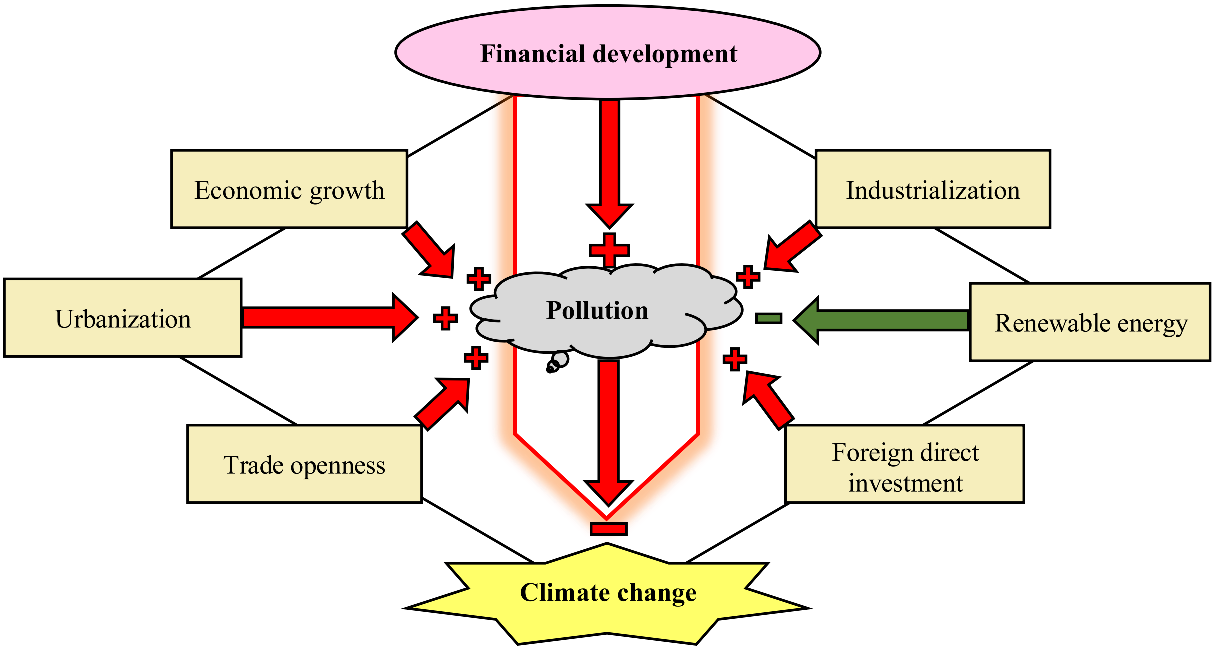


Figure 4. Impact of financial development on environmental pollution and climate change

Countries must pursue a transition to an affordable, reliable, and sustainable energy system to reduce dependence on fossil fuels, achieve sustainable and emission-free economic growth, decrease pollution, and address the climate change crisis. Realizing these goals requires a well-developed financial system that can facilitate investments in renewable energy, prioritize energy-efficient practices, and support the adoption of clean energy technologies and infrastructure. Therefore, serious efforts must be undertaken to reform and establish financial regulations, instruments, and institutions in alignment with these objectives. To this end, the following measures should be pursued:

- Reforming financial policies and regulatory frameworks with the aim of expeditiously decarbonizing economic activities, and more importantly, the incentive mechanisms of financial institutions for decision-making of market participants (This policy is implementable in developed and developing countries through a phased approach, training, and provision of simple financial incentives such as low-interest loans. In least-developed countries, it can be implemented through pilot projects, training, and small direct financial incentives, and gradually expanded as financial and regulatory capacities improve).
- The enforcement of punitive regulations, including penalties or prohibitions on financing, directed towards energy-intensive and environmentally detrimental industries (In developing countries, it can be executed via a balanced system of incentives and penalties, taking into account the limited financial, technological, and regulatory capacities, so as to maintain both environmental effectiveness and economic growth. In least-developed countries, experimental regulatory frameworks accompanied by international technical and financial support can serve as an initial step for the gradual implementation of the policy).
- Development of the financial market, aiming at optimizing the allocation of financial resources and providing adequate financial support to low-carbon companies for participation in green projects (In developed and developing countries, it can advance by strengthening financial infrastructure, providing interest rate subsidies or establishing green guarantee funds, and by utilizing international financial cooperation. In least-developed

countries, pilot projects supported by international technical and financial assistance can serve as a basis for establishing initial green financial mechanisms).

- Establishing green financial institutions (green deposits and investments), with the aim of increasing the availability of financial resources for environmentally friendly projects, for example, by designing punitive credit mechanisms (high interest rates) for heavily polluting companies, and incentive-based mechanisms (preferential interest rates) for low-carbon companies (In developing countries, it can be executed through pilot green institutions, preferential credit lines, and capacity-building programs. In least-developed countries should act as before explained).
- Designing a stock market strategy aimed at the public disclosure of environmental performance information of listed companies (In developed countries, it is implementable through financial transparency regulations and environmental reporting requirements for listed companies. In developing countries, it can advance by establishing simplified reporting frameworks, providing legal incentives, and collaborating with local and international stock exchanges. In least-developed countries should act as before explained).
- Enhancing public awareness and sensitivity pertaining to climate change in order to increase the willingness to invest in low-carbon and socially responsible enterprises (In developed countries, public awareness can be enhanced through targeted media campaigns, environmental education programs, and the disclosure of corporate environmental and climate-related information. In developing countries, this policy can be implemented through simplified educational programs, capacity-building workshops, and local initiatives in collaboration with international organizations. In least-developed countries, pilot and gradual actions, supported by international technical and financial assistance and institutional capacity-building for educational institutions and stock exchanges, can serve as a foundation for improving public knowledge and climate sensitivity).

Declarations

Ethics Approval This study did not involve human or animal subjects, and no formal ethics approval was required.

Availability of Data and Material The data used in this study are accessible from publicly available databases.

Conflicts of Interest/Competing Interests The authors declare that they have no conflicts of interest or competing interests related to this study.

Authors' Contributions All authors contributed equally to the conception, data collection, analysis, interpretation, writing, and final approval of the manuscript.

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