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Importing innovation or indigenous innovation: Evaluating the effect of climate finance on promoting environmental sustainability in developing countries☆

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ABSTRACT

This paper examines the influence of climate finance on the CO_2 emissions and explores the underlying mechanisms from the perspectives of external and indigenous innovations, with a cross-country panel dataset encompassing 140 developing countries from 2002 to 2022. The results indicate that climate finance has a negative and significant impact on CO_2 emissions. Specifically, a one-standard-deviation increase in climate funds correlates with an approximate 3.31 % reduction in per GDP CO_2 emissions. However, heterogeneity analysis reveals that in the least developed countries, climate finance does not significantly reduce carbon emissions and, in some cases, may even enhance the carbon emissions. Mechanism analysis suggests that climate finance promotes environmental sustainability by introducing external innovation rather than promoting indigenous innovation in developing countries. These results shed new light on the pollution halo hypothesis in developing nations.

1. Introduction

Greenhouse gas accumulation is causing severe environmental degradation, with catastrophic impacts on societies and ecosystems, challenging climate mitigation and adaptation efforts (IPCC, 2021; You et al., 2022). Numerous policy instruments have been implemented to tackle the environmental challenges, including carbon pricing, emission standards, direct technological interventions, financial tools like climate finance and so on. Among them, climate finance has grown in prominence as developing countries struggle with green funding gaps (Fu et al., 2011; Iacobuţă et al., 2022). As a fundamental element of international climate negotiations, climate finance is considered crucial for helping developing countries address sustainability challenges (Carfora and Scandurra, 2019; Lee et al., 2022a). However, there remains uncertainty regarding the effectiveness of these funds in the most underdeveloped nations, and whether it can foster external innovation or indigenous innovation in these countries. Indigenous innovation refers to innovation activities that are developed within the boundaries of a domestic firm or national context, relying primarily on internal R&D capabilities, local knowledge bases, and human capital. It emphasizes self-reliance and is often motivated by strategic autonomy or geopolitical constraints (Fu et al., 2011; Wu et al., 2013; Zhang et al., 2023). While external innovation refers to innovation that is driven by the adoption of knowledge, technologies, or practices from external sources, including foreign firms, research institutions, joint ventures, or licensing arrangements (Wu et al., 2013; Zhang et al., 2023).

The efficacy of climate finance in driving green innovation varies across nations, contingent on their environmental performance and their ability to efficiently utilize the provided funds (Tennant et al., 2024; Wang et al., 2022.) Regarding the Environmental Kuznets Curve (EKC) theory, for developed nations, climate finance has the potential to enhance green innovation and mitigate environmental degradation (Apergis, 2016). Nevertheless, the least developed countries exhibit the greatest demand for climate finance, as evidenced by Robinson and Dornan (2017). Conversely, these same nations possess the weakest capacity to implement measures aimed at achieving their mitigation and adaptation objectives, and this is a challenge underscored by Tennant et al. (2024). As the recipient countries for the least developed countries, climate finance funds aren't always invested in climate mitigation and adaptation projects. Hook (2021) notes that climate finance typically

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extends support retrospectively, concentrating on the specific demands of initial responses and recovery efforts. Moreover, if renewable energy alternatives are not as economically attractive as traditional energy sources, industries might hesitate to transition or choose renewable technologies, especially when climate finance funding is limited (Nchofoung et al., 2024).

Another significant barrier for recipient countries is the insufficient financial capacity to effectively absorb and utilize climate finance. Many developing nations face institutional weaknesses, poor governance, and inadequate financial systems, which make it difficult for them to manage large-scale climate projects efficiently. As a result, there is a risk of funds being misallocated or wasted on poorly designed or executed projects (Lee et al., 2022b). Furthermore, the complexity and lack of transparency in climate finance mechanisms often discourage private sector participation, which is crucial for scaling up efforts to address climate change (Iacobuţă et al., 2022). Therefore, for the least developed countries, their innovation pathway tends to prioritize importing innovation over indigenous innovation. The literature suggests that technology transfer, including both foreign direct investment (FDI) and imports, plays a crucial role in boosting technological innovation in emerging economies, particularly when these countries lack the necessary domestic R&D capabilities (Elkomy et al., 2021; Wang and Liu, 2024).

However, this technology developed in industrialized countries might not be directly applicable to developing nations. Moreover, technology transfer can have mixed effects depending on the level of absorptive capacity within the receiving economy (Elkomy et al., 2021; Fu et al., 2011). Indigenous innovation is equally critical, particularly in the context of green finance initiatives in developing countries. Research highlights that indigenous efforts in technology development and adaptation are often more suited to local conditions compared to imported technologies (Fu et al., 2011). The integration of local innovation systems, including R&D activities and the use of locally appropriate technologies, enables these economies to develop their green finance solutions in a way that aligns with their unique socio-economic and environmental conditions (Fu et al., 2011; Nchofoung et al., 2024). This is particularly relevant for sustainable practices and the development of green technologies that are suited to local environmental challenges. Considering the variances in developmental requirements and the capacity to utilize resources, the process by which climate finance fosters low-carbon development in developing nations remains obscure. It is imperative to conduct further studies to identify the channels through which climate finance can stimulate low-carbon growth, particularly in underdeveloped emerging economies that confront substantial challenges in the pursuit of sustainable development and decarbonization.

This study utilizes cross-country panel data from 140 developing nations (2002–2022) to investigate the influence of climate funding on environmental sustainability and its pathways in encouraging low-carbon development strategies. Our results reveal that climate finance has substantially reduced CO_2 emissions in underdeveloped nations. Specifically, a one-standard-deviation increase in climate finance is associated with a projected reduction of approximately 3.31 % in CO_2 emissions. However, heterogeneity analysis indicates that in lesser-developed emerging economies, climate finance was found ineffective in decreasing carbon emissions and may sometimes even increase emissions. Further investigation shows that climate finance promotes environmental sustainability primarily through the introduction of externally-sourced innovation rather than by promoting indigenous innovation. These research findings focus on the applicability of the pollution halo hypothesis (Duan and Jiang, 2021) in developing nations.

The marginal contributions are as follows. First, with FDI as indicators of introducing external innovation and national-level R&D expenditure[1] as a proxy for indigenous innovation, we examine whether climate finance affects environmental performance through indigenous innovation or external innovation in developing countries. To the authors' best knowledge, this paper provides the cross-country empirical evidence on the underlying mechanisms of climate finance's impact on carbon reduction. Second, our results address two debates surrounding economic development and environmental conservation, i.e., the Porter Hypothesis and the EKC Hypothesis. We provide evidence supporting the EKC hypothesis in developing countries (Cole, 2004; Awaworyi Churchill et al., 2020). Third, according to our research, climate finance is ineffective at reducing carbon emissions, as it relies on external rather than indigenous innovation. This suggests the absence of the pollution halo effect in these countries.

This paper is structured as follows: The theoretical framework and hypotheses are presented in Section 2, followed by a description of the data and methodology in Sections 3 and 4. Section 5 presents the results and discussion, with conclusions and implications provided in Section 6.

2. Theoretical analysis and hypotheses

Climate finance, a unique instrument in international finance, is critical to achieving environmental sustainability. The major role of climate finance among the recipient nations is helping them address the impact of climate change and promote environmental sustainability (Carfora et al., 2017). In particular, developing nations can advance the creation of low-carbon societies with aid from mitigation funds (Lee et al., 2022a; Pickering et al., 2017). The prominence of and need for changing energy systems and achieving net-zero emissions have been emphasized in order to increase the investment towards the climate to accomplish a transition for a sustainable and environmentally friendly world in this decade (Anbumozhi et al., 2016; the Climate Policy Initiative, 2021). Examinations on the impacts of climate funds allocated to biosphere protection and renewable energy using the PSM technique were conducted by Carfora and Scandurra (2019). They found that nations receiving 'fast-start' climate financing experienced a decrease in greenhouse gas emissions and a more significant shift towards renewable energy sources. The following hypothesis was formulated based on previous research works and the research gap.

H1. Climate finance improves environmental sustainability in developing countries.

Green finance has emerged as a transformative force in aligning economic development with environmental sustainability in developing countries (Carfora et al., 2017). It supports innovation both through the introduction of foreign technologies and by fostering indigenous innovation, and these two pathways differ fundamentally in terms of mechanisms and outcomes. Green finance often facilitates technology transfer by enabling access to mature, environmentally friendly technologies developed abroad. This process typically involves foreign direct investment (FDI), equipment imports, and international partnerships. These transfers lead to efficiency improvements when the technologies matched the local capabilities and knowledge base (Elkomy et al., 2021; Wang et al., 2025). Cohen (2000) emphasize that absorptive capacity is critical for latecomer firms. Figueiredo and Cohen (2019) exemplify how developing countries leverage green finance to achieve technological catch-up through a mix of external knowledge absorption and incremental innovation. As economic globalization expands, technology spillovers from openness are increasingly seen as a major driver of technological advancement in beneficiary countries (Huang et al., 2017; Huang et al., 2020). However, developing countries often find it more efficient to adopt foreign technologies developed in advanced economies. In theory, if innovations could be easily diffused and adopted,

[1] We also use the number of technicians (*Technician*), and the number of registered trademarks (*Trademark*) to measure indigenous innovation.

regardless of their type or complexity, technologically lagging countries could quickly bridge the gap by adopting the most innovative technologies from developed nations (Grossman and Helpman, 1994; Romer, 1994; Lee et al., 2022b). With the hope of "exchanging market access for technology", many developing nations have joined a "race to the bottom" by providing various financial and fiscal incentives to attract foreign direct investment (FDI) (Fu et al., 2011). This occurs through mechanisms such as demonstration effects, employment linkages, and vertical integrations within supply chains (Glass and Saggi, 2002).

While both channels are important, their optimal deployment depends on the stage of development and sectoral characteristics. Developing countries with weak R&D systems and high technological gaps have limited capacity for indigenous innovation (Lee et al., 2022a; Rai and Funkhouser, 2015). However, green finance providers and recipients have the immediate need for solutions to address pressing environmental challenges. Consequently, developing countries initially focus on foreign technology adoption supported by green finance. Mazzoleni and Nelson (2007) note that public research institutions in resource-rich countries tend to focus on incremental improvements tailored to local conditions. Lee and Malerba (2017) highlight that institutional support primarily targets scaling existing technologies to meet global sustainability standards. This pattern mirrors that in renewable energy sectors, where major developing economies such as India and China have prioritized solar and wind technology imports over domestic R&D (Gallagher, 2014).

However, over time, as absorptive capacities and R&D infrastructure improve, green funding increasingly supports indigenous innovation ecosystems. The Malaysian case illustrates how technological innovation can significantly reduce CO_2 emissions; its success hinges on effective financing mechanisms, institutional frameworks, and policy coherence (Raihan et al., 2022).

To sum up, while green finance in developing countries may contribute to environmental goals, much of this funding initially focuses on importing technologies from advanced economies, which typically offer more immediate and reliable solutions. However, this reliance on foreign technology is typically complemented by efforts to build indigenous innovation capacities to ensure long-term sustainability. The following hypothesis is formulated based on the above analysis:

H2. Climate finance affects environmental sustainability mainly through introducing external innovation rather than promoting indigenous innovation in developing countries.

While green finance can stimulate technological change in developing countries, its effectiveness in reducing carbon emissions is contingent on the level of economic development, institutional readiness, and the country's ability to absorb and adapt foreign technologies. Absorptive capacity is defined as the potential of an organization to recognize, merge, and leverage external intelligence to improve its operations and boost productivity (Cohen and Levinthal, 1989; Girma, 2005). The cultivation of absorptive capacity heavily relies on the human capital and R&D investments within the recipient nations. In large emerging economies, the role of foreign technology in driving innovation efficiency has been explored (Elkomy et al., 2021; Wang et al., 2025), as these transfers match the local capabilities and knowledge base (Fu et al., 2011). In countries like Malaysia, technological innovation, particularly in renewable energy, is increasingly seen as a pathway to achieving environmental sustainability goals, but the innovation is often spurred by external technology inputs rather than purely local development (Raihan et al., 2022). In lesser-developed emerging economies, green finance struggles to reduce carbon emissions, as those countries lack the infrastructure, human capital, and local innovation systems to fully integrate advanced technologies. Foreign technologies often do not align perfectly with local needs, creating inefficiencies. For example, the impact of foreign technology and R&D on productivity in Egypt was found to be stronger in technology-intensive sectors than in more internationally oriented industries, which lacked the necessary absorptive capacity (Elkomy et al., 2021). This suggests that while foreign technology inflows can stimulate innovation in certain contexts, they do not necessarily lead to broad-based emission reductions in developing economies. Constraints such as talent shortages, limited R&D activities, and a low proportion of skilled workers, further impede the ability to absorb external technologies in lesser-developed emerging economies (Girma, 2005).

Additionally, institutional readiness impacts the effectiveness of green finance in reducing carbon emissions. In lesser-developed emerging economies, the slow implementation of climate policies and insufficient scaling of climate finance hinder the full potential of green finance (Iacobuţă et al., 2022). Without proper alignment of climate finance with national priorities, these countries struggle to adopt clean technologies effectively, limiting their ability to achieve carbon emission reductions. By contrast, green finance proves more effective in higher-income developing countries, which tend to have better institutional frameworks, more developed human capital, and greater absorptive capacity to adapt imported technologies. In these environments, foreign technology transfer is effectively complemented by indigenous innovation, enhancing the implementation efficiency of green technologies. For instance, countries like Malaysia that have significantly invested in renewable energy and technological innovation demonstrate more promising emission reduction outcomes (Raihan et al., 2022).

H3. Climate finance does not significantly reduce carbon emissions in lesser-developed emerging economies.

3. Data description

We obtain our data from several databases. The selection of developing economies is based on the categorization of the countries on the OECD's official website. The dependent variable in this study is carbon emissions, taken from the Global Carbon Atlas database. As the primary anthropogenic greenhouse gas, CO_2 emissions effectively capture environmental degradation caused by human activities associated with economic growth. In previous studies, this indicator has often served as a proxy for assessing environmental quality, considering its significant role in causing climate-induced environmental deterioration (Chen and Lee, 2020; Ehigiamusoe et al., 2020). Thus, we employ CO_2 emissions as the dependent variable to gauge environmental sustainability.

Njangang et al. (2024) and Zhao et al. (2022) discussed the bifurcation of climate funds (CF) into two distinct categories: Mitigation finance funds (MF) and Adaptation finance funds (AF). Adaptation finance funds are geared towards adjusting to the anticipated or actual influence on climate change, while mitigation finance funds are primarily focused on reducing greenhouse gas emissions (Pickering et al., 2017). The OECD Development Assistance Committee (OECD-DAC), which annually compiles comprehensive statistics on sanctioned developmental aid and finances provided to the developing countries from bilateral and multilateral sources, served as the source of climate financing data. Additional data were obtained from the World Development Indicators (WDI) database.

4. Research design

4.1. Baseline models

We explore climate finance's impact on carbon emissions for selected developing economies by using the following baseline models:

$$CO2\_GDP_{it} = \alpha_0 + \alpha_1 lnAF_{it} + \alpha_2 Controls + \delta_i + \varphi_t + \varepsilon_{it} \tag{1}$$

$$CO2\_GDP_{it} = \alpha_0 + \alpha_1 lnMF_{it} + \alpha_2 Controls + \delta_i + \varphi_t + \varepsilon_{it} \tag{2}$$

$$CO2\_GDP_{it} = \alpha_0 + \alpha_1 lnCF_{it} + \alpha_2 Controls + \delta_i + \varphi_t + \varepsilon_{it} \tag{3}$$

Where t and $i$represent the recipient year and the country, correspondingly. The dependent variable *CO2_GDP* denotes CO_2 emissions per unit of GDP. For the explanatory variables *lnAF*, *lnMF*, and *lnCF*, we employ the natural logarithms of two types of climate funds (adaptation finance funds and mitigation finance funds) and their sums (total climate finance funds) to quantify climate finance. *Controls* stand for control variables including total population (*POP*), secondary industry output (*Secondary*), tertiary industry output (*Tertiary*), Outward Foreign Direct Investment (O*FDI*), GDP growth rate (*GDPgrowth*), GDP per capita (*GDPpercent*) and surface area of the recipient countries (*lnSurface_area*). δ and φ symbolize year and country's fixed effects, and ε_{it} is the random error term. The coefficient we most concern is α_1, as α_1 shows how climate finance influence CO_2 emissions in developing countries.

Explicitly, some previous studies highlight the significant influence of population dynamics on environmental quality (Lee et al., 2022b; Zhang et al., 2021). Some scholars argue that urbanization driven by population growth can improve infrastructure, which may subsequently reduce energy consumption and improve environmental standards (Guo et al., 2022). Conversely, others demonstrate that larger populations increase energy consumption and carbon emissions, ultimately degrading environmental quality (Su et al., 2021).

Meanwhile, we consider the production of the secondary sector to be indicative of increased economic expansion and industrial development, which generally lead to higher carbon emissions (Li and Lin, 2015; Li et al., 2022a). In the same way, we control the tertiary industry output to see how service sector development impacts CO_2 emissions. Following Fu et al. (2011), Balsalobre-Lorente et al. (2019) and Li et al. (2022b), we use national-level R&D expenditure (*RD_expend*), the count of technicians (*Technician*), and the count of registered trademarks (*Trademark*) to measure indigenous innovation, while FDI (*FDI*) and international technological cooperation (*Tech_coop*) to measure introducing innovation.

Finally, we account for OFDI and GDP. Validations for the verification and application of reverse technology spillovers in combination with Outward Foreign Direct Investment (OFDI) have been conducted by many scholars (Van Pottelsberghe De La Potterie and Lichtenberg, 2001; Head et al., 1999; Kogut and Chang, 1991), which means investors can learn and introduce advanced technologies through OFDI projects. This spillover effect can not only facilitate technological innovation, but also promote green production in investor countries (Pan et al., 2020). Though OFDI usually brings benefits to both sides, investors may deliberately divert polluting firms abroad through outward investment to optimize their own environmental performance (Lin and He, 2023; Wang and Liu, 2024). GDP represents economic growth, where increased activity typically raises energy consumption, leading to greater pollution and reduced environmental quality. Existing studies consistently show GDP's positive correlation with carbon emissions (Gyamfi et al., 2022; Hassan et al., 2022).

4.2. Descriptive statistics

Table 1 presents the definitions of all variables, while Table 2 shows the descriptive statistics. The average carbon emissions per GDP (*CO2_GDP*) is 0.2417, ranging from a minimum of 0.0420 to a maximum of 1.0791, whereas the average total carbon emissions (*lnCO2*) amount to 8.7696, with minimum and maximum values of 3.7865 and 14.4623, respectively. These results reflect substantial variation in both total emissions and carbon emissions per GDP across countries. The mean values of *lnAF*, *lnMF*, and *lnCF* are 16.5819, 16.2655 and 17.1587, respectively. Similarly, considerable variations exist in climate finance allocations across various nations.

Table 1
List of variables, definitions, and data sources.

Variable	Definition	Source
CO2_GDP	CO_2 emissions per GDP (kg per PPP $)	Global Carbon Atlas
lnCO2	Natural logarithm of CO_2 emissions (kt)	Global Carbon Atlas
lnAF	Natural logarithm of adaptation climate finance funds (constant 2022 US$, million)	OECD-DAC
lnMF	Natural logarithm of mitigation climate finance funds (constant 2022 US$, million)	OECD-DAC
lnCF	Natural logarithm of global climate funds (constant 2022 US$, million)	OECD-DAC
AFgdp	Adaptation finance funds (% of GDP)	OECD-DAC
MFgdp	Mitigation finance funds (% of GDP)	OECD-DAC
CFgdp	Global finance funds (% of GDP)	OECD-DAC
POP	Natural logarithm of total population (per people)	WDI
Secondary	Secondary industry output (% of GDP)	WDI
Tertiary	Tertiary industry output (% of GDP)	WDI
OFDI	Outward Foreign Direct Investment (% of GDP)	WDI
GDPgrowth	GDP growth rate (annual %)	WDI
GDPpercent	GDP per capita (one thousand dollars, constant 2015 US$)	WDI
lnSurface_area	Natural logarithm of surface area (sq. km)	WDI
RD_expend	Research and development expenditure (% of GDP)	WDI
Technician	Natural logarithm of the number of technicians in R&D (per million people)	WDI
Trademark	Natural logarithm of the number of registered trademark applications (nonresident and resident, by count)	WDI
FDI	Foreign Direct Investment (% of GDP)	WDI
Tech_coop	Natural logarithm of technological cooperation grants (BoP, current US$)	WDI

5. Results and discussion

5.1. Correlation test

We conduct a correlation analysis to assess potential multicollinearity, as presented in Table 3, which reveals low correlation coefficients among the regressors. In addition, we also find the average variance inflation factors are 2.40, 2.41, and 2.40, the threshold of 10. These results indicate that multicollinearity does not play a significant role and is not a concern in our analysis.

5.2. Baseline results

This section selects the most appropriate econometric approach by estimating both fixed and random effects. Table 4 columns (1), (3), and (5) report the results for the fixed effect models by using Eqs. (1)–(3), while columns (2), (4), and (6) present the results for random effect models. Hausman test results confirm that the fixed effect model outperforms the random effect model in our case.

Specifically, columns (1) and (3) specify the estimation of climate adaptation funds (*lnAF*) and climate mitigation funds (*lnMF*) on CO_2 emissions per GDP (*CO2_GDP*), respectively. Columns (5) provides the estimation of climate funds (*lnCF*) on CO_2 emissions per GDP (*CO2_GDP*). The coefficient of *lnAF* is negative and it is found to be statistically significant (1 % level), as indicated by Column (1), which indicates that more climate adaptation funds are associated with reduced CO_2 emissions. Economically, a one-standard-deviation increase in climate adaptation funds for about 3.937 leads to a 0.0083 reduction (-0.0021×3.937) in per GDPCO_2 emissions, equating to about 3.42 % of the sample's average CO_2 emissions per GDP (i.e., 0.242). Similarly, column (3) also shows a significant and negative coefficient of *lnMF*, indicating that more climate mitigation adaptation funds are associated with reduced CO_2 emissions. A one-standard-deviation increase in climate mitigation funds for about 3.852 is

Table 2
Descriptive statistics.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	N	Mean	p50	SD	Min	Max
CO2_GDP	2892	0.2417	0.1850	0.1996	0.0420	1.0791
lnCO2	2627	8.7696	8.7554	2.3555	3.7865	14.4623
lnAF	2892	16.5819	17.2327	3.9371	0	21.5758
lnMF	2892	16.2655	16.9609	3.8517	0	21.0966
lnCF	2892	17.1587	17.8329	3.9936	0	22.0578
AFgdp	2892	0.0163	0.0019	0.0459	0	0.5305
MFgdp	2892	0.0106	0.0014	0.0359	0	0.4681
CFgdp	2892	0.0269	0.0035	0.0789	0	0.9986
POP	2892	15.5856	15.9200	2.1978	9.3016	20.9704
Secondary	2808	26.6175	24.4859	12.6047	2.7586	86.6696
Tertiary	2772	51.4079	51.5066	11.5846	6.4481	94.1483
OFDI	2501	0.6617	0.1387	3.3291	−32.0426	75.9995
GDPgrowth	2889	3.7922	4.1287	5.8357	−50.3385	86.8267
GDPpercent	2892	4.5325	3.0616	4.4235	0.3382	19.8843
lnSurface_area	2762	11.4735	12.1065	2.6108	3.4012	15.9574
RD_expend	949	0.3914	0.2805	0.3492	0.0054	2.4067
Technician	462	4.3281	4.3129	1.2156	1.2093	6.6275
Trademark	2892	3.7847	0.0000	4.5854	0.0000	13.6459
FDI	2833	4.4310	2.8959	6.2997	−37.1727	103.3374
Tech_coop	2681	17.6672	17.9045	1.3814	13.6647	20.1475

associated with a 0.0073 decrease (-0.0019×3.852) in CO_2 emissions per GDP, equating to about 3.02 % of the sample's average CO_2 emissions per GDP. Column (5) shows a significantly negative coefficient of *lnCF*, indicating that more climate funds are associated with reduced CO_2 emissions. A one-standard-deviation increase in climate funds for about 3.994 is associated with a 0.0080 decrease (-0.0020×3.994) in CO_2 emissions per GDP, equating to about 3.31 % of the sample's average CO_2 emissions per GDP.

The findings align with hypothesis H1 and corroborate the results of Carfora and Scandurra (2019) and Lee et al. (2022a) proving that the climate funds can mitigate the overuse of fossil fuels and lower greenhouse gas emissions. Our baseline findings suggest that climate finance does not support the "pollution haven" hypothesis. There is no clear evidence indicating that climate finance exacerbates environmental issues in recipient countries by causing significant pollution transfer. This reinforces the notion that climate finance is instrumental in tackling environmental issues and climate change. Moreover, although the random effect model performs less effectively than the fixed effect model, the results from columns (2), (4), and (6) still show significantly negative coefficients for all three climate finance proxy variables. This suggests that our empirical findings are robust across different model specifications.

The results regarding the control variables suggest that the majority of them significantly influence CO_2 emissions. For example, the coefficient of population size (*POP*) is positive, and it is significant (1 % level), suggesting that countries with larger populations produce more CO_2 emissions. This finding aligns with reality, as larger populations imply greater potential emissions from daily activities and economic activities, leading to higher CO_2 production. The coefficient for the secondary industry output (*Secondary*) is not significant, whereas the coefficient for the tertiary industry (*Tertiary*) is significantly positive, suggesting that greater industrialization doesn't automatically lead to higher CO_2 emissions, while a more developed service sector tends to raise emissions. Although industrialization can lead to rapid fossil fuel consumption and significant emissions (Li and Lin, 2015; Li et al., 2022a), developing countries benefit from a latecomer advantage, adopting mature renewable energy technologies during industrialization to mitigate potential environmental pressures. Therefore, industrialization's impact on CO_2 emissions in emergent nations is mixed, which is reflected in the non-significant coefficient. A higher level of service sector development suggests more economic activity, indicating more CO_2 emissions (Fourcroy et al., 2012; Zhang et al., 2015).

We also noticed that OFDI (*OFDI*) retains a positive impact on CO_2 releases, which directly might be linked with the "pollution haven" hypothesis (Bommer, 1999; Ozatac et al., 2017), suggesting that OFDI tends to relocate polluting industries to developing nations, potentially causing environmental harm that lingers after the investment has withdrawn. However, the empirical results cannot yet confirm whether OFDI's "pollution haven" effect is mitigated within the framework of climate finance. This issue will be further examined and discussed in the subsequent analysis of this paper. The GDP growth rate (*GDPgrowth*) possesses no significant effect on CO_2 releases, while higher per capita GDP (*GDPpercent*) is associated with lower CO_2 emissions because the countries with *GDPpercent* are more economically developed and thus adopt low-carbon and carbon-reduction technologies to combat environmental degradation, achieving more sustainable growth.

5.3. Robustness tests

This section evaluates the robustness of our findings by conducting multiple sensitivity tests. First, this section further replaces the measure of climate finance by using climate funds per unit of GDP to conduct robustness tests and their results are shown in columns (1)–(3) of Table 5. Observations proved that the coefficients for the substituted independent variables (*AFgdp*, *MFgdp*, *CFgdp*) remain significantly negative, which are consistent with our baseline findings.

Second, we switch the dependent relative variable to the log value of CO_2 emissions (*lnCO2*) and re-estimate regression models which is shown as the results in the columns (4) to (6) in Table 5. All coefficients of the independent variables persist significantly negative value proving their robustness of the baseline findings.

Third, to mitigate potential reverse causality concerns, we conduct robustness checks using one-period-lagged explanatory and control variables. As presented in Table 6, we re-estimate our empirical model using CO_2 emissions per GDP (*CO_2_GDP*) at time t + 1 as the dependent variable. The results demonstrate remarkable consistency with our baseline findings - all independent variables maintain their statistically significant negative coefficients, thereby confirming the robustness of our core results.

Fourth, we exclude BRICS nations (Brazil, Russia, India, China, and South Africa) to mitigate outlier effects. Unlike other developing economies, BRICS countries combine rapid growth with high CO_2 emissions (Lee et al., 2022b). Their energy demand shifts global trends, making growth-environment tradeoffs critical. Table 7 presents the emprical results using the samples without BRICS countries. The climate finance variables again show significantly negative coefficients, confirming

Table 3
Pearson & Spearman coefficient of correlation tests.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) CO2_GDP	1										
(2) lnAF	−0.1641***	1									
(3) lnMF	−0.1649***	0.9791***	1								
(4) lnCF	−0.1670***	0.9979***	0.9873***	1							
(5) POP	−0.0890***	0.3748***	0.4054***	0.3741***	1						
(6) Secondary	0.2662***	−0.0193	−0.0114	−0.0220	0.3494***	1					
(7) Tertiary	0.0532*	−0.2171***	−0.2281***	−0.2172***	−0.4176***	−0.5190***	1				
(8) OFDI	0.0378*	0.0032	0.0050	0.0025	0.0054	0.0457**	−0.0891***	1			
(9) GDPgrowth	−0.0572*	0.1281***	0.1214**	0.1237***	0.1306**	0.1303***	−0.1973***	0.0729***	1		
(10) GDPpercent	0.2755***	−0.5304***	−0.5427***	−0.5367***	−0.2838***	0.1987***	0.3582***	0.0388*	−0.0659***	1	
(11) lnSurface_area	0.0360*	0.3193***	0.3526***	0.3190***	0.8710***	0.4780***	−0.5478***	0.0074	0.1365***	−0.2381***	1

Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively.

their beneficial impact after excluding BRICS nations - consistent with our baseline findings.

Finally, to address potential dynamic persistence and endogeneity concerns, we employ a dynamic panel model with both one-step and two-step system generalized method of moments (GMM) estimators for robustness checks. Table 8 reports the estimated parameters together with the results of the specification tests for the validity of the instruments, including AR(1), AR(2), and Hansen tests. The results consistently demonstrate that climate finance significantly reduces carbon emissions. In addition, the coefficients on the lagged emission term (*L.CO2_GDP*) confirm substantial persistence in carbon emissions. All AR(1) tests are statistically significant, while the AR(2) and Hansen tests fail to reject the null hypotheses ($p > 0.1$), confirming the validity of our instruments and the appropriateness of the system GMM specification. Overall, these results further corroborate the robustness of our baseline findings.

5.4. Mechanisms

The mediation effect models are employed to examine the mechanisms through which climate finance facilitates environmental quality improvement. Two dimensions are focused on: indigenous innovation and external innovation.

As per Porter and Van Der Linde (1995), the Environmental Porter Hypothesis posits that economic development and environmental protection can achieve a "win-win" outcome, implying that economic growth doesn't have to be at odds with environmental conservation. Conversely, the "Pollution Haven" hypothesis speculates open free trade beside variable ecological regulations, industries that are more polluting are inclined to shift from economies with stringent environmental rules to those with laxer standards (Walter and Ugelow, 1979). Meanwhile, the EKC hypothesis suggests an inverted U-shaped relationship between the economic growth and pollution in the environment, indicating that contamination levels in the environment tend to rise whenever there is a growth in economy, later starts to decline as income levels increase beyond a certain point (Zhao et al., 2020; Liu et al., 2021). Despite ongoing academic debates, there is a consensus that government environmental policies and innovation play crucial roles in shaping these dynamics (He et al., 2020; Zhao et al., 2020).

Scholars agree that green innovation requires substantial upfront investment and faces significant uncertainties (Carrión-Flores and Innes, 2010). This leads to greater financial constraints for green innovation projects compared to conventional projects. Continuous public investment in climate finance can incentivize firms to conduct R&D investments and upgrade green technologies, encouraging them to adopt higher environmental standards and phase out pollution-intensive products. This, in turn, helps reduce CO_2 emissions and improve environmental outcomes. However, faced with high initial investment costs, developing countries, particularly the lesser-developed emerging economies, often face a trade-off between two options: (1) engaging in indigenous innovation, which involves high entry barriers and low probabilities of success; or (2) adopting technology from developed economies and engaging in introducing innovation, which has a higher success rate and lower costs, but may be subject to external restrictions.

Core indicators for measuring indigenous innovation include R&D investment, scientific talent, patents, and trademarks (Hall et al., 2005). While patent data are readily available, they measure innovation output rather than quality, making citation counts a preferred quality metric (Li et al., 2022b). However, patent-based measures face limitations, as many innovations—particularly in developing countries at early technological stages—fail to meet patentability criteria, rendering patent counts unsuitable for assessing their innovation. As alternatives, trademark data capture high-value innovations without patent restrictions (Fu et al., 2011). R&D investment and talent pools offer broader applicability: even without patentable outputs, they reflect innovation efforts and lay foundational groundwork, serving as robust proxies (Li et al.,

Table 4
Baseline results.

	(1)	(2)	(3)	(4)	(5)	(6)
	Fixed effect	Random effect	Fixed effect	Random effect	Fixed effect	Random effect
Variables	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0021***	−0.0023***				
	(0.0005)	(0.0005)				
lnMF			−0.0019***	−0.0021***		
			(0.0005)	(0.0005)		
lnCF					−0.0020***	−0.0022***
					(0.0005)	(0.0005)
POP	0.0747***	0.0194**	0.0741***	0.0189*	0.0747***	0.0193**
	(0.0164)	(0.0098)	(0.0164)	(0.0098)	(0.0164)	(0.0098)
Secondary	0.0005	0.0009***	0.0005	0.0009***	0.0005	0.0010***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Tertiary	0.0015***	0.0018***	0.0015***	0.0018***	0.0015***	0.0018***
	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
OFDI	0.0018***	0.0018***	0.0017***	0.0018***	0.0018***	0.0018***
	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)	(0.0004)
GDPgrowth	−0.0003	−0.0004*	−0.0003	−0.0004*	−0.0003	−0.0004*
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
GDPpercent	−0.0168***	−0.0139***	−0.0168***	−0.0139***	−0.0168***	−0.0139***
	(0.0015)	(0.0014)	(0.0015)	(0.0014)	(0.0015)	(0.0014)
lnSurface_area	−0.0331	−0.0199**	−0.0316	−0.0196**	−0.0328	−0.0199**
	(0.0237)	(0.0085)	(0.0237)	(0.0085)	(0.0237)	(0.0085)
Constant	−0.5253	0.1597	−0.5377	0.1595	−0.5297	0.1600
	(0.3926)	(0.1011)	(0.3932)	(0.1012)	(0.3927)	(0.1011)
Observations	2336	2337	2336	2337	2336	2337
R^2	0.937		0.937		0.937	
Overall R^2		0.063		0.064		0.063
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes		Yes		Yes	
Hausman test	96.92		96.70		96.99	
	[0.0000]		[0.0000]		[0.0000]	

Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

Table 5
Alternative specifications with different dependent/independent variables.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	CO2_GDP	CO2_GDP	CO2_GDP	LnCO2	LnCO2	LnCO2
AFgdp	−0.1217***			−0.712**		
	(0.0412)			(0.2788)		
MFgdp		−0.1342***			−0.5082**	
		(0.0501)			(0.2320)	
CFgdp			−0.0742***			−0.3748**
			(0.0251)			(0.1462)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2336	2336	2336	2222	2222	2222
R^2	0.937	0.937	0.937	0.994	0.994	0.994
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

2022b). Thus, we select national-level R&D expenditure (*RD_expend*), the count of technicians (*Technician*), and the count of registered trademarks (*Trademark*) as proxy variables for indigenous innovation.

Key indicators for measuring importing innovation include FDI and international technological cooperation. FDI, especially from more developed regions, often introduces advanced technologies and production methods through demonstration effects (Fu et al., 2011; Balsalobre-Lorente et al., 2019). While these technologies may not be cutting-edge for developed economies, they can represent advanced production techniques for developing countries. Consequently, FDI serves as a standard metric for assessing importing innovation. Additionally, international technological cooperation reduces R&D costs and enables knowledge sharing, accelerating the diffusion and application of advanced technologies. It is therefore widely employed as a proxy variable for measuring importing innovation (Fu et al., 2011).

Next, the mediation effect models are employed in this section to investigate the mechanisms through which climate finance supports national carbon reduction. Tables 9 and 10 report the results of indigenous innovation and introducing innovation, respectively. From Panel A in Table 9, it can be correlated that, although negative correlations exist between climate finance and national R&D expenditure in columns (1) to (3), the coefficients of *RD_expend* in columns (4) to (6) are not statistically significant. This suggests that *RD_expend* does not serve as a mediating factor. Similarly, the results in Panels B and C indicate the number of technicians and registered trademarks also fail to demonstrate a mediating effect. These findings suggest that, at present, indigenous innovation does not play a major role through which climate finance promotes carbon reduction in developing countries.

These findings provide partial support for hypothesis H2. Given that developing countries are often at an early stage of development, their weak R&D systems and shortage of innovative talent may hinder climate finance from being directly channeled into indigenous innovation

Table 6
One-period lagged explained and control variables.

	(1)	(2)	(3)
Variables	F.CO2_GDP	F.CO2_GDP	F.CO2_GDP
lnAF	−0.0018***		
	(0.0005)		
lnMF		−0.0016***	
		(0.0005)	
lnCF			−0.0017***
			(0.0004)
Control variables	Yes	Yes	Yes
Observations	2331	2331	2331
R^2	0.935	0.935	0.935
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Note: F.CO2_GDP denotes t + 1 period CO2_GDP. *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

Table 7
Excluding BRICK countries.

	(1)	(2)	(3)
Variables	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0019***		
	(0.0006)		
lnMF		−0.0017***	
		(0.0006)	
lnCF			−0.0018***
			(0.0005)
Control variables	Yes	Yes	Yes
Observations	2256	2256	2256
R^2	0.934	0.934	0.934
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

projects. Even when such investments occur, they may not be efficiently translated into enhanced innovation capacity. These factors could explain why climate finance fails to significantly boost recipient countries' R&D expenditure, the number of innovation personnel, or home-grown trademarks and brands—in other words, a failure of the indigenous innovation mechanism. These results align with the views of Rai and Funkhouser (2015) and Lee et al. (2022a).

Next, we turn to the results related to introducing external innovation. Table 10 presents the empirical results for these proxies. From Panel A, it is clear that the coefficients for all climate finance variables across columns (1)–(3) are significantly (1 % level). This indicates that climate finance investments in developing countries present substantial profit opportunities and high returns on investment, thereby attracting considerable foreign investment (Jeon et al., 2013; Huang et al., 2017). In columns (4) to (6), the coefficients of *FDI* were likewise significantly positive, suggesting FDI does act a mediating function. Specifically, climate finance investments in emergent nations serve to attract greater FDI, which in turn facilitates the transfer of advanced technologies and production techniques, subsequently reducing carbon emissions in these countries. Similarly, the results in Panel B show that technological cooperation also acts as a mediating factor.

These findings further demonstrate that within the climate finance framework, OFDI's pollution haven effect is mitigated, giving rise to a 'pollution halo' effect. This phenomenon likely stems from recipient developing countries absorbing advanced technology spillovers and transfers embedded in climate finance investments, thereby enhancing their green innovation capacity and investment efficiency. Even for nations with underdeveloped R&D systems and significant technological gaps, the adoption and assimilation of foreign technological innovations can contribute to addressing domestic climate challenges and advancing environmental sustainability. These results align with the perspectives of Wang et al. (2025), Lee et al. (2022a), and Omri et al. (2014), who argue that climate finance investments in developing countries foster more intensive development patterns through strengthened technological cooperation, ultimately contributing to carbon emission reduction. Moreover, these findings provide additional support for research hypothesis H2.

5.5. *Heterogenous analysis*

The stage of economic development in developing countries determines their approach to adopting innovation-driven economic growth. For an underdeveloped country, the bigger the challenges it faces in pursuing indigenous innovation, but it also stands to gain more in terms of climate improvements through innovation. To explore this further, we analyzed the heterogeneity of developing countries in CO_2 emissions between less developed and more developed countries, aiming to enhance the effectiveness of advocating for increased climate financing. Our focus was on three categories of lesser-developed emerging economies: (1) the United Nations' list of Least Developed Countries (LDCS), (2) Small Island Developing States (SIDS), and (3) Countries with the lowest per capita income (LICS) based on income

Table 8
GMM models.

	Two-step GMM			One-step GMM		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0046*			−0.0039**		
	(0.0024)			(0.0018)		
lnMF		−0.0031*			−0.0030*	
		(0.0018)			(0.0017)	
lnCF			−0.0042*			−0.0035**
			(0.0021)			(0.0017)
L.CO2_GDP	0.9206***	0.9223***	0.9217***	0.8990***	0.9023***	0.8990***
	(0.0428)	(0.0408)	(0.0414)	(0.0466)	(0.0482)	(0.0470)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2236	2236	2236	2236	2236	2236
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
AR (1) Test	0.088	0.043	0.077	0.006	0.005	0.006
AR (2) Test	0.983	0.888	0.958	0.330	0.205	0.312
Hansen Test	0.283	0.208	0.230	0.161	0.168	0.155

Note: L.CO2_GDP denotes t-1 period CO2_GDP. *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

Table 9
Indigenous innovation mechanism.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	RD_expend	RD_expend	RD_expend	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0039*			−0.0034***		
	(0.0024)			(0.0007)		
lnMF		−0.0038			−0.0032***	
		(0.0024)			(0.0007)	
lnCF			−0.0038			−0.0032***
			(0.0023)			(0.0007)
RD_expend				−0.0221	−0.0215	−0.0219
				(0.0169)	(0.0170)	(0.0169)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	863	863	863	863	863	863
R^2	0.877	0.877	0.877	0.944	0.944	0.944
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Technician	Technician	Technician	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0030			0.0011		
	(0.0084)			(0.0009)		
lnMF		−0.0056			0.0023*	
		(0.0088)			(0.0012)	
lnCF			−0.0047			0.0015
			(0.0080)			(0.0010)
Technician				0.0053	0.0055	0.0054
				(0.0065)	(0.0065)	(0.0065)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	425	425	425	425	425	425
R^2	0.920	0.920	0.920	0.950	0.950	0.950
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	lnTrademark	lnTrademark	lnTrademark	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	−0.0156			−0.0021***		
	(0.0258)			(0.0005)		
lnMF		−0.0166			−0.0019***	
		(0.0260)			(0.0005)	
lnCF			−0.0168			−0.0020***
			(0.0249)			(0.0005)
Trademark				0.0001	0.0001	0.0001
				(0.0004)	(0.0004)	(0.0004)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2336	2336	2336	2336	2336	2336
R^2	0.671	0.671	0.671	0.937	0.937	0.937
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Panel A R&D expenditure as the mediation variable.
Panel B Technicians as the mediation variable.
Panel C Trademarks as the mediation variable.
Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

classification. We compared the differences between these extremely underdeveloped countries and their peers, and their obtained empirical results were clearly shown in the Table 11 insight in Panels A, B, and C.

First, for LDCS, columns (1) to (3) of Panel A show that all three climate finance variables enter the regression with significantly positive coefficients, suggesting that climate finance has, paradoxically, led to increased carbon emissions. This outcome may be caused by the following potential mechanisms: First, the limited fiscal resources, infrastructure, and institutional capacity of least developed countries (Ameli et al., 2020; Haque et al., 2020) force them to prioritize development goals over emission reduction targets when facing this fundamental trade-off (Nor and Mohamed, 2024). Second, technology transfers predominantly led by developed nations often mismatch local needs, and when coupled with weak technological absorptive capacity in recipient countries, they inadvertently undermine indigenous low-carbon practices, ultimately increasing emissions (Nor and Mohamed, 2024). Third, industrial relocation and resource exploitation from developed countries trigger hidden carbon leakage, effectively creating "pollution havens" (D'Arcangelo and Galeotti, 2025; Misch and Wingender, 2024; Ozatac et al., 2017). In contrast, columns (4) to (6) indicate that in less developed but not extremely underdeveloped countries, climate finance continues to have a carbon-reducing effect.

Second, for SIDS, columns (1)–(3) of Panel B illustrate that coefficients of the three climate finance variables are not statistically significant and are close to zero, indicating that climate finance does not produce a substantial impact on carbon reduction in these countries. These results are likely to be due to the limited fiscal funds and small fiscal scale of SIDS, which frequently face greater constraints in

Table 10
Introducing external innovation mechanism.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	FDI_in	FDI_in	FDI_in	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	0.1272***			−0.0022***		
	(0.0404)			(0.0005)		
lnMF		0.1106***			−0.0020***	
		(0.0400)			(0.0005)	
lnCF			0.1210***			−0.0021***
			(0.0385)			(0.0005)
FDI				0.0013***	0.0012***	0.0013***
				(0.0004)	(0.0004)	(0.0004)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2335	2335	2335	2335	2335	2335
R^2	0.491	0.490	0.490	0.939	0.939	0.939
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Tech_coop	Tech_coop	Tech_coop	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	0.0560***			−0.0037***		
	(0.0142)			(0.0010)		
lnMF		0.0527***			−0.0030***	
		(0.0131)			(0.0010)	
lnCF			0.0551***			−0.0035***
			(0.0141)			(0.0010)
Tech_coop				0.0085**	0.0078**	0.0084**
				(0.0033)	(0.0033)	(0.0033)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2259	2259	2259	2259	2259	2259
R^2	0.950	0.950	0.950	0.931	0.930	0.931
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Panel A FDI as the mediation variable.
Panel B Technical cooperation as the mediation variable.
Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

mobilizing domestic resources and rely heavily on imported goods. These constraints limit the availability of funds for mitigating climate risks and promoting sustainable development, Guillaumont (2010) and Scandurra et al. (2020). While, the results in columns (4) to (6) suggest for non-SIDS developing countries, climate finance still contributes to reductions in carbon emissions.

Finally, for LICS, the coefficients of the three climate finance variables are significantly positive in columns (1) to (3) of Panel C. Conversely, for developing countries with relatively higher per capita incomes, the coefficients of the three climate finance variables in columns (4) to (6) are significantly negative. These findings indicate that, in lesser-developed emerging economies, climate finance fails to reduce carbon emissions and instead exacerbates them, whereas in other developing countries, climate finance has a carbon-reducing effect. These results align with the earlier outcomes, highlighting varying impacts of climate finance with respect to the level of financial development.

Overall, these findings suggest that while climate finance can play a substantial role in reducing carbon discharges in more advanced emergent nations, it might also pave the way for increased emissions in the least developed countries, where economic imperatives and structural constraints can hinder the effective use of such funds for environmental goals. Regarding the underlying causes, as noted by Iacobuţă et al. (2022) and Elkomy et al. (2021), in least-developed developing countries, the sluggish implementation of climate policies and inadequate scale of climate financing may hinder the full potential of green finance. Without proper alignment between climate finance and national priorities, these nations face significant challenges in effectively adopting clean technologies, consequently constraining their capacity to achieve carbon reduction targets. These findings support the hypothesis H3, highlighting the need for tailored climate finance strategies that account for the specific developmental challenges faced by different groups of developing countries.

6. Conclusions

Using panel data from 140 developing countries spanning 2002 to 2022, our empirical analysis reveals that climate finance plays a decisive role in lowering CO_2 emissions in recipient nations. Specifically, an expansion in climate finance equivalent to one standard deviation correlates with an approximate 3.31 % reduction in per GDP CO_2 discharges. Conversely, the influence of climate finance is not uniform across all developing nations. In the lesser-developed emerging economies, climate finance shows either no effect on emission reductions or, in some cases, is linked to an increase in emissions. The mechanism analysis indicates that the beneficial environmental effects of climate finance in developing nations are driven primarily by introducing external innovation, rather than by promoting indigenous innovation. These results align with the pollution halo hypothesis, emphasizing the positive role of overseas green funds in promoting environmental sustainability within developing economies.

According to above findings, we several propose policy recommendations to augment the efficacy of climate finance investments while mitigating potential risks. First, considering that climate finance substantially lowers corbon discharges in developing countries, we should increase climate finance investment to strengthen emission reduction efforts. Specifically, governments and international organizations are encouraged to increase funding, particularly in advancing green technologies and supporting low-carbon projects. Additionally, it’s important to recognize that climate finance doesn’t operate in isolation. To

Table 11
Heterogeneous results.

	LDCS			Non-LDCS		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	0.0077***			−0.0027***		
	(0.0019)			(0.0005)		
lnMF		0.0055***			−0.0025***	
		(0.0019)			(0.0005)	
lnCF			0.0081***			−0.0025***
			(0.0019)			(0.0005)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	630	630	630	1706	1706	1706
R^2	0.891	0.890	0.892	0.937	0.937	0.937
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

	SIDS			Non-SIDS		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	0.0002			−0.0026***		
	(0.0005)			(0.0007)		
lnMF		0.0005			−0.0024***	
		(0.0005)			(0.0007)	
lnCF			0.0003			−0.0025***
			(0.0004)			(0.0007)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	532	532	532	1804	1804	1804
R^2	0.981	0.981	0.981	0.923	0.923	0.923
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

	LICS			Non-LICS		
	(1)	(2)	(3)	(4)	(5)	(6)
Variables	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP	CO2_GDP
lnAF	0.0030*			−0.0023***		
	(0.0018)			(0.0005)		
lnMF		0.0029*			−0.0020***	
		(0.0017)			(0.0006)	
lnCF			0.0033*			−0.0021***
			(0.0017)			(0.0005)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	327	327	327	2009	2009	2009
R^2	0.971	0.971	0.971	0.930	0.930	0.930
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

Panel A Least developed countries and their peers.
Panel B Small island developing states and their peers.
Panel C Least income countries and their peers.
Note: *, **, *** indicate that the coefficient is significant at 10 %, 5 %, and 1 %, respectively. Robust standard errors in parentheses.

maximize emission reduction outcomes, it must work in tandem with complementary policies like carbon pricing, regulatory reforms, and public-private partnerships (PPPs). Carbon pricing provides economic incentives while climate finance supplies funding support; regulatory reforms establish mandatory standards to ensure transition direction; and PPPs share risks to accelerate technology implementation. Strengthening these policy synergies will systematically drive the low-carbon transition and achieve effective emission reduction.

Second, it is imperative to strengthen climate finance support for less-developed economies, with a focus on infrastructure development, capacity building, and technology transfer. Given the finding that climate finance has in some cases increased carbon emissions in least-developed countries, particular vigilance must be exercised to guard against potential carbon leakage and fund misuse in climate-related projects, preventing these regions from becoming "pollution havens". For other developing nations, tailored strategies should be also implemented based on national development levels: emerging economies should integrate carbon pricing with green industrial policies, while middle-income countries can leverage blended finance instruments for just transitions. Across all climate finance initiatives, stringent environmental standards must be enforced through enhanced lifecycle monitoring, with special attention paid to achieving an optimal balance between economic development and ecological conservation in underprivileged regions.

Third, developing country governments should strike a balance between domestic green innovation and introduced innovation, with strategic emphasis on directing climate finance towards domestic innovation to unlock its potential. While climate finance can drive a pollution halo effect by introducing advanced green technologies that reduce environmental pressures in recipient countries, there is also the risk of dependency and potential pollution risks. Therefore, it is critical not to overlook the role of indigenous innovation, despite its higher cost and substantial resource investment. Building local green innovation capacity is essential for long-term sustainability, reducing reliance on external solutions, and ensuring resilience in addressing environmental issues. Policymakers should adopt a flexible framework that integrates both external innovation and local research and development efforts to enhance their ability to tackle environmental challenges effectively.

Future studies related to climate finance can consider exploring the trade-off between relying on foreign green innovation and fostering indigenous innovation in recipient countries. Research could focus on developing optimal models for integrating imported green technologies with local innovation capabilities, analyzing the economic and environmental benefits of building domestic green R&D capacities. Future work could also examine how to lower the barriers to domestic innovation in developing countries, including access to finance, technological transfer, and capacity-building programs.

CRediT authorship contribution statement

Jinhua Zhang: Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yafei Li:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruonan Du:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xiuping Hua:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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