Journal of Human-Social Nexus

Contents lists available at: journals.absresearchacademy.com

Research Article

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Green Finance and the Environmental Efficiency of FDI in OECD Economies

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Article info

Received: 2025-10-16

Revised: 2025-12-23

Accepted: 2026-02-01

Published: 2026-02-02

Keywords

FDI; Green finance; Environmental efficiency; OECD countries; DEA-econometrics

DOI

https://doi.org/10.64939/jhsn.1.1.0003

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A B S T R A C T

This study examines the relationship between foreign direct investment (FDI) and environmental efficiency in OECD countries, with particular emphasis on the moderating role of green finance over the period 2010–2022. Using a range of econometric techniques, including Tobit, PCSE, FGLS, and two-step System GMM estimations, the results consistently indicate that FDI has a significant negative effect on environmental efficiency, providing evidence in support of the pollution haven hypothesis. In contrast, green finance is found to enhance environmental performance, although its statistical significance varies across model specifications. Importantly, the interaction between FDI and green finance is positive and statistically significant, suggesting that green finance can mitigate the adverse environmental effects associated with FDI inflows, consistent with the pollution halo mechanism. The analysis further shows that urbanization, industrialization, trade openness, and natural resource dependence significantly affect environmental efficiency. The findings highlight the importance of strengthening green finance mechanisms and environmental governance to ensure that FDI inflows contribute to, rather than undermine, sustainable development objectives in OECD economies.

HOW TO CITE

Fatema, N. (2026). Green Finance and the Environmental Efficiency of FDI in OECD Economies. Journal of Human-Social Nexus, 1(1). https://doi.org/10.64939/jhsn.1.1.0003

Introduction

The pursuit of environmental sustainability has become a defining challenge of the twenty-first century, with growing attention directed toward the ways in which economic and financial activities shape ecological outcomes (Hart & Ahuja, 1996; Suleymanov et al., 2023; Wang & Taghizadeh-Hesary, 2023; Xu et al., 2021; Xu et al., 2021). Among the multiple drivers of environmental performance, foreign direct investment (FDI) and green finance stand out as two influential forces that can either enhance or hinder environmental efficiency (Gong, 2023; Mehmood & Kaewsaeng-on, 2024; Ping & Shah, 2023; Zhang & Zhou, 2016; Zhang et al., 2023). FDI plays a pivotal role in economic development by fostering capital accumulation, technology diffusion, and employment creation (Alfaro et al., 2004; Gupta et al., 2022; Iamsiraroj & Doucouliagos, 2015). However, its environmental consequences are context dependent. While FDI may introduce cleaner technologies and sustainable management practices, it can also aggravate pollution levels when investments target resource-intensive or environmentally lax sectors (Chen et al., 2023; Gong, 2023).

In contrast, green finance represents an emerging paradigm that channels financial resources into projects and initiatives designed to protect the environment, lower carbon emissions, and promote sustainable development (Dai et al., 2022; Siddik et al., 2023; Zheng et al., 2021). It encompasses a variety of financial instruments and policy mechanisms such as green bonds, sustainable loans, and fiscal incentives that encourage environmentally responsible investment (Guang-Wen & Siddik, 2022; X. Zhang et al., 2022). Over the past decade, green finance has gained significant traction as countries around the world have intensified their commitments to achieving carbon neutrality and facilitating the transition to low-carbon economies (Mehmood & Kaewsaeng-on, 2024; Ping & Shah, 2023). Within this global landscape, OECD nations have emerged as leaders in advancing green financial practices and implementing environmental policy frameworks (Safi et al., 2024; Zhong et al., 2024). Given their large inflows of FDI and active engagement in green finance initiatives, these countries provide an ideal setting to investigate how these two forces interact shaping environmental efficiency.

Despite a growing body of literature on FDI and green finance, several important research gaps remain. Prior studies have documented mixed and often contradictory findings on the environmental effects of FDI, suggesting that these impacts vary across institutional settings and time periods (He et al., 2024; P. Liu et al., 2024). Much of the existing research focuses on the direct influence of FDI or green finance on environmental outcomes such as CO_2 emissions, ecological footprints, or environmental quality (Dao et al., 2024; Yadav et al., 2024). While some scholars report that green finance helps mitigate environmental degradation (Chien et al., 2024; Udeagha & Muchapondwa, 2023), others have found adverse or insignificant effects depending on regional and policy contexts (Zhao et al., 2024). However, very few studies have examined the moderating role of green finance in the relationship between FDI and environmental efficiency, particularly in OECD economies (Jin et al., 2023; Safi et al., 2024; Tufail et al., 2024; Wang & Taghizadeh-Hesary, 2023; Zhong et al., 2024). This gap is particularly relevant because OECD countries not only receive substantial volumes of FDI but also face diverse environmental challenges and strong policy commitments toward sustainability.

To address these gaps, this study investigates how FDI influences environmental efficiency in OECD countries from 2010 to 2022, emphasizing the moderating effect of green finance. Specifically, it examines (i) the direct impact of FDI on environmental efficiency, (ii) the contribution of green finance to improving environmental performance, and (iii) how green finance modifies the FDI–environmental efficiency relationship. Control variables, including trade openness, industrialization, urbanization, and natural resource management, are incorporated to ensure a comprehensive analysis. Accordingly, the study seeks to answer the following research questions: What is the direct effect of FDI on environmental efficiency in OECD countries? How does green finance influence environmental efficiency? Does green finance moderate the link between FDI and environmental efficiency, and if so, in what direction? By addressing these questions, the study aims to offer new empirical insights into how green financial mechanisms can help reconcile economic expansion with environmental protection, thereby contributing to the formulation of more sustainable development strategies within OECD economies.

This study contributes to the existing literature and policy debate by examining the previously overlooked moderating influence of green finance on the relationship between foreign direct investment (FDI) and environmental efficiency in OECD economies. It advances a more comprehensive understanding of how financial mechanisms can shape the environmental consequences of international investment. By integrating FDI and green finance into a single analytical framework, this research reveals how environmentally oriented financial instruments can offset the potential ecological drawbacks of FDI, thus aligning economic expansion with sustainability objectives. Employing robust econometric approaches including Tobit, PCSE, FGLS, and two-step GMM models over the period 2010-2022, the analysis offers a methodologically rigorous and context-sensitive perspective. Moreover, by incorporating relevant control variables such as trade, industrialization, urbanization, and natural resource management, the study provides a holistic assessment of the determinants influencing environmental efficiency. From a policy standpoint, the findings underscore the pivotal role of green finance in mitigating the environmental risks associated with FDI inflows. The results offer actionable insights for governments, regulatory bodies, and financial institutions seeking to design policies that attract foreign investment while upholding environmental sustainability. Beyond its empirical contributions, the study also enriches the broader discourse on sustainable finance and investment, offering guidance for international organizations and stakeholders involved in fostering low-carbon, resilient economies.

The rest of the paper is organized as follows: Section 2 reviews the relevant literature and theoretical background; Section 3 details the data, variable construction, and econometric methodology; Section 4 presents and discusses the empirical results; and Section 5 concludes with key findings, policy implications, and recommendations for future research.

Theoretical Foundation, Literature Review and Hypothesis Development

Theoretical Foundation

The relationship between foreign direct investment (FDI) and environmental efficiency is shaped by two competing theoretical mechanisms: the pollution haven hypothesis (PHH) and the pollution halo hypothesis. The PHH argues that multinational enterprises relocate pollution-intensive activities to countries with weaker regulations, thereby reducing environmental efficiency. Conversely, the pollution halo hypothesis posits that foreign firms introduce cleaner technologies, advanced managerial practices, and stricter environmental standards, ultimately improving environmental performance (P. Liu et al., 2024). Green finance serves as a critical moderating mechanism that influences which of these two forces dominates. In economies with a well-developed green finance ecosystem, the cost of capital for environmentally friendly projects is reduced, and financial penalties for polluting behavior are higher. This incentivizes foreign firms to adopt cleaner technologies and comply with rigorous environmental standards. However, in economies where green finance is underdeveloped, FDI may gravitate toward emissions-intensive sectors due to weaker financial and regulatory pressures, thereby reinforcing the PHH effect.

Figure 1 presents the conceptual framework of the study, highlighting the relationships between Foreign Direct Investment (FDI) and Environmental Efficiency (EE). The Pollution Haven Effect suggests that FDI can lead to decreased environmental efficiency (FDI↑ → EE↓), while the Pollution Halo Effect implies that FDI may improve environmental efficiency (FDI↑ → EE↑). Green finance acts as a moderator, strengthening the PHE and improving EE, while weakening the PHE by mitigating the negative environmental impacts of FDI. This framework emphasizes the role of green finance in balancing economic growth and environmental sustainability.

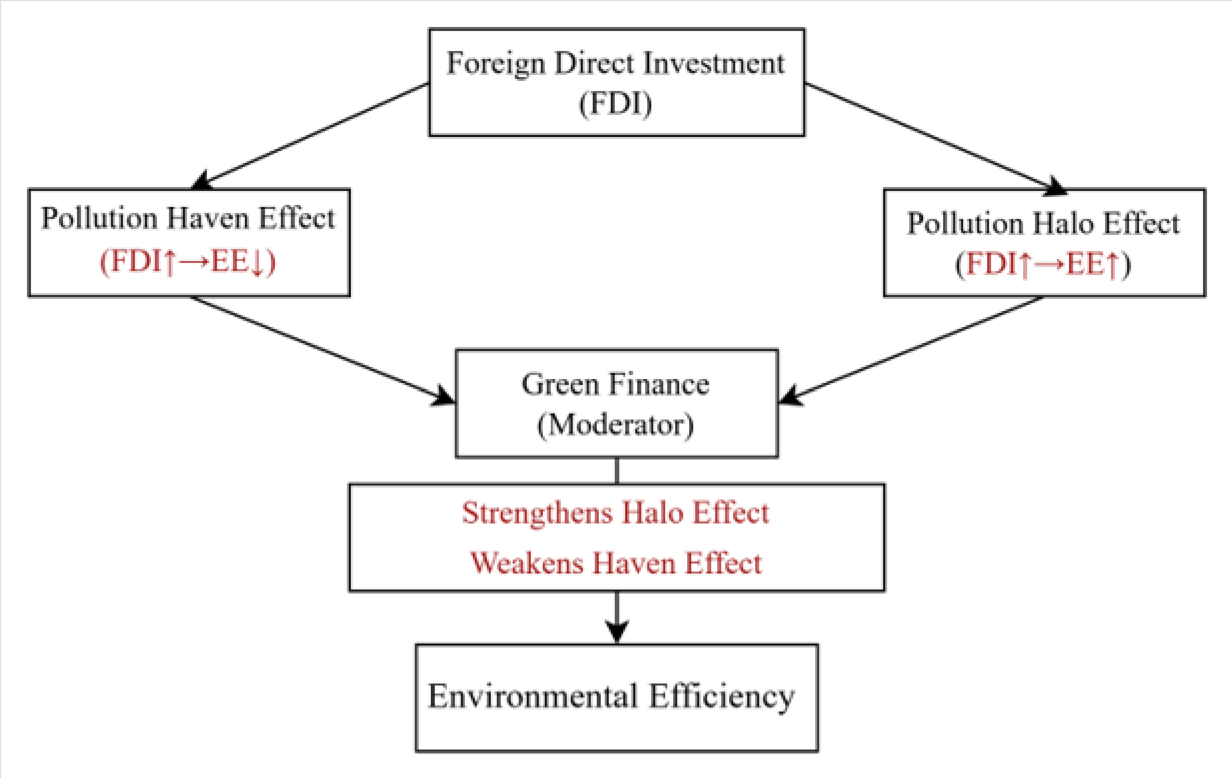

Figure 1. *Conceptual framework of the study*

Literature Review

The relationship between FDI and environmental efficiency has received growing scholarly attention, largely because its effects vary significantly across countries and regions. For instance, He et al. (2024) employed a spatial difference-in-differences approach and found that FDI had no significant impact on CO2 emissions in China, whereas P. Liu et al. (2024) reported mixed effects of Chinese outward FDI on CO2 emissions across 46 Belt and Road Initiative (BRI) countries. In contrast, X. Liu et al. (2024) showed that FDI can enhance eco-efficiency in China, suggesting that its environmental impact depends on local institutional and regulatory conditions. However, other studies present a more pessimistic picture Soto (2024) found that FDI increases the ecological footprint in Latin American economies, while Boateng et al. (2024) demonstrated that FDI contributes to higher CO2 emissions across 182 countries. Similarly, Viglioni et al. (2024) documented a positive link between FDI and CO2 emissions in G20 nations, indicating potential environmental risks associated with investment inflows. Against this backdrop, the present study investigates how green finance moderates the relationship between FDI and environmental efficiency in OECD countries from 2010 to 2022. Given the mixed empirical evidence, examining the moderating influence of green finance provides an opportunity to understand how environmentally oriented financial mechanisms can offset FDI's adverse environmental effects and guide sustainable investment strategies.

In addition, extensive evidence highlights the positive contribution of green finance to environmental sustainability across diverse contexts. Dao et al. (2024) found that green financial policies significantly reduced ecological footprints in OECD nations, while Yadav et al. (2024) reported that green finance lowered CO2 emissions in BRICS economies. Zhao et al. (2024) observed a similar negative association between green finance and corporate carbon emissions in China, and studies by Chien et al. (2024) and Udeagha and Muchapondwa (2023) confirmed that green finance fosters environmental sustainability in Indonesia and BRICS countries, respectively. Collectively, these findings underscore green finance as a transformative tool capable of promoting cleaner growth and improving environmental efficiency, particularly when integrated with FDI. This study thus aims to bridge the existing knowledge gap by empirically exploring the moderating role of green finance in the FDI–environmental efficiency nexus within OECD economies, offering actionable insights for policymakers seeking to align investment flows with sustainability goals.

FDI and environmental efficiency

The relationship between foreign direct investment (FDI) and environmental efficiency remains complex and context-dependent, as demonstrated by a growing body of empirical research. He et al. (2024) applied a spatial DID) model to examine the effect of FDI on CO_2 emissions in China between 2004 and 2015, finding no significant relationship. In contrast, P. Liu et al. (2024), using Driscoll–Kraay estimations across 46 Belt and Road Initiative (BRI) countries from 2005 to 2018, reported mixed effects of Chinese outward FDI on environmental performance. Within China, X. Liu et al. (2024) utilized the Theil Index and Geodetector methods and identified a positive link between FDI and eco-efficiency over 2006–2020, implying that FDI can improve environmental performance under favorable institutional and technological conditions. Conversely, studies in other regions have yielded less encouraging results. Soto (2024), employing the STIRPAT framework, found that FDI worsens ecological footprints in Latin America during 1990-2022, while Boateng et al. (2024), using an IV-GMM approach, observed that FDI increases CO_2 emissions in a global sample of 182 countries from 2000 to 2018. Similarly, Dilanchiev et al. (2024) and Viglioni et al. (2024) documented a positive relationship between FDI and CO_2 emissions in major remittance-receiving and G20 economies, respectively, underscoring FDI's potential to intensify environmental degradation. However, Wang et al. (2024) found that high-quality FDI enhances energy–carbon emission efficiency in China from 2001 to 2019, suggesting that the environmental effects of FDI depend largely on its quality and target sectors. These findings highlight that the impact of FDI on environmental efficiency is far from uniform, varying across countries, industries, and methodological approaches, and shaped by differences in regulatory frameworks, investment types, and environmental governance.

Green finance and environmental efficiency

Recent studies have increasingly highlighted the critical role of green finance in enhancing environmental efficiency across various regions and economic contexts. Dao et al. (Dao et al., 2024) employed a quantile regression approach to analyze the impact of green financial policies on the ecological footprint within OECD nations from 2000 to 2019, finding a significant negative relationship. Similarly, Yadav et al. (Yadav et al., 2024) utilized the CS-ARDL model to examine BRICS economies from 2011 to 2019, reporting that green finance effectively reduces CO_2 emissions. Zhao et al. (Zhao et al., 2024) supported these findings through their respective GMM and IV and Fixed Effects analyses, revealing negative impacts of green finance on environmental degradation and corporate carbon emissions in the BRI region and China, respectively. Moreover, studies by Safi et al. (Safi et al., 2024) and Wang et al. (2024) using MMQR and 2SLS with System GMM methodologies, further confirmed the negative link between green finance and CO_2 emissions in OECD nations and urban areas of China. However, not all findings were negative; Chien et al. (Chien et al., 2024) and Wei et al. (Wei et al., 2024) identified positive influences of green finance on environmental sustainability in Indonesia and BRICS countries, respectively, using the STIRPAT and QARDL methods. This positive correlation was echoed in research by Udeagha and Muchapondwa (Udeagha & Muchapondwa, 2023) and Hunjra et al. (Hunjra et al., 2023) who found that green finance enhances environmental sustainability and sustainable development in BRICS and developing countries. These varied results underline the nuanced and context-dependent effects of green finance on environmental efficiency, highlighting its potential as a transformative tool for sustainable development when effectively implemented.

Hypothesis Development

FDI and Environmental Efficiency

Although some studies highlight the potential for foreign direct investment to transfer cleaner technologies and managerial expertise, growing empirical evidence indicates that FDI can also undermine environmental efficiency especially when investment flows into pollution-intensive sectors. Research in Latin America, global samples, and G20 economies consistently shows that FDI increases CO_2 emissions and expands ecological footprints (Soto, 2024; Boateng et al., 2024; Viglioni et al., 2024). Even in countries with relatively strong institutions, foreign investors may still prioritize cost reduction over environmental protection, leading to greater energy consumption, resource depletion, and emissions leakage. Furthermore, multinational firms sometimes exploit regulatory loopholes, weak enforcement mechanisms, or sectoral disparities within otherwise strict regulatory environments. This allows pollution-intensive activities to persist, even in high-income regions. Evidence from Belt and Road countries also demonstrates that the environmental impact of FDI varies widely depending on investment structure, host-country regulatory responsiveness, and sectoral composition (P. Liu et al., 2024). Thus, even in OECD economies, FDI may contribute to environmental degradation if regulations are unevenly enforced or if investment is concentrated in carbon-intensive industries.

H1: Foreign direct investment may negatively contribute to environmental efficiency in OECD countries.

Green Finance and Environmental Efficiency

Green finance plays a vital role in enhancing environmental performance by supporting low-carbon transitions and incentivizing sustainable investments. Empirical findings across OECD, BRICS, and developing countries consistently show that green finance reduces CO_2 emissions, ecological footprints, and corporate carbon intensity (Dao et al., 2024; Yadav et al., 2024; Zhao et al., 2024; Safi et al., 2024). Green financial instruments channel funding into renewable energy, energy efficiency projects, and clean technologies, enabling firms to improve resource use and reduce environmental pressure. Given the relatively advanced financial architectures in OECD countries, green finance is expected to facilitate widespread adoption of environmentally friendly technologies and strengthen environmental regulation effectiveness.

H2: Green finance has a significant positive effect on environmental efficiency in OECD countries.

Moderating Role of Green Finance in the FDI–Environmental Efficiency Relationship

The net environmental impact of FDI depends heavily on the regulatory and financial environment of the host country. When green finance mechanisms are underdeveloped, FDI may lean toward pollution-intensive industries due to lower compliance costs and limited incentives for cleaner production aligning with the pollution haven hypothesis. Conversely, strong green finance systems alter firms' investment choices by lowering financing costs for green technologies, increasing the cost of pollution, and promoting environmentally responsible behavior among both domestic and foreign firms. Empirical evidence supports the idea that green finance enhances environmental governance and guides investment toward sustainability-oriented sectors (Chien et al., 2024; Wei et al., 2024; Udeagha & Muchapondwa, 2023). Thus, in OECD economies where green financial markets are relatively mature, green finance should help counteract the negative environmental effects of FDI by steering foreign investment toward cleaner activities and accelerating technological upgrading.

H3: Green finance positively moderates the relationship between FDI and environmental efficiency, reducing the negative environmental impact of FDI.

Data and Methodology

Data sources

This study uses data from 2010 to 2022 for OECD countries, constrained by the availability of relatively recent data on fintech and green finance.

Table 1. Descriptive statistics of input and output variables

I/O	Variables	Unit	Mean	Maximum	Minimum	Std. Dev.
Input	Labor	Kg of oil equivalent	19441429	1.69E+08	187550	30545748
	Capital stock	USD	3.91E+12	5.20E+13	3.75E+10	7.81E+12
	Energy consumption	Labor force	4198.04	18178.14	1392.606	2752.867
Output	GDP	USD	1.57E+12	2.54E+13	1.38E+10	3.42E+12
	CO2 emission	Kiloton	354402.5	5392109	1063.4	835168.2

Environmental efficiency is measured using the Epsilon-Based Measure of the Data Envelopment Analysis (DEA) approach.

Table 2. Variables and descriptive statistics

Variables	Unit	Source	Mean	Max	Min	Std. Dev.	J-B	Prob.
Environmental efficiency (EBE)	EBM DEA-Score	Author calculation	0.564	1.091	0.278	0.167	38.875	0.000
Foreign Direct Investment (FDI)	% of GDP	WDI	1.263	6.150	-6.671	1.745	204.011	0.000
Amount of investment in green bond (GF)	USD	CBI	19.018	25.931	-94.916	11.168	46116.440	0.000
Industrialization (INDS)	% of GDP	WDI	3.142	3.885	2.341	0.260	23.710	0.000
Natural resource management (TNR)	% of GDP	WDI	-1.295	3.344	-9.160	2.166	108.090	0.000
Urbanization (lUB)	% of population	WDI	4.362	4.587	4.045	0.131	27.459	0.000
Trade (TD)	% of GDP	WDI	4.461	5.974	3.152	0.528	7.804	0.020

Note: WDI: world development indicators; CBI: climate bonds initiative.

The input and output variables, detailed in Table 1, are sourced from the World Development Indicators (WDI, 2024). Table 2 describes all variables, with fintech finance and green finance data obtained from Crunchbase and the Climate Bonds Initiative, respectively, while other control variables are drawn from WDI (2024). Green finance is operationalized using the volume of green bond issuance, which constitutes the most consistent and internationally comparable proxy available for OECD countries. Although other components of green finance such as green loans or ESG-related funds are important, comprehensive cross-country data for these indicators are not consistently available over time. Green bonds represent a major segment of market-based green finance and align closely with sustainable investment flows. Crunchbase provides comprehensive data on startups and investments (Uddin et al., 2024), and the Climate Bonds Initiative supports global low-carbon investment through green bond certification.

Table 3. Results of the Multicollinearity test

Variable	VIF	1/VIF
lFDI	1.06	0.940
lGF	1.02	0.984
lINDS	1.22	0.821
lTNR	1.29	0.777
lUB	1.22	0.817
lTD	1.18	0.846
Mean VIF	1.17	

Environmental efficiency

In this study, we employed the Epsilon-Based Measure (EBM) Data Envelopment Analysis (DEA) to evaluate environmental efficiency. This choice was motivated by the need to overcome certain limitations inherent in the Slack-Based Measure (SBM) model. The SBM model, which is non-radial, focuses on slack variable efficiencies. Unlike radial models, it does not assume proportional reductions in inputs or outputs. Instead, it aims to maximize inadequacies in both inputs and outputs by identifying data facts that are furthest from the efficient frontier. However, the SBM model's approach has a notable drawback: it can distort the original ratio information when projecting values onto the efficiency frontier. This distortion can lead to inconsistent or unreliable results. To address this issue, we turned to a modified version of the EBM model, incorporating undesirable outputs. This modified EBM model, as proposed by (Tone & Tsutsui, 2009) in 2010, offers a more robust framework for evaluating ecological efficiency. The environmental efficiency evaluation is represented using the EBM model, formulated as follows:

$$\theta^* = min \frac{\alpha - \eta_x \sum_{k=1}^{n} \frac{\phi_k^- t_k^-}{x_{kn}}}{\beta + \eta_y \sum_{l=1}^{0} \frac{\phi_l^{+g} u_l^{+b}}{y_{ln}} + \eta_y \sum_{m=1}^{p} \frac{\phi_m^{-b} \upsilon_m^{-b}}{b_{mn}}} \quad (1)$$

s.t.

$$\sum_{r=1}^{q} x_{kr}\mu_r + t_k^- = \alpha x_{kn} k = 1, 2, \ldots, n \quad (2)$$

$$\sum_{s=1}^{t} y_{ls}\mu_s - u_l^{+g} = \beta y_{ln} l = 1, 2, \ldots, 0 \quad (3)$$

$$\sum_{u=1}^{v} b_{mu}\mu_u + \upsilon_m^{-b} = \beta b_{mn} m \ldots, p \quad (4)$$

$$(\mu)_r \geq 0, t_k^- \geq 0, u_l^{+g} \geq 0, \upsilon_m^{-b} \geq 0 \quad (5)$$

Here, n denotes the total number of inputs, desirable and undesirable are signified by o and p respectively. The terms t_k^- slack variable associated with input k. It represents the excess amount of input k that can be reduced without affecting the output levels. u_l^{+b} slack variable associated with desirable output l. It represents the shortfall in desirable output l that can be increased. And υ_m^{-b} slack variable associated with undesirable output m. It indicates the excess amount of undesirable output m that can be reduced. Additionally,ϕ_l^{+g} eight assigned to desirable output l. This weight reflects the relative importance of increasing the desirable output and ϕ_m^{-b} weight assigned to undesirable output m. This weight reflects the relative importance of reducing the undesirable output. θ is the efficiency score, which ranges from 0 to 1. A value of 1 indicates full efficiency, whereas values less than 1 indicate inefficiency.

Table 4. Results of panel unit root tests

Variables	CADF		CIPS	
	Level	First difference	Level	First difference
EBE	-0.987	-2.423***	-1.342	-2.417***
lFDI	-2.026*	-2.534***	-2.751***	-4.211***
lGF	-1.186	-2.139***	-2.100*	-3.310***
lINDS	-1.787	-2.019*	-1.757	-2.742***
lTNR	-0.588	-2.088*	-1.200	-3.153***
lUB	-1.452	-2.361***	-1.935	-4.900***
lTD	-1.339	-2.058*	-1.503	-2.277***

Note: Significant at *p < 0.1, * * p < 0.05, * * *p < 0.01.

Table 5. Results of the Westerlund cointegration test.

Statistics	Value	Z-value	P-value
Gt	-5.588***	-22.762***	0.000
Ga	-13.472*	-1.339*	0.090
Pt	-13.749**	-2.094**	0.018
Pa	-11.890***	-2.781***	0.003

Ho: no cointegration
*** null hypothesis rejection at 1% significance level.

For the analysis, we selected specific input and output factors to assess the environmental efficiency of each Decision-Making Unit (DMU).

Input Variables:

Capital Stock: The capital stock for each country was computed using the perpetual inventory method. The formula for calculating the capital stock is:

$$C_{i,t} = (1 - \delta_{i,t})\, C_{i,t-1} + I_{i,t} \tag{6}$$

where: $C_{i,t}$ signifies the capital stock for nation i in the year t. The present gross fixed capital formation for nation i in the year t is represented as $I_{i,t}$. The depreciation rate of the capital, indicated by $\delta_{i,t}$, is established at 6%. For the baseline year (2010), the capital stock was approximated by taking the fixed capital formation of that year and dividing it by 10%.

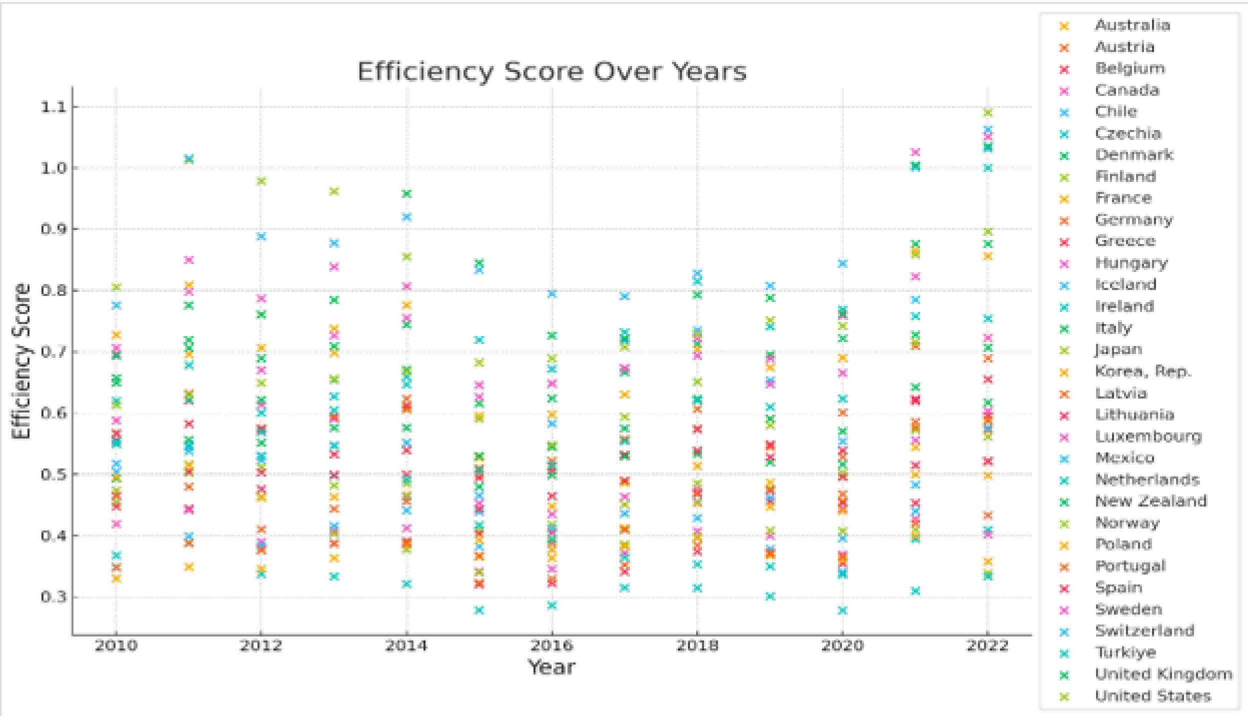

Figure 2. *Environmental Efficiency Scores of OECD Countries.*

Labor: This variable represents the total number of individuals engaged in productive activities within each country. It encompasses the workforce involved in generating goods and services, reflecting the human capital contribution to the production process.

Energy Consumption: This refers to the total amount of energy utilized by each country, measured in specific units such as kilowatt-hours or joules. It includes all forms of energy consumed in various sectors like industry, transportation, and households, indicating the extent of energy use necessary to sustain economic activities.

Desirable Output Variable:

Gross Domestic Product (GDP): Measured in current US dollars (USD), GDP is the primary indicator of a country's economic output. It quantifies the total market value of all finished goods and services produced within a nation over a specified period, serving as a key measure of economic performance and growth.

Undesirable Output Variable:

CO_2 Emissions: Expressed in kilotons, this variable tracks the total emissions of carbon dioxide resulting from a country's economic activities. It reflects the environmental impact associated with the production and consumption processes, highlighting the level of greenhouse gases released into the atmosphere, which contributes to global climate change. Figure 2 shows the environmental efficiency scores of OECD countries.

Methodology

Preliminary Tests

Prior to performing the main estimations, several diagnostic procedures were implemented to verify the validity and robustness of the panel data results. The first step involved testing for cross-sectional dependence (CSD), as countries in the sample are often economically and financially interlinked through trade, investment, and policy cooperation. Such interconnections may lead to correlated error structures across panels, and neglecting them could result in inefficient or biased coefficient estimates (Breusch & Pagan, 1980; Pesaran et al., 2004; Chudik & Pesaran, 2013). To identify the presence of CSD, we applied the Lagrange Multiplier (LM) test proposed by Breusch and Pagan (1980) along with the bias-corrected version suggested by Pesaran et al. (2004), where the null hypothesis assumes cross-sectional independence and the alternative indicates interdependence among units. Next, the slope homogeneity test of Pesaran and Yamagata (2008), an extension of Swamy's (1970) methodology, was employed to examine whether the slope coefficients remain consistent across countries. Rejection of the null hypothesis in this test implies heterogeneity in the estimated slopes, indicating that relationships between variables differ across panel members. Furthermore, the second-generation unit root tests, namely the Cross-Sectionally Augmented Dickey–Fuller (CADF) and the Cross-Sectionally Augmented Im–Pesaran–Shin (CIPS) tests (Pesaran, 2007), were applied to check the stationarity properties of the series while accounting for cross-sectional dependence. These tests average individual CADF statistics to determine whether each variable contains a unit root. Finally, to explore the existence of a long-run association among variables, the Westerlund (2008) panel cointegration test was conducted. This test, grounded in a panel error-correction framework, allows for heterogeneity across cross-sections and provides four test statistics G_t, G_α, P_t, and P_α to evaluate the null hypothesis of no cointegration. A rejection of the null supports the existence of a stable long-run equilibrium relationship among the model variables.

Table 6. Results of cross-sectional dependence test

Variables	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
	Statistic	Statistic	Statistic	Statistic
EBE	2679.028***	69.311***	67.977***	42.112***
lFDI	600.244***	3.309***	1.976**	1.933*
lGF	1722.591***	38.944***	37.611***	12.699***
lINDS	1652.053***	36.705***	35.371***	8.003***
lTNR	2362.594***	59.264***	57.931***	36.745***
lUB	6040.265***	176.030***	174.697***	59.859***
lTD	2574.176***	65.982***	64.648***	38.729***

Ho: No cross-sectional dependence
Note: Significant at *p < 0.1, * * p < 0.05, * * *p < 0.01.

Table 7. Results of the Slope Homogeneity test

	Delta	p-value
	2.591**	0.010
adj.	5.236***	0.000

Ho: slope coefficients are homogenous
Note: Significant at *p < 0.1, * * p < 0.05, * * *p < 0.01.

Regression estimation

Tobit Regression

In this study, we employ the Tobit regression model to analyze the censored nature of our dependent variable, which is restricted to a certain range, typically between 0 and 1. The Tobit model, introduced by (Tobin, 1958), is particularly suitable for scenarios where the dependent variable is censored, that is, it has a substantial fraction of observations that cluster at a limiting value, such as zero. This approach allows for a more accurate estimation of the relationships between the dependent and independent variables under these conditions.

The standard Tobit model can be expressed as follows:

$$y_i^* = \beta_0 + \sum \beta_i x_{it} + \nu_i \tag{7}$$

Here, y_i represents the environmental efficiency calculated by the DEA technique, x_{it} the explanatory variables representing the factors affecting efficiency, β_0 the intercept, β_i the variable coefficients, and ν_i the error term.

$$y_i = \{\, y_i^* \text{ if } y_i^* > 0,\ 0 \text{ if } y_i^* \leq 0 \,\} \tag{8}$$

This formulation implies that the observed y_i equals the latent variable y_i^* when y_i^* is positive, and is censored to zero otherwise. This allows the Tobit model to account for the clustering of data points at the censoring threshold.

PCSE Regression

PCSE is an advanced econometric technique developed by (Beck & Katz, 1995) to address issues of heteroskedasticity and contemporaneous correlation in panel data analysis. This methodology improves the efficiency and accuracy of standard error estimates in the context of panel data regression models. This method demonstrates reduced sensitivity to outlier estimates and generates estimates that are free from serial correlation. It is particularly advantageous for use with time-series and cross-sectional data, ensuring precise and reliable standard error estimations (Bailey & Katz, 2011; Millo, 2014; Reed & Webb, 2010). The estimation process for PCSE begins with the standard OLS estimation of the regression parameters using the following model:

$$y_{it} = \alpha + \beta x_{it} + \epsilon_{it} \tag{9}$$

Where, y_{it} is the dependent variable for unit i at time t, x_{it} is the vector of explanatory variables, α is the intercept, β is the vector of coefficients, and ϵ_{it} is the error term. The OLS estimation provides unbiased estimates of the coefficients but potentially biased standard errors.

Next, the residuals from the OLS estimation are computed:

$$\hat{\Omega} = \frac{1}{T}\sum_{t=1}^{T}\hat{\epsilon}_t\left(\hat{\epsilon}'\right)_t \tag{10}$$

Here $\hat{\epsilon}_t$ is the vector of residuals at time t, and T is the number of time periods.

PCSE using the estimated covariance matrix $\hat{\Omega}$:

$$Var\left(\hat{\beta}\right)_{PCSE} = \left((X)^{'}X\right)^{-1}(X)^{'}\hat{\Omega}X\left(X^{'}X\right)^{-1} \tag{11}$$

The diagonal elements of this matrix provide the corrected standard errors for the coefficient estimates.

Finally, to ensure robustness, this study employed two additional methods: Two-step system Generalized Method of Moments (GMM) and Feasible Generalized Least Squares (FGLS). FGLS effectively addresses issues of cross-sectional dependence and heterogeneity. Meanwhile, two-step system GMM is utilized to tackle endogeneity problems.

Findings

Environmental efficiency

Figure 2 visualizes the environmental efficiency scores of various countries over multiple years. Each point corresponds to a specific country's score in a given year, color-coded for easy identification. Countries like Canada, Australia, Germany, Japan, and the United States show consistently high and stable environmental efficiency scores, indicating robust environmental management and effective policies that sustain high efficiency in environmental performance over time. Austria, Belgium, France, and South Korea also exhibit stable scores, though moderately high, reflecting balanced environmental policies that ensure steady performance. In contrast, countries such as Chile, Italy, Spain, Mexico, and Turkey display significant variability in their environmental efficiency scores, indicating fluctuations due to changing environmental policies, economic conditions, or external factors impacting their environmental performance differently over the years. This variability suggests that these countries experienced periods of reform, varying policy effectiveness, or external environmental pressures affecting their efficiency.

Figure 3 shows Technical Efficiency (TE), Pure Technical Efficiency (PTE), and Scale Efficiency (SE) scores of OECD countries. Countries like Australia, Austria, and Belgium demonstrate high scores across all metrics, indicating strong resource utilization and effective management. Canada and the Czech Republic also perform well, particularly in SE. Chile has a higher SE score but lower TE and PTE, suggesting optimal scale but inefficiencies in resource use and management. Finland, France, Germany, and Japan have high SE scores but show variability in TE and PTE, pointing to potential improvements in management practices. Luxembourg, the Netherlands, and New Zealand excel in all areas. Spain, Sweden, Switzerland, the UK, and the USA show balanced high efficiency, reflecting robust economic and managerial practices.

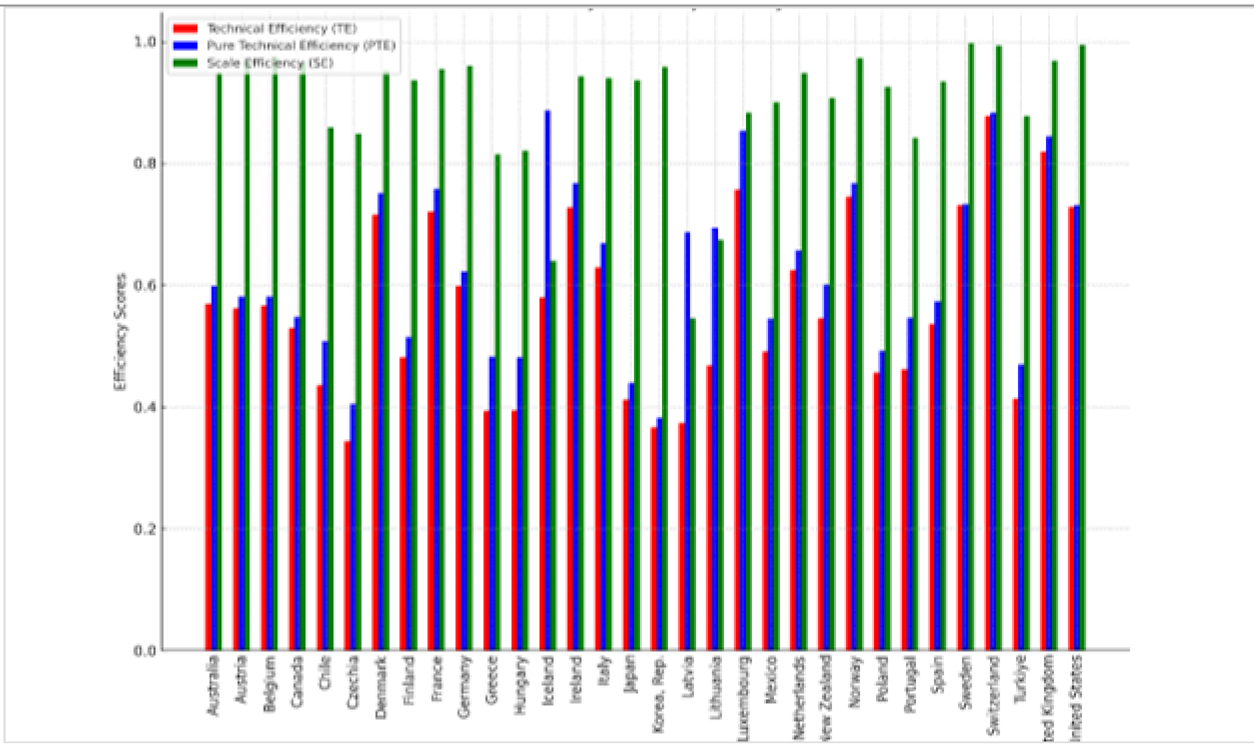

Figure 3. *Efficiency scores of OECD countries*

Preliminary tests

The preliminary diagnostic tests were conducted to ensure the robustness and reliability of the panel data analysis. The multicollinearity test results (Table 3) show that all Variance Inflation Factors (VIFs) range between 1.02 and 1.29, with a mean value of 1.17 well below the critical threshold of 10 indicating no multicollinearity issue. To identify cross-sectional dependence, we applied the Breusch–Pagan LM, Pesaran scaled LM, bias-corrected scaled LM, and Pesaran CD tests, all of which produced significant statistics (Table 4), leading to the rejection of the null hypothesis and confirming the existence of cross-sectional dependence among units. The slope homogeneity test results (Table 5) reported Delta and adjusted Delta statistics of 2.591 and 5.236, respectively, both significant, implying slope heterogeneity across cross-sections. Furthermore, the stationarity of variables was examined using the CADF and CIPS tests (Table 6), revealing that most variables were non-stationary at levels but achieved stationarity after first differencing, except for *lFDI* and *lGF*, which were stationary at levels. Lastly, the Westerlund cointegration test (Table 7) rejected the null hypothesis of no cointegration, confirming a stable long-run equilibrium relationship among the variables. Thus, these tests validate the suitability of the dataset and the chosen econometric techniques for robust panel estimations.

Results

Direct analysis

We employed the Tobit regression model and the PCSE model due to their distinctive advantages in addressing specific data characteristics. The Tobit model is particularly suited for handling limited dependent variables, providing robust estimates in the presence of censoring. On the other hand, the PCSE model is adept at managing cross-sectional dependence and heterogeneity, ensuring more reliable and efficient estimates in panel data settings with these complexities. The Tobit regression model results, as displayed in Table 8, provide valuable insights into the determinants of EBE. The analysis reveals that FDI negatively affects environmental efficiency, with a coefficient of -0.008, significant at the 10% level. This suggests that higher levels of foreign direct investment may lead to decreased environmental efficiency. This could be attributed to the potential introduction of less environmentally friendly technologies or practices by foreign firms, which may not prioritize environmental standards as rigorously as local regulations.

Table 8. Tobit and PCSE Regression Results for Environmental EBE- Direct Analysis

Variables	Tobit	PCSE
lFDI	-0.008*	-0.008*
	(0.002)	(0.004)
lGF	0.008***	0.007**
	(0.003)	(0.003)
lINDS	-0.122***	-0.122***
	(0.037)	(0.022)
lTNR	-0.005	-0.004
	(0.004)	(0.003)
lUB	0.132*	0.133***
	(0.076)	(0.035)
lTD	0.006	0.004
	(0.018)	(0.014)
Constant	0. 162	0.173
	(0.411)	(0.177)

Note: Robust standard errors in parentheses; *p < 0.1, * * p < 0.05, * * *p < 0.01.

Table 9. GMM and FGLS Regression Results for EBE- Direct Analysis

Variables	2 step System GMM	FGLS
lFDI	-0.024***	-0.008**
	(0.003)	(0.004)
lGF	0.058***	0.010***
	(0.003)	(0.002)
lINDS	-0.182***	-0.155***
	(0.064)	(0.029)
lTNR	0.006	-0.004
	(0.004)	(0.003)
lUB	0.065	0.082**
	(0.071)	(0.040)
lTD	0.018	-0.018
	(0.025)	(0.013)
Constant	-0.499	0.528**

	(0.451)	(0.253)
AR (1)	z = -1.57	
AR (2)	z = -0.98	
Hansen test	chi2 (20) = 27.85*	

Note: Robust standard errors in parentheses; *p < 0.1, * * p < 0.05, * * *p < 0.01.

GF exhibits a positive and significant impact on environmental efficiency, with a coefficient of 0.008, significant at the 1% level. This reveals that investments in green finance are crucial for improving environmental efficiency. Green finance typically supports projects focused on renewable energy, energy efficiency, and sustainable practices, which directly contribute to better environmental outcomes.

The PCSE regression results also presented in Table 8, provide a comprehensive analysis of the determinants of EBE while accounting for potential issues in panel data such as heteroscedasticity and autocorrelation. Consistent with the Tobit model, the coefficient for FDI remains -0.008 and is significant at the 10% level. This consistent finding reinforces the idea that higher levels of foreign direct investment may adversely impact environmental efficiency, potentially due to similar reasons as mentioned in the Tobit estimation. Green finance continues to show a positive effect on environmental efficiency with a coefficient of 0.007, significant at the 5% level. This result supports the critical role of green finance in enhancing environmental efficiency. By funding projects that promote sustainability and energy efficiency, green finance contributes to better environmental outcomes.

Table 10. Tobit and PCSE Regression Results for EBE- Interaction Analysis

Variables	Tobit	PCSE
lFDI	-0.169***	-0.168*
	(0.064)	(0.091)
lGF	0.005	0.005
	(0.003)	(0.002)
lFDI*lGF	0.007**	0.007*
	(0.002)	(0.004)
lINDS	-0.129***	-0.129***
	(0.037)	(0.022)
lTNR	-0.003	-0.003
	(0.004)	(0.003)
lUB	0.117	0.118***
	(0.075)	(0.034)
lTD	0.017	0.014
	(0.018)	(0.016)
Constant	0.281	0.289*
	(0.409)	(0.170)

Note: Robust standard errors in parentheses; *p < 0.1, * * p < 0.05, * * *p < 0.01.

The analysis also reveals that industrialization (lINDS) significantly reduces environmental efficiency, with a strong negative impact indicated by coefficients of -0.122 in both the Tobit and PCSE models, significant at the 1% level. This is likely due to the high energy consumption and emissions associated with industrial activities. Conversely, total natural resources rents (lTNR) have negligible and insignificant effects on environmental efficiency, with coefficients of -0.005 (Tobit) and -0.004 (PCSE), suggesting that these revenues do not directly enhance environmental efficiency, possibly due to their diverse uses. Urbanization (lUB) is positively associated with environmental efficiency, with coefficients of 0.132 (Tobit) and 0.133 (PCSE), significant at the 10% and 1% levels, respectively. This implies that urban areas, with their advanced infrastructure and efficient technologies, contribute to better environmental outcomes. Finally, trade (lTD) has a small positive but statistically insignificant effect on environmental efficiency, with coefficients of 0.006 (Tobit) and 0.004 (PCSE), indicating that trade does not directly impact environmental efficiency significantly in this context.

Interaction analysis

The analysis reveals that green finance significantly moderates the relationship between FDI and environmental efficiency. The Tobit regression results indicate that FDI negatively affects environmental efficiency (–0.169, significant at 1%), while green finance has a positive but statistically insignificant direct effect. However, the interaction between FDI and green finance is positive and significant at the 5% level, suggesting that green finance mitigates the adverse environmental impact of FDI by channeling investments toward sustainable practices. In the PCSE model, the negative effect of FDI persists (–0.168, significant at 10%), and the moderating effect of green finance remains positive and significant at the 10% level. Among the control variables, industrialization consistently exhibits a significant negative impact on environmental efficiency, whereas urbanization has a positive and significant effect. Natural resource management and trade, however, do not show meaningful associations. Overall, these findings highlight green finance's crucial role in transforming FDI into a driver of environmental sustainability and underscore the importance of integrating green financial mechanisms into policy frameworks to enhance environmental efficiency in OECD countries.

Table 11. GMM and FGLS Regression Results for EBE- Interaction Analysis

Variables	2 step System GMM	FGLS
lFDI	-0.552***	-0.145***
	(0.156)	(0.043)
lGF	0.026***	0.006**
	(0.007)	(0.002)
lFDI*lGF	0.025***	0.006***
	(0.007)	(0.002)
lINDS	-0.250***	-0.156***
	(0.062)	(0.029)
lTNR	0.003	0.003
	(0.004)	(0.003)
lUB	0.003	0.088**
	(0.094)	(0.041)

lTD	0.054**	-0.003
	(0.019)	(0.014)
Constant	0.471	0.537***
	(0.576)	(0.252)
AR (1)	z = -1.51	
AR (2)	z = -0.42	
Hansen test	chi2(19) = 23.28	
Note: Robust standard errors in parentheses; *p < 0.1, * * p < 0.05, * * *p < 0.01.		

Robustness Check

Table 10 presents the robustness results from the two-step System GMM and FGLS estimations. The findings consistently show that FDI has a negative and statistically significant effect on environmental efficiency, whereas green finance exerts a positive and highly significant influence. These results are consistent with the Tobit and PCSE estimates reported in Table 8, confirming the robustness of the baseline findings.

On the other hand, Table 11 reports the robustness analysis of the moderating effect using the two-step System GMM and FGLS models. The interaction term is positive and statistically significant across all specifications, indicating that green finance effectively mitigates the adverse impact of FDI on environmental efficiency. These findings are consistent with the Tobit and PCSE interaction results presented in Table 9, further confirming the robustness and stability of the moderating relationship.

Discussions

This study explores the complex nexus between FDI and environmental efficiency in OECD countries from 2010 to 2022, emphasizing the moderating role of green finance. Using advanced econometric approaches, including Tobit, PCSE, FGLS, and two-step GMM estimations, the results consistently reveal that FDI exerts a significant negative effect on environmental efficiency across all models. This outcome aligns with prior findings (e.g., Boateng et al., 2024; He et al., 2024) indicating that FDI often exacerbates environmental degradation, particularly when directed toward pollution-intensive industries in the absence of strong regulatory frameworks. These results highlight the necessity of designing FDI policies that incorporate environmental safeguards to ensure that foreign investment contributes to sustainable rather than environmentally harmful growth.

The results also show that green finance positively influences environmental efficiency, although the strength of this relationship varies across estimation methods. Consistent with studies such as Yadav et al. (2024) and Chin et al. (2024), this finding demonstrates that green finance facilitates emission reductions and supports the transition toward sustainable development by channeling funds into environmentally responsible projects and clean technologies. The variation in statistical significance across models suggests that the effectiveness of green finance depends on institutional quality, financial development, and the degree of policy enforcement within OECD economies.

A key contribution of this study lies in the positive and significant interaction between FDI and green finance, confirming that green finance moderates and mitigates the environmental risks associated with FDI. By steering investment flows toward sustainable sectors and promoting the adoption of green technologies, green finance enables countries to balance economic expansion with ecological preservation. Among the control variables, industrialization consistently exhibits a negative effect on environmental efficiency, reaffirming the need for cleaner industrial strategies. Urbanization shows mixed outcomes positive in some models, insignificant in others reflecting its dual potential to either improve or strain environmental quality. Trade presents both positive and inconsistent effects, indicating that its environmental impact depends on trade composition and regulatory standards. The findings emphasize the crucial role of green finance in transforming FDI into a catalyst for sustainability and call for integrated policy frameworks that leverage financial innovation to enhance environmental efficiency across OECD nations.

Conclusion, Policy Implications, and Limitations

Conclusion

This study examines the relationship between FDI and environmental efficiency in OECD countries, emphasizing the moderating role of green finance. The findings reveal that FDI consistently has a significant negative effect on environmental efficiency, whereas green finance contributes positively to environmental performance, though its influence varies across models. Notably, the positive and significant interaction between FDI and green finance confirms that green finance effectively mitigates the environmental harm associated with FDI. The control variables exhibit mixed effects, reflecting the multifaceted nature of factors shaping environmental efficiency. The results highlight that fostering green finance and enforcing robust environmental regulations are critical for OECD countries to attract sustainable FDI, enhance environmental efficiency, and advance long-term sustainability objectives.

Policy Implications

The results of this research highlight various important policy implications for relevant authorities, officials, the private sector, and global bodies. Governments should prioritize promoting green finance initiatives to enhance environmental efficiency by offering tax incentives, subsidies, and grants for green projects, thereby encouraging businesses to adopt sustainable practices. Additionally, stringent environmental regulations must be implemented to mitigate the negative impacts of FDI, ensuring that foreign investments comply with national and international environmental standards. To attract sustainable FDI, governments should establish clear guidelines and incentives for environmentally friendly investments, aligning foreign capital flows with environmental goals.

Furthermore, regulators play a crucial role in enhancing environmental oversight to ensure that FDI does not compromise environmental standards. This includes regular environmental impact assessments and audits to monitor compliance. Supporting the development and issuance of green bonds and other financial instruments is essential for mobilizing private capital towards green investments, fostering sustainable development. Furthermore, regulators should mandate comprehensive reporting and transparency for both FDI and green finance initiatives, enabling stakeholders to accurately assess the environmental impact of investments and make informed decisions.

The private sector must integrate sustainability into its core business strategies by investing in green technologies and practices that enhance environmental efficiency. Leveraging green finance opportunities to fund sustainable initiatives can improve a company's environmental footprint while enhancing profitability and market reputation. Collaboration with governments and regulators is vital to align operations with environmental standards, leading to the development of effective and mutually beneficial environmental policies. Moreover, international bodies should promote and enforce global environmental standards for FDI and green finance, ensuring consistency and effectiveness across borders. Facilitating the transfer of knowledge and green technologies to developing and emerging economies, along with providing technical assistance and capacity-building programs, will support these countries in enhancing their environmental efficiency and implementing green finance strategies effectively. **Figure 4** shows the policy recommendations for improving environmental sustainability in OECD countries.

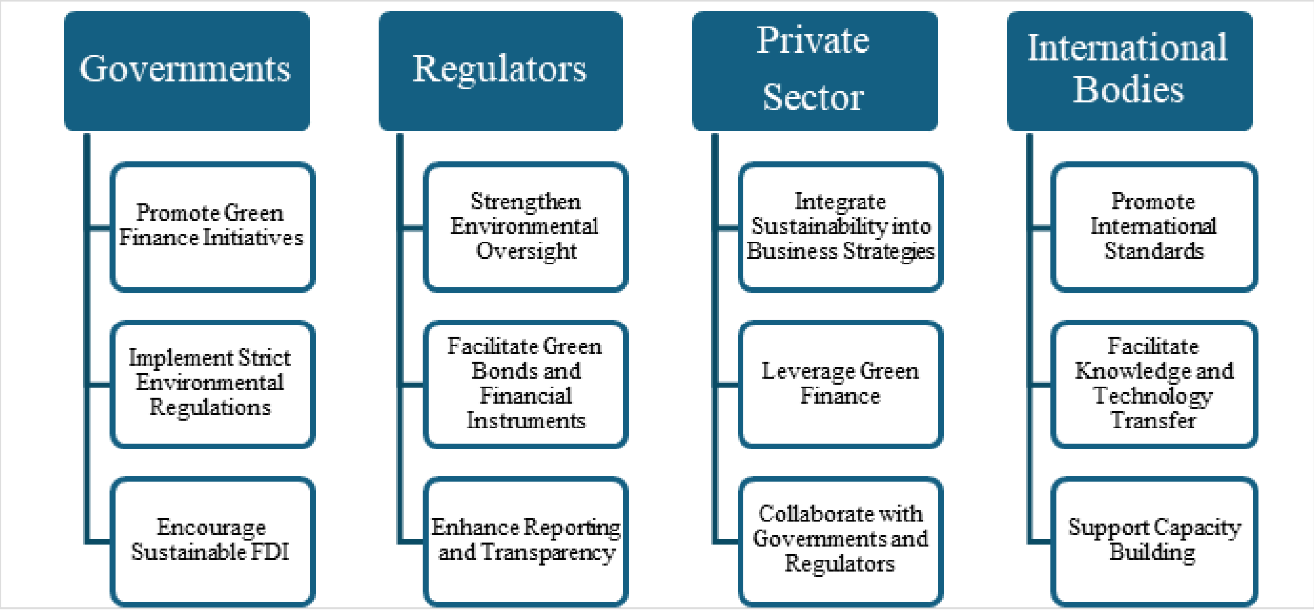

Figure 4. *Policy recommendations for promoting environmental sustainability in OECD countries.*

Study Limitations and Avenues for Future Studies

While this study offers valuable insights, it is not without limitations. First, the analysis focuses exclusively on OECD countries, which may limit the applicability of the findings to other regions with distinct economic structures and environmental policies. Second, the study period (2010–2022), though relatively recent, may not fully capture the long-term dynamics between FDI, green finance, and environmental efficiency. Although subsample analyses based on low, medium, and high FDI or green finance levels could yield further insights, the limited number of observations in the OECD sample restricts the feasibility of such estimations. Future research with larger or more heterogeneous samples could undertake this extension. Third, data limitations may have restricted the inclusion of additional explanatory variables or introduced minor measurement inconsistencies. Fourth, the research relies primarily on quantitative methods, potentially overlooking qualitative dimensions such as policy frameworks or institutional behavior that could further explain the observed relationships. Lastly, despite employing robust econometric approaches, potential issues related to omitted variables or endogeneity cannot be completely dismissed. Future studies should extend the analysis to a broader set of countries and time periods, incorporate mixed-method approaches, and consider institutional and policy factors to provide a more comprehensive understanding of the nexus between FDI, green finance, and environmental sustainability.

Acknowledgments

The author declares that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Funding

This research received no external funding.

Author contributions

Nazneen Fatema: Conceptualization, Methodology, Validation, Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Investigation, Visualization, Supervision.

Declaration of competing interest

The authors declare no conflicts of interest.

Ethics statement

Not applicable.

Data availability

Data available on request from the corresponding author.

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