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Research article

The impact of green FDI on environmental quality in less developed countries: A case study of load capacity factor based on PCSE and FGLS techniques

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ABSTRACT

This paper examines the effect of green foreign direct investment (GFDI) on environmental quality (EQ) in 34 less-developed countries (LDCs) from 2003 to 2021. We analyze balanced panel data using Feasible Generalized Least Squares (FGLS) and Panel-Corrected Standard Errors (PCSE). Our findings reveal several vital insights: (1) GFDI helps improve EQ. (2) Environmental costs associated with economic growth are negative. (3) Trade openness positively influences EQ. (4) EQ is enhanced by institutional quality, energy use, and population expansion in the chosen countries. (5) The existence of a U-shaped curve was established. This is valuable to the relatively scanty literature on GFDI, especially in LDCs. To the best of our awareness, this study simultaneously employs the Load Capacity Factor (LCF) and Total Value of Announced Greenfield projects as proxies for environmental sustainability and GFDI for the first time. Secondly, incorporating PCSE and FGLS models in this context is an innovative methodological strategy. The present research work provides to the existing theoretical and empirical discussions on GFDI and EQ and has practical implications that inform policy-making.

1. Introduction

The rise in foreign direct investment (FDI) has increasingly become one of the main engines of economic development, especially in our modern society. The case is particularly evident with FDIs where investors seek profitable opportunities, especially in developing and LDCs. In this case, one of the essential concerns concerning FDI is its environmental impact [1]. However, FDIs adversely affect EQ, as they enhance economic growth and technology advancement within the host country. As a result, this theory has brought forth the "Pollution Halo" hypothesis, and it is argued that FDI could encourage eco-friendly goods and technologies and thus raise EQ at home destinations [2]. The Pollution Halo hypothesis opposes another well-known hypothesis, the "Pollution Haven." Xu and colleagues say that the Pollution Haven hypothesis points out that FDI might result in relocating industries with high pollution from developed nations to developing nations [3]. As such, it may lead to reduced environmental qualities in the receiving countries. This discussion has generated substantial interest and academic studies regarding the disputes over the Pollution Halo and Pollution Haven hypotheses.

GFDI is when foreign investors inject clean technologies, practices, projects, and capital into a host country. This type of investment

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aims to support development and tackle issues like pollution, climate change, and resource depletion. By adopting sustainable technologies and practices, foreign investors can enhance performance and assist in moving to a less-carbon market. GFDI can include investing in energy projects, energy-efficient infrastructure, waste management systems, and sustainable agriculture practices [4]. Over the years, GFDI has gained attention due to the need to combat climate change and foster sustainable development [5]. Governments and international organizations have acknowledged its potential to increase the economy and sustainable conditions [6,7].

Regarding LDCs, in the last decade, they have witnessed a decrease in different types of investment due to some multidimensional crises faced by LDCs [8]. The repercussions of the multidimensional crisis are apparent in several categories of investment flows. International project finance (IPF), which often includes numerous lenders and is commonly used in infrastructure and extractive sectors, saw the most significant impact. In the year 2022, there was a decrease of 42% in the number of IPF agreements compared to the year 2019. Additionally, the value of these deals saw a decline of 76%. During the same time frame, there was a significant decline of 55% in the quantity of greenfield project announcements made by multinational enterprises (MNEs), corresponding to 40% in their overall value [8]. The issue at hand is of significant importance for LDCs since both forms of investment are vital in fostering the expansion of productive capacity and basic infrastructure. Consequently, they are vital for sustainable development [9].

There are some valid reasons why this study has focused on LDCs. ① Environmental conditions in LDCs frequently suffer because of insufficient resources and regulations, coupled with a higher dependence of the population on natural resources [10]. For this reason, it becomes crucial for such nations to understand how GFDI impacts their EQ to protect them from further deterioration. ② GFDI can be a catalyst for pro-environmental changes. Pollution reduction through investment can be in clean technologies such as renewable energy or sustainable agriculture and waste management that help conserve natural resources and curb greenhouse gas emissions [11]. Conducting research on this matter can provide insights into the effectiveness of such investments in attaining sustainable development. ③ The GFDI may create employment and boost LDCs' economies. Nevertheless, it may result in environmental deterioration if improperly handled. The balance of economic development and environmental protection determines whether we have sustained long-term, shared, and sustainable growth [12]. ④ According to Erdogan [13], studying the implications of GFDI could provide valuable insights into policy measures aimed at luring and fostering eco-investments, among other policies. These include designing incentives, framework laying for regulation, and establishing systems that monitor the performance of investments to determine their compliance with environmental objectives [14]. ⑤ The significance of sustainable development and environmental protection is stressed in many international agreements and initiatives, like the Paris Agreement and the SDGs. Understanding the effect of GFDI allows for harmonizing national aspirations with global desires. ⑥ Host countries receive much-needed advanced technologies, skilled personnel, and best management practices through GFDI [7,15]. Knowing how such technologies are adopted and domesticated in local contexts empowers LDCs to handle their environmental challenges better.

The principal aim of this study is to make a scholarly addition to the current empirical discussion regarding GFDI and EQ, particularly in LDCs. Balanced panel data from 2003 to 2021 covering 34 LDCs has been gathered and examined using the statistics software STATA 17 in order to accomplish so. The gathered data was analyzed using the Corrected Panel standard error and Generalized Least Squares methods. Indeed, the PCSE and FGLS are valuable techniques for analyzing complex data structures. PCSE is designed for panel data analysis, addressing errors in time and diverse entities like individuals, countries, or organizations. Colin and colleague [16] highlight the importance of PCSE in addressing issues like heteroskedasticity and autocorrelation. By adjusting standard errors, PCSE ensures more accurate and reliable results, especially in scenarios with numerous cross-sections and short periods [17]. FGLS, on the other hand, improves the precision and dependability of estimates compared to Ordinary Least Squares (OLS). Using a two-step approach, FGLS estimates residual structure and transforms data to eliminate these issues, allowing OLS to be applied to adjusted data [16]. As in the present investigation, the number of entities is much higher than the observation time, which makes the PCSE and FGLS models perfectly suitable.

This study's primary contribution is to the body of knowledge regarding GDFI and EQ in LDCs, as there is a dearth of research on the topic, particularly in these regions. To the best of our understanding, this analysis is the first to use the aggregate value of Announced Greenfield Projects and the Load Capacity Factor (LCF) combined as proxies for the environment and GFDI. Applying the PCSE and FGLS models in this situation would be another novelty.

Below is a breakdown of the remaining sections of the paper: The literature review section provides a synopsis of the empirical and theoretical trends; the data and methodology section discuss the data and the empirical technique that was used; the results and discussion section present the various findings. The section on policy implications and conclusion provides a summary and suggestions.

2. Literature review

2.1. Theoretical and empirical trends

2.1.1. Theoretical trends

Regarding the literature review, multiple theories exist treating the concept of FDI and the environment. The most known and debated are the following: The Pollution Haven Hypothesis (PHH), the Pollution Halo Hypothesis (PHAH), the Environmental Kuznets Curve (EKC), and the Porter Hypothesis (PH).

2.1.1.1. Pollution haven/halo hypothesis. Copeland as well as Taylor established the PHH theory in 1994. It is a well-known economic theory. Indeed, the PHH displays that globalization and FDI may have environmental impacts. This hypothesis states that multinational corporations (MNCs) locate production facilities in host countries to reduce operative costs, where environmental regulation is negligent, and avoid strict environmental standards in their home countries. The PHH assumes environmental rules significantly affect production costs. Compliance with rigorous environmental standards can be costly for enterprises in nations with severe policies. Thus, MNCs may go to countries with lax environmental rules where compliance is cheaper. The so-called "Race to the Bottom scenario" suggests that countries to attract FDI and remain competitive may be tempted to lower their environmental standards. This might increase global pollution and environmental deterioration, especially in developing countries where MNCs seek cost reductions.

The PHH's validity has been tested empirically with varied results. There is evidence of pollution havens, although their magnitude and influence on global pollution are still debated [18–20]. The link between FDI and environmental performance is complicated and depends on industry, host country, and multinational business practices [21,22]. However, the PHH critics say the theory oversimplifies multinational corporate behavior. The critics argue that corporations evaluate labor costs, market access, and infrastructure availability in addition to environmental rules when investing [22]. Additionally, global firms are increasingly aware of the need for sustainable practices and may implement eco-friendly technology and practices independent of host country legislation [23,24].

The PHH poses critical policy issues. The need to attract FDI and boost economic growth must be balanced with environmental and public health concerns. Environmental legislation, enforcement, and incentives for sustainable activities must be carefully balanced [25].

The PHH is opposed theory of PHAH. Indeed, the pollution halo assumption proposed by Zarsky [26] supports that Multinational Corporations (MNCs), through FDI, contribute to enhancing EQ. This hypothesis indicates that the advanced technologies and practices brought by the MNCs to the host countries can significantly lower emissions and improve EQ in the developing world. Numerous studies have demonstrated that advanced green manufacturing technologies disseminated by foreign-funded companies can introduce sustainable low-carbon concepts, energy-efficient methods, and emission-mitigating technologies [27–29]. Overall, whereas the Pollution Halo Hypothesis encourages FDI toward host countries, the Pollution Haven Hypothesis provides a framework for understanding the potential environmental consequences of FDI. While it highlights a valid concern regarding standards of environment to the bottom tree, it is essential to recognize that a complex interplay of factors influences the behavior of multinational corporations [21,30,31].

2.1.1.2. Porter Hypothesis (PH). The PH was established by Michael Porter in 1991. The main point of this hypothesis is that environmental regulations can boost industry innovation and competitiveness. Environmental regulations have traditionally been thought to increase business costs and decrease profitability and competitiveness. The PH challenges the idea that strict environmental regulations hinder economic competitiveness. Instead, it claims that well-crafted environmental laws can boost innovation and productivity, giving companies and governments a competitive edge. Porter says environmental restrictions spur technical innovation. When regulations are strict, companies are motivated to invest in environmentally friendly and more effective technology. Thus, resource use, waste, and pollution can decrease. The hypothesis also suggests that environmentally sustainable companies may gain a competitive edge. Resource efficiency and waste reduction can reduce production costs for organizations. Those who value environmental sustainability may prefer companies with strong environmental performance, which boosts brand image and customer loyalty.

However, some critics say the PH may vary by sector and area [31]. This may be true in businesses with high innovation and competition but not in sectors with limited technology options or high regulatory compliance costs [32]. According to the theory, organizations are logical and forward-thinking, which may conflict with their immediate goal of increasing profits.

The Porter Hypothesis also requires enabling institutions and regulations. Governments must create and enforce innovative and fair business regulations [33]. In practical terms, attaining an optimal equilibrium between safeguarding the environment and fostering economic development is a multifaceted and situation-dependent undertaking [34,35].

The Porter Hypothesis posits a compelling argument regarding the correlation between economic competitiveness and environmental legislation. While the notion has garnered considerable interest and support, its practical implementation requires a thorough analysis of industrial dynamics, legal structures, and the possibility of technological progress [33].

2.1.1.3. The environmental Kuznets Curve theory (EKC). An inverse U-shaped connection between the degradation of the environment and economic advancement is suggested by the EKC theory. The theoretical framework suggests that EQ declines when a nation expands economically and incomes grow. Environmental damage decreases as civilization improves its interaction with the environment after a certain point of economic progress. It was economist Simon Kuznets in 1955 who proposed EKC. The relationship between income inequality and economic advancement was depicted as an inverted U in Kuznets' original Kuznets Curve. The EKC expands on the preceding concept by analyzing the relationship between EQ and economic prosperity. The EKC hypothesis states that early economic development increases pollution and environmental degradation when nations industrialize and urbanize. This problem is caused by natural resource extraction and industrial machinery use. As a nation develops and its economy improves, it adopts sustainable development methods and emphasizes environmental care.

Oversimplification and narrow application are two main complaints against the EKC theory. Critics argue that identifying a turning point is flexible but may show substantial variations depending on factors, including the quality of governance, technology availability, and the pollutant in question. Loss of biodiversity and other environmental problems may also buck the general trend in the Environmental Kuznets Curve [36–38]. Stern and colleagues pointed out econometric criticisms about the EKC theory, such as heteroskedasticity, simultaneity, omitted variables bias, and cointegration issues [39]. Furthermore, critics of EKC models argue that they assume environment and economic development are independent, implying no feedback loop between income and environmental pollution [40].

2.1.2. Empirical trends

In the empirical literature, plenty of scholars have discussed the FDI and EQ concerns [41–44]. The literature about specifically GFDI is rare regarding quantity and quality. The following passage overviews the literature about GFDI and EQ.

In his research, Johnson [4] focuses on analyzing the impact of investments (FDI) in promoting sustainable development, particularly in the context of "GFDI." He examines the practices of FDI concerning sustainability, explores the regulatory frameworks that influence FDI towards environmentally friendly initiatives and investigates how environmental considerations are integrated into financial markets. The paper highlights in the context of developing countries the role of FDI in achieving the expansion areas and meeting the pledges outlined in the Paris Climate Agreement [4].

Another study using cross countries method investigates how GFDIs enhance sustainability within MNEs. Analyzing a dataset of 1217 FDIs in energy sectors from 1997 to 2015 reveals that GFDIs align with MNEs' broader commitment to sustainability and drive a greater focus on specialized green technologies. They also impact the extent and quality of MNEs' innovative technological capabilities [45].

Almazrouie and colleague [7] used a qualitative approach to examine the implications of FDI through a mini-review of 20 academic articles composed of developed, developing, and less developed countries as samples. The findings suggest that FDI often leads to degradation, such as biodiversity loss, deforestation, and greenhouse gas emissions. However, greenfield investments emerge as a solution for mitigating these challenges. The study recommends that governments adopt strategies when implementing FDI, considering environmental contexts across different regions.

In their study, Golub and colleague [46] delve deeper into GFDI and its potential positive environmental impact. It thoroughly examines the frameworks related to FDI, its magnitude, and the limitations it faces. Additionally, it analyzes obstacles in 30 different countries.

In his research, Zheng [47] examined the influence of knowledge stocks derived from GFDI firms on the green innovation of local companies in the developing country of China. He proposed a novel approach to define and quantify GFDI, which involved considering four key factors: the business description of FDI firms with specific environmentally-friendly keywords, the green patenting activities of FDI firms, the prior art associated with FDI firms' patents, and the patenting activities of investors in FDI firms. The results indicate no significant influence of knowledge stocks of GFDI businesses on domestic green innovation, mainly when these GFDI firms operate in the same industry as domestic enterprises. On the contrary, the research has revealed that a marginal increase of 1% in knowledge stocks, which may be attributed to GFDI businesses operating in downstream sectors, leads to an approximate 0.732% rise in the number of green patents filed by domestic firms.

According to Castellani and colleagues [48], the term "green-tech FDI ″ refers to the phenomenon of international investments, specifically targeting sectors that prioritize developments in environmental technology. Sectors are classified according to their proclivity to engage in patent filings within green technology while concurrently establishing a correlation between FDIs and these specific businesses. The research indicates that the inflow of greenfield FDI substantially impacts the specialization of geographical

Table 1
EQ and FDI summary on various research work.

Authors	Period of investigation	Methodology	Conclusion
Solarin et al., 2017 [50]	From 1980 to 2012	ARDL	PHH
Sharma & Rana, 2019 [51]	From 1982 to 2013	Toda Yamato & ARDL	PHH
Sun et al., 2017 [52]	From 1980 to 2012	ARDL	PHH
Tang & Tan, 2015 [53]	From 1976 to 2009	Granger Causality	PHAH
Shahbaz & Rouleaud, 2018 [54]	From 1955 to 2016	ARDL & Bootstrap	PHH
Lau et al., 2014 [55]	From 1970 to 2008	ARDL & Granger Causality	PHH
Suki et al., 2020 [56]	From 1961 to 2016	QARDL	EKC
Bello & Adeniyi, 2010 [57]	From 1970 to 2006	ARDL	PHH
Merican & Mulai, 2012 [58]	From 1970 to 2001	ARDL	PHH/PHAH
Lee, 2013 [59]	From 1971 to 2009	Fixed Effect	PHH
Shahbaz et al., 2015 [60]	From 1975 to 2012	FMOLS & DH Causality	PHH/PHAH
Jungho, 2016 [61]	From 1981 to 2010	Pedroni & PARDL	PHH
Wang et al., 2019 [62]	From 2004 to 2010	SBM-DDF	PH
Bakirtas & Cetin, 2017 [63]	From 1982 to 2011	VAR	PHAH
Al-Mulali & Ozturk, 2015 [64]	From 1996 to 2012	Pedroni, FMOLS, VECM	PHH
Mert & Bölük, 2016 [65]	Non-balanced	ARDL	PHAH
Mert et al., 2019 [66]	Non-balanced	ARDL	PHH
Destek & Okumus, 2019 [67]	From 1982 to 2013	Cointegration & CCE	NA
Lorente et al., 2019 [68]	From 1990 to 2013	FMOLS, DOLS & DH	PHAH
Zafar et al., 2019 [69]	From 1990 to 2014	CUP-FM and CUP-BC	EKC
Aminu et al., 2023 [70]	From 1995 to 2019	FMOLS	EKC
Albulescu et al., 2019 [71]	From 1980 to 2010	Panel Quantile Regression	NA
Seker et al., 2015 [72]	From 1974 to 2010	ARDL, Granger & Hatemi	PHH
Terzi & Pata, 2019 [73]	From 1974 to 2011	Toda Yamamoto	PHH
Koçak & Sarkgunesi, 2017 [74]	From 1974 to 2013	MAKI, DOLS, Hatemi	PHH
Kılıçarslan & Dumrul, 2017 [75]	From 1974 to 2013	Johansen cointegration	PHH
Öztürk & Oz, 2016 [76]	From 1974 to 2011	MAKI, DOLS	PHAH
Mutafoglu, 2012 [77]	From 1987 Q1 to 2009 Q4	Granger & Johansen	PHH

areas in green technology, with a particular emphasis on research and development endeavors. However, when technological proximity is not minimal, FDIs in research and development of green technology do not facilitate the acquisition of green technology from its first stages. Instead, they assist regions already specialized in green technology to maintain their specialization over a prolonged period.

Finally, in the table below are some studies about FDI and the environment involving the theories above. Table 1 below is extracted from the study conducted in Turkey by Mert and Calar [49].

Remarks: NA denotes an indeterminate answer.

3. Data collection

3.1. Selection of sample

The research work aims to demonstrate how GFDI affects the environment in LDCs. To achieve this objective, a balanced panel data from 34 LDCs has been selected from 2003 to 2021. The accessibility of the necessary data for this investigation determines the choice of the sample. Indeed, according to the World Bank, there are in total 46 countries listed as LDCs in 2023. Due to the unavailability or incomplete data about some of the 46 LDCs, 34 LDCs have been selected as samples. Table 2 depicts the thirty-four LDCs.

3.2. Variable selection

Our dependent variable is the Load Capacity Factor (LCF), obtained through the division of the bio-capacity by each country's ecological footprint. The reason why LCF has been selected as an EQ measure proxy is based on the fact that the generally used measured proxies, such as CO2 emissions and Ecological footprint, present some areas for improvement. CO2 emissions proxy provides details on the air pollution situation, which is not the only determinant of EQ. Indeed, EQ determinants go beyond of just air pollution proxy; they include water and soil pollution. The shortcoming of the ecological footprint is that it needs to consider the supply side of ecological conditions [78]. Indeed, it focuses only on the environmental deterioration resulting from human use of the planet's resources, in other words, the demand side. Thus, Siche [78] suggest using the LCF to evaluate how flexible the variables affectingEQ are in the particular situation.

The key independent variable is the GFDI, the total value announced greenfield FDI projects reported by the World Investment Report of UNCTAD. According to Mai [79], up to now, there has yet to be a unified concept of GFDI and its measurement method. The difficulty in identifying and quantifying GFDI was noted in a UNCTAD report from 2008 [80]. Nevertheless, in an attempt to define it, it has split GFDI into two categories: carbon-free processes and low-carbon goods and services. Indeed, the two-part definition proposed by UNCTAD includes activities beyond national environmental norms, known as "compliant plus," and direct production of environmental products and services within host nations. However, it does not estimate the flows of GFDI. In 2010, UNCTAD [81] highlighted low-carbon FDI as a significant component of GFDI. It defines it as the process by which multinational corporations transfer technologies, practices, or products to host countries, aiming to reduce greenhouse gas emissions compared to industry standards. This FDI aims to gain access to low-carbon technology, processes, and products. Amendolagine and colleagues [45] adopt the four-step approach Glachant and Dechelepretre [82] proposed to identify GFDI. The outcome of that process is quantifying the amount of FDI associated with climate change. This is achieved by examining the holdings of foreign subsidiaries of businesses that own at least one patent relating to climate change technologies.

We added seven control variables directly linked to the EQ: Total GDP (GDP) at constant 2015 in US dollar [83–85]; Institution Quality (IQ) measured on a scale of from 1 to 5 [86–89]; Trade openness (Trade) measured as the sum of exports and imports on the

Table 2
List of selected countries.

List of selected countries	
Angola	Lesotho
Bangladesh	Madagascar
Benin	Mali
Bhutan	Mauritania
Burkina Faso	Mozambique
Burundi	Myanmar
Cambodia	Nepal
Central African Republic	Niger
Chad	Rwanda
Comoros	Senegal
Democratic Republic of Congo	Sierra leone
Ethiopia	Solomon Islands
The Gambia	Sudan
Guinea	Timor-Leste
Guinea-Bissau	Togo
Haiti	Uganda
People's Republic of Laos	United Republic of Tanzania

GDP [90,91]; Population growth (POP) measured as annual growth percentage [92–94]; Energy Consumption (ENERGY) measured as energy use per person [95].

Indeed, the economic development level indicated here by the total GDP is a crucial component of EQ degradation [96,97]. Indeed, expanding economic activity inside a nation leads to a corresponding rise in greenhouse gas, which harms the environment, as Sarkodie and colleagues [98] highlighted. Considering the potential impact of economic progress on the environment, this study selects the total GDP as an indicator.

Following the PH hypothesis, a country's institutions and stringent rules incentivize multinational corporations to invest in sustainable and more efficient technologies. As a result, there is a potential reduction in resource consumption, waste generation, and pollution, which implies a favorable environmental impact. This hypothesis is supported by Tang [99] as well as Ibrahim and colleagues [89], who found that education and institution quality contribute positively to the environment in sub-Saharan Africa. Accordingly, the institution quality index is added as a control variable to observe its impact in this context.

The link between trade and EQ is complex and contingent upon the specific environmental pollutants and nations involved [100]. Using CO2 and nitrous oxide as environmental pollutants, Tran [101] concluded a harmful effect of trade on the EQ in 66 developing nations. Therefore, it will be interesting to observe, in our case, the effect of trade on the LCF as an environmental quality indicator.

With a population growth rate of 2.32% in 2022, LDCs population growth is on a growing trend [102]. Based on the existing literature stipulating both negative and positive effects of population growth on EQ [103,104], the annual growth of the population was selected as an indicator in our context to determine its impact on LCF.

The most significant share of the total primary energy consumption of LDCs is based on biomass energy [105]. Therefore, as biomass is considered renewable energy [106], a positive effect on LCF is expected in our context. The energy consumption per capita is used as an indicator in this study.

Table 3 and 4 below detail and describe the variables (see Table 4).

3.3. Methodology

3.3.1. Specification of the econometric models

Our first step consists of specifying a baseline model with LCF expressed as a linear function of the control variables:

$$\text{lnlcf}_{it} = \beta_0 + \beta_1 \ln \text{green}_{it} + \beta_2 \text{controls}_{it} + \varepsilon_{it} \quad (1)$$

The GFDI square was added to the baseline equation to verify the presence of the GFDI-Kuznets curve.

$$\text{lnlcf}_{it} = \gamma_0 + \gamma_1 \text{lngreen}_{it} + \gamma_2 lngreen_{it}^2 + \gamma_3 controls_{it} + v_{it} \quad (2)$$

Where *lnlcf* represents the environmental quality, *lngreen* represents green FDI, *lngreen*^{2} represents green FDI square, controls represent the control variables, ε_{it}, v_{it} represents the error term.

Referring to Adeleye [17], our GFDI-Kuznets curve is verified under the following conditions: (i) $\gamma_1 < 0, \gamma_2 > 0$ illustrates a curve with a U-shaped pattern; (ii) $\gamma_1 > 0$, $\gamma_2 < 0$ exhibits an inverted U-shaped pattern, which aligns with the Environmental Kuznets Curve (EKC). The calculation of the turning point for GFDI is derived through $\grave{\tau} = (0.\grave{\gamma}_1\grave{\gamma}_2)$; (iii) $\gamma_1 > 0, \gamma_2 > 0$ demonstrates a consistently ascending linear connection; (iv) $\gamma_1 < 0, \gamma_2 < 0$ showcases a consistently descending linear correlation; and (v) $\gamma_1 = 0, \gamma_2 = 0$ displays an even correlation. The moment at which Equation (2)'s initial derivative with respect to GFDI approaches zero is the turning point.

3.3.2. Lasso model selection

To identify the most appropriate predictors with optimal performance for our dependent variable, we utilized the Least Absolute Shrinkage and Selection Operator model (Lasso). Lasso regression, a variant of linear regression employing shrinkage techniques [107], involves pulling data values toward a central point, such as the mean. The Lasso procedure promotes the development of straightforward and sparse models, characterized by fewer parameters. This regression method is particularly advantageous for models exhibiting significant multicollinearity or situations where automation of specific aspects of model selection, such as variable selection or parameter elimination, is desired [107,108]. For more stability and robustness, four components of the Lasso techniques were used:

Table 3
Variables description.

Variable	Log form	Description	Sources
Load Capacity Factor	lnlcf	Biocapacity/Ecological footprint	Global Footprint Network
Green FDI	lngreen	Total value of greenfield project in US dollars	World Investment Report
GDP	lngdp	GDP value (constant USD 2015)	World Development Indicator
Institution Quality	lniq	Scale of 1–5	Political Terror Scale
Trade openness	lntrade	Share of GDP	World Development Indicator
Population Growth	lnpop	Annual growth	World Development Indicator
Energy Consumption	lnenergy	Energy use per capita	U.S. EIA; Energy Institute Statistical Review of World Energy (2023) (OurWorldInData)

Table 4
Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Load Capacity Factor	646	1.401	1.275	0.128	7.407
Green FDI	646	796.882	1722.634	0	16275.01
GDP	646	2.109e+10	3.273e+10	7.422e+08	1.951e+11
Trade Openness	646	62.169	30.346	12.199	158.895
Institutions Quality	646	3.019	1.055	1	5
Population Growth	646	2.397	0.876	−0.402	5.078
Energy Consumption	646	2117.013	4033.067	105.11	27785.359

the lasso cross-validation (CV), adaptive lasso, and the AIC and BIC criteria.

Indeed, the standard lasso is a statistical method that uses a fixed constant as a penalty term, which is then multiplied by the absolute values of the coefficients. However, this approach treats all coefficients equally, which may not be ideal when some predictors are more important than others [109]. Adaptive lasso addresses this issue by assigning different penalty weights to each coefficient based on their estimated importance, aiming to penalize less important coefficients more heavily [109]. The lasso function can be written as follows:

$$\text{minimize}\left\{\frac{1}{2}\sum_{i=1}^{n}\left(y_i-\beta_0-\sum_{j=1}^{p}x_{ij}\beta_j\right)^2+\lambda\sum_{j=1}^{p}w_j|\beta_j|\right\} \quad (3)$$

Here, n is the number of observations, p is the number of predictors, y_i is the response variable for the i-th observation, x_{ij} is the i-th observation of the j-th predictor, β_0 is the intercept, β_j are the coefficients being estimated, λ is the regularization parameter, w_j are the adaptive weights for each predictor.

3.3.3. Cross-section dependence (CD), unit root, and cointegration test

3.3.3.1. Cross-sectional dependency. When analyzing panel data, a cross-sectional correlation is expected to be found. The interaction of different countries inside the same economic-social network, the geographical effect, etc., are the causes of this [110,111]. By considering cross-sectional variation in panel data, prediction mistakes and discrepancies can be prevented [112,113]. The following is the LM test that Breusch with Pagan CD suggested:

$$Y_{it}=\alpha_i+\beta_i X_{it}+\varphi_{it} \quad (4)$$

where X_{it} is an independent variable having $k\times 1$ vectors. $t=1, 2, \ldots, T$ displays the dimension of time. $i=1, 2, \ldots, N$ defines the dimensions of cross-sectional. The null hypothesis for CD states that (Cov(φit, φjt) = 0), while the alternative hypothesis asserts that (Cov (φit, φjt) ≠ 0). These are selected using the LM test.

$$\text{LM}=T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij} \quad (5)$$

The modified version is used for the cross-sectional dependency, which is the Pesaran [111]:

$$\text{CD}=\sqrt{\frac{2T}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{(T-k)\hat{\rho}_{ij}^2-E\left[(T-k)\hat{\rho}_{ij}^2\right]}{\text{var}\left[(T-k)\hat{\rho}_{ij}^2\right]}} \quad (6)$$

Here $\hat{\rho}_{ij}$ in Eq. (6) stands for the correlation coefficient derived from using Eq. (4) for every cross-section dimension *i*. Additionally, *T* refers to the sample size, while *N* indicates the panel size.

3.3.3.2. Second generation unit root test. The second-generation unit root testing tool created by Pesaran (CIPS) is used to perform the unit root test. First-generation tests for unit roots are, in fact, inappropriate when CD is present. Pesaran [111] developed CIPS, which is calculated by taking the average of the $CADF_i$.

$$\Delta Y_{i,t}=\alpha_i+\beta_i Y_{i,t-1}+\gamma_i\overleftarrow{Y}_{t-1}+\delta_i\Delta\overleftarrow{Y}_{i,t}+\varepsilon_{it} \quad (7)$$

$$\text{CIPS}=\frac{1}{N}\sum_{i=1}^{N}CADF_i \quad (8)$$

The CADF in Eq. (8) represents the statistics of individual cross section *i* established by *t* ratio of β_i in Eq. (7).

③ Westerlund Cointegration Test. The conventional cointegration tests are inappropriate because CD is present here. Consequently, Westerlund's [114] cointegration test is employed. Below is the formula in Eq. (9).

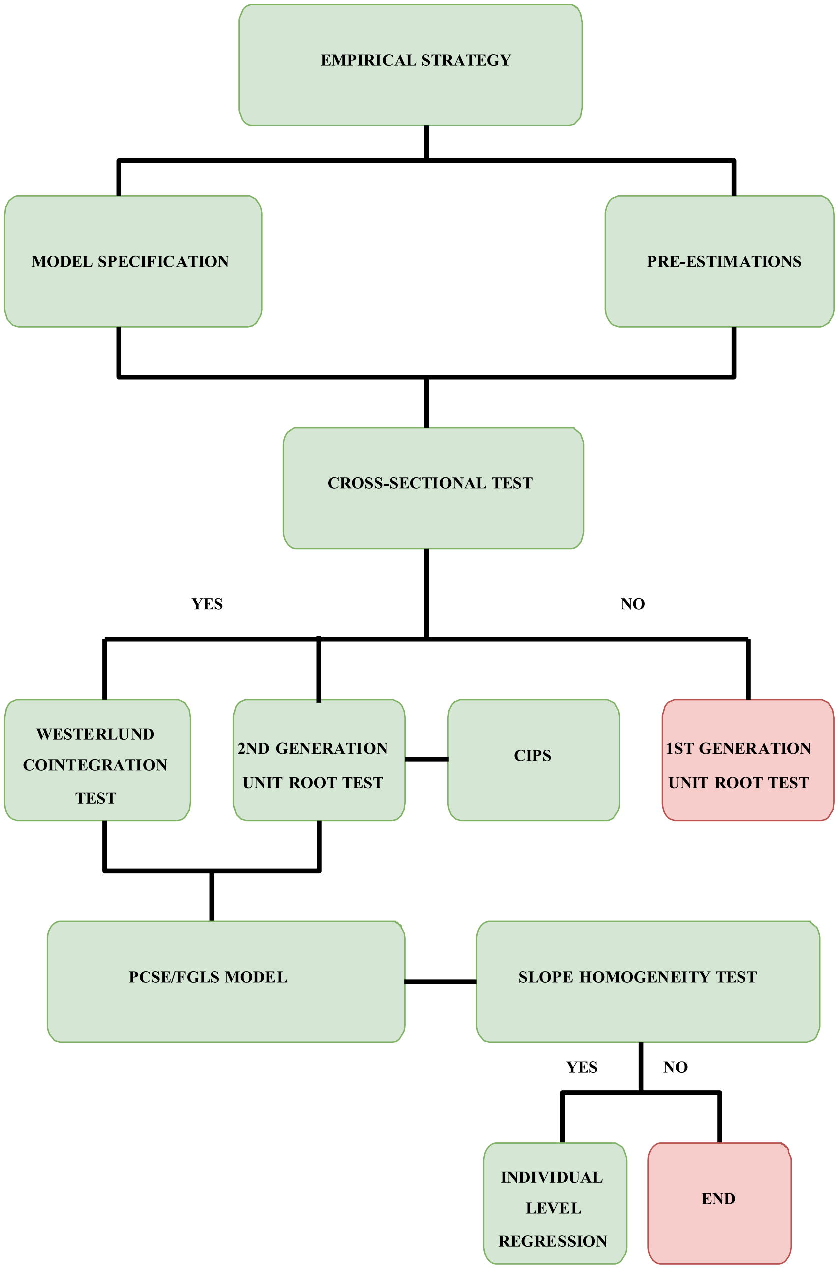

Fig. 1. Empirical strategy.

$$\Delta Y_{i,t} = \delta_i' d_t + \epsilon_i \left(Y_{i,t-1} - \beta_i' X_{i,t-1} \right) + \sum_{j=1}^{p} \varphi_{ij} Y_{i,t-j} + \sum_{j=0}^{p} \varphi_{ij} X_{i,z-j} + \mu_{i,t} \quad (9)$$

Where ϵ_i is the coefficient value that denotes the equilibrium correction rate. Eq. (10) includes group mean statistics, including panel statistics as proposed by Westerlund in 2007 [114].

$$\begin{aligned} G_\tau &= \frac{1}{N} \sum_{=1}^{N} \frac{\epsilon_i}{\text{Se}\ (\dot{\epsilon}_i)} \\ G_\alpha &= \frac{1}{N} \sum_{i=1}^{N} \frac{T\epsilon_i}{e_i(1)} \\ P_\tau &= \frac{\dot{\epsilon}_i}{\text{Se}\ (\hat{\epsilon}_i)} \\ P_\alpha &= T\hat{\epsilon} \end{aligned} \quad (10)$$

This analysis uses least squares estimates of error term ϵi and temporal dimension T to present statistics. Pτ & Pα statistics show cointegration throughout the entire panel, whereas Gτ along with Gα statistics evaluate cointegration to be a minimum of one cross-section unit.

3.3.4. Slope heterogeneity test

The slope homogeneity test proposed by Pesaran and Yamagata [115] was employed in this investigation. Pesaran and Yamagata [115] proposed an enhanced methodology for analyzing the coherence of slope coefficients inside an integrated solution, building upon Swamy's [116] original method. Eq. (11) displays the delta test statistic $\widetilde{\Delta}$ and $\overline{\Delta_{\text{adj}}}$.

$$\begin{aligned} \widetilde{\Delta} &= \sqrt{N}\left(\frac{N^{-1}\zeta - k}{\sqrt{2k}}\right) \sim X_k^2 \\ \widetilde{\Delta}_{\text{adj}} &= \sqrt{N}\left(\frac{N^{-1}\zeta - k}{v(T,k)}\right) \sim N(0,1) \end{aligned} \quad (11)$$

Where k stands for independent variables, S for the Swamy statistic, and N for the total cross-section units. The null hypothesis is accepted at a 5% significance level, while the cointegration coefficient is regarded as homogenous if the test's p-value exceeds 5%. Large and tiny samples can benefit from using $\widetilde{\Delta}$ and $\widetilde{\Delta}$_adj, respectively. $\widetilde{\Delta}$ _adj is a "mean-variance bias adjusted" variant of $\widetilde{\Delta}$. Therefore, error cannot be autocorrelated using the usual delta test ($\widetilde{\Delta}$). The slope homogeneity test's HAC robust variant, described by Blomquist J., Westerlund [117], as well as Pesaran along with Yamagata [115], relaxes the requirements for uniformity along with serial independence in order to provide a different robust version of the test. Then Δ_{HAC} and $(\Delta_{HAC})_{\text{adj}}$ tests are proposed as a two-step robust estimation procedure in Eq. (12).

$$\begin{aligned} \Delta_{HAC} &= \sqrt{N}\left(\frac{N^{-1}s_{HAC} - k}{\sqrt{2k}}\right) \sim X_k^2 \\ (\Delta_{HAC})_{adj} &= \sqrt{N}\left(\frac{N^{-1}s_{HAC-k}}{v(T,k)}\right) \sim N(0,1) \end{aligned} \quad (12)$$

The employed methodology is displayed in the following figure (see Fig. 1).

Table 5
Lasso model selection results.

ID	lambda	No.of non-zero coef	Out of sample R-squared		CV mean predictor error
Standard Lasso Cross-Validation					
[a]32	0.0120818	6	0.2011		0.3733111
Adaptive Lasso Cross-Validation					
[a]111	0.000454	6	0.2118		0.3683314
AIC					
[a]32	0.0120818	6	0.2011	AIC (877.8878)	NA
BIC					
[a]31	0.0132598	6	0.2002	BIC (907.6639)	NA

[a] lambda selected by CV.

Table 6
Selected coefficients.

Name	CV	AIC	BIC	Adaptive
Lngreen	X	X	X	X
Lngdp	X	X	X	X
Lnenergy	X	X	X	X
Lnpop	X	X	X	X
Lniq	X	X	X	X
Lntrade	X	X	X	X
Constant	X	X	X	X

Note: X stands for selected predicators.

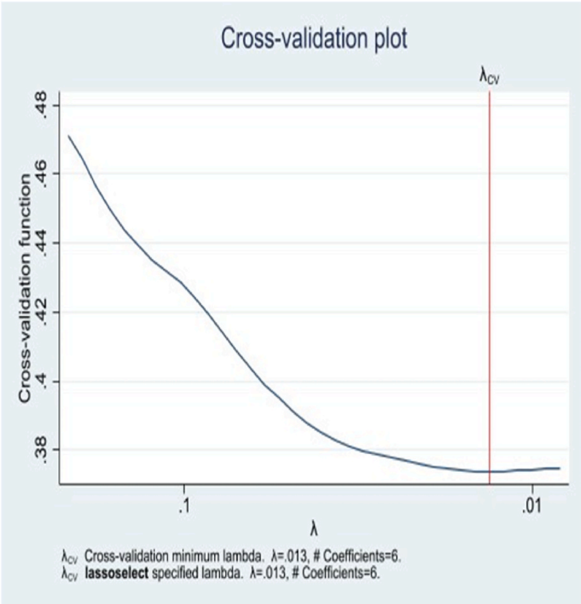

Fig. 2. BIC cv plot.

4. Discussion of results

4.1. *Lasso model selection results*

As shown in Tables 5 and 6 and Figs. 2 and 3 the outcomes of the deployed techniques for model selection selected six predictors. Indeed as it can be seen in the plot of Figs. 2 and 3, the cross-validation plot for Lasso regression illustrates the model's performance over a range of λ values. The optimal value of λ, denoted by λcv, is 0.013, where the model achieves the lowest cross-validation error, suggesting a good balance between bias and variance. At this λ, the model retains 6 non-zero coefficients, indicating that 6 features are deemed significant for predicting the outcome. The plot guides the selection of λ to ensure the model is neither overfitting nor underfitting while maintaining a parsimonious set of predictive features.

4.2. *Cross-sectional dependency, second generation unit root, and Westerlund Cointegration Test results*

As we are dealing with panel data, cross-sectional dependency might occur due to some proxies pre-cited in the methodology part. We conducted a CD test showing CD dependency within all the variables (Table 7).

Having confirmed CD, we can move to the next step, which is the second-generation unit root test. At I(1), the unit root test demonstrates that except lngreen and lniq, the remaining variables are stationary at the first difference, which implies we are dealing with I(0) and I(1) (Table 7).

The cointegration test is the final component of the pre-estimation. The Westerlund panel test result indicates a considerable cointegration presence, which is presented in Table 7 and validates the long-term link between the variables.

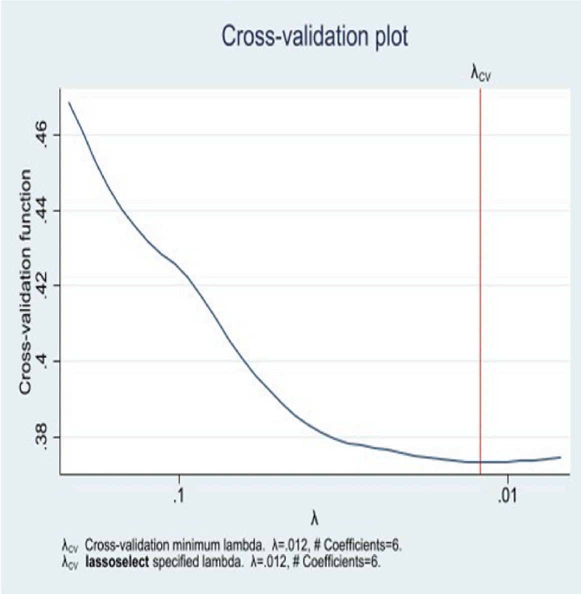

Fig. 3. AIC cv plot.

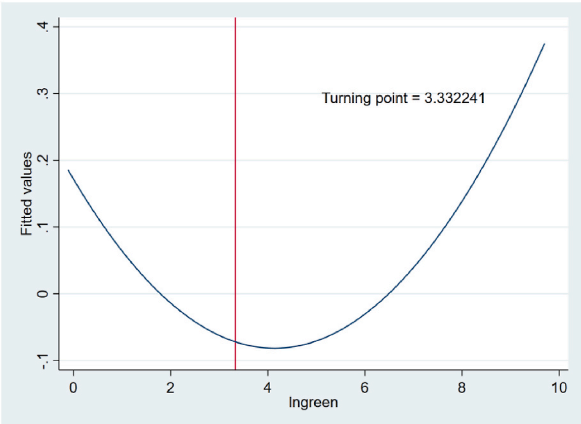

Fig. 4. Turning point.

4.3. Baseline regression result

In this regression, we used the PCSE and the FGLS approach as a robustness test to confirm the outcomes of the PCSE model. PCSE is a static panel data technique suitable for long-run analysis; it controls cross-sectional dependency, auto-correlation, and heteroscedasticity. It is suitable in our case as it is applicable whenever the temporal parameters are smaller than a given number of cross-sections [17].

The outcome of Table 8 shows a positive as well as substantial effect of lngreen on the lnlcf (models 1 and 2), which is confirmed by the robustness test outcome in models (3) and (4). As for the GFDI-Kuznets curve verification in models (5) and (6), we failed to validate the EKC hypothesis as the square term of GFDI displayed a positive output. However, this output indicates the presence of a shape of U-pattern, which supports the PHAH at the early stage and then turns into the PHH after reaching a specific turning point (3.33) (Fig. 4). For the primary concern, the results indicate that a component growth in GFDI contributes 0.21% increases positively to support environmental sustainability. It is in adequation with the study conducted on GFDI by Amedolagine and colleagues [45], who discovered the GFDIs improve multinational corporations' general environmental sustainability perspective. The study conducted by Tripath and colleagues [118] also put out greenfield investment as a viable and economically sustainable approach to tackle environmental challenges and guarantee both environmental and financial viability.

Based on our findings, economic development displays a detrimental and statistically significant impact on EQ, which aligns with the existing literature about economic growth and EQ nexus [119–121]. In addition, because of its positive and substantial impact, the institution's quality is critically important regarding environmental challenges, a point supported by the PH hypothesis.

Our result also indicates a positive impact effect between population growth and EQ. There is disagreement in the literature regarding the connection between EQ and population expansion, even though the majority is for the adverse effect. Indeed, research depicted by Babiso and colleagues [122] in Kenya and Ethiopia highlighted that population growth and agriculture intensification have improved soil and water resources. Begum and colleagues [123] found no significant impact between population growth and per capita emission in Malaysia. Using the ARDL approach, Sulaiman and Abdul-Rahim [124] found that population was not a determinant of CO2 emissions in Nigeria. The growing population can increase human capital, leading to creativity and technical advancements. This can result in more efficient and environmentally friendly technology, potentially addressing environmental issues, as shown by Ugur and colleagues [125]. Indeed, they found that human capital positively affects EQ in the USA.

Furthermore, a positive relationship between trade openness and EQ was found. Indeed, according to the existing literature, under some circumstances, trade openness may contribute favorably to the environment. A potential explanation might be the growing tendency to adopt cleaner technologies, resource efficiency, and diversification of economies. Multinational corporations often introduce cleaner and more sustainable technologies, replacing outdated production methods with more environmentally friendly alternatives. Moreover, specialization in production allows countries to focus on their comparative advantages, leading to efficient resource allocation and reducing resource-intensive activities [100,126–130]. A controversial outcome is that energy usage in LDCs has a favorable effect on EQ. This pattern may be supported by looking at the breakdown of the overall consumption of energy in the examined countries, which shows that nearly 70% of total energy usage is accounted for by energy from renewable sources [105].

4.4. Slope homogeneity test results

The outcomes of the Pesaran slope heterogeneity indicate a substantial amount of slope variation, as indicated in Table 9. As a result, we can divide the data set into seven distinct regions: West Africa, Southern Africa, East Africa, Central Africa, Asia, the Caribbean, and Oceania. We ran a regression model on each regional group; the outcome is displayed in Table 10.

4.4.1. Heterogeneity regression outcome

The interpretation of the regional level regression is restricted to our core variables, the dependent variable lnlcf, and the key independent variable lngreen. As seen in Table 10, all the regions except the Caribbean region have shown a positive relationship. The negative correlation displayed by the Caribbean region could be explained through the following factors: Ren and colleagues [131] investigate that pollution of the environment has a negative effect on green investment, which leads to a greater degree of regional corruption, contributing to an incremental decline in green investment's contribution to reducing environmental pollution. Furthermore, in this study, GFDI in the Caribbean region represented by Haiti is facing challenges due to natural disasters, inadequate infrastructure, political instability, insecurity, and institutions collapsing [132]. Inadequate energy, transportation, and water supply can hinder the success of green projects. Political instability in that region can also hinder long-term planning for sustainable initiatives [133].

Moreover, the effectiveness of green investments often depends on strong institutions and governance structures, which can be impeded by the region's institutional capacity [134,135]. Community engagement and participation are also crucial for successful green investments. In that region, communication, education, and community involvement hurdles may influence adopting sustainable practices, adding complexity to the overall challenges faced by green initiatives [136].

The Central Africa region showed the highest value of GFDI impact, which is 0.46%. Indeed, that region stands as a biodiversity hotspot, emphasizing the importance of investments in conservation and sustainable land use practices [137]. With its vast rainforests like the Congo Basin, Central Africa is pivotal in climate change mitigation efforts due to their significant role in carbon sequestration [138]. And that can explain a comparatively bigger impact of GFDI on that region. Moreover, implementing sustainable forestry practices and preventing deforestation are vital strategies to address environmental challenges effectively. Green investments in clean energy infrastructure have the potential to meet the region's energy needs and play a crucial role in reducing reliance on fossil fuels, thereby promoting environmental sustainability [139].

However, while implementing environmentally friendly projects through GFDI, much attention should be paid to the

Table 7
Pre-estimation analysis results.

Variable	Pesaran Cross-sectional Test	Pesaran Unit Root Test CIPS	
		Level	First Difference
Lnlcf	54.163***	−2.666	−4.801***
Lngreen	2.136**	−4.144***	/
Lngdp	86.905***	−1.271	−3.162***
Lntrade	9.496***	−2.446	−3.894***
Lniq	2.705***	−3.379***	/
Lnpop	3.368 ***	−2.062	2.872***
Lnenergy	42.832***	−2.177	−3.672***
Westerlund cointegration test			
Variance ratio		0.0012***	

***p < 0.01, **p < 0.05, *p < 0.1.

Table 8
PCSE and FGLS regression results.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
Lngreen	0.219***	0.0466***	0.207***	0.0425**	−0.0835	−0.0803
	(0.0147)	(0.0152)	(0.00873)	(0.0170)	(0.0621)	(0.0606)
lngreen2					0.0125**	0.0120**
					(0.00595)	(0.00557)
Lniq		0.752***		0.745***	0.741***	0.739***
		(0.0936)		(0.0944)	(0.0941)	(0.0934)
Lnenergy		0.114***		0.114***	0.113***	0.113***
		(0.0368)		(0.0368)	(0.0367)	(0.0367)
Lnpop		0.376***		0.382***	0.382***	0.385***
		(0.0707)		(0.0716)	(0.0713)	(0.0704)
Lngdp		−0.177***		−0.163***	−0.172***	−0.166***
		(0.0158)		(0.0304)	(0.0305)	(0.0165)
Lntrade		0.408***		0.428***	0.410***	0.419***
		(0.0529)		(0.0649)	(0.0652)	(0.0529)
Constant				−0.387	0.176	
				(0.716)	(0.761)	
Observations	501	501	501	501	501	501
R-squared	0.368	0.244				0.251
Number of c_id	34	34	34	34	34	34

Standard errors in parentheses.
***p < 0.01, **p < 0.05, *p < 0.1.

Table 9
Slope homogeneity test.

Pesaran, Yamagata (2008) Slope heterogeneity test	
Delta	P-Value
5.903	0.000
adj. 7.758	0.000
Blomquist, Westerlund (2013) Slope heterogeneity test	
Delta	P-Value
19.794	0.000
adj. 26.015	0.000

implementation methods. Indeed, green initiatives often require extracting natural resources like minerals and metals for renewable energy technology like solar panels and wind turbines. However, this process can lead to habitat loss, water pollution, and ecosystem disturbance, particularly in extracting rare earth minerals, crucial components in renewable energy systems [140]. FDI initiatives focusing on renewable energy development can significantly alter land use patterns, leading to deforestation and converting natural ecosystems into industrialized zones. This can result in habitat loss and fragmentation, impacting local biodiversity and causing significant changes in land use patterns [141].

Environmentally friendly sectors like biofuel production and hydropower use may significantly demand water resources, exacerbating water shortage issues in areas already experiencing water stress due to excessive water use in these environmentally friendly sectors [142,143].

Green technology production, including electric car batteries and solar panels, often requires significant energy, potentially releasing greenhouse gas emissions and pollutants because the source of energy originates from resources that are not renewable, highlighting the need for sustainable energy sources [144]. FDI is increasing demand for environmentally friendly resources like lithium for batteries. This could lead to resource shortages and supplier conflicts, causing adverse environmental consequences and escalating societal conflicts, especially in countries that supply these resources [145].

5. Conclusions and policy implications

5.1. Conclusions

This study aims to elucidate the influence of GFDI on EQ of LDCs. Data from 2003 to 2021 was gathered, encompassing a balanced panel of 34 LDCs. We adopted the PCSE and FGLS techniques for our analysis. Our findings suggest: (1) A favorable correlation exists between GFDI and EQ. Specifically, a unit increase in GFDI within these countries bolsters EQ by 0.21%. (2) However, economic expansion negatively impacts environmental health. (3) Trade openness appears to enhance EQ. (4) Factors such as institutional quality, energy utilization, and population growth have been found to enhance EQ in the countries under study. (5) The presence of a U-shaped curve in our data set is validated.

Table 10
Regional-level regression results.

VARIABLES	West Africa	East Africa	Southern Africa	Central Africa	Asia	Caribbean	Oceania
Lngreen	0.177***	0.0908***	0.247***	0.464***	0.297***	−0.171***	0.260***
	(0.00930)	(0.00726)	(0.0196)	(0.0949)	(0.0563)	(0.0159)	(0.0407)
Observations	157	81	66	68	113	11	5
R-squared	0.704	0.666	0.694	0.322	0.387	0.913	0.890
Number of c_id	11	5	4	5	7	1	1

Standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

5.2. Policy implications

Based on the findings of this paper, the following policy suggestions are given:

(1) Promoting green foreign investment through incentives; (2) Promote and implement sustainable trade policies; (3) Improving institutional quality and governance; (4) Supporting sustainable energy consumption; (5) Strengthen the incorporation of population growth into the environmental conservation policies. (6) Regularly monitor and assess the environmental effect; (7) Foster environmental education and enhance awareness.

Promoting GFDI strategies may entail tax incentives or other financial inducements, simplified administrative procedures, and targeted advertising campaigns to attract private capital into environment-friendly enterprises. There is a need for long-term sustainable economic development plans that recognize the benefits of clean and renewable power. Policymakers should contemplate incorporating environmental norms and regulations into trade agreements to guarantee that heightened trade does not result in environmental deterioration.

Efficient implementation of environmental legislation and policies requires enhancing institutional quality and governance. One way of achieving this would be through strategies that improve openness and accountability and enhance capabilities in these governmental organizations.

Integrating population growth management with environmental conservation can occur through improving education prospects, medical services, provision of family planning services, and sustainable use of resource management practices.

Enhancing the effectiveness of policies and programs requires regular monitoring and evaluation of their impact on the environment. This allows for any modifications needed. These may include environmental education and awareness programs that develop an enabling societal ethos of ecological accountability by individuals, enterprises, and organizations. Finally, encouraging research and innovation in green technology is also desirable.

These policy recommendations aim to provide an adequate response to the survey findings and lobby for a total approach to improving the EQ in LDCs. However, such guidelines must be adjusted according to the specific environment of every country. In addition, continuous monitoring and updating of policies must lead to lasting achievements.

For future perspectives, as GFDI is multiform, it would be interesting to target a specific field of GFDI in less developed countries, for example, agriculture, and conduct research. Adding to that, a comparative study between International Projects Finance (IPF) and Greenfield Projects in LDCs would permit to show the most efficient projects to focus on in the future.

Data availability statement

The data supporting the findings of this study is available on request from the corresponding author or can be find through the following links:

Green FDI data World Investment Report; Load capacity factor Global Footprint Network; Institutional quality Political Terror Scale; Energy consumption U.S. EIA; Energy Institute Statistical Review of World Energy (2023) (OurWorldInData); The remaining data are available on World Development Indicator.

CRediT authorship contribution statement

Mahamane Famanta: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abid Ali Randhawa:** Writing – review & editing, Validation, Supervision, Resources, Investigation. **Jiang Yajing:** Validation, Supervision, Resources, Investigation, Formal analysis.

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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