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Foreign direct investment, trade openness and environmental pollution in Pakistan: does renewable energy mitigate environmental degradation?

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Environmental sustainability is a critical and urgent challenge of the modern world. Pakistan continues to struggle with balancing economic growth and environmental protection. In recent years, Pakistan has faced severe environmental issues, notably air pollution. This study investigates the impact of foreign direct investment (FDI) and trade openness on environmental pollution and examines how this relationship is moderated by renewable energy. Using Pakistan's annual data from 1990 to 2022, the ARDL model and the Granger Causality technique employ for empirical analysis. The results indicate that FDI and trade openness increase environmental pollution in the short run and long run. Furthermore, the results reveal that renewable energy not only directly reduces environmental pollution but also significantly mitigates the negative environmental impacts of FDI and trade openness in both the short run and long run. Granger causality results further confirm that FDI, trade openness, and renewable energy consumption have a significant influence on environmental pollution, thereby reinforcing their predictive power. Furthermore, the results are validated through Dynamic OLS and Fully Modified OLS techniques. The findings support the Environmental Kuznets Curve (EKC) and Pollution Halo Hypothesis. However, these results underscore the crucial need for policies that strategically link FDI and trade openness with renewable energy policies to reduce environmental pollution while promoting economic development.

KEYWORDS

ARDL, CO2 emissions, environmental pollution, foreign direct investment, renewable energy, trade openness

1 Introduction

Environmental sustainability is crucial for ensuring the long-term wellbeing of human societies and ecosystems. It promotes the responsible management of natural resources, preserves ecosystem balance, and reduces environmental degradation, all to protect the planet for future generations (Wang et al., 2024). Environmental concerns have gained global attention recently, predominantly in low-income countries, where economic activities have come at a significant environmental cost. Pakistan exemplifies this dilemma, experiencing significant environmental degradation alongside its economic expansion. The primary sources of environmental stress include elevated carbon dioxide (CO_2) emissions, deforestation, excessive fossil fuel consumption, and unregulated industrial activity (Ahmad and Hussain, 2024; Khan et al., 2023).

Economic globalization, through FDI inflow and trade openness, is widely regarded as a driver of development. Classical and neoclassical economic theories emphasize these tools as mechanisms for enhancing productivity and technological diffusion (Borensztein et al., 1998; Ali and Akhtar, 2024). However, these frameworks often overlook the environmental consequences associated with economic expansion. Empirical research has revealed that FDI as well as trade openness can be a source of environmental degradation, especially in cases where host countries do not have strict environmental policies (Munir and Ameer, 2020; Nadeem et al., 2020; Deng et al., 2024). This is in line with the Pollution Haven Hypothesis (PHH) that is based on the assumption that pollution-intensive industries tend to locate in countries with weak environmental regulations. Conversely, the Environmental Kuznets Curve (EKC) Hypothesis proposes that there is an inverted-U association between income and environmental degradation, such that pollution rises throughout the initial stages of development and decreases as the economy matures and regulatory policies advance (Saud et al., 2024). Although there is growing evidence of environmental stressors associating with FDI and trade, little has been done in the literature regarding renewable energy as a possible moderating factor to such relationship. The use of renewable energy, such as solar, wind, and hydropower energy, has become an effective measure against pollution caused by the use of fossil-based energy sources (Aziz et al., 2024; Ullah and Lin, 2024). Its integration into industrial production and trade activities may serve as a pivotal mechanism for mitigating environmental harm while sustaining economic growth.

Air pollution is among the most persistent environmental issues in developing economies, posing a significant challenge to environmental sustainability. Factors such as rising carbon dioxide (CO_2) emissions, deforestation, and the overuse of natural resources continue to strain fragile ecosystems (Hussain et al., 2022; Ahmad and Hussain, 2024). Over the past 3 decades, Pakistan has experienced substantial economic growth, primarily driven by increased FDI inflows, trade liberalization, and rising energy consumption. While this growth has led to advancements in infrastructure and industrial output, it has also contributed to severe environmental degradation. The country is experiencing alarming increases in air and water pollution, which significantly impact public health and overall wellbeing (Khan et al., 2023). According to the World Bank, Pakistan's CO_2 emissions have been consistently rising, highlighting the urgent need for strategies to mitigate the environmental consequences of economic activities (http://documents.worldbank.org/curated/en/099950111072234047). As Pakistan continues integrating into the global economy, balancing industrial expansion with ecological sustainability remains a critical challenge that demands immediate attention.

Regarding economic liberalization policies, Pakistan's economic development has been driven by FDI inflows, particularly since the 1980s and 1990s. These reforms opened the country to international investors, and foreign investors have greatly expanded the manufacturing, telecommunications, and energy sectors (Ali and Akhtar, 2024). FDI benefits the economy by increasing capital inflows, technological innovations, managerial expertise, and job creation. However, the environmental impact of FDI is primarily determined by the type of investment and the regulatory framework under which it occurs. FDI can benefit economic growth, but it also raises severe environmental concerns. Emissions from the production and use of fossil fuels, as well as mines and resource exploitation, are the major contributing factors to environmental degradation, and investments in the high emitters, such as fossil fuel energy production, mining, and resource extraction, add to a significant extent (Nadeem et al., 2020). If directed toward highly polluting areas, FDI can also exacerbate ecological harms, leading to sectoral deforestation, air and water pollution, or biodiversity loss (Tsoy and Heshmati, 2024). However, FDI may also support environmental sustainability when directed toward cleaner industries. Investing in renewable energy can help to lower pollution emissions from industrial expansion and keep the spread of pollution more minimal (Li et al., 2022). For this reason, the environmental consequences of FDI depend on which industries are supported and, to some degree, on the policies and regulations that govern which industries attract FDI. For economic growth and environmental preservation to be balanced, it is essential to encourage FDI in sustainable sectors and implement stricter ecological regulations for high-pollution industries.

Trade openness has a dual impact on the economy. On the one hand, it drives economic growth by expanding market access, fostering competition, and facilitating the transfer of technology and innovation (Arif et al., 2022). These factors enhance industrial productivity and overall economic efficiency. However, in developing countries like Pakistan, trade liberalization often prioritizes cost reduction over environmental sustainability, leading to increased pollution (Azhar and Khalil, 2007). Weak regulatory frameworks exacerbate environmental degradation as industries expand without adequate pollution control measures in place. The PHH suggests that lax environmental policies attract pollution-intensive industries, worsening air and water contamination (Fayaz et al., 2024; Deng et al., 2024). Empirical evidence shows that trade-induced ecological damage is more severe in developing countries due to weak institutional oversight (Zafar et al., 2013). Higher industrial and manufacturing activity also often leads to increased pollution emissions and resource depletion (Le et al., 2016). Conversely, trade openness can promote environmental sustainability when paired with strong regulations. Integration into global markets provides access to cleaner technologies, which can reduce pollution over time (Leal and Marques, 2022). Moreover, pressure from high-income trading partners can encourage more environmentally friendly production practices, resulting in long-term environmental benefits (Zafar et al., 2019; Yang et al., 2022).

However, energy consumption, particularly the role of renewable energy, is crucial for Pakistan's economy, given its economic and environmental challenges. Pakistan has historically faced persistent energy crises and relied heavily on fossil fuels, including oil, gas, and coal, to meet its growing energy demands.

This dependence has led to significant environmental consequences, particularly in the form of increased CO_2 emissions and other greenhouse gases contributing to climate change (Aziz et al., 2024). In contrast, solar power, along with wind energy and hydropower, offers a clean and sustainable power option compared to fossil fuels. The growth of renewable energy in energy supply systems leads to lower CO_2 emissions, which helps achieve environmental sustainability goals (Akram et al., 2020; Ullah and Lin, 2024). However, despite recent government initiatives promoting renewable energy, its adoption remains limited due to financial constraints, restricted access to advanced technology, and inconsistent energy policies (Kamran et al., 2020). Integrating renewable energy in FDI can play a transformative role in reducing environmental pollution. When multinational firms incorporate renewable energy into their production processes, it mitigates the adverse ecological effects of FDI by reducing fossil fuel consumption and promoting cleaner industrial operations (Rafindadi et al., 2018; Song et al., 2024). Similarly, renewable energy integrated into trade openness can contribute to environmental sustainability. Trade liberalization increases industrial production and energy consumption, which, if reliant on fossil fuels, leads to higher emissions (Grossman and Krueger, 1995). However, when investments in renewable energy accompany trade openness, pollution levels decline as businesses adopt cleaner production technologies (Hdom and Fuinhas, 2020; Zhang et al., 2021; Yang et al., 2022).

The trends of CO_2 emissions, FDI, trade openness, and renewable energy in Pakistan from 1990 to 2022 are shown in Figure 1. CO_2 emissions have a continual upward trend, indicating that economic activities and energy consumption are increasing over time. FDI trends exhibit fluctuations, with peaks in the first decade of the 2000s and the first half of the 2010s, marking periods of financial liberalization and increased investor confidence, and declines that may be associated with political or global economic instability. The trend in trade openness gradually increases with some variability, indicating a steady approach towards global economic integration. Until the 2010s, renewable energy was minimal; yet, a notable rise suggests a shift towards sustainable energy options in recent years. This figure illustrates Pakistan's economic and environmental evolution, highlighting a late but growing emphasis on renewable energy amid increasing emissions.

The impacts of FDI and trade openness on environmental pollution have been tested in many empirical studies (Azhar and Khalil, 2007; Zafar et al., 2013; Nadeem et al., 2020; Munir and Ameer, 2020; Nasir et al., 2022; Ahmad et al., 2023; Fayaz et al., 2024; Bekun et al., 2024). Also, literature highlights the contribution of renewable energy to the mitigation of environmental degradation (Akram et al., 2020; Khattak et al., 2020; Chen et al., 2023; Aziz et al., 2024; Ullah and Lin, 2024). But, to our knowledge there is no research that examines the moderating influence of renewable energy in reducing the impact of FDI and trade openness on the environment. Majority of the earlier researches have concentrated on the PHH or the Pollution Halo Hypothesis. Nevertheless, these studies fail to adequately involve the role of renewable energy as one of the key factors in determining environmental pollution. Further, the available literature hardly talks about the case of Pakistan which is a developing country with rapid industrialization, rising inflow of FDIs and also with major environmental issues. This paper addresses this gap by investigating composite impacts of FDI, trade openness and renewable energy on environmental pollution in Pakistan. Contrary to the past literature, the study focuses on the role played by renewable energy in reducing the environmental impact of economic activities such as FDI inflows and trade openness, which provide new knowledge on sustainable economic development strategies.

This study is significant for several reasons. First, it contributes to the academic discourse by providing empirical evidence on the combined impact of FDI, trade openness, and renewable energy on environmental pollution, particularly in a developing country context. By integrating these key economic factors, the study offers a nuanced understanding of their interactions and implications for environmental policy. Second, the findings have important policy implications for Pakistan. The results underscore the need for a strategic shift toward renewable energy adoption in the industrial and trade sectors. The study suggests that promoting renewable energy in FDI-backed industrial projects can mitigate environmental damage while maintaining economic growth. Policymakers can utilize these insights to design trade and

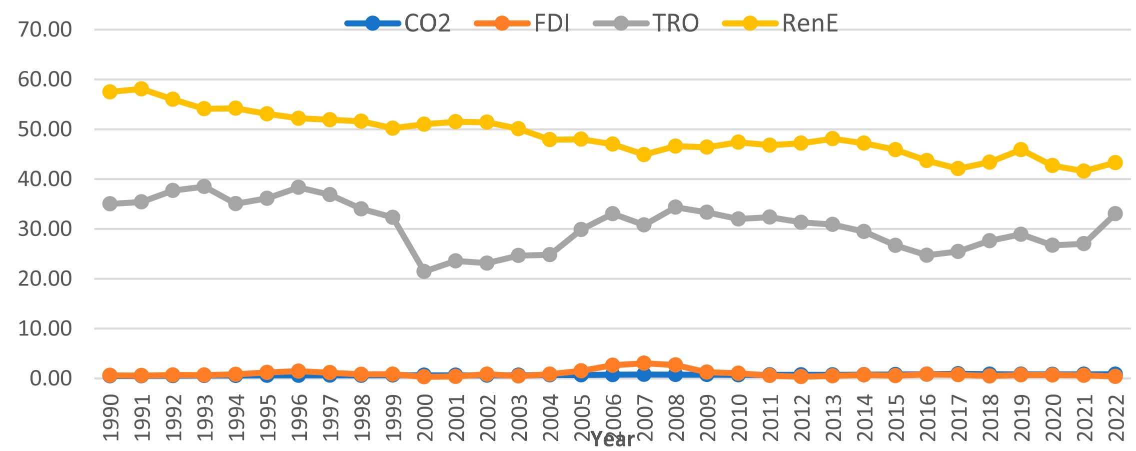

FIGURE 1
Trends of CO_2 emissions, FDI inflows, trade openness, and renewable energy in Pakistan.

investment policies that encourage green technologies and sustainable industrial practices. Thirdly, this study is valuable for international investors and multinational corporations seeking to align their investments with the Sustainable Development Goals. The study underscores the importance of environmentally responsible investment strategies and the role of government regulations in ensuring that FDI and trade liberalization do not come at the cost of environmental degradation. By addressing these critical gaps and providing actionable recommendations, this study offers a roadmap for balancing economic growth with environmental sustainability, making it a valuable resource for researchers, policymakers, and industry stakeholders.

The structure of the paper is as follows: Section 2 summarizes the current literature; Section 3 details the theoretical background; Section 4 discusses data and methodology; Section 5 discusses and presents the findings. Section 6 concludes with policy recommendations, and Section 7 provides the practical recommendations and contributions in the knowledge.

2 Literature review

2.1 FDI and environmental pollution

A large number of studies have been carried out to determine the impacts of FDI inflows on environmental pollution in the developing countries including Pakistan but the findings of these studies have been mixed. The PHH finds some support in the studies that indicate that FDI contributes to the rise in pollution due to the influx of industries with poor environment-related regulations (Munir and Ameer, 2020; Nadeem et al., 2020; Nasir et al., 2022). In particular, Munir and Ameer (2020) revealed that FDI as well as industrialization have led to significant growth of CO_2 emissions in Pakistan. Additionally, Nadeem et al. (2020) used the ARDL methodology on the Pakistani data since 1974 to 2014 and revealed that the inward FDI was a contributor of CO_2 emissions in the long term. Similarly, Nasir et al. (2022) ascertained that higher FDI translated to more pollution emissions in Pakistan, and the effect was stronger during the periods of higher industrial activity.

Conversely, the Pollution Halo Hypothesis argues that FDI may also bring new cleaner technologies and result in an improvement in the environment (Shahbaz et al., 2015; Demena and Afesorgbor, 2020). To illustrate, Demena and Afesorgbor (2020) conducted a meta-analysis of all the studies and found out that, on average, FDI lowers emissions when technological spillovers are taken into account. In a similar way, Shahbaz et al. (2015) indicated that FDI improves the quality of the environment in Asian developing nations due to modernization of technology. In addition, the literature highlights that effectiveness of FDI on the environment depends on economic systems and regulating frameworks of the host country (Haug and Ucal, 2019; Acheampong et al., 2019). Haug and Ucal (2019) used panel data from emerging economies and found that, depending on host country policies, FDI can have a negative environmental impact. Acheampong et al. (2019) found that FDI raises emissions in resource-abundant developing countries while fostering green investment in knowledge-intensive economies. Some studies highlight how environmental regulations can help reduce pollution from FDI (Li et al., 2020; Tsoy and Heshmati, 2024), suggesting that zero to favorable environmental policies can steer FDI toward sustainable sectors. These studies suggest that FDI can harm the environment; however, this effect is not uniform, and the level of state intervention is a key determinant of its ecological consequences.

Hypothesis 1: FDI inflow significantly increases the environmental pollution in Pakistan.

2.2 Trade openness and environmental pollution

Economic and environmental literature has extensively examined trade openness and its impact on environmental pollution in developing countries, particularly Pakistan. Azhar and Khalil (2007) analyzed the environmental impacts of trade activities in Pakistan, highlighting the depletion of natural resources and increased pollution resulting from industrial expansion. Le et al. (2016) provided international evidence supporting the EKC, which suggests that while trade openness initially exacerbates pollution, it ultimately leads to improvements as income levels rise and environmental policies strengthen. Fayaz et al. (2024) examined the moderating role of energy consumption in the trade-environment nexus for Pakistan and China, emphasizing the importance of sustainable energy practices in mitigating environmental damage. Similarly, Feridun et al. (2006) investigated trade liberalization in Nigeria and found that weak ecological regulations contribute to pollution.

Shahbaz et al. (2015) reviewed the environmental impacts of globalization in India and their comparison with that of Pakistan concerning trade policies. The study by Zafar et al. (2013) examined the relationship between trade openness and corruption in Pakistan to reach a conclusion that weak governance increases the extent of environmental degradation and makes it difficult to implement practices of sustainable trade. Khan et al. (2023) examined the effects of trade to Pakistan environment and how cleaner production methods could be used to reduce the negative externalities to its environment. Managi and Kumar (2009) examined technological changes brought about through trade focusing on how such changes can be oriented towards economic growth and sustainability of the environment. Antweiler et al. (2001) have formulated a theoretical model of determining the effects of free trade on the environment, implying that depending upon the levels of income and regulatory policies, and the composition of industries that relate to it, the effect of free trade on the environment is either positive or negative. Frankel and Rose (2005) examined the causality between trade and environmental quality whose findings have provided good policy implications to developing countries. These researches indicate that although trade openness promotes economic growth, its environmental effects differ depending on the effectiveness of the institution systems, technological development and good governance in the developing economies such as Pakistan.

Hypothesis 2: Trade openness significantly increases the environmental pollution in Pakistan.

2.3 Renewable energy and environmental pollution

It is worth noting that renewable energy resources have played an essential role in protecting the environment. According to Chen et al. (2023), greenhouse gas emissions have decreased remarkably through increased environmentally friendly investments in renewable energy resources. Cleaner energy sources lead to a less polluted environment and introduce a low-carbon economy. In this context, Sayed et al. (2021) emphasized that the decarbonization of the energy supply to its maximum extent must be achieved, which is possible through the use of renewable energy resources. They indicated that solar power is the most common renewable energy resource, leading to a pollution-free environment. Countries worldwide are working to improve their renewable energy systems and replace them with conventional ones.

Furthermore, Agbede et al. (2021) stated that energy use can be considered a serious concern for environmental deterioration and the release of carbon, which in turn affects economic growth. Their study confirms that the environment has deteriorated by about 0.41% with every 1% increase in primary energy consumption. Additionally, Achuo et al. (2022) discuss the ecological modernization theory, which emphasizes restructuring societies to promote efficient and environmentally sustainable options for energy and production. The theory explains that society becomes modernized when it adopts modern technologies rather than clinging to traditional ways. Therefore, clean production should be used to achieve high environmental sustainability and reduce pollution.

According to the studies by Khattak et al. (2020) and Sayed et al. (2021), renewable energy resources have a significant impact on the environment, which varies across different regions. For instance, in developing countries, non-renewable energy resources play a significant role in degradation, whereas using renewable energy resources in developed regions is more effective in reducing carbon emissions. Therefore, they are convinced that to implement decarbonization in both countries, especially developing ones, it is essential to build strong institutions supporting renewable energy consumption initiatives. In this context, Ullah and Lin (2024) reported that different countries are focusing on renewable energy sources to combat global warming issues and protect the environment. Their study highlighted that utilizing renewable energy resources promotes environmental conservation, reduces the country's reliance on foreign energy sources, and generates new employment opportunities in Pakistan. It aligns with the broader perspective of Aziz et al. (2024), who reported that economic growth at the expense of the environment is ultimately useless. Thus, adopting energy means improving a country's economic conditions, which is a matter of concern. Thus, the use of renewable energy resources, such as hydroelectric and solar energy, is growing, thereby reducing the pace of environmental deterioration. For instance, Zahan and Chuanmin (2021) found that China's environmental safety was severely compromised by its dependence on coal, and it needs to replace it with environmentally friendly options. Thus, environment-friendly policies are required to encourage a pollution-free environment by focusing on and investing in more renewable energy resources.

Hypothesis 3: Renewable energy significantly decreases the environmental pollution in Pakistan.

2.4 Renewable energy and FDI

Rising energy demand directly affects the economic development of a country negatively and this is mainly because of the rise in the emission of greenhouse gases like carbon dioxide, which is caused by the use of fossil fuels and other aspects. Renewable sources are of paramount significance in enhancing energy efficiency and reducing pollution levels, alongside other factors. It is essential to note that multinational companies tend to prefer renewable sources of energy more than local enterprises, and this preference is a key factor in the energy transition that benefits the country's further development (Li et al., 2022). Similarly, Dilanchiev et al. (2024) stated that a country's economic development, associated with international financial flows, is linked to environmental quality, thereby elevating it to the level of sustainable development. The role of FDI in promoting renewable energy is significant, as it provides the required technology and capital to reduce pollution.

The carbon management processes involve using renewable sources of energy, which help lessen the harmful effects of FDI on greenhouse gas emissions. If countries empower their economies by investing in renewable energy sources, they can attract FDI without adversely affecting the environment. The carbon emissions that negatively correlate with FDI will improve, and the country can achieve its sustainable development goals. The sustainable performance of a country can be improved through more efficient and cleaner production processes, facilitated by the transformative role of renewable energy sources (Osei, 2024). It is imperative to mention that it was found that carbon emission intensity was mitigated with the help of renewable energy, which was facilitated by the FDI due to the improvement in technological innovation (Deng et al., 2024). Nevertheless, Huang et al. (2022) and Deng et al. (2024) also state that the intensity of the emission increases sometimes without the incorporation of renewable energy sources because countries invest more in the industries that are pollution-intensive after FDI. Therefore, it is essential to recognize that policies should also consider utilizing renewable energy sources, in addition to promoting financial development. The external capital, real income, and advancements increased through increasing FDI, which requires more energy. This energy should be utilized sustainably, necessitating the implementation of strategic and sustainable energy policies to capitalize on its positive implications for FDI (Samour et al., 2022).

Hypothesis 4: Renewable energy mitigates the adverse effect of FDI inflow on environmental pollution in Pakistan.

2.5 Renewable energy and trade openness

Trade openness, measured through a country's total trade, imports, or exports, is a factor directly linked to renewable energy sources. Grossman and Krueger (1995) provided a theoretical framework that explained the link between renewable energy and trade openness through the effects of technology, scale, and composition. The example considered in this regard is that of OECD countries, which have a higher use of renewable energy sources and an encouraging status of trade openness (Zhang et al., 2021). Hdom and Fuinhas (2020) and Yang et al. (2022) also analyzed this association. They reported that trade openness is crucial in promoting the transfer and growth of sustainable energy products, services, and technologies worldwide. Trade openness safeguards the state's welfare by enhancing energy efficiency through the achievement of a renewable energy transition, a key insight for scholars, researchers, and policymakers interested in renewable energy and trade economics.

It is suggested that more ecological footprints are generated through trade openness, primarily due to the increased use of energy resources. However, nations worldwide are working to achieve the Sustainable Development Goals and align their international trade with sustainable practices. These steps to reduce ecological degradation include a decrease in dependency on traditional energy resources and an increase in reliance on renewable energy resources (Akram et al., 2020; Ullah and Lin, 2024). The use of renewable energy thus helps mitigate environmental degradation. It can then be used with trade openness, which leads to sustainable economic development, as in the case of developing countries (Abbasi et al., 2022). Therefore, considering these factors, Zafar et al. (2019) recommended that policies discouraging the use of fossil fuel-based energy be implemented urgently to promote the use of renewable energy. The trade openness of emerging economies may also be raised with other nations to promote green technology.

Hypothesis 5: Renewable energy mitigates the adverse effect of trade openness on environmental pollution in Pakistan.

3 Theoretical review

Striking a balance between the economy and the environment is the main concern of Pakistan. The theories used in this study are EKC hypothesis, PHH and Porter Hypothesis to study the complex relationship between FDI, trade openness, renewable energy and environmental pollution in Pakistan so that a sound analytical framework is developed to understand economic-environmental linkages. According to Porter and Linde (1995), the Porter Hypothesis demonstrates how properly planned environmental regulations promote technological advancements that unite economic success with better environmental practices. According to Grossman and Krueger (1995), the EKC suggests that environmental degradation maintains an inverted U-shaped relationship with rising economic development. Consequently, higher industrial activity generates increased pollution during the initial growth stages, but income growth leads to environmental improvements through improved pollution control and the adoption of cleaner technologies. Stern (2004) challenges this claim because it does not work appropriately in developing economies such as Pakistan, which face institutional constraints and technological barriers that prevent pollution reduction. Fossil fuel dependence and weak environmental law enforcement practices in Pakistan may lengthen the pollution growth phase, as demonstrated by Grossman and Krueger (1995).

However, Dinda (2005) confirmed that the EKC remains valid only when economies transition away from resource-intensive sectors, which Pakistan has not yet achieved. Stringent environmental regulations, according to the Porter Hypothesis, enable businesses to increase their innovativeness, which decreases environmental pollution and improves economic performance (Porter and Linde, 1995). According to Ambec et al. (2013), the positive effects of stringent regulations require proper enforcement, which Pakistan lacks due to inconsistent governance procedures. Stern (2004) raised doubts regarding the EKC, which led to Porter's hypothesis, which maintains that proper environmental regulations might prevent pollution duration. However, this theory cannot be implemented effectively in Pakistan because institutions limit its possibilities.

According to Copeland and Taylor (2004), the PHH in which FDI may worsen the environment in developing countries through industrial reallocation toward regions with poor environmental monitoring protocols, likely explains the situation in Pakistan, since its regulatory standards are insufficient. The Pollution Halo Hypothesis, established by Zarsky (1999), demonstrates how FDI transfers advanced, environmentally sustainable technologies into the host country, as it follows Grossman and Krueger (1995) theory about the downward EKC trend. According to the Porter Hypothesis, rigorous environmental rules encourage multinational corporations to adopt environmentally preferable operations that benefit society (Porter and Linde, 1995). The study by Ambec et al. (2013) highlights that a lack of enforcement capabilities hinders regulatory innovation in Pakistan. The environmental effects of FDI in Pakistan hinge on the investment sectors between manufacturing and renewable energy, as they affect environmental performance, according to Copeland and Taylor (2004). This aligns with the institutional criticisms of environmental standards by Stern (2004) and Dinda (2005). Through the scale effect, trade liberalization increases production levels and emissions while exporting textile products and manufactured goods, creating economic benefits that harm Pakistan's environment. The composition effect determines industry realignment from more to less polluting sectors, and the technique effect focuses on adopting advanced pollution-reducing technologies (Grossman and Krueger, 1995). Developing nations face hurdles in adopting advanced technology due to inadequate infrastructure and a lack of essential skills, as noted by Stern (2004) and Rafique and Rehman (2017), who identified these challenges in Pakistan. Ambec et al. (2013) state that developing nations face challenges in adopting environmental policies due to international market pressures, which are particularly strong in Pakistan because of its economic reliance on trade and weak international position. The overall impact of trade openness in Pakistan depends on maintaining economic advantages. Pakistan faces structural impediments that prevent it from transitioning away from inadequate energy infrastructure, inconsistent policies, and financial constraints, thus prolonging the upward trend of the EKC (Rafique and Rehman, 2017). Khan et al. (2020) presented evidence that Pakistan achieves significant emission reductions through the adoption of renewable energy under a stable policy framework. However, Ambec et al. (2013) state that inadequate institutions hinder these results. When integrated into economic planning, Grossman and Krueger (1995) indicate that renewable energy consumption would optimize environmental advantages from trade and investment. However, Pakistan faces ongoing political turmoil and financial challenges, which supports Stern (2004) argument for customized analysis.

4 Data and methodology

4.1 Data

The study presents a comprehensive empirical analysis by using annual time series data for Pakistan from 1990 to 2022. The dependent variable is environmental pollution (EnvP), and the study measure it using carbon dioxide (CO_2) emissions *per capita*. This approach is justified by the fact that CO_2 emissions *per capita* are a reliable and readily accessible indicator of environmental pollution. Many researchers consider CO_2 emissions to be a good measure of environmental pollution, as seen in Wang et al. (2024) and Ahmad and Hussain (2024). CO_2 is mainly produced by industrial activity and the use of fossil fuels, which are important for FDI and trade-driven economic growth. By using *per capita* values, the study can compare emissions with the population of a country, which measures the environmental impact of each person's activities. In addition, the World Bank's database includes CO_2 emissions data that are regularly reported, internationally standardized, and accessible for the entire study period. Therefore, CO_2 *per capita* is often used as a dependable, widely recognized, and policy-related measure of environmental pollution.

The key independent variables include FDI inflow (FDI), trade openness (TRO), and renewable energy (RenE). Additionally, three control variables are included: population growth (POP), capturing annual percentage changes in population; GDP growth (GDP); and industrialization (INZ). A summary of the variables, their expected relationships, and data sources is provided in Table 1, demonstrating the thoroughness of the study.

4.2 Model and methodology

This study uses the Autoregressive Distributed Lag (ARDL) model to investigate the model empirically. The rationale of selecting the ARDL technique in the study is generally founded on its suitability in estimating the dynamic relations as confirmed by Pesaran and Shin (1995), Pesaran et al. (2001), and Nkoro and Uko (2016) among others. In addition, the ARDL is appropriate in the present analysis since it is able to determine both long-term and short-term dynamics simultaneously. In order to apply the ARDL approach, the study identified the best lag length in each of the models with the help of Akaike Information Criterion (AIC). AIC option is more desirable because it is used to select models that make good predictions when the size of the sample is not so large, which applies to the current study data. The choices of these lag structures allow study to achieve the following: no serial correlation in the residuals, and the ability of the model to describe short-term and long-term relations. In order to determine the optimal lag length, the study estimated the unrestricted ARDL models of all the dependent variables and used the one with the least value of AIC. Moreover, due to ARDL bounds testing, researchers have a chance to study the long-run behavior of a system, and at the same time, they can control the short-run behavior (Pesaran et al., 2001).

This method is more effective than traditional methods for several reasons. Unlike the Johansen technique, the variables incorporated into the ARDL framework do not necessarily have to be integrated into the same order; they could be integrated into order one or order zero. This makes it more realistic to apply to actual data where variables might be integrated at different levels. Additionally, the ARDL addresses the issue of serial correlation in residuals, which can lead to bias in other approaches. It also becomes capable of accommodating the autocorrelation in the data by including the lagged values for the variables, thereby providing more reliable estimates (Nkoro and Uko, 2016). In addition, one of the crucial advantages of the ARDL approach is that it considers both the short-run and long-run relationships between the concerned variables, thereby offering a compelling insight into the fluctuations between them (Kripfganz and Schneider, 2023). The ARDL framework provides unbiased and efficient outputs, making it the preferred choice over other models.

In order to confirm the validity of the empirical results the study applied a rigorous and comprehensive test that includes methods like the Granger Causality, Dynamic OLS, and Fully Modified OLS. The use of these various methods of analyzing

TABLE 1 Variables, descriptions and sources.

Variables	Description	Signs	Sources
Environmental Pollution (EnvP)	Log of CO_2 emissions (metric tons *per capita*)		WDI, WB
Foreign Direct Investment (FDI)	Foreign direct investment, net inflows (% of GDP)	+	
Trade (TRO)	Trade (% of GDP)	+	
Renewable Energy (RenE)	Renewable energy consumption (% of total final energy consumption)	−	
Population (POP)	Population growth (annual %)	+	
GDP	GDP growth (annual %)	+	
Industrialization (INZ)	Industry (including construction), value added (% of GDP)	+	

Notes: WDI refers to the World Development Indicator; WB stands for the World Bank. These datasets are publicly accessible through the WDI portal (https://databank.worldbank.org/source/world-development-indicators).

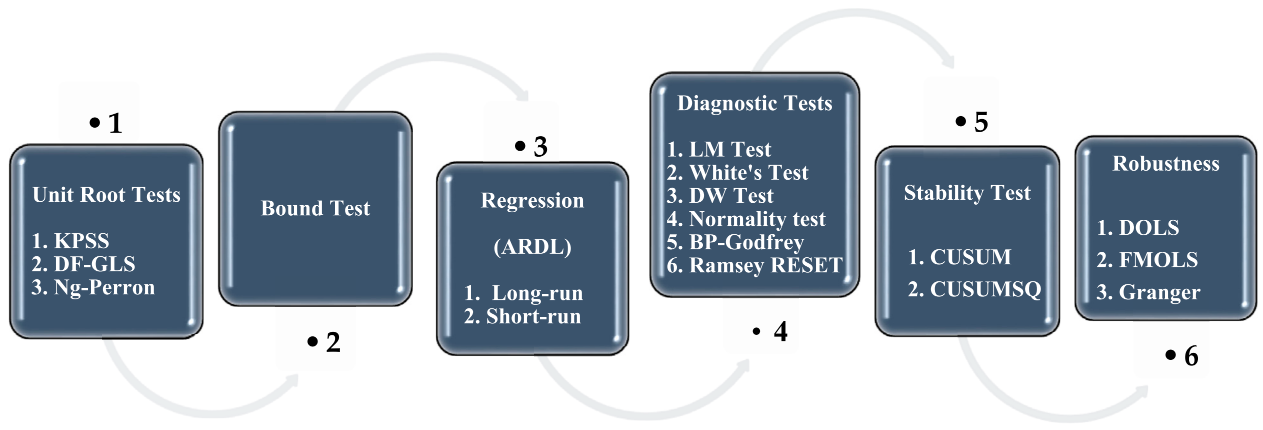

FIGURE 2
Estimation flowchart. Source: Author's construction.

the relationships between the variables has made the results of the study more accurate and consistent relative to other perspectives. Through these alternative methodologies, the study can assess the relationship between the variables and confirm the reliability of the results, thereby providing a more comprehensive perspective on the findings. The estimation flowchart is also present in Figure 2.

The empirical models used in this study are represented by Equations 1–3.

Model 1

$$\mathrm{EnvP} = \alpha o + \alpha_1 (FDI) + \alpha_2 (TRO) + \alpha_3 (RenE) + \alpha_4 (Pop) + \alpha_5 (GDP) + \alpha_6 (INZ) + \varepsilon_0 \tag{1}$$

Model 2

$$\mathrm{EnvP} = \beta o + \beta_1 (FDI) + \beta_2 (TRO) + \beta_3 (\mathrm{RenE}) + \beta_4 (\mathrm{RenE} * FDI) + \beta_5 (Pop) + \beta_6 (GDP) + \beta_7 (INZ) + \varepsilon_0 \tag{2}$$

Model 3

$$\mathrm{EnvP} = \delta o + \delta_1 (FDI) + \delta_2 (TRO) + \delta_3 (\mathrm{RenE}) + \delta_4 (\mathrm{RenE} * TRO) + \delta_5 (Pop) + \delta_6 (GDP) + \delta_7 (INZ) + \varepsilon_0 \tag{3}$$

Equation 1 analyzes the direct impact of FDI, trade openness, and renewable energy on environmental pollution. In Equation 2, the study explores the role of renewable energy in the nexus between FDI and environmental pollution. Similarly, in Equation 3, the study explores the role of renewable energy in the nexus between trade openness and environmental pollution. To examine how FDI and trade openness impact environmental pollution when considering renewable energy, the study takes the partial derivative of Equation 2 and Equation 3 with respect to the FDI and trade openness, respectively.

$$\frac{\partial (EnvP)}{\partial (FDI)} = \beta_1 + \beta_4 RenE \tag{4}$$

$$\frac{\partial (EnvP)}{\partial (TRO)} = \delta_2 + \delta_4 RenE \tag{5}$$

Equations 4, 5 represented the conditional impact.

A significant part of the methodology involves reformulating all three models into the ARDL equation form. This transformation is a key step, enabling the use of both the short-run and the long-run dynamics of the variables under consideration. The ARDL models can be represented in the following manner.

4.2.1 ARDL framework of model 1

$$\begin{aligned}\Delta EnvP_t = {} & \alpha o + \alpha_1 (FDI)_{t-1} + \alpha_2 (TRO)_{t-1} + \alpha_3 (RenE)_{t-1} \\ & + \alpha_4 (Pop)_{t-1} + \alpha_5 (GDP)_{t-1} + \alpha_6 (INZ)_{t-1} \\ & + \sum_{i-1}^{K} \zeta_1 \Delta EnvP_{t-i} + \sum_{i-0}^{K} \zeta_2 \Delta FDI_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_3 \Delta TRO_{t-i} \\ & + \sum_{i-0}^{K} \zeta_4 \Delta RenE_{t-i} + \sum_{i-0}^{K} \zeta_5 \Delta Pop_{t-i} + \sum_{i-0}^{K} \zeta_6 \Delta GDP_{t-i} \\ & + \sum_{i-0}^{K} \zeta_7 \Delta INZ_{t-i} + \mu_t\end{aligned} \tag{6}$$

$$\begin{aligned}EnvP_t = {} & \alpha o + \sum_{i-1}^{K} \zeta_{1i} EnvP_{t-i} + \sum_{i-0}^{K} \zeta_{2i} FDI_{t-i} + \sum_{i-0}^{K} \zeta_{3i} TRO_{t-i} \\ & + \sum\nolimits_{i-0}^{k} \zeta_{4i} RenE_{t-i} + \sum_{i-0}^{K} \zeta_{5i} Pop_{t-i} + \sum_{i-0}^{K} \zeta_{6i} GDP_{t-i} \\ & + \sum_{i-0}^{K} \zeta_{7i} INZ_{t-i} + \mu_t\end{aligned} \tag{7}$$

$$\begin{aligned}\Delta EnvP_t = {} & \alpha o + \sum_{i-1}^{K} \zeta_{1i} \Delta EnvP_{t-i} + \sum_{i-0}^{K} \zeta_{2i} \Delta FDI_{t-i} + \sum_{i-0}^{K} \zeta_{3i} \Delta TRO_{t-i} \\ & + \sum\nolimits_{i-0}^{k} \zeta_{4i} \Delta RenE_{t-i} + \sum_{i-0}^{K} \zeta_{5i} \Delta Pop_{t-i} + \sum_{i-0}^{K} \zeta_{6i} \Delta GDP_{t-i} \\ & + \sum_{i-0}^{K} \zeta_{7i} \Delta INZ_{t-i} + \sum_{i-0}^{K} \lambda (ECM) + \mu_t\end{aligned} \tag{8}$$

TABLE 2 Descriptive statistics.

Variables	EnvP	FDI	TRO	RenE	POP	GDP	INZ
Mean	0.610	0.937	30.744	48.673	5.412	4.134	20.288
Median	0.712	0.696	31.318	47.900	5.442	4.260	20.405
Maximum	0.918	3.035	38.499	58.100	5.722	7.831	22.930
Minimum	0.505	0.309	21.459	40.500	5.008	−1.274	17.158
Std. Dev.	0.101	0.665	4.7871	4.533	0.216	1.997	1.7618
Observations	33	33	33	33	33	33	33

4.2.2 ARDL framework of model 2

$$\begin{aligned}\Delta EnvP_t = \beta_0 &+ (FDI)_{t-i} + \beta_2 (TRO)_{t-i} + \beta_3 (RenE)_{t-i} \\ &+ \beta_4 (RenE \times FDI)_{t-i} + \beta_5 (POP)_{t-i} + \beta_6 (GDP)_{t-i} \\ &+ \beta_7 (INZ)_{t-i} + \sum\nolimits_{i-1}^{k} \zeta_1 \Delta EnvP_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_2 \Delta FDI_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_3 \Delta TRO_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_4 \Delta RenE_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_5 \Delta RenE_{t-i} \times \Delta FDI_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_6 \Delta POP_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_7 \Delta GDP_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_8 \Delta INZ_{t-i} + \mu_t \end{aligned} \quad (9)$$

$$\begin{aligned}EnvP_t = \beta o &+ \sum_{i-1}^{\kappa} \zeta_{1i} EnvP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{2i} FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{3i} TRO_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{4i} RenE_{t-i} + \sum\nolimits_{i-0}^{\kappa} \zeta_{5i} RenE_{t-i} * FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{6i} POP_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{7i} GDP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{8i} INZ_{t-i} + \mu_t \end{aligned} \quad (10)$$

$$\begin{aligned}\Delta EnvP_t = \beta o &+ \sum_{i-1}^{\kappa} \zeta_{1i} \Delta EnvP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{2i} \Delta FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{3i} \Delta TRO_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{4i} \Delta RenE_{t-i} + \sum_{i-0}^{\kappa} \zeta_{5i} \Delta RenE * \Delta FDI_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{6i} \Delta Pop_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_{7i} \Delta GDP_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{5i} \Delta RenE * \Delta FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{6i} \Delta Pop_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{7i} \Delta GDP_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_{8i} \Delta INZ_{t-i} \sum_{i-0}^{\kappa} \lambda (ECM) + \mu_t \end{aligned} \quad (11)$$

4.2.3 ARDL framework of model 3

$$\begin{aligned}\Delta EnvP_t = \delta_0 &+ \delta_1 + \delta_2 (TRO)_{t-i} + \delta_3 (RenE)_{t-i} \\ &+ \delta_4 (RenE \times TRO)_{t-i} + \delta_5 (Pop)_{t-i} + \delta_6 (GDP)_{t-i} \\ &+ \delta_7 (INZ)_{t-i} + \sum\nolimits_{i-1}^{k} \zeta_1 \Delta EnvP_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_2 \Delta FDI_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_3 \Delta TRO_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_4 \Delta RenE_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_5 \Delta RenE \times \Delta TRO_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_6 \Delta Pop_{t-i} \\ &+ \sum\nolimits_{i-0}^{k} \zeta_7 \Delta GDP_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_8 \Delta INZ_{t-i} + \mu_t \end{aligned} \quad (12)$$

$$\begin{aligned}EnvP_t = \delta o &+ \sum_{i-1}^{\kappa} \zeta_{1i} EnvP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{2i} FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{3i} TRO_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{4i} RenE_{t-i} + \sum\nolimits_{i-0}^{k} \zeta_{5i} RenE_{t-i} * TRO_{t-i} + \sum_{i-0}^{\kappa} \zeta_{6i} Pop_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{7i} GDP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{8i} INZ_{t-i} + \mu_t \end{aligned} \quad (13)$$

$$\begin{aligned}\Delta EnvP_t = \delta o &+ \sum_{i-1}^{\kappa} \zeta_{1i} \Delta EnvP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{2i} \Delta FDI_{t-i} + \sum_{i-0}^{\kappa} \zeta_{3i} \Delta TRO_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{4i} \Delta RenE_{t-i} + \sum_{i-0}^{\kappa} \zeta_{5i} \Delta RenE^{*} \Delta TRO_{t-i} \\ &+ \sum_{i-0}^{\kappa} \zeta_{6i} \Delta Pop_{t-i} + \sum_{i-0}^{\kappa} \zeta_{7i} \Delta GDP_{t-i} + \sum_{i-0}^{\kappa} \zeta_{8i} \Delta INZ_{t-i} + \mu_t \end{aligned} \quad (14)$$

Equations 6–14 represents the ARDL framework.

5 Results and discussion

5.1 Descriptive statistics, correlation matrix and variance inflation factor

The descriptive statistics described in Table 2 indicate a normal distribution for most variables, as the mean and median values are in close proximity. For instance, the average of EnvP is 0.610, which is very close to its median of 0.712, and the average of RenE is 48.673, which is also very close to its median of 47.9. However, FDI exhibits a higher mean, 0.937, than its median, 0.696, indicating positive skewness. Additionally, EnvP and INZ show lower standard deviations, suggesting less variation or fluctuation compared to other variables.

The correlation matrix results in Table 3 show that FDI and trade openness exhibit a moderate positive correlation with environmental pollution (0.556, 0.446), signifying that increased multinational firms and trade activities are associated with rising emissions. In contrast, renewable energy has a robust negative correlation (−0.841) with EnvP, highlighting the crucial role of renewable energy in reducing emissions. The results also show that population growth strongly correlates with EnvP (r = 0.812), suggesting that more rapid population growth is associated with higher pollution emissions. GDP and INZ also show positive correlations with EnvP.

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TABLE 3 Correlation matrix.

Variables	EnvP	FDI	TRO	RenE	POP	GDP	INZ
EnvP	1.00						
FDI	0.556	1.00					
TRO	0.446	0.290	1.00				
RenE	−0.841	0.408	0.574	1.00			
POP	0.812	0.122	0.640	0.542	1.00		
GDP	0.419	0.528	0.638	0.314	0.255	1.00	
INZ	0.389	0.226	0.935	0.514	0.532	0.631	1.00

TABLE 4 Variance inflation factor estimates.

Variables	VIF	1/VIF
FDI	2.23	0.45
TRAD	3.05	0.33
RenE	1.16	0.86
POP	2.15	0.47
GDP	3.98	0.25
IND	1.92	0.52

A VIF test is applied to evaluate for multicollinearity in the independent variables. This is crucial, as multicollinearity can distort standard errors and coefficient estimates, compromising the interpretability of results from the regression analysis. In Table 4, it is shown that there are no issues of multicollinearity, as all the VIF values are less than 10, a widely recommended threshold for multicollinearity. This is a significant finding, reassuring us that the model's estimates are valid and not skewed by multicollinearity issues. The VIF ratio values, ranging from 1.16 (RenE) to 3.98 (GDP), indicate no correlation between explanatory variables. Similarly, all the 1/VIF values, lying between 0.25 (GDP) and 0.86 (RenE), are well above the threshold of 0.1. This enhances the validity of the analysis and the policy implications derived from the regression coefficients, which account for the independent contribution of each variable.

5.2 Unit root analysis

To check the stationarity, the study employs multiple tests, including KPSS, DF-GLS, and Ng–Perron, to enhance the tests' robustness since each test addresses different aspects of stationarity and possibly small sample sizes and structural breaks. The rationale for using these tests is that if the data is non-stationary, it causes spurious results and misrepresents the relationship among variables. These tests, therefore, guarantee that the models used in the analysis do not contain the non-stationary behavior of the variables and provide accurate coefficient estimates. The results in Table 5 show that FDI, RenE, POP, and GDP are stationary at their level and, therefore, can be subjected to direct analysis. On the other hand, variables including EnvP, TRO, and INZ are stationary at first difference with significant 'p' values in DF-GLS and Ng–Perron. These mixtures of I (0) and I (1) justified the application of ARDL since this technique enables the modeling of variables with different integration levels, which provides the model's accuracy.

5.3 Regression analysis

5.3.1 Bound test estimates of ARDL

The ARDL bound test is used to identify both short-term and long-term relationships between variables, regardless of their integration order (I(0) or I(1)). This makes it ideal for analyzing time-series data with mixed stationarity. The test uses F-stat to assess the model's overall fit, with the upper bound serving as a critical threshold for rejecting the null hypothesis, which assumes no relationship between the variables. In Table 6, the results show that for Model 1, the F-stat (3.15) exceeds the upper bound (2.94) at the 10% significance level, indicating a long-run relationship. Similarly, F-stat (3.16) in Model 2 surpasses the critical value (2.89). In Model 3, the F-stat (3.30) exceeds the upper bound (2.94) at both 10% and 5% significance levels, supporting long-run cointegration between the variables. Overall, the results provide the basis for applying the ARDL approach to establish the dynamic interconnection and causality between the variables over time.

5.3.2 Long-run estimates of ARDL

The study examined the long-run estimates of the models through the long-run ARDL coefficients presented in Table 7. The dependent variable in each model is environmental pollution (EnvP), and the independent variables are FDI inflow (FDI), trade openness (TRO), renewable energy (RenE), population growth (POP), GDP growth, and industrialization (INZ). Model 2 and Model 3 contain the interaction term variables, except for the first model. Model 2 entails the interaction of renewable energy with the FDI (RenE*FDI), while Model 3 includes the interaction of renewable energy with trade openness (RenE*TRO).

FDI demonstrates a consistently positive and significant relationship with environmental pollution (EnvP) across all three models (Model 1: $\alpha_1 = 0.3777$, $p < 0.01$; Model 2, $\beta_1 = 0.501$, $P < 0.01$; Model 3, $\delta_1 = 0.383$, $P < 0.05$). FDI tends to foster industrial development, resource use, and energy consumption, and, in

TABLE 5 Unit root estimates.

Variables	At level 1(0)			At 1st difference 1(1)		
	KPSS	DF-GLS	Ng-Perron	KPSS	DF-GLS	Ng-Perron
EnvP	<0.01	<0.1	>0.1	>0.1	<0.01	<0.05
FDI	>0.1	<0.01	<0.01	>0.1	<0.01	<0.01
TRO	<0.05	>0.1	>0.1	>0.1	<0.01	<0.05
RenE	>0.1	<0.05	<0.05	>0.1	<0.01	<0.01
Pop	>0.05	<0.1	<0.05	>0.1	<0.01	<0.01
GDP	>0.1	<0.05	<0.05	>0.1	<0.01	<0.01
INZ	<0.05	>0.1	>0.1	>0.1	<0.01	<0.01

TABLE 6 Bound test estimates of ARDL models.

Test-stat	Significance level	Model 1		Model 2		Model 3	
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
	10%	1.99	2.94	1.92	2.89	1.99	2.94
	5%	2.27	3.28	2.17	3.21	2.27	3.28
	1%	2.88	3.99	2.73	3.9	2.88	3.99
F stats		3.15		3.16		3.30	
K		6		7		6	

Notes: Lag lengths for each ARDL, model were selected based on the AIC.

TABLE 7 Long-run results of ARDL.

Dep Var: EnvP	1	2	3
FDI	0.377*** (0.102)	0.501*** (0.108)	0.383** (0.146)
TRO	0.265* (0.142)	0.460** (0.149)	0.457** (0.153)
RenE	−0.963*** (0.458)	−0.482** (0.149)	−0.543*** (0.120)
RenE*FDI		−0.355*** (0.158)	
RenE*TRO			−0.327** (0.091)
POP	0.363*** (0.097)	0.332* (0.165)	0.893* (0.220)
GDP	0.676*** (5.692)	0.531** (0.155)	0.776* (0.215)
INZ	0.242*** (0.108)	0.516** (0.159)	0.101* (0.031)
Constant	3.217*** (0.645)	3.870*** (0.698)	4.734* (1.886)

Notes: Standard errors are in the parentheses, ***, **, and *, indicating significance at the 1%, 5%, and 10% levels.

turn, increase carbon emissions. As foreign investment increases, development in areas such as manufacturing, construction, and energy leads to an increase in environmental impacts on Pakistan's growth. These results are in line with the findings of Munir and Ameer (2020), Nadeem et al. (2020), and Nasir et al. (2022), who noted that FDI contributed to environmental degradation in Pakistan. In this regard, the study highlights that FDI has both developmental and adverse effects on the economy, enhancing economic growth and development, while also having environmental impacts that increase industrial output and resource consumption. This relationship is consistent with the Pollution Haven Hypothesis, which posits that FDI inflows may increase emissions because high-pollution industries relocate to countries with more lenient environmental standards (Bekun et al., 2024). Thereby emphasizing the need for sustainable and environmentally friendly FDI policies for the country.

Furthermore, the results reveal that trade openness has a positive and significant relationship with environmental pollution in all three models, model 1 ($\alpha_2 = 0.265$; $p < 0.1$), model 2 ($\beta_2 = 0.460$; $p < 0.05$), and model 3 ($\delta_2 = 0.457$; $p < 0.05$). When trade openness increases, industries develop to help facilitate the need for resources and the carbon emissions requirement in countries such as Pakistan, which focuses much of its energy on fossil energy sources. The results are consistent with the studies of Azhar and Khalil (2007), Zafar et al. (2013), Khan et al. (2023), and Ahmad et al. (2023), which also noted that trade openness contributes to environmental pollution in Pakistan and developing countries. Moreover, the results also support the PHH hypothesis. The findings support the importance of strategies and regulations for trade growth with environmentally friendly prospects and encourage more sustainable industrial approaches.

The results reveal that renewable energy has a negative effect on environmental pollution in all three models, indicating that the use of renewable energy sources helps to minimize CO_2 emissions (For Model 1, $\alpha_3 = -0.963$, $p < 0.01$; for Model 2, $\beta_3 = -0.482$, $p < 0.05$; for Model 3, $\delta_3 = -0.543$, $p < 0.01$). These results suggest that the shift toward renewable energy adoption as a mitigation measure may reduce the adverse environmental impacts of energy consumption. These results support the findings of Akram et al. (2020), Aziz et al. (2024), and Ullah and Lin (2024), who also identified that renewable energy is more environmentally friendly than non-renewable energy. The nature of the negative relationship between renewable energy and pollution may be explained by the fact that renewable energy sources like wind, solar, and hydropower systems are environment friendly and have very low CO_2 emissions during the generation of power compared to fossil fuels, which are the major culprits in air pollution and climate change. As Pakistan shifts towards renewable energy sources, it can help reduce the amount of CO_2 emissions generated from energy consumption.

In Model 2, the study incorporates the interaction term between renewable energy and FDI (RenE*FDI) to investigate how renewable energy influences the relationship between FDI and environmental pollution. The results show that the interaction between renewable energy and FDI has a negative effect on environmental pollution, indicating that using renewable energy sources helps minimize the adverse impact of FDI on environmental pollution (Model 2, $\beta_4 = -0.355$, $p < 0.01$). To better illustrate this relationship, the study substitutes the estimated coefficients into Equation 15:

$$\frac{\partial(EnvP)}{\partial(FDI)} = 0.501\text{-}0.355\,(RenE) \tag{15}$$

Equation 15 illustrates the marginal effect of FDI on environmental pollution (EnvP) as a function of renewable energy usage (RenE). This implies that the environmental impact of FDI is not fixed but varies with the level of renewable energy consumption. Specifically, when renewable energy usage is zero, a one-unit increase in FDI leads to a 0.501-unit increase in environmental pollution. However, as the share of renewable energy increases, the marginal effect of FDI on pollution decreases by 0.355 units for each additional unit of RenE. This negative interaction term suggests that renewable energy mitigates the environmental harm associated with FDI. Renewable energy helps by reducing fossil fuel consumption, introducing advanced clean technology, and supporting industries in their growth with low carbon emissions. When foreign companies invest, they increase industrial output and consume more energy, which can create environmental problems. Moreover, renewable power solutions replace wasteful processes through cleaner and more sustainable approaches. The shift toward renewable energy enables industrial sectors to meet their growth objectives while promoting environmental sustainability. Rafindadi et al. (2018) also demonstrated that incorporating renewable energy into high FDI economies helps reduce air pollution. According to the studies by Song et al. (2024), green technologies accompanied by FDI help reduce air pollution levels. Therefore, policymakers need to incorporate renewable energy solutions within investments made by foreign investors to achieve better results.

In Model 3, the study used the interaction term between renewable energy and trade openness (RenE*TRO) to examine how renewable energy influences the relationship between trade openness and environmental pollution. The results (Model 3: $\delta_4 = -0.327$, $p < 0.05$) show that combining renewable energy use with trade openness decreases environmental pollution levels. To better illustrate this relationship, the study substitutes the estimated coefficients into Equation 16:

$$\frac{\partial(EnvP)}{\partial(TRO)} = 0.457\text{-}0.327\,(\mathrm{Ren}\,E) \tag{16}$$

Equation 16 presents the marginal impact of trade openness (TRO) on environmental pollution (EnvP) as a function of renewable energy usage (RenE). This suggests that the impact of trade openness on environmental pollution decreases as the share of renewable energy increases. Specifically, in the absence of renewable energy (i.e., when RenE = 0), a one-unit increase in trade openness leads to a 0.457 unit increase in environmental pollution. However, each additional unit of renewable energy reduces this marginal effect by 0.327 units. This negative interaction implies that renewable energy use can effectively mitigate the environmental degradation associated with trade openness. Renewable energy helps reduce environmental pollution from increased production activities by guiding businesses toward cleaner, more sustainable operations. However, challenges remain: a reliance on fossil fuels or resource-intensive business practices in activities associated with trade limits the environmental advantages that renewable energy systems can provide. The findings suggest that combining trade openness with renewable energy helps grow economies more sustainably by using better environmental practices.

The study includes population growth, GDP growth, and industrialization as control variables to evaluate their influence on environmental pollution. The results reveal that rising population growth has a positive impact on pollution levels, as growing population numbers drive increased energy use and waste output, resulting in higher pollution rates. The results align with the study by Mohsin et al. (2019), who demonstrated that rising population numbers typically intensify environmental degradation, as both energy consumption and resource use increase. Moreover, population growth creates obstacles to waste management and pollution control, which enhances existing environmental stress. Furthermore, GDP growth has a positive correlation with environmental pollution, indicating that economic expansion generates more significant emissions when industries operate at full capacity, while also requiring higher energy consumption. The growth of an economy leads industries to expand operations using power-intensive production methods

TABLE 8 Short-run results of ARDL.

Dep Var: EnvP	1	2	3
D(EnvP(-1))	0.598*** (0.148)	0.463*** (0.114)	0.181*** (0.045)
D(FDI)	0.148** (0.052)	0.126*** 0.023	0.180*** (0.045)
D(TRO)	0.355*** (0.158)	0.843*** (0.097)	0.903*** (0.131)
D(TRO(-1))	0.291** (0.158)	0.327** (0.091)	0.698*** (0.112)
D(RenE)	−0.843*** (0.147)	−0.221** (0.045)	−0.312* (0.175)
D(RenE (−1))	−0.645*** (0.113)	−0.431** (0.036)	−0.533** (0.213)
D(RenE*FDI)		−1.186*** (0.352)	
D(RenE*FDI(-1))		−1.107** (0.409)	
D(RenE*TRO)			−1.757** (0.753)
D(POP)	0.111** (0.051)	0.397** (0.159)	
D(GDP)	0.840** (0.291)		0.688*** (0.115)
D(INZ)	0.521*** (0.158)	0.333* (0.169)	0.384* (0.197)
ECM(-1)*	−1.722*** (0.454)	−2.211*** (0.259)	−2.965*** (0.470)
R^2	0.751	0.839	0.881
Adj. R^2	0.645	0.767	0.809
DW-Stat	2.108	2.290	2.154
F-stat	14.22	11.58	16.75

Notes: Standard errors are in the parentheses, ***, **, and *, indicating significance at the 1%, 5%, and 10% levels.

that result in elevated pollution levels. These findings support the EKC hypothesis by showing that pollution levels grew during the initial stages of development but decreased later as economies adopted cleaner technology and services (Grossman and Krueger, 1995). Moreover, industrialization significantly increases pollution volumes through secondary processes dependent on fossil fuels and weak regulatory enforcement programs. The results align with the study by Hao et al. (2022), which found that industrial expansion leads to significant pollution increases, primarily through traditional energy-intensive industrial activities.

5.3.3 Short-run estimates of ARDL

The short-run ARDL estimates, presented in Table 8, indicate a significant relationship between FDI, trade openness, and environmental pollution. The positive coefficients for D(FDI) and D(TRO) for all three models indicate that FDI and trade liberalization contribute to pollution generation in the short run. FDI and trade liberalization lead to increased environmental degradation, likely due to the rise in industrial output and energy usage from fossil fuel-intensive industries that accompany the expansion of the input. These findings clarify the role of economic factors in environmental pollution. Renewable energy has a negative impact on environmental pollution across all models. Replacing fossil fuels with renewable technologies leads to reduced pollution and mitigated environmental degradation through cleaner and more responsive energy solutions. Moreover, renewable energy consistently demonstrates its ability to address environmental issues associated with fossil fuel consumption, making it essential in environmental management. Ullah and Lin (2024) reported that renewable energy is crucial for reducing emissions while meeting global climate targets. These findings demonstrate the remarkable potential of renewable energy to establish sustainable environmental practices by reducing the environmental impact of traditional energy sources.

The interaction term between renewable energy and FDI (RenE*FDI) exhibits a negative (−1.186***) impact, which persists in its lagged value (−1.107**) on environmental pollution levels in Model 2. The results suggest that renewable energy mitigates environmental damage associated with FDI inflows. Renewable energy programs should be included in FDI policies to minimize environmental degradation. Furthermore, the interaction term between renewable energy and trade openness (RenE*TRO) in Model 3 has a negative impact on environmental pollution (−1.757), indicating that trade openness and renewable energy adoption lead to reduced environmental effects. Trade openness, characterized by reduced dependency on fossil energy systems and trade-related operations, demonstrates a lower environmental impact.

Furthermore, Error Correction Model (ECM) coefficients, which capture the speed at which environmental pollution returns to its long-run equilibrium after a short-run disturbance, are negative and statistically significant in all models. In Model 1, the ECM coefficient of −1.722 indicates that the long-run adjustment process of the system is occurring at a rate of 172 percent per annum. Model 2 has a higher adjustment rate of 211 percent per annum, with an ECM coefficient of −2.211,

TABLE 9 DOLS and FMOLS estimates.

Dep. Var: EnvP	DOLS			FMOLS		
	1	2	3	1	2	3
FDI	0.222***	0.181***	0.409***	0.254***	0.217**	0.619*
	(0.073)	(0.053)	(0.026)	(0.053)	(0.106)	(0.336)
TRO	0.210**	0.393**	0.824***	0.143*	0.266**	0.175***
	(0.080)	(0.158)	(0.182)	(0.141)	(0.028)	(0.047)
RenE	−0.182***	−0.472**	−0.215***	−0.295**	−0.219**	−0.157***
	(0.052)	(0.227)	(0.069)	(0.043)	(0.056)	(0.066)
RenE *FDI		−0.161***			−0.239***	
		(0.027)			(0.092)	
RenE * TRO			−0.361***			−0.381***
			(0.115)			(0.089)
Pop	0.112**	0.264***	0.208***	0.246***	0.361***	0.217***
	(0.056)	(0.061)	(0.055)	(0.079)	(0.097)	(0.012)
GDP	0.163***	0.443**	0.227*	0.485***	1.175***	0.214*
	(0.028)	(0.210)	(0.120)	(0.091)	(0.022)	(0.118)
INZ	0.157***	0.803**	0.408*	0.311***	0.413***	0.189*
	(0.026)	(0.352)	(0.127)	(0.075)	(0.099)	(0.021)
Constant	2.207***	2.059***	3.734***	2.704***	2.186**	3.142***
	(0.315)	(0.831)	(1.252)	(0.471)	(1.077)	(0.461)

Notes: Standard errors are in the parentheses, ***, **, and *, indicating significance at the 1%, 5%, and 10% levels.

TABLE 10 Diagnostic tests estimate.

Tests	1		2		3	
	T-stat	P-value	T-stat	P-value	T-stat	P-value
Serial Correlation LM	1.412	0.212	0.547	0.685	0.612	0.287
White's test	1.617	0.212	0.821	0.652	1.078	0.438
Durbin–Watson	1.991	-	2.031	-	2.012	-
Normality Test	1.122	0.422	0.612	0.059	0.342	0.515
Breusch-Pagan-Godfrey	1.723	0.152	0.721	0.651	0.062	0.774
Ramsey RESET Test	0.021	0.823	0.061	0.645	0.311	0.534

implying a quicker return to equilibrium values after shocks. The ECM coefficient (−2.965) in Model 3 states that the long-run adjustment process from short-run shocks is very fast at an annual adjustment rate of 296 percent per annum. This rapid adjustment demonstrates possible mechanisms of stable shifts in the environmental system, which can be considered a temporary imbalance, underscoring the necessity of integrating short-term economic goals with long-term environmental objectives. These results confirm the indicators of Pakistan's ecological system, demonstrating a high potential for achieving sustainable growth despite temporary fluctuations resulting from the country's FDI, industrialization, and trade liberalization processes. However, these results also underscore the importance of policies that integrate FDI and trade liberalization with renewable energy policies, aiming to mitigate environmental degradation while fostering economic development.

5.4 Robustness check

The study verifies the results through different techniques, including Dynamic OLS and Fully Modified OLS tests. These

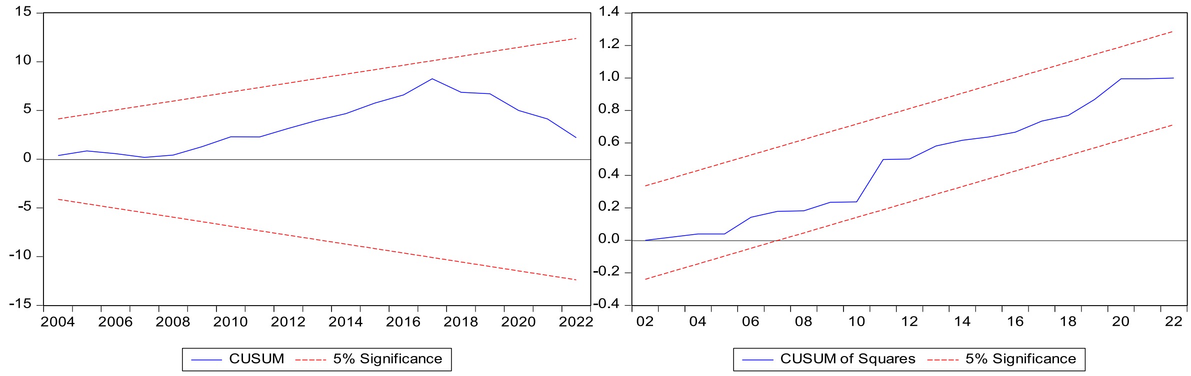

FIGURE 3
CUSUM and CUSUMSQ of model 1.

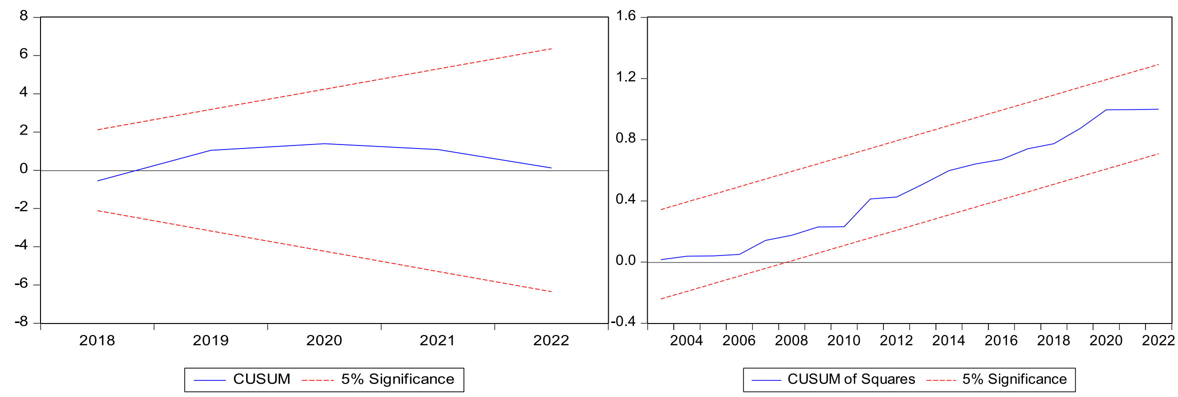

FIGURE 4
CUSUM and CUSUMSQ of model 2.

alternative methods help validate ARDL model results, ensuring the conclusions are independent of the model.

The estimations from DOLS and FMOLS match the estimates of ARDL models. The consistent findings across the various methods demonstrate the reliability and robustness of the results, further reinforcing the objectivity of the conclusions. The results presented in Table 9 show that FDI and trade openness increase environmental pollution across all the models in the DOLS and FMOLS methods, respectively. Conversely, the findings indicate that renewable energy effectively reduces pollution across all DOLS and FMOLS models. The interaction terms (RenE*FDI) and (RenE*TRO) reveal that using renewable energy lowers the environmental damage caused by FDI and trade openness in both DOLS and FMOLS across all models, respectively. These results indicate that Pakistan needs to urgently plan the integration of renewable energy with trade partnerships and foreign investment strategies. By integrating renewable energy into industrial operations supported by FDI and trade, Pakistan can deliver powerful environmental benefits to the country. Moreover, officials must develop benefits for renewable energy customers and structure trade and investment systems to support sustainability targets. When Pakistan combines renewable energy policies with its economic plans, it can achieve better growth and save its environment.

5.5 Diagnostic tests

The study rigorous approach to confirming the reliability of the long-run ARDL results involved conducting several diagnostic tests, including the Serial Correlation LM test, the White test, the Durbin-Watson test, the Normality test, the Breusch-Pagan test, and the Ramsey RESET test. The results of these tests, presented in Table 10, demonstrate that all the models provided reliable results. Importantly, no serious statistical problems were detected, further validating the robustness of the analyses.

The p-values obtained under the Serial Correlation LM test are 0.212, 0.685, and 0.287 with the corresponding models 1, 2, and 3, respectively, and all are greater than the 5 percent significance level, which supports the null hypothesis of no serial correlation. The White test diagnostics (p-values 0.212, 0.652, and 0.438) and Breusch–Pagan test (P-values: 0.152, 0.651, and 0.774) showed no problem of heteroscedasticity since p-values >0.05. The Durbin–Watson statistic values for the models are 1.991, 2.031, and 2.012. These values are close to 2, indicating no serious autocorrelation issue in the residuals. Hence, no evidence of autocorrelation exists, which validates the reliability of the model's estimates. The normality test's p-values of 0.422, 0.059, and 0.515 demonstrate that residuals also follow the normal

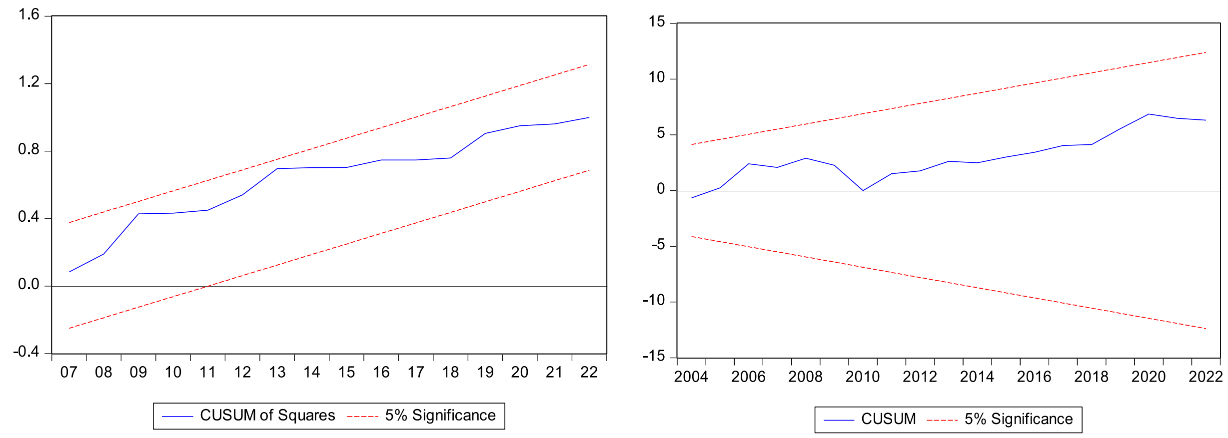

FIGURE 5
CUSUM and CUSUMSQ of model 3.

distribution in most cases since none of the p-values is less than 0.05 in all three models. Additionally, the Ramsey RESET test is performed to determine model specification mistakes. The Ramsey RESET test p-values obtained are above the conventional 0.05 test level. Model 1, Model 2, and Model 3 values are 0.823, 0.645, and 0.534, respectively, implying that all models can be used without concern of misspecification. Thus, the Ramsey RESET test outcomes provide empirical evidence for the proper specification of the models. By maintaining standard significance levels above 0.05 or range areas (such as Durbin-Watson near 2), the models are reasonable and suitable for making conclusions and recommendations.

5.6 Stability estimates

In order to determine the stability of the ARDL models, the study employs two significant diagnostic tests that include CUSUM test and CUSUMSQ test. CUSUM test is used to test the consistency of the coefficients of regression over the analysis time. Conversely, the CUSUMSQ test check to see whether the variability of these coefficients will be consistent across time. A combination of these tests assures the level of reliability and robustness of the model, as reported by Kripfganz and Schneider (2023). The results present that all the three models portray high levels of stability at 5% level of significance. This stability is visually supported by Figures 3–5, which clearly illustrate the models' reliability. Furthermore, these findings confirm stability and reinforce the models' effectiveness, offering a solid foundation for accurate predictions and practical applications. The consistent stability across the models enhances the confidence in their accuracy and strengthens the potential for informed decision-making.

5.7 Granger causality estimates

The Granger causality test is applied to check the presence of any influence between economic (FDI, Trade openness and renewable energy) and environmental variables (CO_2 emissions). It also seeks to establish whether values of one variable in the past can be used to foretell values of another variable in future, which direction the influence is. The study took the first difference of all the non-stationary variables prior to the application of the test. Due to this shift, causal inferences gained in strength and reliability (Lopez and Weber, 2017). The results, as shown in Table 11 indicate that there exist considerable associations between FDI, environmental pollution, trade openness and renewable energy consumption.

TABLE 11 Granger causality results.

Causal direction	Test-stat	P-value
FDI → EnvP	7.212	0.001***
TRO → EnvP	6.175	0.003***
RenE→ EnvP	5.518	0.043**
EnvP → FDI	0.712	0.281
TRO → FDI	3.712	0.073*
RenE → FDI	1.321	0.188
EnvP → TRO	0.987	0.256
FDI → TRO	3.872	0.071*
RenP → TRO	1.012	0.315
EnvP → RenE	2.254	0.165
FDI → RenE	0.156	0.771
TRO → RenE	4.594	0.049**

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

The results reveal that FDI significantly Granger-causes environmental pollution, indicating that past FDI inflows can strongly predict future pollution levels, likely due to related industrial activities. Additionally, both trade openness and renewable energy consumption are found to Granger-cause environmental pollution at the 1% and 5% significance levels, indicating that both factors influence environmental pollution. A bidirectional relationship, significant at the 10% level, exists between trade openness and FDI, suggesting they both support each other.

Additionally, greater trade openness is found to lead to increased renewable energy use, suggesting that it facilitates countries' adoption of cleaner energy by either sharing or following international technology and standards. The results indicate that trade openness plays a key part in determining trends in the environment and investments, and urge governments to create policies that support sustainable economic growth.

6 Conclusion and policy recommendations

This study examined the impact of FDI and trade openness on environmental pollution and explored how renewable energy moderates this impact. The study utilized Pakistan's annual time-series data from 1990 to 2022 and employed ARDL, Granger Causality, DOLS, and FMOLS techniques for empirical analysis. Firstly, the study found that FDI inflows are associated with increased industrial activity and resource consumption, thereby exacerbating environmental challenges. These findings highlight the environmental costs of economic growth driven by FDI, emphasizing the need to implement policies that address these adverse effects. Secondly, the study found that trade openness caused greater environmental pressures. This is attributed to increased industrial activities, resource utilization, and the use of fossil fuels to meet trade needs. With the right policies and interventions, these benefits can be maximized while minimizing the environmental impact. Thirdly, the study found that advancement in the renewable energy reduces CO2 emissions. The implications drawn from the research suggest that the increased adoption of renewable energy is an effective strategy for reversing some of the effects of conventional energy use, such as fossil energy. In this context, the impact of renewable energy sources on environmental sustainability is recognized as it supports the development and use of clean energy, ultimately leading to a world free from carbon-based energy sources and the implementation of sustainable energy development. Fourthly, the study found that renewable energy mitigates the adverse impact of FDI and trade openness on environmental pollution. Renewable energy mitigates the adverse environmental effects of FDI by reducing fossil fuel dependence, enhancing the exchange of green technologies, and enabling cleaner industrial development. Moreover, renewable energy mitigates environmental damage from trade operations by providing clean energy that reduces CO_2 emissions and facilitates environmentally friendly trade practices. Renewable energy is a key catalyst for reducing environmental pollution resulting from the interactions between FDI and trade openness.

6.1 Policy recommendations

Pakistan should introduce new incentives and revise its regulations to effectively link renewable energy promotion with FDI and trade openness. One way is for the government to offer tax holidays, remove duties on renewable energy equipment, and accelerate depreciation for industries integrating clean technologies. Establishing renewable energy usage quotas in Special Economic Zones (SEZs), where FDI is concentrated, can help ensure that industrial growth aligns with environmental sustainability. Additionally, a "Green FDI Certification" program could be established to attract and highlight environmentally responsible investors. The government should introduce environmental limits for export sectors and connect preferential trade or financial benefits to companies that meet these standards. These actions would send a strong signal to international investors about Pakistan's commitment to sustainable development.

Additionally, international and institutional cooperation are necessary for these strategies to be effective over time. A dedicated renewable energy and trade facilitation authority can be established to streamline regulatory approvals and coordinate policy between ministries. The government should encourage public-private partnerships to help build large-scale renewable energy systems by donating land, providing guarantees, or investing in equity. At the same time, private partners supply the capital and expertise. Pakistan should incorporate environmental terms into its bilateral trade agreements and engage in exchanging green technologies. Training in ISO 14001 and informing industries about low-carbon trade can help local businesses become stronger. These policies will help create a clear plan for connecting economic growth with environmental sustainability by incorporating renewable energy into FDI and trade.

7 Recommendations and contribution to knowledge

7.1 Practical recommendations

This study offers several practical recommendations aimed at promoting sustainable economic development in Pakistan. Firstly, there is a pressing need to attract FDI into environmentally sustainable sectors. Policymakers should design incentives to direct FDI toward renewable energy industries, such as solar, wind, and hydropower. By doing so, the country can reduce its dependence on pollution-intensive industries while benefiting from advanced technologies and foreign capital.

Secondly, trade liberalization policies must be aligned with environmental protection goals. Trade openness should be accompanied by regulations that enforce clean production standards and encourage the import and export of green technologies. Without such measures, trade expansion may lead to increased industrial emissions and ecological degradation. Thirdly, the environmental regulatory framework in Pakistan should be updated and more strictly enforced. Weak enforcement currently enables high-emission industries to operate unchecked, undermining environmental quality.

Fourth, the government should actively subsidize renewable energy infrastructure. Public investments, tax incentives, and concessional loans can accelerate the adoption of clean energy, making it more accessible to industries and households. Finally, FDI agreements should incorporate technology transfer clauses to facilitate the adoption of low-carbon technologies by domestic firms.

This will enhance energy efficiency and reduce the environmental footprint of economic activities.

7.2 Contribution to knowledge

This study offers important contributions across empirical, theoretical, and conceptual dimensions. Empirically, it is one of the first investigations in the context of Pakistan that examines the moderating effect of renewable energy in the relationship between FDI, trade openness, and environmental pollution. Unlike prior research that focuses primarily on direct effects, this study introduces interaction terms specifically, renewable energy with FDI and renewable energy with trade openness—to assess how clean energy consumption can mitigate environmental harm. The findings, based on annual data from 1990 to 2022, are statistically validated using robust econometric tools including ARDL bounds testing, Granger causality, Dynamic OLS, and Fully Modified OLS. This comprehensive methodology ensures the reliability of both short-run and long-run estimates, making the results not only novel but also empirically rigorous.

Theoretically, this research extends the PHH and the EKC hypothesis by integrating renewable energy as a moderating force. Traditional environmental economic theories suggest that liberal economic policies often exacerbate environmental degradation in developing countries. However, the inclusion of renewable energy in this framework shows that cleaner energy systems can reduce the negative externalities of globalization. By demonstrating how the turning point in the EKC may arrive earlier with strong renewable energy integration, this study contributes to a more dynamic understanding of economic-environmental interactions in developing economies like Pakistan. It also refines the assumptions of the PHH by showing that the presence of renewable energy can buffer the environmental impact of FDI inflows.

Conceptually, the study introduces a conditional interaction model that captures the non-linear and interconnected nature of globalization, energy systems, and environmental sustainability. It goes beyond simple causality and proposes a more realistic framework wherein the effect of economic liberalization on environmental outcomes depends heavily on the structure and share of renewable energy in the country's energy mix. This framework is particularly useful for countries navigating both industrial development and environmental conservation. The conceptual contribution lies in its emphasis on energy composition as a key determinant in environmental policy and economic planning.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XH: Conceptualization, Validation, Data curation, Supervision, Methodology, Writing – review and editing, Project administration, Software, Writing – original draft, Investigation, Resources, Visualization, Funding acquisition, Formal Analysis. WA: Software, Writing – original draft, Visualization, Investigation, Funding acquisition, Resources, Writing – review and editing, Methodology, Validation, Formal Analysis, Project administration, Supervision, Data curation, Conceptualization. MU: Writing – original draft, Conceptualization, Resources, Formal Analysis, Visualization, Project administration, Supervision, Funding acquisition, Methodology, Validation, Writing – review and editing, Investigation, Software, Data curation. VA: Writing – review and editing, Writing – original draft, Visualization, Software, Resources, Formal Analysis, Methodology, Conceptualization, Validation, Project administration, Supervision, Investigation, Data curation, Funding acquisition. CF: Writing – review and editing, Writing – original draft, Supervision, Investigation, Formal Analysis, Software, Funding acquisition, Project administration, Resources, Methodology, Data curation, Visualization, Validation, Conceptualization. NC: Investigation, Supervision, Formal Analysis, Methodology, Data curation, Writing – review and editing, Software, Writing – original draft, Conceptualization, Resources, Funding acquisition, Validation, Visualization, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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