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The Impact of Public-Private Partnership Investment in Energy and Technological Innovation on Ecological Footprint: The Case of Pakistan

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Abstract: This novel research looked into the role of public-private partnership investment in energy in affecting Pakistan's long-term environmental sustainability. Employing time series data from 1992 to 2018 and utilizing the autoregressive distributive lag model (ARDL) model, we found a long-term equilibrium association of ecological footprint with public-private partnership investment in energy, technological innovation, economic growth, and trade openness. Our outcomes showed a significant positive association between public-private partnership investment in energy and ecological footprint in the long-run and the short-run, specifying that the increase in public-private partnership investment in energy affects the environmental sustainability of Pakistan. Similarly, our study confirmed that technological innovation, economic growth, and trade openness increase the ecological footprint in Pakistan. It demonstrates that these factors are unfavorable to the sustainable environment in Pakistan. Furthermore, robustness check findings are analogous to the results of ARDL estimates, utilizing dynamic ordinary least squares and fully modified ordinary least squares. On the basis of the research conclusions, a multi-pronged sustainable development goal (SDG) model was proposed that addresses SDG 8 and SDG 13 while incorporating SDG 17 as a medium.

Keywords: public-private partnership investment in energy; ecological footprint; technological innovation; economic growth; trade openness; Pakistan

Citation: Chunling, L.; Memon, J.A.; Thanh, T.L.; Ali, M.; Kirikkaleli, D. The Impact of Public-Private Partnership Investment in Energy and Technological Innovation on Ecological Footprint: The Case of Pakistan. *Sustainability* **2021**, *13*, 10085. https://doi.org/10.3390/su131810085

Academic Editor: Donato Morea

Received: 2 August 2021
Accepted: 3 September 2021
Published: 9 September 2021

1. Introduction

Since the 1950s, environmental degradation has been a critical danger and a continuing impediment to sustainable progress due to a variety of environmental concerns such as deforestation, resource depletion, climate change, and water losses and scarcity [1]. The growing increase in greenhouse gases (GHGs) is not only a threat to the sustainability of the natural environment, but it also has an impact on human life. Therefore, the researchers examined and detailed the different environmental quality drivers and indicated how environmental performance might be improved generally. Recently, among other things, public-private partnership investment in energy has been a prominent focus and a key driver of environmental sustainability. In particular, the impact of PPIE on carbon dioxide (CO_2) emissions and consumption-based CO_2 emissions has been seen in the available literature [2–4]. However, no definitive findings have been obtained in prior studies on the environmental quality impact of the stated parameter.

The CO_2 emissions and consumption-based CO_2 emissions have been utilized to measure environmental quality in the available studies. Nevertheless, CO_2 emissions and consumption-based CO_2 emissions as a measure for environmental degradation do not take into account resources such as forests, fishing, oil, mining, and soil [5]. In this context, ecological footprint (EF) is generally recognized as a more comprehensive indication of environmental pollution [6–8]. The EF comprises six domains that define the broad paradigm of environmental performance: fishing grounds, forest land, farmland, grazing land, carbon footprint, and build-up land. Although, to our understanding, no evidence exists on the impact of public-private partnership investment in energy on the ecological footprint in the context of Pakistan. In Pakistan, the biocapacity is barely 0.3 gha per capita, whereas the ecological footprint of Pakistan is 0.9 gha per capita. Sustainability needs a footprint smaller than biocapacity; therefore, Pakistan experienced an ecological deficiency of 0.6 percent in 2017 [9]. This ecological imbalance shows that the ecological need for commodities and services is higher than the ecosystem availability inside Pakistan. Continuous environmental deficits contribute to rapid use rather than the restoration of renewable resources, which, in turn, contributes to biodiversity loss, the loss of ecological resources, and even ecosystem breakdown. As per the Paris Agreement, Pakistan plans to reduce 20% of its GHG emissions by 2030, charging the nation USD 40 billion. In general, developing nations are the most exposed to the adverse effects of climate change as they have the poorest technical support to minimize the hazard. In confronting the climate transition, Pakistan must build long-term policies to combat the macroeconomic parameters that affect the ecosystem, which is also a stimulating aspect of this work.

Therefore, the aims of modifying energy generation and scarce money are becoming increasingly crucial in renewable energy initiatives. Public-private partnerships bring together abundant opportunities, funds, and resources to build collaboration for energy initiatives and a sustainable future. However, there is no agreement on the idea of public-private partnerships. A public-private partnership is a sort of project cooperation between governments, non-profit organizations, and for-profit enterprises to produce a more useful result than would be possible operating alone. More specifically, it means establishing a long-term partnership between the public and private sectors in order to supply products and services to a specific public at a reasonable cost [10]. The private sector spends alongside the public sector, allowing for the centralization of initiatives, reducing risks and costs, and promoting the exchange of ideas and insights. In a broader sense, it includes a wide range of short- and long-term contractual arrangements, such as organizing, divestment, financing, development, and maintenance. According to Cui et al. [11], the broad spectrum of such management methods in public-private partnerships includes a variety of specific forms, such as private finance initiatives (PFI), build-operate-transfer (BOT), and reconstruct-operate-transfer (ROT).

In Pakistan, public-private partnerships have various initiatives, including energy, urban management, transportation infrastructure, and environmental conservation. Pakistan is one of the major public-private partnership marketplaces in South Asia, with over USD 200 billion invested in the energy sector between 1992 and 2018 [12]. With rising evidence of global warming and an energy shift away from fossil fuels and toward clean energy, sustainable growth is critical [13,14]. Furthermore, the chosen variable PPIE as a factor of ecological footprint has not been investigated for Pakistan. As a result, this study is an attempt to fill a vacuum in the existing literature. In light of this prospect, the goal of this study was to investigate the empirical cointegration and the long- and short-run dynamics of PPIE on the ecological footprint in Pakistan. The major contributions of this study to the existing literature are as follows. First, this is the first study to check the impact of public-private partnership investment in energy on ecological footprint, considering the essential role of technological innovations in Pakistan. Second, in addition to established approaches, this study applied Bayer and Hanck [15], which combines non-cointegration tests to confirm the cointegration of parameters. Third, we utilized the autoregressive distributed lag (ARDL) model to examine the long-run and short-run relationships between variables. The present work used fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) methods to test the robustness of the ARDL estimate. Finally, the novel insights of the study extend the current research on public-private partnerships in energy investment, which is critical for country policymakers. The next section covers the literature review. Section 3 contains the data collection and methodological framework in detail. The findings and discussion are documented in Section 4. Section 5 summarizes the study with policy suggestions.

2. Literature Review

This research explored the connection between public-private partnership investment in energy and environmental quality in Pakistan by taking into account the role of technological innovations. This motivated us to split the available literature review into two sections: (a) public-private partnership investment in energy and environmental quality relationship and (b) the association between technological innovations and environmental quality.

2.1. Nexus between Public-Private Partnership Investment in Energy and Environmental Quality

The necessity of public-private partnership investment for energy production transformation is undeniably important, particularly for nations with unfulfilled financial demands, such as Pakistan. On the contrary, it is critical to include research that addresses the effects of public-private partnership investment in energy on environmental performance. There has been little empirical research on the relationship between PPIE and environmental quality. Shahbaz et al. [3] conducted one of the first studies on the impact of public-private partnership investment in energy on carbon emissions in China over the period of 1984 to 2018. Applying the bootstrap (autoregressive distributed lag) ARDL cointegration technique, empirical findings revealed that the association between public-private partnership investment in energy and carbon emissions is positive, resulting in a deterioration of environmental performance. Likewise, Ahmad and Raza [16] investigated the influence of public-private partnership investment in energy on CO_2 emissions in Brazil from 1984 to 2018. Applying the ARDL approach for empirical investigation, they discovered that public-private partnership investment in energy affects environmental performance in the long-run by increasing pollution; nevertheless, public-private partnership investment in energy has a negative impact in the short-run. Khan et al. [2] studied the impact of public-private partnership investment in energy on consumption-based carbon emissions in China from Q1 1990 to Q2 2017. For long-run estimates, they used fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and canonical cointegration regression (CCR). According to the study's findings, public-private partnership investment in energy contributes to greater consumption-based CO_2 emissions. Kirikkaleli and Adebayo [4] investigated the impact of PPIE on consumption-based carbon emissions in India between Q1 1990 and Q4 2015. For empirical analysis, the FMOSL and DOLS methods were used in the study. The study's findings revealed that public-private partnership investment in energy is detrimental to environmental quality. Similarly, Adebayo et al. [17] studied the long-run and causative impacts of public-private partnership investment in energy on environmental sustainability in the East Asian and Pacific countries from 1992 to 2015. According to the findings of the ARDL, FMOLS, and DOLS, public-private partnership investment in energy increases carbon emissions. Furthermore, the frequency causality analysis revealed that, in the long-run, PPIE is the primary cause of carbon emissions.

Moreover, some other studies exist on public-private partnerships and their impact on different measures/regions. For example, Martiniello et al. [18] studied the influence of public-private partnerships on energy performance contracting (EPC). They demonstrate how sustainable long EPC-public–private partnerships can prosper from a hybrid contractual framework in which the profit-sharing ratio fluctuates throughout the deal to assure the same net present value to both public and private parties. This article aids public decision-making by recommending contracts that can shift energy and managerial concerns. Furthermore, it aids in understanding the balance between public and private interests in a long-term EPC-public-private partnership contract. Another study by Morea & Balzarini [19] examined the influence of bankability of a public-private partnership on the latest agricultural advancement in Sub-Saharan Africa. The authors disclosed that public and private partners could successfully join in equally agreeable venture capital. Besides, innovation has emerged as a key pillar of countries around the globe as they seek to build more productive services. It is well established and reported that governments are progressively involving the private sector to establish public value through tools such as acquiring out or public–private partnerships [20]. Furthermore, energy efficiency initiatives and sustainable development have a strong relationship; it is growing particularly important to create public knowledge about the significance and comfort of energy-efficient structures for both private and social advantages. In this situation, it is critical to establish, analyze, and maintain accurate indicators to assist stakeholders in infrastructure activities and governments in decision-making [21,22].

2.2. Nexus between Technological Innovation and Environmental Quality

Technological innovation is anticipated to have a substantial influence on pollution mitigation. Technological innovation, together with environmental regulation, has lowered pollution levels and increased environmental sustainability in host countries. Numerous studies have been conducted to investigate the relationship between technological innovation and environmental quality. For example, Sun et al. [23] evaluated the association between patent technology and CO_2 emissions in China. The researchers discovered that technological improvement reduces carbon emissions dramatically. Furthermore, their comparison investigation revealed that, when linked to other regions, the Eastern region is more successful in implementing innovations and eco-friendly solutions. Similarly, Jin et al. [24] investigated the effect of technological innovations on China's carbon emissions. Their empirical findings indicate that technological innovations in the energy industry improves the efficiency of the energy system, hence lowering CO_2 emissions. As a result, the government must spend on energy research to ensure minimal carbon emissions. Likewise, Li et al. [25] investigated the impact of technological innovations on CO_2 emissions in China. They concluded that technological innovations have a negative effect on pollution.

Additionally, Lantz & Feng [26] examined the effect of population, income, and technological advancement on Canada's CO_2 emissions. According to them, population growth and income levels raise CO_2 emissions, whereas technical advancement lowers CO_2 emissions. Their empirical findings revealed that technology advancements and changes in economic structure would contribute to carbon emission reductions. Likewise, Sohag et al. [27] analyzed the effect of technological innovations on CO_2 emissions in Malaysia. Their empirical analyses indicate that technological advancements increase energy efficiency and decrease CO_2 emissions. Additionally, the researchers' highlight that replacing outdated technologies with innovative technologies must be feasible only through public-private partnerships, as such partnerships can foster innovation in renewable and energy-efficient technologies. Chen & Lei [28] studied the impact of technological innovation on the environment–energy growth relationship in 30 countries from 1980 to 2014. They discovered a significant negative association between technological innovation and carbon emissions, and they implied that high carbon-producing nations could reduce pollution by raising investments in technical innovations. Shahbaz et al. [29] analyzed the impact of energy innovation on environmental quality in France from 1955 to 2016. They found that energy innovation enhances environmental quality. Álvarez-Herránz et al. [30] examined the relationship between air pollution and energy innovation in Organization for Economic Co-operation and Development (OECD) nations from 1990 to 2012. The empirical findings indicated that developing nations should raise their budgets for energy sector development and increase the availability of renewable energy to decrease CO_2 emissions. Danish & Ulucak [31] and Khan and Ulucak (2020) investigated the impact of technological innovation on sustainable development in the economics of Brazil, Russia, India, China, and South Africa (BRICS) from 1992 to 2014. Their empirical studies demonstrated that environmental technology contributes greatly to sustainable development in the BRICS economies. They proposed that the BRICS economies increase energy sector innovation in order to meet sustainability goals and sustainable progress.

It is essential to note that the available literature on the public-private partnership investment in the energy-environment relationship has ignored a significant role of technological innovations and ecological footprint in this linkage. Technological innovation is a critical element for developing economies by decreasing the emissions level and therefore enhances the quality of the environment. Moreover, the association between public-private partnership investment in energy and ecological footprint has not yet been examined in the case of Pakistan. By adding technological innovation into the public-private partnership investment in the energy-environment nexus, we might be able to acquire reliable, accurate findings while also eliminating the dilemma specification concern.

3. Data and Methodology

3.1. Theoretical Framework and Data Descriptions

This study examined the impact of public-private partnership investment in energy (PPIE) and technological innovations (TI) on the ecological footprint (EF) while controlling economic growth (GDP) and trade openness (TOP) in Pakistan. According to Buso and Stenge [32], public-private partnerships are not only beneficial for domestic productivity through investment, but they are also important for the country's ecology. They went on to say that transformation via decentralization of energy generation by public-private partnership investment in the energy sector could have an effect on environmental sustainability by influencing pollution levels. By bringing energy advancements and energy-efficient equipment, technological innovations may have an impact on environmental performance [29]. According to [33,34], economic advancement is the primary reason for high pollution levels because economic growth is dependent on high energy consumption, which gradually impacts the quality of the environment. Similarly, trade can have both beneficial and bad effects on the environment. Negative implications include a high level of carbon-emitting skill, extensive usage of transport, and so on [35]. The premise that trade will raise profits and allow for the development of clean technologies across countries is founded on a positive rationale. Richer nations may then control technologies for alternative energy sources, which will ultimately benefit the environment. Based on these claims, we design the specific ecological footprint model as following:

$$EF_t = f(PPIE_t, TI_t, GDP_t, TOP_t) \quad (1)$$

where EF_t, $PPIE_t$, TI_t, GDP_t, and TOP_t are the ecological footprint, public-private partnership investment in energy, technological innovations, economic growth, and trade openness, respectively. We transformed all parameters to a natural log for empirical examination to use a log-linear formation instead of a linear formation. Shahbaz, Lean, et al. [36] concluded that a log-linear form offers much more constant and accurate outcomes. The log-linear function of the ecological footprint is as follows:

$$\ln EF_t = \alpha_0 + \alpha_1 \ln PPIE_t + \alpha_2 \ln TI_t + \alpha_3 \ln GDP_t + \alpha_4 \ln TOP_t + \varepsilon_t \quad (2)$$

where ln is natural-log, and ε_t shows an error term presumed to have a normal distribution. PPIE increases environmental quality if $\alpha_1 < 0$, otherwise the environment is degraded by a rise in PPIE. We expect $\alpha_2 > 0$ if TI is not environment friendly, if not $\alpha_2 < 0$. We expect $\alpha_3 > 0$ if the link between economic growth and EF is positive, if not $\alpha_3 < 0$. TOP raises environmental degradation and impedes environmental performance if $\alpha_4 > 0$, if not $\alpha_4 < 0$.

This study used time-series data from 1992–2018. The data on the ecological footprint (in terms of global hectares per capita) were taken from Global Footprint Network. Public-private partnership investment in energy (current USD), economic growth (constant 2010 USD), and trade openness (% of GDP) were gathered from World Development Indicators. However, the data on technological innovations measure the number of patent applications submitted each year downloaded from the World Intellectual Property Organization

(WIPO). To solve the drawback of a small sample, we exploited the quadratic match-sum technique to transfigure annual time series data into quarterly data. This procedure modifies temporary deviancies in data whilst also altering it from low to high frequency and decreasing point-to-point data deviations [37]. This method is also reflected as the most widely used technique due to its greater accuracy [38]. The data sources for all parameters are listed in Table 1. The graphical trend of each variable can be seen in Figure 1. It illustrates that Pakistan's ecological footprints are rising due to less attention given towards environmental policies and energy-efficient technologies. However, public-private partnership investment in energy shows a mixed trend during the study period (1992–2018). It depicts that the instability in Pakistan causes low investment via public-private partnership investment in energy as we could observe a drastic decline in public-private partnership investment in energy after 2017. Economic growth showed an upward trend during the study period. Besides, technological innovations and trade openness indicated a mixed direction (downward/upward) with high fluctuations in Pakistan. Similarly, Figure 2 shows the flow chart of the analysis we conducted in this study.

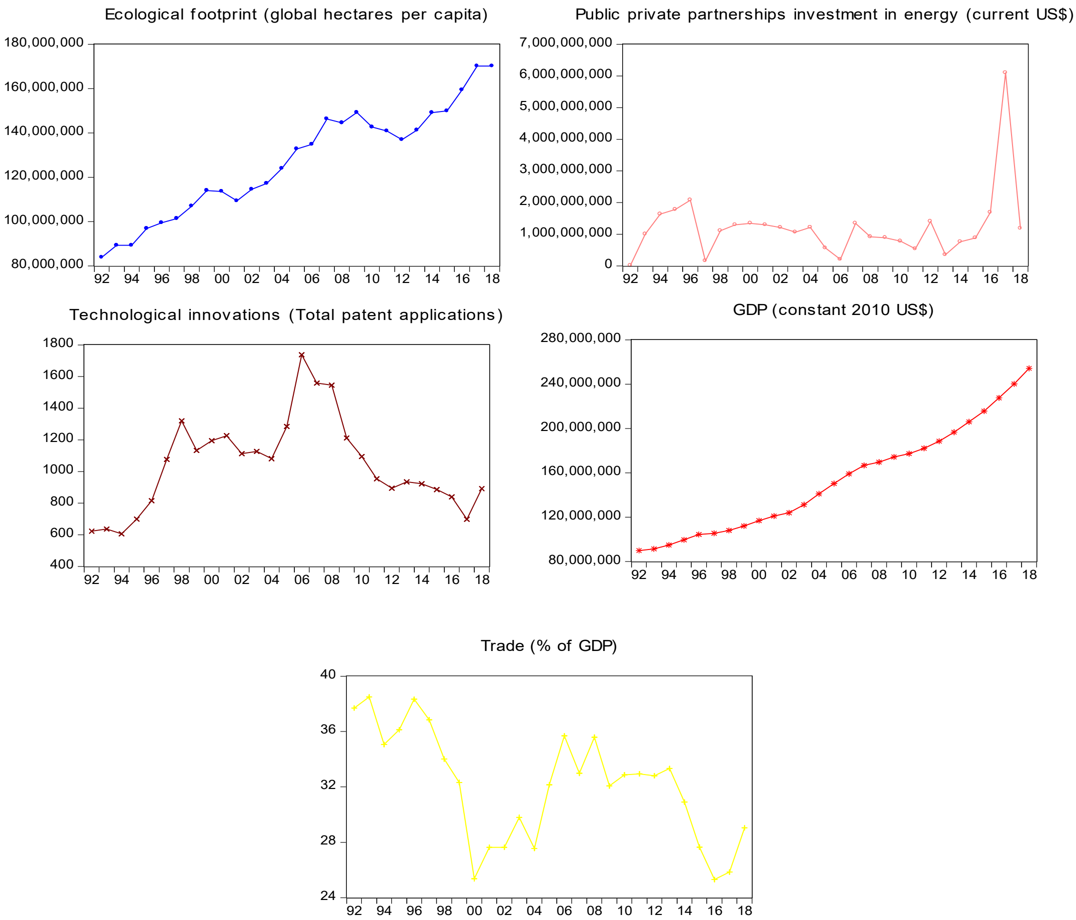

Figure 1. Trend of study variables.

Table 1. Data description.

Variables	Definition	Source
EF	Ecological footprint (is an aggregate of six dimensions, i.e., carbon, build-up land, grazing land, fishing grounds, forest land, and cropland in terms of global hectares per capita)-	Global Footprint Network
PPIE	Public-private partnership investment in energy (current USD)	World Development Indicators
TI	Technological innovation measure as the number of patent applications submitted each year	World Intellectual Property Organization (WIPO)
GDP	GDP (current USD)	World Development Indicators
TOP	Trade openness (% of GDP)	World Development Indicators

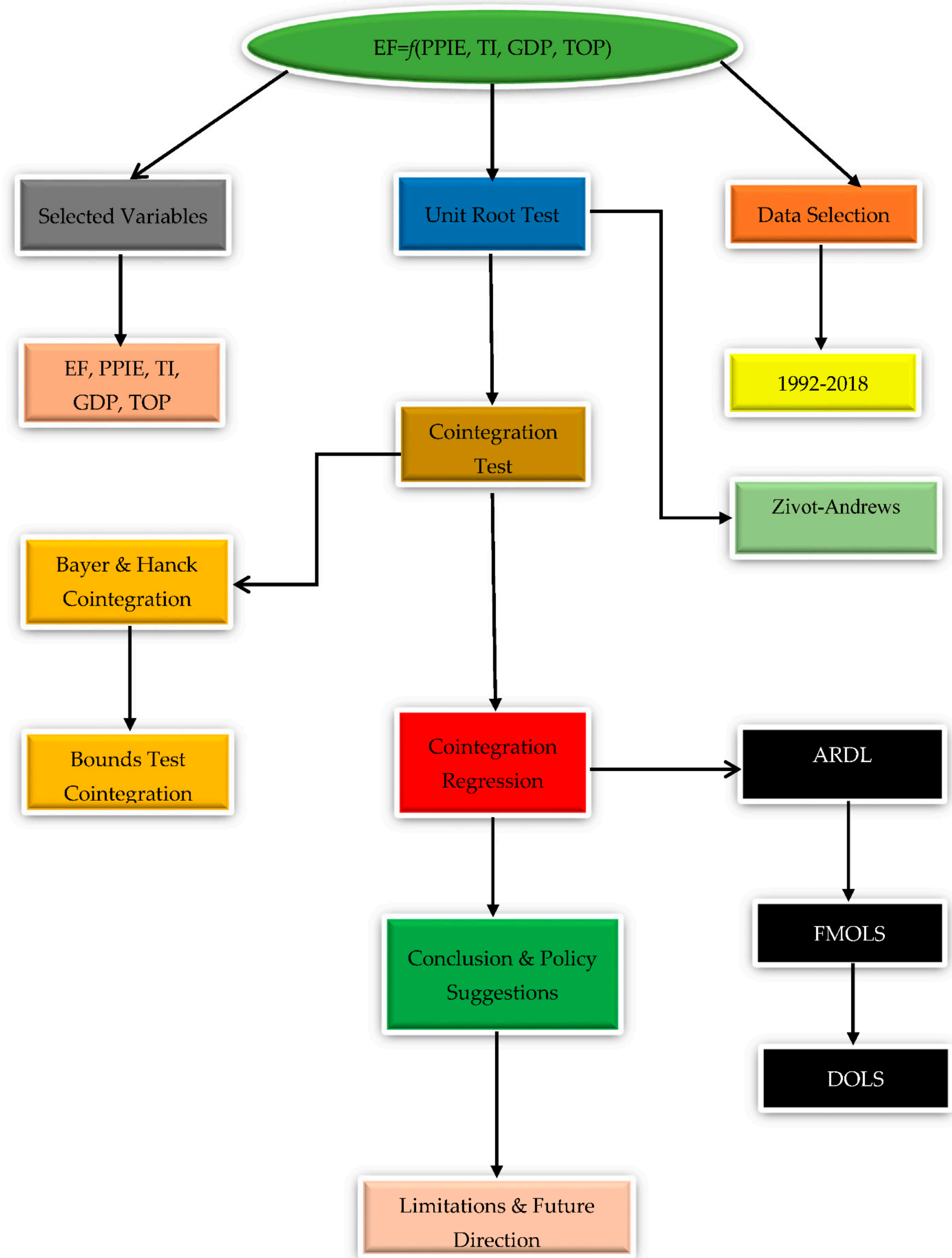

Figure 2. Flow chart of the analysis.

3.2. Methodological Framework

3.2.1. Unit Root Test

According to [7], if there is an indication of a structural break in a series, traditional unit root tests could produce inaccurate findings. Accordingly, the present study used Zivot & Andrews' [39] unit root test to capture the series' stationarity properties with single structural breaks.

3.2.2. Bayer and Hanck's Cointegration Test

To reveal long-run cointegration among the study variables, following [17,40], we used the cointegration technique developed by [15], which is the combination of Engle and Granger [41] (EG), Johansen [42] (JO), Peter Boswijk [43] (BO), and Banerjee et al. [44] (BDM) cointegration approaches. This cointegration approach focuses on eliminating unwanted numerous test methods in order to provide realistic assessments of the challenges generated by other cointegration tests [45]. In the Bayer & Hanck cointegration method, the probability values of all these approaches are united, and the probability values of particular methods are incorporated using Fisher's formula:

$$\text{EG-JO} = -2\,[\ln(\text{PEG}) + \ln(\text{PJO})] \tag{3}$$

$$\text{EG-JO-BO-BDM} = -2\,[\ln(\text{PEG}) + \ln(\text{PJO}) + \ln(\text{PBO}) + \ln(\text{PBDM})] \tag{4}$$

If the result of the examined test statistic exceeds the critical levels set by Bayer & Hanck, the alternative hypothesis of cointegration is used.

3.2.3. Autoregressive Distributed Lag (ARDL) Test

We used the ARDL methodology proposed by Pesaran et al. [46] in our empirical analysis. The following is the rationale for our choice of this approach. First, it can be used when the sample size is small. Second, it can be used even if the variables are in mixed order, like I(0) and I(1). Third, as compared to the usual cointegration test, it yields more accurate results. Fourth, it solves the issue of autocorrelation by choosing suitable lags. Specific lags can be used to increase the number of variables used in the estimating approach to boost accuracy even more. Finally, as Danish et al. [47] advised this technique aids in the derivation of a dynamic error-correction model (ECM) via a simple linear transition mechanism. The unrestricted error correction model (UECM) is followed, and the empirical equation for Equation (2) is as follows:

$$\begin{aligned} \ln EF_t = \varphi_0 + \theta_1 \quad & \ln PPIE_{t-1} + \theta_2 \ln TI_{t-1} + \theta_3 \ln GDP_{t-1} + \theta_4 \ln TOP_{t-1} \\ & + \sum_{i=1}^{\rho} \pi_1 \Delta \ln EF_{t-i} + \sum_{j=0}^{\rho} \pi_2 \Delta \ln PPIE_{t-i} + \sum_{j=0}^{\rho} \pi_3 \Delta \ln TI_{t-i} \\ & + \sum_{j=0}^{\rho} \pi_4 \Delta \ln GDP_{t-i} + \sum_{j=0}^{\rho} \pi_5 \Delta \ln TOP_{t-i} + \mu_t \end{aligned} \tag{5}$$

The Δ is the first difference operator. In the perspective of Equation (5), the null hypothesis of cointegration (H0: $\pi_1 \neq \pi_2 \neq \pi_3 \neq \pi_4 \neq \pi_5 \neq 0$) should be investigated with the alternative hypothesis (H1: $\pi_1 = \pi_2 = \pi_3 = \pi_4 = \pi_5 = 0$). For cointegration assessment, we used the bound testing approach to obtain the F-value. If the F-statistics exceed the upper bound limit, it shows the presence of cointegration. However, if the F-statistics fall within the lower bounds, no cointegration is demonstrated, and thus the null hypothesis of no cointegration is validated. The outcomes are ambiguous if the F-statistic falls between the top and lower bounds. Because cointegration has been confirmed, the ARDL model may now be used to examine both long-run and short-run dynamics. The ARDL model's suitability was further assessed by employing stability measures such as the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals (CUSUMSQ). Finally, several sensitivity tests were run to check that the model composition is appropriate.

3.2.4. Robustness Checks

Moreover, we evaluated our results' robustness through ARDL estimation using fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) regression approaches. Phillips and Hansen [48] stated that FMOLS is a stochastically impartial and valid semi-parametric technique for eliminating correlation concerns [49]. On the other hand, DOLS adds lags and leads to predictor parameters, making the error term in the cointegrating model orthogonal to stochastic regressor trends. FMOLS and DOLS can help with serial correlation and endogeneity issues in the equation by coping with disturbance parameters [50,51].

4. Results and Discussion

Table 2 demonstrates the descriptive statistics of the variables utilized in the current research. The natural logarithm form of the ecological footprint, public-private partnership investment in energy, technological innovations, economic growth, and trade openness was employed in this research. This was executed to validate that the parameters met the normality conditions. The ecological footprint fluctuated from 8.2353 to 7.9078; public-private partnership investment in energy ranged from 9.8345 to 5.5811; technological innovation varied from 3.2508 to 2.7765; economic growth ranged from 11.4146 to 10.9521, and trade openness ranged from 1.5898 to 1.3955. Moreover, the Jarque–Bera p-values disclosed that all the variables correspond to normality.

Table 2. Descriptive statistics.

	EF	PPIE	TI	GDP	TOP
Mean	8.095188	8.914934	3.000853	11.16518	1.502825
Median	8.122268	9.027469	3.022914	11.17669	1.516293
Maximum	8.235380	9.834529	3.250893	11.41469	1.589801
Minimum	7.907848	5.581134	2.776553	10.95212	1.395501
Std. dev.	0.087176	0.552671	0.121952	0.136502	0.055364
Skewness	−0.326825	−3.074922	−0.083042	0.050976	−0.339342
Kurtosis	2.039677	17.27150	2.347148	1.756918	2.035185
Jarque–Bera	3.072651	1.733234	2.042102	2.000410	4.261663
Probability	1.048011	1.203671	0.360216	0.130191	1.243681
Observations	108	108	108	108	108

In the next stage of the empirical investigation, we checked the stationarity of the data utilized in the empirical analysis. Thus, we employed the Zivot & Andrews unit root test with an endogenously defined structural break. Table 3 indicates the findings, which show that ecological footprint, technological innovations, economic growth, and trade openness have a unit root problem at levels except for public-private partnership investment in energy. Nevertheless, after taking the first difference, we discovered that all of the parameters became stationary. This specifies the robustness of the unit root exploration that ecological footprint, technological innovations, economic growth, and trade openness are integrated at I(1). As environmental regulations and the public-private partnership investment in the energy model are implemented, along with technical improvements, economic policies, and trade liberalization, many structural breakdowns may emerge.

The Bayer & Hanck combined cointegration technique was used in this work to investigate the cointegration characteristics of indicators. The findings of the Bayer & Hanck test are shown in Table 4. The findings provide the presence of a significant cointegration link between ecological footprint, public-private partnership investment in energy, technological innovation, economic growth, and trade openness at a 5% significance level. Besides, we also used the ARDL bounds check to validate the Bayer & Hanck test results. Table 5 displays the findings of the ARDL bounds test. The empirical findings reveal that the variables are cointegrated in the long-run.

Table 3. Zivot–Andrews (ZA) unit root test.

			At Level		
Variables	**EF**	**PPIE**	**TI**	**GDP**	**TOP**
Test statistic	−3.7715	−5.4216 ***	−3.2465	−2.3848	−3.1256
Break year	2009Q2	2014Q4	2008Q2	2002Q2	2004Q2
			First Difference		
Test statistic	−5.7709 ***	−5.5369 ***	−5.2607 **	−5.3963 ***	−5.8908 ***
Break year	2007Q2	2006Q2	2008Q2	2007Q2	2000Q4

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

Table 4. Bayer & Hanck cointegration test.

	Fisher Statistics	**Fisher Statistics**	**Decision**
	EG-JO	EG-JO-BO-BDM	
EF = *f*(PPIE, TI, GDP, TOP)	14.7005	29.4081	There is cointegration
	Critical value	Critical value	
5%	10.576	20.143	

Table 5. Results of ARDL bound test approach.

Estimated Model	**Lag Selection**	**F-Value**	**Remarks**
EF = *f*(PPIR, TI, GDP, TOP)	3,3,2,0,0	4.6441 **	Conclusive
Critical value bounds			
Significance	I0 bound	I1 bound	
10%	2.45	3.52	
5%	2.86	4.01	
2.5%	3.25	4.49	
1%	3.74	5.06	

Note: ** indicates significance at 5% levels.

In the next stage, we investigated the long- and short-run linkages between ecological footprint, public-private partnership investment in energy, technological innovation, economic growth, and trade openness after establishing cointegration between the parameters. Hence, we employed the ARDL method to explore the impacts of public-private partnership investment in energy, technological innovations, economic growth, and trade openness on the ecological footprint in the context of Pakistan. The outcomes of the ARDL long- and short-run estimations are documented in Table 6. The outcomes of the ARDL long-run estimation are described as follows. First, the findings demonstrated that public-private partnership investment in energy has a favorable impact on the ecological footprint in Pakistan. If all other variables stay unchanged, an increase in public-private partnership investment in energy will reduce environmental sustainability by 0.0175 percent. This outcome is akin to the results of [17], who discovered a positive relationship between public-private partnership investment in energy and pollution in East Asia and Pacific regions. This outcome is justifiable due to the low investment in renewable/technological innovations projects via the public-private partnership in Pakistan, which causes degradation of the environment. Moreover, as can be seen in Figure 1 (public-private partnership investment in energy (current USD)), Pakistan has recorded around USD 200 billion during 1992–2018, besides a high USD 6.098 billion public-private partnership investment in energy in the year 2017; however, as a result of political instability in mid-2017, Pakistan saw a massive decline in public-private partnership investment in energy. Therefore, the Pakistan government should focus on more public-private partnership investment in energy to enhance the quality of the environment via technological advancement and renewable energy projects. Second, we found some exciting findings regarding technological innovation. We found that technological innovation increases the ecological footprint. A 1 percent upsurge in technological innovation increases ecological footprint by 0.1241 percent. It shows that progress in technological innovation worsens the quality of the Pakistani atmosphere. This outcome is compatible with the outcomes of Dauda et al. [52] for the Middle East and North Africa (MENA) and the BRICS economies and Villanthenkodath & Mahalik [53] for India, which show that new technology harms environmental sustainability. Our findings also refute the findings of Shahbaz et al. [29] for France, Lin & Zhu [54] for China, and Ahmad & Raza [16] for Brazil. They all found that technological innovation has a positive effect on environmental quality. According to our findings, Pakistan's growth pace is increasing, but less emphasis is placed on environmentally friendly technology. This might be one of the causes for technological innovation's negative impact on Pakistan's natural atmosphere. Therefore, the Pakistani government needs to enhance the usage of green technologies to save the environment for the future.

Table 6. Results of ARDL estimation.

Regressor	Coefficient	Standard Error	*p* Value
Long-run estimate			
PPIE	0.0175 **	0.0077	0.0253
TI	0.1241 ***	0.0200	0.0000
GDP	0.5808 ***	0.0182	0.0000
TOP	0.4263 ***	0.0215	0.0000
C	−3.0215 ***	0.1601	0.0000
Short-run estimate			
PPIE	0.0078 **	0.0031	0.0137
TI	0.0866 ***	0.0282	0.0028
GDP	0.1045 ***	0.0227	0.0000
TOP	0.1334 ***	0.0307	0.0001
CointEq(-1)	−0.1799 ***	0.0379	0.0000
R^2	0.9982		
F-Statistics	4340.278		0.0000
DW Stat	2.0628		
Breusch–Godfrey Serial Correlation LM Test	1.2638		0.2875
ARCH Test	0.1474		0.7018
Ramsey RESET Test	1.3423		0.1825

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

Third, there was confirmation of a positive link between economic growth and ecological footprint, which specifies that a surge in economic growth damages environmental quality. This finding is consistent with previous studies [33,55], which also discovered a positive relationship between economic growth and pollution. The primary reason for the positive correlation is that the major sources of energy for industry and agriculture are fossil fuels, resulting in an increased economic boom and decreased environmental sustainability [56,57]. Another potential reason could be the rise in environmental pollution caused by an industrial expansion in Pakistan linked to the growth of infrastructure and economic capitalization, all of which positively impact financing and economic activity and thus increase energy usage. This finding should serve as a wake-up call to environmental administrators and policymakers in Pakistan to reduce their ecological footprint. Fourth, the effect of trade openness on ecological footprint appeared positive and significant in the long-run. According to the results, trade openness has an impact on pollution in Pakistan. Our findings are comparable with previous research by Shabir et al. [58] in developed and developing countries and Fan et al. [59] in South Asia. In the long-run, trade openness exacerbated environmental pollution in Pakistan. It can be stated that Pakistan is attaining more trade at the cost of low environmental quality. This outcome can be defended in a couple of scenarios. Firstly, the scale effect may have added to pollution by increasing the volume of the economy as a result of the growth in exports. Secondly, given two rationales, the technique effect might not have played a role in lowering pollution: (a) the government's security of domestic industry from global competitors will not force local markets to switch to energy-efficient technologies, and (b) imported technologies in the form of machinery are not environmentally friendly. This finding also suggests that future research should look into imported technologies in light of environmental concerns.

The short-run outcomes are also documented in Table 6. These outcomes are similar to the long-run findings. We note that public-private partnership investment in energy has a positive impact on ecological footprint at a 5 percent significance level. Technological innovation is positively connected with the ecological footprint at a 1 percent significance level. The association between economic development and ecological footprint is also positive at a 1 percent significance level. Similarly, the connection between trade openness and ecological footprint is also positive at a 1 percent significance level. Moreover, the value of the lag error term (CointEq(-1)) specifies the rate of adjustment and is significant at the 1 percent level. This means that any short-run divergence from the long-run course is rectified by 17.99 percent each year. The negative sign reflects the long-term bond formed [44]. Likewise, the value of R^2 is 0.99. This suggests that the independent variables described 99 percent of the dependent variable. The error term accounts for the remaining 1 percent.

We also performed several diagnostic tests such as serial correlation, Ramsey, and heteroscedasticity. The results revealed that the model had no miss specification or serial correlation. Additionally, the CUSUM and CUSUMSQ in Figure 3 demonstrate that the model is reliable. Furthermore, the present research used FMOLS and DOLS long-run estimators to corroborate the ARDL long-run estimation results. Table 7 summarizes the empirical results of the DOLS and FMOLS. The outcomes were consistent with the ARDL long-run estimate.

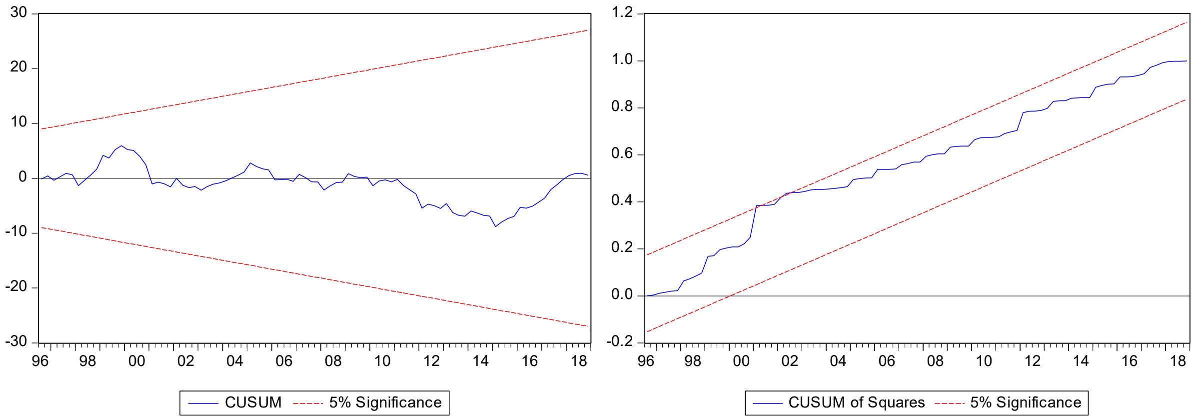

Figure 3. CUSUM and CUSUM of squares.

Table 7. Results of robustness checks (FMOLS & DOLS).

Variables	FMOLS	DOLS
PPIE	0.0152 *** −3.0789 [0.0027]	0.0200 *** −2.6421 [0.0098]
TI	0.1403 *** −8.3556 [0.0000]	0.1512 *** −8.0576 [0.0000]
GDP	0.5893 *** −34.8994 [0.0000]	0.5941 *** −33.2761 [0.0000]
TOP	0.4452 *** −45.1636 [0.0000]	0.4289 *** −20.2113 [0.0000]
Constant	−3.7281 *** (−40.1393) [0.0000]	−3.2150 *** (−23.3513) [0.0000]

Note: *** indicate significance at 1% level. () contains *t*-statistics, [] contains *p*-values.

5. Conclusions and Policy Suggestions

One of the issues confronting humanity today is environmental sustainability. As a result, environmental sustainability has grabbed the interest of international organizations, governments, and researchers worldwide. To the best of the investigator's understanding, the long-run effects of public-private partnership investment in energy and technological innovation on the ecological footprint in Pakistan have not been thoroughly investigated. Hence, the current study sought to fill this research gap by employing Bayer & Hanck cointegration and ARDL estimation methods to investigate the effects of partnership investment in energy, technological innovation, economic growth, and trade openness on Pakistan's ecological footprint. According to the results of the Bayer & Hanck cointegration test, all parameters are cointegrated links.

The results suggest that all the variables (i.e., public-private partnership investment in energy, technological innovation, economic growth, and trade openness) increase the ecological footprint both in the long- and short-run. It implies that all the factors studied in the research contributed to the degradation of the environmental quality in Pakistan. The outcomes of the study are consistent with the conclusions of [17,53,57,59]. Moreover, the robustness check results of fully modified ordinary least squares and dynamic ordinary least squares are also similar to the outcomes of the autoregressive distributed lag model estimation. It has been proposed that, based on the study's findings, policies may be developed to fulfill the United Nations Sustainable Development Goals.

Therefore, as policy advice, firstly, this research reveals that public-private partnership energy investment in Pakistan has a negative impact on the environment. Public-private partnerships in energy must therefore be strengthened and enhanced guidelines implemented. Public-private cooperation in renewable energy sources should be encouraged by the government. In addition, Pakistan can create a low-carbon industry by having domestic carbon emissions trading channels created through the cooperation of municipal and provincial financial and information councils, energy protection and emissions-reducing organizations, and other streamlined departments, using a framework where provinces and major cities would implement their low-emissions initiatives and trading processes. Secondly, we advocate for a stronger reliance on technological innovation in Pakistan to promote renewable consumption, to support Pakistan's low-carbon economy transformation, and to aggressively encourage and establish the research and development of low-emissions platforms, such as those for clean advancement and utilization of coal energy and the development of a circular economy and industrial and household waste recycling. Moreover, the government can assist markets by establishing a clear policy framework that offers long-term benefits in cutting greenhouse gas emissions and that continuously promotes new technologies that strengthen environmental performance. Thirdly, the government of Pakistan must exhibit caution when developing policies that promote growth at the expense of environmental sustainability. Pakistan should impose stricter environmental rules to limit the consequences of environmental deterioration as it grows substantially. Pakistan should concentrate corporate sector efforts to improve energy efficiency and cut down on environmental pollution while also enabling financiers to fund more in businesses with a greater focus on the atmosphere and ecological investment. Finally, taxes on importing energy-intensive equipment and emissions-friendly items must be applied.

Despite the fact that this study provided important research findings, more research in numerous areas is needed. Although the current study used appropriate econometric approaches, the main constraint in this empirical research was the lack of data beyond the study period. Finally, comparable research should be conducted in the future utilizing different countries and alternative environmental sustainability indicators.

Author Contributions: Conceptualization: J.A.M. and M.A.; methodology: M.A. and D.K.; formal analysis and investigation: J.A.M., M.A. and T.L.T.; writing—original draft preparation: J.A.M., M.A. and D.K.; writing—review and editing: L.C., J.A.M., M.A. and T.L.T.; software: M.A. and D.K.; project administration: L.C. and J.A.M.; supervision: L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research has no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available for sharing from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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