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Pakistan's Sustainability Quotient: Exploring the Nexus of Green Technology, Renewable Energy, and Ecological Footprint

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Abstract

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Keywords: Green Technology, Renewable Energy, Ecological Footprint, Economic Growth, Pakistan

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Pakistan's Sustainability Quotient: Exploring the Nexus of Green Technology, Renewable Energy, and Ecological Footprint

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Contents

Abstract

As a developing country, Pakistan is more dependent on conventional, non-friendly energy sources and technology that increases its ecological footprint and causes environmental degradation. The study's primary goal is to analyze the environmental issues by advocating renewable energy usage and green technological innovation in Pakistan. Using data from 1980 to 2021, the results based on the ARDL model confirm an Environment Kuznet Curve hypothesis in the long and short run. Further, the growing green technological innovation positively relates to improved environmental quality in Pakistan. Environmental quality and renewable energy consumption are also positively associated.

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Introduction

In recent decades, energy demand has surged significantly due to extensive socio-economic development and advancements in human welfare globally. Despite the great efforts by many countries to enhance renewable energy production and consumption, fossil fuel remains the leading source of energy production, representing about 80% of the energy production categorized by diverse income brackets (Al-Mulali et al., 2016). World-leading agencies, such as the United Nations' Kyoto Protocol (1997), make serious efforts to enhance environmental health through sustained economic growth. The economic collapse, firm reliance on fossil fuels-based energy supplies, and the advanced transition of economies lead to environmental degradation (Saleem et al., 2019). Environmental sustainability has sacrificed over achieving stable economic growth and severe issues like environmental degradation, mass pollution, and depleted natural resources (Danish et al., 2020). The ecological footprint in South Asia rose from 0.63 global hectares (gha) per person in 1961 to 1.12 gha by 2017 (Dogan et al., 2022). The carbon footprint associated with forest products grew from 0.05 gha per head in 1961 to 0.12 gha per head in 2017. There was a considerable increase in carbon footprint- the proportion grew from 0.1 gha per person in 1961 to 0.59 gha per person in 2017.

The treadmill theory considers environmental degradation as a result of natural resource exploitation and economic expansion (Schnaiberg & Gould, 2000; Schnaiberg, 1980). The ecological modernization and endogenous growth theory, however, favor the notion that technological breakthroughs may assist countries in achieving sustainable economic growth by employing alternative means while protecting environmental quality. The environmental transition theory considers rapid urbanization and its agglomeration effect as the fundamental cause of bringing the environment at risk. Economies use clean technology as they get wealthier, adhere to stricter environmental rules, and implement structural reforms to better their connection with the environment.

Technological innovation must play a crucial role in environmental protection; it helps conserve energy and brings economic efficiency through traditional and renewable energy use. Technological innovation enhances renewable energy capacity, increasing the total supply to fulfill the current and future energy demand. There are limited resources (oil, coal, and other non-renewable inputs), As a result, renewable energy is expected to become the dominant energy source in the future, considering the growing population and energy demand (Chien et al., 2021).

Pakistan is deemed 'on track' in tackling climate change by the (UNDP, 2021). See SDGs report (2023)

It is primarily due to the various policies and initiatives of the government to improve environmental conditions and maintain control over the constantly changing climate. These include the Protected Areas Initiative, Clean and Green Pakistan, the Ten Billion Tree Tsunami, Recharge Pakistan, and many others by NGOs and private sectors. Despite many initiatives, Pakistan remains vulnerable to the negative impacts of climate change. It is the fifth most vulnerable nation on the Global Climate Risk Index (2020). The World Bank (2022) assessment report shows that over 75 million Pakistanis have been impacted by climate-related disasters over the past thirty years, with projected economic losses of over USD 29 billion. The adverse effects of climate change on human health and ecosystems will increase over time due to the expected extreme temperatures. South Asia's bio-capacity and ecological footprint disparity widened from 0.13 gha/capita to 0.71 gha/capita in 1961 and 2017, respectively. The ecological footprint in Pakistan increased from 0.55 gha/capita in 1961 to 0.77 gha/capita in 2017. The carbon footprint grew from 0.09 gha/capita in 1961 to 0.38 gha/capita in 2017. This discrepancy proves that demand for material resources in the region outpaced bio-capacity (Yousaf et al., 2021).

Renewable energy promises to reduce CO_2 emissions; however, its possible influence on the ecological footprint necessitates further investigation. This study aims to fill this gap by exploring the relationship between renewable energy and the ecological footprint in Pakistan.

Literature Review

The following two aspects review the literature.

Environmental Degradation and Green Technological Innovation

Huber (2000) outlines the connection between abundant natural resources, green technology innovations, renewable energy consumption, and ecological footprint considering ecological modernization theory. Huber states that the ecological modernization hypothesis relates to modern industrialized civilizations and how they deal with environmental challenges.

Feng et al. (2009) and Ali et al. (2016) consider urbanization and income as the key factors to environmental degradation and technological innovation as a beneficial tool that helps reduce carbon emissions. Weber and Neuhoff (2010) also verified that technical innovation produces more environmentally friendly, energy-efficient equipment. To examine the growing trend of adopting green technology innovation in the Turkish economy, Ustaoğlu & Yıldız (2012) and

Mohsin et al. (2021) assert that green technology has enormous potential for future growth and environmental protection when mitigating climate change.

Interestingly, Ganda (2019) and Bai et al. (2020) found contradicting results in the case of developing economies that increased energy efficiency leads to more CO_2 emissions. Conventional energy sources, primarily used in developing countries, significantly contribute to environmental damage. FDI and CO_2 emissions are positively correlated, indicating that both the type of investment and regulatory frameworks need to be carefully considered (Hunjra et al., 2024). Therefore, technical advancements cause a rise in carbon emissions. Zhao et al. (2015) identified an inverse relationship between R&D in green technologies and environmental well-being. (Töbelmann & Wendler, 2019) utilized panel data from 27 European Union member states and found that technological innovation does not reduce CO_2 emissions; however, environmental innovation helps lower CO_2 emissions in these countries.

Chien et al. (2021) confirmed the EKC framework in Pakistan and observed a negative relationship between technical advancement and renewable energy. Other studies have also looked at the growing trend in CO_2 emissions across many growing economies and found conflicting results that opened new discussion doors in this field. Many studies have argued that developing green technologies can improve environmental quality [see, for instance, Schiederig et al., 2012; Lee & Min, 2015; Gao et al., 2018]. Similar results were found by Miao et al. (2017) and Godil et al. (2021) for China, stating that technical advancement, economic expansion, and renewable energy impact CO_2. Cheng and Yao (2020) also investigated the Chinese case, demonstrating that, on average, the carbon intensity can be reduced by 0.051% against an increase of 1% in technological innovation. Green technology has enormous potential for future growth and environmental protection, significantly when mitigating climate change (Ustaoğlu & Yıldız, 2012; Nawaz et al., 2021; Dorri & Shahini,2024).

Environmental Degradation and Renewable Energy Consumption

The impact of traditional energy sources on environmental deterioration has been the subject of extensive investigation. Various studies have extensively covered the linkages between energy and the environment. Others focused on how renewable energy sources affect environmental deterioration. The literature suggests that non-renewable energy sources often lead to increased carbon emissions. For example, Saboori and Sulaiman (2013) found that the rising non-renewable energy use contributes to more significant environmental degradation in Malaysia. Similar results are found by Rehman and Rashid (2017) in SAARC countries, Sharif and Raza (2016), and Kousar et al. (2020) in Pakistan.

Liu et al. (2007) proposed that while energy use is crucial for economic and social well-being, the direct impact of traditional energy on the ecosystem is increasingly problematic for the economy. Consequently, there is a pressing need for replacements of conventional energy sources to enhance environmental quality and stimulate economic growth. Renewable energy sources represent a viable alternative to improve environmental quality and promote economic development (Demirbas, 2000). Natural resources such as hydro, solar, and wind can generate energy without compromising the environment. Given the importance of natural energy sources, researchers have examined the linkages between alternative sources and ecological quality. For example, Apergis and Payne (2009) analyzed the connection between renewable energy and environmental quality using data from 1974 to 2004 from the United States. They showed that utilizing renewable energy helps to lower greenhouse gas emissions.

Sarkodie and Adams (2018) observed a significant influence of natural energy sources on emission reductions in South Africa. Their study reveals a 1 percent growth in non-renewable energy leads to an increase of 10,436 kt in CO_2 emissions; on the other hand, a 1 percent growth in renewable energy results in a reduction of 2,855 kt in CO_2 emissions. Similarly, Panwar et al. (2011) emphasize the positive impact of renewable energy on environmental effectiveness. Tsoutsos et al. (2003) and Wang and Wang (2015) support the view and demonstrate the advantages of solar and wind energy, respectively, in enhancing environmental quality. Additionally, Sharif et al. (2020) found that renewable energy significantly diminishes the ecological footprint over the long term, based on data from Turkey from 1965 to 2017. By analyzing panel data from 140 countries, Acheampong and Opoku (2023) conclude that the ecological footprint follows a U-shaped relationship with economic growth. Kalmaz and Kirikkaleli (2019) also confirm a long-term relationship between CO_2 emission, energy consumption, and macroeconomic factors.

In contrast, Bai et al. (2020) discovered that technological advancement increases environmental pollution in low-income economies. Considering these conflicting findings, experts have begun developing green technology innovations. Green technology includes several patents registered, trademarks, and grants allocated for environmental protection (Shan et al., 2021).

The discussion above effectively explores the dynamic relationships between green technology, environmental degradation, and renewable & non-renewable energy sources. While a few studies in Pakistan examine the impacts of renewable energy and green technology on ecological deterioration, this work has successfully addressed existing theoretical and methodological gaps in the literature.

The Empirical Model and Methodology

For the empirical investigation, this study used data from 1980 to 2021. It adopts the environmental frameworks of Shan et al. (2021) and Chien et al. (2021) for empirical analysis. This model explicitly considers factors influencing the ecological footprint, including technological advancements (e.g., patents and trademarks) that facilitate new investments and enhance methods for integrating various production inputs to generate output, along with international technology spillovers (Technical Grants), which may deter a country from making substantial investments in environmental R&D, as it can benefit from the research conducted by others—reducing duplication and allowing for investment in other areas. It leads to an overall gain in innovation. According to technological transfer theory, the international or horizontal perspective of technology transfer allows developing economies to acquire, adapt, implement, and disseminate renewable energy technologies from other countries, thereby fostering further innovation through the capabilities gained. The following model is employed from the above discussion:

$$EFP_t = \beta_0 + \beta_1 GDP_t + \beta_2 GDP_t^2 + \beta_3 NRR_t + \beta_4 PTGI_t + \beta_5 REC_t + \epsilon_t \quad \dots(1)$$

The description of the variables is displayed in Table 1.

Table 1

Description of the Variables

Variables	Description	Data Source
EFP	Ecological footprint per capita: measured as global hectares per person	Global Footprint Network
GDP	GDP per capita	
NRR	Total natural resources rents (% of GDP)	
REC	Renewable energy consumption is measured as a percentage of total energy usage.	
PTGI	1: Total patent applications 2: Total number of trademark applications 3: Technical cooperation grants (million USD)	WDI (2023)

The GDP^2 shows the non-linear per capita GDP, reflecting the Kuznets association between environmental degradation and per capita income. The PTGI denotes the patents, trademark, and grant index, a Principal Component Analysis index for technological innovation constructed on the three variables mentioned. ϵt is supposed to be a white noise error term at subscript time *t*. We transformed the variables into a natural log to normalize all series and interpret the results as elasticities.

Following Usman and Hammar (2021) and Sinha et al. (2019), PTGI assessed three significant indicators to compile the green technological innovation index. It is formulated using the following equation.

$$PTGI_t = \beta_1 Patent_t + \beta_2 Trademark_t + \beta_3 Technical\ Grants_t + \epsilon_t \quad ...(2)$$

The PCA for the PTGI method converts highly correlated indicators into principal components. The main issue with using them for PTGI is their high correlation. As a result, a single indication, such as a patent, trademark, or technical grant, may not accurately reflect Pakistan's experience with green technology advances.

ARDL Bound Test Approach

The theory of environmental degradation may fluctuate due to various macroeconomic and policy factors, which makes it challenging to establish a long-term association. Based on the level of integration (checked by the ADF unit root test), the ARDL cointegration method is implied to verify the long-run relationship. Pesaran et al. (1997) state that the ARDL bound test approach of cointegration helps estimate long-run coefficients and Narayan and Narayan (2004) have contributed more development to this approach. However, before using the ARDL regression estimation, the analysis must be determined using the Pesaran et al. (2001) bound test approach.

Results and Discussion:

Unit root test

Table 2 displays the Augmented Dickey-Fuller (ADF) unit root results; the results advocate a mixed integrated series. The REC is integrated at level; the remaining variables are stationary in the first differences. Therefore, the ARDL bound test approach is appropriate for addressing the mixed-order integrated series.

Table 2

Results of ADF Unit Root Test

Variables	Level		1st difference	
	C	C & T	C	C & T
	t-stats	t-stats	t-stats	t-stats
EFP	-1.394	-1.933	-5.774*	-5.729*
GDP	-0.992	-2.717	-4.052**	-4.055**
PTGI	-2.352	-2.294	-7.063*	-6.951*
NRR	-1.971	-2.360	-6.427*	-6.384*
REC	1.860**	5.01*		

*Note: C & T shows intercept and linear time trends. ** and * shows 10% and 5% significance levels, respectively.*

ARDL Bound Test

The ADF test results suggest that the ARDL model suits the empirical analysis. The ARDL findings in Table 3 reveal that the computed F-statistics exceeded the upper bound I(1) critical values at the 1%, 5%, and 10% significance levels. As a result, we reject the null hypothesis of no long-run relationship between green technological innovation, renewable energy, and the ecological footprint. These results align with the findings of Rehman et al. (2017), Sabir and Gorus (2019), and Khalid et al. (2021), which also confirm a long-run relationship between the ecological footprint and the independent variables. Therefore, it is crucial to analyze both the long-run and short-run effects of technological innovation, economic growth, and renewable energy on the ecological footprint.

Table 3

Cointegration Results based on the ARDL Bound Test Approach

Significance	Critical Bound Values	
	I(0) Bound	I(1) Bound
10%	2.457	3.529

Significance	Critical Bound Values	
5%	2.865	4.013
2.50%	3.256	4.491
1%	3.741	5.067
F-statistic	8.029	

Null Hypothesis: No long-run relationship

Results Discussion

Table 4 presents the long-run and short-run elasticity coefficients for green technological innovation, renewable energy, natural resources, and both linear and non-linear income growth. The results show that the model is moving toward long-run equilibrium, as indicated by the significant and negative coefficient for the Error Correction Mechanism (ECM), which reflects convergence to the desired equilibrium. Moreover, the findings highlight both linear and non-linear relationships between per capita GDP and per capita ecological footprint in Pakistan, in both the long and short run. The statistical significance of these relationships supports the Environmental Kuznets Curve hypothesis, which posits that environmental degradation increases with initial rises in per capita income but eventually decreases as per capita income continues to grow. The results are consistent with Aggeri (1999), Chien et al. (2021), and Pathiranage (2024). However, the long-run coefficient for renewable energy was insignificant, which may be attributed to Pakistan's status as a developing country with relatively lower levels of natural resource extraction than developed nations.

In contrast, the coefficient of green technical innovation (PTGI) is negatively correlated with ecological footprint, highlighting the pivotal role of green innovation. As technology advances over time, it positively affects environmental quality in the long and short run. A 1% increase in PTGI in the long run reduces environment degradation by 0.08%. Likewise, in the short run, an increase in green technological innovation decreases environmental degradation by, on average, 0.05%. This underscores the potential for positive change as governments and businesses increasingly focus on R&D to create environmentally friendly capital goods and boost production technology efficiency, thereby reducing environmental harm. These findings are consistent with the literature, such as Chien et al. (2021), Irandoust (2016), Weber and Neuhoff (2010), and Feng et al. (2009).

The results of renewable energy consumption reveal a significant and positive impact on the ecological footprint in Pakistan, indicating that an increase in renewable energy consumption also causes environmental deterioration in Pakistan. This finding underscores the need for sustainable energy practices, as Pakistan's reliance on hydro-energy necessitates more water and land, endangering marine life and agricultural land and resulting in an increasing ecological footprint. The results support the Al-Mulali et al. (2016).

Table 4

Long-run and short-run coefficients

Long Run Coefficients				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
Intercept	-28.825	11.639	-2.477	0.020
GDP_t	6.979	3.375	2.068	0.049
GDP_t^2	-0.424	0.244	-1.737	0.095
NRR_t	0.036	0.029	1.237	0.228
$PTGI_t$	-0.085	0.019	-4.561	0.000
REC_t	0.039	0.009	4.113	0.000
Short Run Coefficients				
ΔGDP_t	4.413	2.452	1.800	0.084
ΔGDP_t^2	-0.468	0.173	2.310	0.001

Long Run Coefficients				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
ΔREC_t	0.023	0.020	1.169	0.253
$\Delta PTGI_t$	-0.053	0.014	3.600	0.001
$\Delta PTGI_{t-1}$	0.023	0.014	1.674	0.107
ΔREC_t	0.007	0.003	2.346	0.027
ΔREC_{t-1}	-0.005	0.003	-1.711	0.100
ΔREC_{t-2}	-0.006	0.003	-1.976	0.059
ECM_{t-1}	-0.632	0.145	-4.357	0.000

Diagnostic Tests

Following the discussion of the ARDL estimates, several diagnostic tests were conducted to ensure the results were reliable (see Table 5). To examine and address issues such as autocorrelation, heteroscedasticity, residual non-normality, and biased functional forms, we utilized several tests, including the LM test for serial autocorrelation, the Breusch–Pagan test for heteroscedasticity, the Jarque–Bera test for residual normality, and the Ramsey RESET test to verify the absence of bias in the functional form.

The results in Table 5 confirm the stability of the used model; there is no issue with autocorrelation and heteroscedasticity (probabilities of the LM test and BP test are greater than a 5% significance level, respectively). Similarly, the J-B test also verifies the normality of residuals. After passing the diagnostic tests, we conclude that the regression results are robust and interpretable, providing a solid foundation for further analysis.

Table 5

Diagnostics Tests

Diagnostic Test		
Serial Correlation Test	F-stats	Prob.
LM Test	0.199	0.660
Heteroscedasticity Test		
BP test	0.458	0.932
Ramsey RESET Test	0.199	0.660
J-B Test	1.216	0.544

Null Hypotheses
LM test – No-serial autocorrelation
BP test - Variance of the errors is constant
Ramsey RESET Test - Functional form is unbiased
J-B test - Residuals are normally distributed

Conclusion

Human activities related to material resource consumption are often blamed for global warming and climate change. This study explores the relationship between environmental sustainability, green technological innovation, and renewable energy consumption in Pakistan within the EKC framework. The empirical results offer valuable insights for policymakers. The findings reveal positive and negative associations between per capita income and per capita ecological footprint. It confirms the EKC framework's applicability in Pakistan, indicating that while initial increases in income lead to a higher ecological footprint, further economic development eventually allows for improvements in environmental quality as income rises. At advanced levels of development, governments and residents are likely to adopt more environment-friendly policies.

Conversely, green technological innovation is negatively associated with the long and short-term ecological footprint, highlighting its significance in reducing Pakistan's ecological footprint. While renewable energy consumption is positively related to the ecological footprint, it also has potential for improvement. Effective management of increased renewable energy use could lead to substantial environmental benefits. This emphasis on the substantial benefits should motivate and inspire continued efforts.

The authorities can incentivize research and development in green technologies through tax breaks, grants, or subsidies for firms involved. Policies that focus on effectively integrating renewable energy sources through improving infrastructure, training for efficient energy use, and establishing guidelines to maximize environmental benefits from increased renewable energy consumption should be developed.

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