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Exploring the Environmental Trade-Offs of Renewable Energy and Green Technology Innovation on Pakistan's Ecological Footprint

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ABSTRACT

Human activities, in the form of material resource consumption and non-renewable energy usage, are significant contributors to global warming and climate change. Pakistan is particularly vulnerable to the impacts of climate change due to its greater dependence on conventional methods of production and consumption. It led to a significant increase in ecological footprint, further exacerbating environmental concerns and highlighting the urgent need for sustainable practices in Pakistan. This study aimed to explore the potential environmental trade-offs of increasing the use of renewable energy and environmentally friendly technology in Pakistan using the Environmental Kuznets Curve framework. Using the time series data from 1980 to 2021, the study employed the ARDL regression model. Our empirical findings suggest the existence of a long-run equilibrium relationship between green technological innovation, renewable energy, natural resources, biocapacity, and economic growth. The study also confirmed the existence of the ECK hypothesis in Pakistan. The findings demonstrate that green technological innovation and biocapacity have a negative impact, whereas renewable energy has a positive effect on the ecological footprint. The extraction of natural resources has a positive impact on the ecological footprint in the short run but not in the long run. The study suggests that policymakers must support other renewable energies such as solar, wind, geothermal, biomass, tidal, and wave energies; protect private property rights; create more opportunities for private investment in green initiatives; and support other private businesses that promote environmental sustainability.

Keywords: Ecological Footprint, Economic Growth, Green Technological Innovation, Renewable Energy
JEL Classifications: Q57, F43, Q55, Q20

1. INTRODUCTION

Over the last several decades, the world has experienced considerable growth in its socio-economic development and human welfare, increasing the massive energy demand in general and for fossil fuels. Despite the great efforts made by many countries to increase the role of renewable energy production and its consumption, fossil fuels remain the dominant sources of energy production, representing about 80% of the energy production categorized by different income levels (Al-Mulali et al., 2016). The efforts made by world-leading agencies, such as the Kyoto Protocol by the United Nations Development Program (UNDP), are concerned with the environment to enhance environmental health through sustained economic growth (United Nations 1998). This Protocol recognizes that economic collapse, higher reliance on energy supplies from fossil fuels, and the advanced transition of economies lead to environmental degradation (Saleem et al., 2020). Although sustainable economic growth has improved the infrastructure, raised living standards, and reduced poverty, it has its drawbacks when countries prefer to advance the preservation of precious lives over environmental concerns. In other words, a sustainable environment sacrifices overachieving stable economic growth, which has serious issues like environmental degradation, mass pollution, and depleted natural resources (Danish et al., 2020).

Pakistan is one among countries, that deems to be "on track" in shape of tackling climate change by the United Nations Development Program (UNDP, 2021). It is significantly due to the various policies and initiatives put in place by the government to improve environmental conditions and keep control over the constantly changing climate. These include the "Protected Areas Initiative," "Clean and Green Pakistan," "the Ten Billion Tree Tsunami," and "Recharge Pakistan." The progress has made, and this country remains particularly vulnerable to the negative impacts of climate change. Additionally, the country ranked as the fifth most vulnerable country on the Global Climate Risk Index in year 2020. Most recent assessment report by World Bank (2022) shows that over 75 million Pakistanis have been impacted by climate-related disasters over the past three decades, with projected economic losses of over $29 billion, or nearly $1 billion annually. The adverse effects on human health, way of life, and ecosystems will increase over time, resulting the expected temperature extremes. The impact of such occurrences, like the heat waves in Peshawar and Karachi or the oppressive fog in Lahore, are starting to have significant health and economic effects.

Consideration should be given to Pakistan's recent efforts in order to address the world's growing environmental problems. Moreover, various legislations and public sector initiatives, policies have been issued and are now in force. Creation of national environment quality standards, environment courts, environmental laboratories, the National Energy Efficiency and Conservation Authority (NEECA), and the improvement of environmental protection agencies (EPAs) at the federal and provincial levels are a few examples of accomplishments (UNDP, 2020). These efforts are not sufficient to address the ecological issues in Pakistan. Perhaps there are many reforms required. It is more important to be concerned about environmental reforms to limit the rising trend of carbon emissions, farmland, and forest product footprints. According to Global Footprint Network's statistics (2023), South Asia's ecological footprint per person increased from 0.63 hectares in 1961 to 1.13 hectares in 2018, while its carbon footprint from forest products increased from 0.05 to 0.13 hectares in 2018. In addition, the region's carbon footprint proportion increased from 0.1 gha/person in 1961 to 0.61 gha/person in 2018, widening the disparity between bio-capacity and ecological footprint from 0.13 to 0.70 hectares per person. Pakistan also experienced a significant increase in its ecological footprint, from 0.55 hectares/person in 1961 to 0.77 hectares/person in 2018, with its carbon footprint proportion increasing from 0.09 to 0.38 gha/person. These figures indicate that South Asia's demand for material resources has outpaced its bio-capacity per capita, particularly in Pakistan (Yousaf et al., 2021).

Pakistan is no exception and has set ambitious renewable energy targets as part of its National Energy Policy from 2013 to 2025. The country has a significant potential for hydropower generation, with an estimated 40,000 MW of potential capacity (NEPRA, 2022). As the hydropower contributes a higher share of electricity generation and a dominating source of renewable energy generation in country. However, in the recent decade, Pakistan focussed on other clean energy, such as solar and wind energy, as well as exploring other new technologies including tidal and geothermal energy. The shift towards other renewable energy sources was driven by several factors, including the need to diversify the energy mix, increasing concerns over the environmental impacts of hydropower, and the declining cost of alternative renewable energy technologies. As a result, the country has set ambitious targets for renewable energy development, intending to generate 20% of the country's electricity from renewable sources by 2025 (NEPRA, 2022). However, Pakistan has failed to meet its targets as a report by Sustainable Development Policy Institute (SDPI, 2022) suggests that a share of renewable energy in the country currently stands only at 5% (Aslam et al., 2022).

Therefore, all stakeholders are accountable for the protection of the environment and its resources, even though the government leads and oversees the nation's environmental sustainability programme. This can be only possible when the country made efforts to encourage technology advancement. Although several studies emphasise the role of technological innovation (hereafter, TI) in environmental protection at the same time, because TI helps to achieve energy conservation, and bring economic efficiency through use of traditional energy as well as renewable energy (Usman and Hammar, 2021; Wang et al., 2020; and Weber and Neuhoff, 2010). Additionally, TI is considered to have the most efficient use and reuse of natural resources in the country Miao et al. (2017). Chien et al. (2020) argued that TI increases renewable energy capacity and thus helps to increase the overall supply to meet the current and future demand for energy. It is a well-known fact that there are limited resources (oil, coal, and other non-renewable inputs), so renewable energy will be the most prominent source of energy in the future due to the ever-growing population and demand for energy (Cheng and Yao, 2021; and Godil et al., 2021). Additionally, it is also considered to be the most environmentally friendly source of power. Several studies, including those by (Mirza and Kawal, 2017; Usman et al., 2020; Waheed et al., 2018; and Zhang et al., 2017), demonstrate the enormous impact of renewable energy on Pakistan's eco-systems. Various existing literature on the same topics encourage a rise in the share of renewable energy in the overall energy mix in order to combat CO_2 emissions globally and in Pakistan. Additionally, emphasising green technology and renewable energy when discussing environmental sustainability sparks a crucial discussion about the future of Pakistan's economy. In terms of tech-based growth and green growth, both contribute to sustainable economic development. Thus, the study aimed to explore the potential environmental trade-offs of increasing the use of renewable energy and environmentally green technology in Pakistan and how these trade-offs could be mitigated.

Pakistan has the lowest share of overall renewable energy production along with the lowest rate of advanced technology adoption, particularly environmental green technology. Due to this fact, there is increasing debate about how the implementation of environmentally friendly technology and renewable energy can address the ecological footprint issues in Pakistan and mitigate the negative impacts of climate change on the economy. Moreover, it is revealed from existing literature that renewable energy can directly reduce CO_2 emissions, but when the ecological footprint is considered, it can have a negative impact on the ecosystem. Therefore, the study aimed to answer the research question, "What are the potential environmental trade-offs of increasing the use of renewable energy and environmentally green technology in terms of their impact on our ecological footprint and how can these trade-offs be mitigated?"

The study is organized in the following manner: Section 2: Summary and analysis of the latest research on the role of technological innovation and renewable energy in reducing environmental damage. Section 3: Theoretical foundation of green technological innovation, energy use, and ecological footprint. Section 4: Data and methodology used in the study. Section 5: Empirical findings, including an analysis of the data collected. Section 6: Summary of the results and policy recommendations.

2. LITERATURE REVIEW

Reviewing the research on green technology, renewable energy in halting environmental damage is the goal of the present study. Considering this, empirical evidence may be obtained globally and in the context of Pakistan.

2.1. Environmental Degradation and Green Technological Innovation

Numerous research studies have investigated the links between technology advancement and environmental deterioration. For example, Feng et al (2009) examined the association between income level, technological advancement, urbanisation, and CO_2 emissions. According to the study's estimations, urbanisation and income per capita had a significant impact on environmental emissions as well as technical advances. They concluded that technological innovation tends to lower the level of carbon emissions by bringing superior technologies into the country. Ali et al. (2016) examined quality of environment and discovered significant contributions to the decrease in CO_2 emissions from energy consumption, economic growth, and technological advancement.

The inverse relationship between technical advancement and environmental degradation was demonstrated by Weber and Neuhoff (2010). The study concluded that technical innovation results in more environmentally friendly, energy-efficient equipment. Irandoust (2016) analysed the relationship between technological advancement, ecological pollution, and renewable energy sources and deduced that these factors considerably lower environmental pollution, which ultimately improves the quality of the environment. Likewise, several other studies asserted that technical advancements in underdeveloped nations do not considerably aid in the decrease of carbon emissions. For instance, it was implied Ganda (2019) that increased energy efficiency increases emissions into the atmosphere. The study came to the further conclusion that conventional energy sources—which are primarily used in developing countries—contribute significantly to environmental damage. Therefore, technical advancements frequently lead to a rise in carbon emissions in developing countries rather than a decrease. Similarly, it has been shown Bai et al. (2020) that technology advancement tends to lead to a rise in environmental degradation in low-income countries. Considering these conflicting findings, experts have begun developing green technology breakthroughs. Sinha et al. (2020) analysed how environmental quality and technological innovation interacted in the N11 economies between 1990 and 2017. They looked at the technology policies of a few other economies again, as well as environmental damage, sustainable economic growth, and clean, reasonably priced energy. Based on the Environmental Kuznets Curve (EKC), they have observed consumption of renewable energy, technological advancement, and other macroeconomic dynamics affect air pollution.

Tobelmann and Wendler (2020) used the generalised method of moments (GMM) in dynamic panel to examine the impact of environmental-innovation nexus on CO_2 emissions in context of 27 EU member countries over the period of 1992 to 2014. Their findings demonstrates that technological innovation does not result in any reduction of CO_2 emissions, although the environmental innovation helps to lower CO_2 emissions in these countries. In this context Pakistan, the recent study conducted by Chien et al. (2021), where they used time series data from 1980 to 2018 to analyse the contribution of technological advancement, globalisation, and renewable energy to lessen environmental deterioration in Pakistan. The research applied use of the Quantile ARDL approach within the EKC framework. The results demonstrated that the EKC hypothesis applied to Pakistan. However, there is a large and positive relationship between economic growth and carbon dioxide emissions. In term of ecological footprint, Sampene et al. (2023) found that the South Asian region follows the Environmental Kuznets Curve (EKC) hypothesis, where initially, economic growth causes an increase in ecological footprint, but as the economy develops, the trend reverses, and environmental degradation decreases. Additionally, agriculture growth, natural resources, and biocapacity contribute to increasing ecological footprint, while renewable energy use, green finance, and growth in ICT help mitigate ecological footprint. Aggeri (1999) also asserts that green technological innovation is often used interchangeably with environmental innovations, which is a practical strategy that lowers environmental pollution and helps an economy thrive.

Many researchers have argued that the development of green technologies can improve environmental quality (Gao et al., 2018; Lee and Min, 2015; Schiederig et al., 2012). On the other hand, Zhao et al. (2015) have found that research and development (R&D) in green technologies has a negative impact on environmental wellness. They concluded that it might be helpful for improving environmental quality but there is no evidence to support this claim. It was also stated that green technological advancements will improve environmental quality Miao et al. (2017) and Godil et al. (2021). Furthermore, they stated that China also controlled CO_2 emission through use of technical innovation over last three decades. Using a Quantile ARDL approach, it is found that technical advancement, economic expansion, and renewable energy all have a large impact on China's carbon dioxide emissions. For the COP 21 agreements, Wang et al. (2020) examined the relationship between CO^2 emissions, GDP growth, technological innovation, financial development, and renewable energy consumption. The study used the panel AMG technique, found a positive and significant relationship between the financial development and CO_2 emissions as well as GDP growth. Meanwhile, to observe the intensity of CO_2 reduction and technological innovation in case of China Cheng and Yao (2021) examined the panel data model from 2000 to 2015. Their findings demonstrate that a percent increase in technological innovation each year for renewable energy decreased the carbon intensity on average 0.051% in China. Other studies have also looked at the growing trend in CO_2 emissions across many growing economies. (Mohsin et al., 2021; Nawaz et al., 2021; and Ustaoglu and Yldz, 2012) have concentrated Turkish economy while examining growing trend in adopting green technology innovation. These studies assert that green technology has enormous potential for the future growth and environmental protection, especially when it comes to mitigating climate change.

2.2. Environmental Degradation and Energy

In this section, the literature is divided in use of renewable and non-renewable energy consumption in relation with environmental degradation.

2.2.1. Environmental degradation and non-renewable energy consumption

The impact of non-renewable energy or traditional energy sources on environmental deterioration has been the subject of extensive investigation. Various studies have extensively covered the energy-environment association. Others focused on how renewable energy sources affect environmental deterioration at the same time. Previous research shown that non-renewable energy sources frequently cause carbon emissions to rise. For instance, empirical research was conducted by Saboori and Sulaiman (2013) to determine how energy use affects environmental pollution in Malaysia. They found that, increasing the use non-renewable energy results in higher environmental degradation.

The similar research was conducted for SAARC countries by Rehman and Rashid (2017), and they discovered a link between traditional energy usage and environmental degradation. On the other hand, Kousar et al. (2020) also shown the negative impacts of traditional energy sources in Pakistani environmental quality reduction. In a similar vein, Sharif and Raza (2016) point to the contribution of traditional energy to the environment degradation. Liu et al. (2008) evaluated the impact of household energy use on environmental emissions and illustrated the pertinent relationships between such factors. Since the use of energy is inevitable for the sake of economic growth and social wellbeing, thus a positive relationship between traditional energy and the ecosystem is becoming a problem for the economy. As a result, scientists have been looking for an alternative form of conventional energy that will both enhance environmental quality and boost economic growth.

2.2.2. Environmental degradation and renewable energy consumption

Among the alternative strategies that enhance environmental quality and materially advance economic development are renewable energy sources Demirbas (2000). To meet household energy needs, energy can be generated by using natural energy sources such as hydro, solar and wind. These energy sources can generate power without compromising the environment. Given the importance of natural energy sources, researchers are starting to examine the association between alternative energy sources and quality of environmental.

For instance, Apergis and Payne (2009) examined the association between renewable energy and quality of environmental using data of American states over the period of 1974 to 2004. They demonstrated that the use and production of renewable energy sources results in a reduction in GHG emissions. Meanwhile, Sarkodie and Adams (2018) also found a strong correlation between the chosen variables when examining the impact of traditional and natural energy sources on CO_2 reduction in the case of South Africa. According to the study, a percent increase in non-renewable energy leads to increase in CO_2 emissions by 10,436 kt. On the other hand, CO_2 emission decreases by 2855 kt for a percent increase in renewable energy. Moreover, Hu et al. (2014) investigated the effect of the economic growth, use of renewable energy, water and air quality of China. This analysis included time period from 2000 and 2011. Based on empirical findings, the study found a inconclusive evidence that the production and use of renewable energy sources significantly affect the air and water pollution, though they may favourably contribute to economic development.

Panwar et al. (2011) argued that renewable energy sources are to be the cleaner sources of energy, and a study revealed that RE has a positive role to play in enhancing the efficacy of the atmosphere. Moreover, Wang and Wang (2015), argued that wind energy is a crucial component of the creation of renewable energy. As a result, they hypothesized such argument through empirical testing. Meanwhile, the finding is supporting in a sense that wind energy's links to environmental contamination and discovered that it really improves the quality of the environment. In line of above study, Tsoutsos et al. (2005) demonstrated that solar energy directly improves environmental quality.

Sharif et al. (2020) re-examined the effects of energy consumption (both renewable and non-renewable) on ecological footprints in case of Turkey. From 1965 until 2017, they used the QARDL method for this purpose. Under all research quantiles, it has been found that the contribution of renewable energy is sufficient to reduce the ecological footprint over the long term. Additionally, the results of the study have supported the existence of the EKC. Using sophisticated quantile modelling, Sharif et al. (2020a) attempt to analyse the relationship between the use of various renewable energy sources and environmental deterioration from 1990 to 2017. The study's findings show that environmental deterioration and the use of renewable energy are causally related in both directions. According to Kalmaz and Kirikkaleli (2019), economic growth, energy consumption and other macroeconomic dynamics may be used to estimate CO_2 emissions in growing economies. Their research's findings support the long-run equilibrium relationship between CO_2 emissions, energy use, and other macroeconomic factors. Like this, it has been shown Bai et al. (2020) that technology advancement tends to lead to a rise in environmental pollution in low-income nations. Considering these conflicting findings, experts have begun developing green technology innovations. Green technology includes number of patents registered, trademarks and grant allocated for environmental protection Shan et al. (2021).

2.3. Research Gap

The discussion above suggests that the literature has adequately addressed the link between green technology and environmental deterioration as well as the interaction between renewable and non-renewable energy production. To the best of our knowledge, there is very little agreement on how renewable energy and green technology contribute to environmental deterioration in terms of Pakistan's ecological footprint. This would logically explain the study's contribution to the field of literature while considering its theoretical and empirical importance. Moreover, the dynamic trade-off between green technology, renewable energy, and environmental quality will be addressed with the help of advanced time-series econometric techniques. As a result, the present study will effectively fill up the existing theoretical or methodological gaps in the area of environmental economics.

3. THEORETICAL FRAMEWORK AND HYPOTHESIS DEVELOPMENT

The relationship between the abundance of natural resources, green technological innovations, renewable energy consumption, and the Ecological footprint is based on the ecological modernization theory that was introduced Huber (2000). According to him, the ecological modernization hypothesis relates that how modern industrialised civilizations deal with environmental challenges. Every non-renewable resource available to mankind has a finite amount on the globe. Rapid production and expansion are depleting present natural resource stocks and continually harming the environment due to poor environmental protections and ever-worsening ecological sustainability Bekun et al. (2019). Moreover, according to the treadmill of production theory, environmental deterioration is a direct result of natural resource exploitation and economic expansion Schnaiberg (1980) and Schnaiberg and Gould (2000). Ecological modernization theory and endogenous growth theory both support the notion that technology breakthroughs may assist countries in achieving sustainable economic growth by employing alternative means while preserving environmental quality. Because environmental transition theory states that when societies transition from a traditional to an industrial base, consumption for energy and urban infrastructure grows, as a result putting the environment's quality at risk. Whenever societies get wealthier, however, they use clean technology, adhere to stronger environmental rules, and implement structural reforms to better their connection with the environment.

3.1. Technological Innovation-Renewable Energy and Environment

Given the environmental concerns, the technology transfer and innovation process differ depending on the invention phase and time. For example, during the industrialization period in the 1960s, input consumption was heavily focused on non-renewable energy sources, such as installing coal and oil-fired plants. Kemp (1994) argued that more ecologically friendly technology is required to address the current environmental issues. They look at ways to implement extreme technological change, such as moving away from energy sources based on hydrocarbons. Radical technologies frequently require lengthy development cycles, specialised infrastructure, and a variety of institutional changes in order to operate. Jaffe et al. (2002) argued that the relationship between technological change and environmental policy has received increasing attention policymakers. By the late 1990s, fast technological innovation had become the typical, and non-renewable energy was slowly replaced with renewable energy, notably in industrialised countries. However, emerging nations continue to rely heavily on non-renewable energy use. Given non-renewable energy's environmental challenges, policymakers are devoting more attention from non-renewable to renewable energies. The literature on technical innovation and renewable energy identifies several processes by which innovation and renewable energy can contribute to enhancing environmental quality.

3.1.1. Green technological innovation

In order to ensure that the transition to ecologically sustainable growth occurs at the least feasible cost to the economy, green technical innovation and the production of new knowledge are key drivers of sustainable environmental balances and economic growth Shan et al. (2021). For example, increasing the amount of these components of production boosts economic output by increasing the labour force or developing equipment and constructing eco-friendly infrastructure. Furthermore, technical advancements and improvements in the quality of these production elements boost productivity and output. Technical advancement and the gathering and applying of knowledge (i.e., Patents and Trademarks) enable new investment and improved methods of integrating the various inputs of production to generate output. Recent investigations, on the other hand, have come to different results. International technology spill overs (Technical Grants), for example, may cause a country to invest less in environmental R&D (since it profits from R&D undertaken by others - reducing duplication and allowing investment elsewhere), resulting in an overall gain in innovation. Gerlagh (2008) discovers that when investment levels climb, knowledge accumulation switches from energy production to energy conservation technologies, implying a higher degree of technical change per unit of expenditure. Carraro et al. (2009) and Carraro et al. (2009a) examine climate policy and show that investing in energy-related R&D does not crowd out investments in other sectors, nor does it result in a decline in the level of human capital.

H_1: Green technology innovation plays a significant role in determining the ecological footprint in Pakistan.

3.1.2. Renewable energy

Additionally, literature on renewable energy use or production includes a number of benefits. First, since renewable energy does not create any toxins, the quality of the environment is unaffected. Second, the use of renewable energy lowers environmental harm through substitution Bilgili et al. (2016) and Majeed and Luni (2019). Fossil fuels are substituted with renewable energy, which reduces future emissions from fossil fuels. Akella et al. (2009) and Tsoutsos et al. (2005) explained the third benefit as; unlike fossil fuels, renewable energy doesn't deplete and doesn't harm the environment by releasing materials from mining and extraction activities. Fourth, the production of dynamic effects via economies of scale and spill over effects improves environmental quality. According to technological transfer theory, the international or horizontal perspective of technology transfer enables developing economies to obtain, modify, implement, and spread renewable energy technologies from abroad and then further drive innovation as a result of the functionality procured through the innovation process. Finally, thermal pollution generated by conventional energy sources may be prevented by adopting renewable energy sources for energy production Akella et al. (2009).

On the other hand, some researchers claim that renewable energy can harm environmental quality. Waste and combustible renewables are not considered clean energy sources. Emissions may rise if they rely heavily on renewable energy sources Jebli and Youssef (2017). Renewable energy sources like geothermal, solar, wind, and biofuels all need a lot of water and land to operate. Due to the scarcity of land and water resources, renewable energy sources will have a negative ecological impact on the environment Al-Mulali et al. (2016). They showed that using renewable energy damages the environment and wastes more water and land, which increases the ecological footprint. Renewable energy's erratic production and lack of suitable storage solutions are further challenges. Due to these factors, massive or large-scale energy production, which is frequently fuelled by fossil fuels, needs a backup power supply Heal (2009) and Forsberg (2009). It was also claimed that renewable energy's mitigating effect is seen after a certain point. Summarizing the above theoretical model, it is concluded that green technological innovation along with renewable energy consumption reduces environmental degradation and the risk of increasing costs derived from the restriction on economic growth. Based on the above theoretical model and existing literature, the following hypothesis is suggested:

H_2: Renewable energy plays a significant role in determining the ecological footprint in Pakistan.

4. EMPIRICAL FRAMEWORK AND HYPOTHESIS TESTING

Examining the effects of green technical innovation, renewable energy, economic growth, and Bio-capacity on Pakistan's ecological footprint from 1980 to 2021. These indicators are consistent with earlier studies such as Agbede et al. (2021), Unal and Aktug (2022), Chien et al. (2021), Sampene et al. (2023) and Shan et al. (2022). We have considered the environment structure of Pakistan in order to examine the influence of the relevant factors. Additionally, they emphasised the three crucial elements that influence environmental quality. However, this study extended the idea of above studies in empirical framework of environmental sustainability. The regression equation used in this study to examine the standard literature in accordance with the environmental degradation framework is as follows:

$$ECOPC_t = \beta_0 + \beta_1 \text{GDPPC} + \beta_2 GDPPC_t^2 + \beta_3 BIOPC_t + \beta_4 RES_t + \beta_5 PCAT_t + \beta_6\ RE_t + \varepsilon_t \quad (4.1)$$

In equation 4.1, the ECOPC shows the ecological footprint measured as a global hectare per person. GDPPC and $GDPPC^2$ show the linear and non-linear form of national income per capita reflecting the Kuznets relationship between environmental degradation and income per capita. BIOPC denotes the biocapacity measured as a global hectare per person. RES denotes the rent of natural resource percentage of GDP. RE denotes renewable energy consumption percentage of total energy consumed. PCAT denotes the PCA index for technological innovation constructed using the following three variables: total patents, total trademarks, and total technical grants. ϵ_t is assumed to be a white noise error term at subscript time t. To normalize all series, we transformed into a natural log to interpret the results as elasticities. The detail description of variables along with their units are mentioned in Table 1.

To compile the green technological innovation index, principal component analysis (PCA) was constructed to assess three major indicators of accordance with Sinha et al. (2020) and Usman and Hammar (2020). The index is formulated using the equation 4.1.1.

$$PCAT_t = \beta_0\ Patent_t + \beta_2\ Trademark_t + \beta_3\ Technical\ Grants_t \quad (4.1.1)$$

The principal component analysis (PCA) for green technological innovation (PCAT) method is used to convert highly correlated indicators into principal components, which are less uncorrelated indicators. The PCA involves several steps, including standardizing the data, calculating the covariance matrix, finding the eigenvectors and eigenvalues, calculating the principal component scores, reducing dimensionality, and reconstructing the original data. In the context of green technological innovation, PCA could be used to identify the underlying factors that contribute to innovation, such as number Patents, trademarks, and technical grants and to reduce the dimensionality of the data to make it more manageable

Table 1: Data description and sources

Variables	Complete description	Data sources
ECOPC	Ecological footprint per capita is measured as global hectares per person	Global Footprint Network
BIOPC	Biocapacity Per capita is measured as global hectares per person	
GDPPC	Gross Domestic Product Per Capita (measured at constant Price 2015)	World Development Indicator
RES	Total natural resources rents (% of GDP)	
RE	Renewable energy consumption percentage of Total energy consumed	
PCAT	1: Total Patent applications by residents and non-residents 2: Total number of trademark applications (direct and via the Madrid system) 3: Technical cooperation grants (in Million current USD)	

for further analysis. The fact that these indicators are highly connected is the main issue with using them for the PCAT. As a result, a single indication, such as a patent, trademark, or technical grant, may not accurately reflect Pakistan's real experience with green technology advances.

4.1. Unit Root Test

The systematic procedure in time series analysis is to check the existence of a long-term association which begins with confirming the order of integration of dependent and independent variables in an equation. Because time series variables are not always stationary and vary over time. Therefore, applying the OLS regression method is unreliable because it violates the important assumption of variables stationarity. The theoretical formulation of several economic models and their derived coefficients may mislead if this important assumption is ignored. As a result, a linear combination of dependent and independent variables having I(d) characteristics might provide insight into why certain linear combinations of I(1) series could be I(0). Therefore, the testing unit root of individual series is done through Augmented Dickey-Fuller (ADF), which is represented as model 4.2:

$$\Delta Y_t = \alpha_0 + \alpha_1 Y_{t-i} + \sum_{k=i}^{n.} d_k \Delta Y_{tk} + u_t \tag{4.2}$$

The y_t in equation 4.2 is a time series variable, and Δ is used as the first difference operator and u_t donates a white noise error term. The ADF unit root test has an advantage in containing individual intercept (I), intercept, and linear time trends (I & T).

4.2. ARDL Regression and Bound Testing Approach

The theory of environmental degradation may fluctuate and converge around a long-term equilibrium limiting "Ceteris paribus" conditions. However, in real life, it is not only economic growth that influences environmental conditions rather other macroeconomic and policy factors. Owing to the difficulties of "spurious regression," it is possible that one will not have a long-term relationship with whether such movement is natural or may be due to other factors. In econometrics analysis, the co-integration approach is superficial to avoid such long-term associations and prevent problems like "spurious regression." Moreover, Pesaran and Shin (1997) introduced the ARDL bound test approach of co-integration having both the I(0) and I(1) properties of dependent and independent series. In their empirical studies, more development has been brought by Narayan and Narayan (2004). This method has other statistical benefits of generating asymptotically normal estimates of the long-run coefficients regardless of whether the underpinning regressors are I (1) or I (0). According to them, the short-run estimated coefficients are consistent, whereas long-run coefficients are super-consistent based on ARDL estimators. But before the ARDL regression estimations, the existence of co-integration between dependent and independent variables is a primarily step. We employed Pesaran et al.'s (2001) bound testing approach to co-integration. According to ARDL bound test statistics, the "null-hypothesis" that there is no long-term association is being evaluated against the alternative-hypothesis that there is a long-term association between dependent and independent variables. This is done by rearranging both equations 4.1 into the ARDL form of the regression equation. The inclusion of lag of dependent and independent variables is used to capture the dynamic relationship between environment with their corresponding measures, as reported in equations 4.1. However, the number of lags is determined by Akaike Information Criterion (AIC). To drive the ARDL regression model, we represented equations as 4.3.

$$\begin{aligned}\Delta ECOPC_t &= \alpha_0 + \alpha_i \Delta GDPPC_t + \alpha_i \Delta GDPPC_t^2 + \\ &\sum_{i=1}^{n}\alpha_i \Delta ECOPC_{t-i} + \sum_{i=1}^{n}\alpha_i \Delta ECOPC_{t-i} + \sum_{i=1}^{n}\alpha_i BIOPC_{t-i} \\ &+ \sum_{i=1}^{n}\alpha_i \Delta PCAT_{t-i} + \sum_{i=1}^{n}\alpha_i \Delta RE_{t-i} + \beta_i GDPPC_t \\ &+ \beta_i GDPPC_t^2 + \beta_i BIOPC_{t-i} + \beta_i RES_{t-i} \\ &+ \beta_i PCAT_{t-1} + \beta_i RE_{t-i} + \varepsilon_t\end{aligned} \tag{4.3}$$

Where lag operator Δ shows short-run dynamics of the model and represented by first part of the equation. α_i are parameters associated with variables. The coefficients β_i are associated with other variables exhibits show long-run co-integration with statistical hypothesis of:

H_0: $\beta_i = \beta_j = \beta_y = \beta_x = 0$ (There is no long-run Co-integration)

H_1: $\beta_i \neq \beta_j \neq \beta_y \neq \beta_x \neq 0$ (There is long-run Co-integration)

Based on computed F-statistics, the decision to accept or reject co-integration is based on whether or not the F-statistics are smaller than the upper and lower critical values. If they are, then the null hypothesis of no co-integration is accepted and the model is abandoned; however, if the computed F-statistics fall between the upper and lower critical values, then the co-integration test is inconclusive. In case of acceptance of the alternative hypothesis through testing at ARDL bounds, long run models are estimated for equation 4.3.1.

$$\begin{aligned}ECPOC_t &= \alpha_0 + \beta_i GDPPC_t + \beta_i GDPPC_t^2 + \sum_{i=1}^{n}\beta_i ECOPC_{t-i} \\ &+ \sum_{i=1}^{n}\beta_i BIOPC_{t-i} + \sum_{i=1}^{n}\beta_i RES_{t-i} + PCAT_{t-i} \\ &+ \sum_{i=1}^{n}\beta_i RE_{t-i} + \varepsilon_t\end{aligned} \tag{4.3.1}$$

Furthermore, the Dynamic Error Model from the ARDL bounds test was used to restore the long-run evidence that was lost due to differencing with the estimated lagged error correction model. The ECM with a year lag also reflects the information about the long-run causal relationship between dependent and independent variables. Hence the short-run ECM equation is presented as 4.3.2.

$$\begin{aligned}\Delta ECOPC_t &= \alpha_0 + \alpha_i \Delta GDPPC_t + \alpha_i \Delta GDPPC_t^2 \\ &+ \sum_{i=1}^{n}\alpha_i \Delta ECOPC_{t-i} + \sum_{i=1}^{n}\alpha_i \Delta BIOPC_{t-i} + \sum_{i=1}^{n}\alpha_i \Delta RES_{t-i} \\ &+ \sum_{i=1}^{n}\alpha_i \Delta PCAT_{t-i} + \sum_{i=1}^{n}\alpha_i \Delta RE_{t-i} + \varphi_i ECM_{t-i} + e_t\end{aligned} \tag{4.3.2}$$

The coefficient φ_i associated with ECM shows the speed of adjustment toward equilibrium and it must be negative and statistically significant.

5. RESULTS AND DISCUSSION

5.1. Descriptive Statistics

Table 2 provides descriptive statistics for the proposed variables, highlighting their patterns and trends over time. The variables, including mean, maximum, minimum, standard deviation, and Jerque-Bera (J-B) test statistics, show low deviation from the mean for all variables except GDP per capita (GDPPC) and PCAT. ECOPC, BIOPC, RES, and RE have small standard deviations, indicating stability over time. The J-B test confirms that all variables follow a normal distribution. The average per capita biocapacity in Pakistan is 0.408 gha with a standard deviation of 0.041 gha, while the ecological footprint is 0.746 gha with a standard deviation of 0.066 gha. GDP per capita averages 1,024 dollars with a standard deviation of 224 dollars. Natural resource rent averages 1.3% of GDP, renewable energy consumption is 13.9%, registered patents average 973/year, and trademarks 25238/year. Technical grants average 196.653 million USD annually. The PCAT index averages 0.121 with a standard deviation of 0.61.

Table 2: Descriptive statistics

Variables	Mean	Maxi	Mini	SD	J-B test	P-value
ECOPC	0.746	0.855	0.617	0.066	2.004	0.367
BIOPC	0.408	0.474	0.315	0.041	1.345	0.345
GDPPC	1024	1474	671	224	1.450	0.484
RE	13.933	18.666	4.318	3.272	1.431	0.489
RES	1.343	2.617	0.729	0.545	3.159	0.176
PCAT	0.121	1.042	0.503	0.614	2.346	0.309
Patents	973	1738	406	311	2.882	0.237
Trademarks	25238	40578	12554	11028	3.453	0.234
Technical Grants	196.653	318.28	71.66	63.201	1.185	0.553

*Data source; WDI, and Ecological footprint network (2020)
**Author estimates
SD: Standard deviation

Table 3: Correlation matrix

	BIOPC	GDPPC	RES	RE	PCAT
BIOPC	1.0000				
GDPPC	−0.8608	1.0000			
RES	−0.2916	0.4066	1.0000		
RE	0.6900	−0.7876	−0.5852	1.0000	
PCAT	−0.2250	0.2429	0.1425	0.0311	1.0000

*Author's estimates

5.2. Correlation Matrix

The correlation matrix is reported in Table 3. The result shows the correlation coefficients between the variables, including BIOPC, GDPPC, RES, RE, and PCAT. The results indicate a strong negative correlation between BIOPC and GDPPC (−0.8608), suggesting that as GDPPC increases, the per capita bio-capacity of Pakistan decreases, which can be interpreted as a potential threat to the environment. The variable RES has a weak negative correlation with GDPPC (0.4066), indicating that as natural resource utilization increases, the GDPPC of Pakistan decreases, which could be due to an inefficient use of natural resource of country. The variable RE has a moderate negative correlation with GDPPC (−0.7876), implying that as the level of renewable energy increases, the GDPPC of Pakistan decreases, which could be due to the country's reliance on non-renewable energy sources. The variable PCAT has a weak positive correlation with GDPPC (0.2429), which indicates that as the green technological innovation increases, the GDPPC of Pakistan also increases. Overall, these results suggest that there is no multicollinearity among the independent variables, and each variable is uniquely associated with the level of environmental degradation in Pakistan.

5.3. Unit Root Test

Table 4 shows the individual unit root test statistics. By allowing both intercepts (I), and time trends (I and T), the t-test statistics corresponding their P-values indicate that there is mixture of I(0) and I (1) integrated series. For instance, RE found to be statistically significant at a 1% therefore the null hypothesis indicating that RE has a unit root is rejected. However, all other time series variables such as ECOPC, BIOPC, GDPPC, PCAT and RES are found to be the first difference stationary allowing both intercept (I) and linear time trend (I and T). Thus, using the ordinary least square regression approach to investigate long run relationship between dependent and independent variables is considered a "spurious regression." To deal with a mixture of integrated series I (0) and I(1) but not I(2), the ARDL bound test approach suggested by Pesaran et al. (2001) is an appropriate technique. Therefore, we have employed ARDL bound test approach for testing long run association in next section.

5.4. ARDL Bound Test

Based on unit root findings, it is confirmed that the ARDL regression model is suitable for investigating the green

Table 4: Unit root test results

Variables	ADF test statistics							
	Level				First difference			
	I		I & T		I		I and T	
	T-stats	P-values	T-stats	P-values	T-stats	P-values	T-stats	P-values
ECOPC	−1.733	0.408	−2.353	0.398	−7.252	0.000	−7.182	0.000
BIOPC	0.259	0.973	−1.420	0.840	−8.773	0.000	−6.823	0.000
GDPPC	−0.470	0.887	−2.239	0.456	−4.582	0.001	−4.490	0.005
PCAT	−2.350	0.258	−2.290	0.234	−7.063	0.000	−6.953	0.000
RES	−2.160	0.223	−2.749	0.224	−6.315	0.000	−6.228	0.000
RE	−2.990	0.044	−5.681	0.000	−7.277	0.000	−7.178	0.000

*Author's estimates: I and T shows intercept and liner time trend technological innovation, renewable energy with ecological footprint, controlling for other factors in Pakistan. To examine the long-run association, the ARDL bound test approach is employed that is suggested by Pesaran et al. (2001). By default, the null hypothesis states that there is no long-term association against the alternative-hypothesis that there is a long-term association between dependent and independent variables. The result reported in Table 5 shows that the calculated F-statistics exceeded the lower bound I (0) and the upper bound critical bounds I (1) at 1, 5 and 10% level of significance. Based on findings, the study failed to accept null hypothesis at a 1% level of significance and accept an alternative hypothesis, which states that there is a long-term relationship between green technological innovation, renewable energy, and ecological footprint along with other controlled variables. This show that there is strong association between proposed variables as stated by other studies such as Chien et al. (2021) and Sampene et al. (2023). They also reported the existence of long-run association between ecological footprint, economic growth other proposed variables in models. It has been established that there is a long-term relationship between ecological footprint and its other measures. Thus, it is important to examine the long-term and short-term relationships of green technological innovation, economic growth, and renewable energy on the ecological footprint. The main purpose of estimating the long and short-term slope coefficients of independent variables is to evaluate their statistical significance individually.

5.5. Long-run and Short-run Coefficients

The result reported in Table 6 shows long run as well short run elasticity coefficients of green technological innovation, renewable energy, natural resource, biocapacity, and linear and non-linear economic growth. The empirical finding demonstrates that there is a long-run equilibrium relationship as the coefficient of ECM_{t-1} (speed of adjustment) found to be statistically significant and as well as negative. It shows convergence towards a long-term equilibrium that is required as stated by Chien et al. (2021) and Sampene et al. (2023). Furthermore, the empirical findings reveal the existence of linear and non-linear relationship between GDPPC and ECOPC in long run as well in short run in the case of Pakistan. The statistical significance of both coefficients (GDPPC and $GDPPC^2$) confirms the existence of the EKC hypothesis, which states that at an initial state, the rise in per capita income degrades the environment, but at a certain stage, doubling the per capita income will help to reduce environmental degradation (Grossman and Krueger, 1991). Our findings are in line with studies by (Chien et al., 2021; and Sampene et al., 2023). For example, using Quantile regression approach Chien et al., (2021) found that many quantiles of economic growth are positive and significantly associated with and carbon dioxide emissions in Pakistan. In term of Ecological footprint, Sampene et al. (2023) used panel dataset of South Asian countries including Pakistan. They found a non-linear association between economic growth and ecological footprint.

Table 5: ARDL bound

Null hypothesis: No long-run relationships exist		
Significance levels (%)	Critical bound values	
	I (0) Bound	I (1) Bound
10	2.45	3.52
5	2.86	4.01
2.50	3.25	4.49
1	3.74	5.06
F-statistic	6.9476	

*Author's estimates

The effect of bio-capacity (BIOPC) on Pakistan's ecological footprint (ECOPC) is negative and significant in the long and short runs. In the long run, the coefficient of BIOPC suggests that a 1% increase in biocapacity per capita leads to a reduced ecological footprint of about 0.16%. However, the short-run coefficient demonstrates that BIOPC has a comparatively higher impact than the long run, suggesting that a 1% increase in BIOPC leads to a decrease in ECOPC by an average of 0.33%. It implies that countries with higher biocapacity per capita tend to have lower per capita ecological footprints, and vice versa. It demonstrates that excess BIOPC leads to improved environmental quality and vice versa. Our findings are different from those of the study (Hassan et al., 2019; Sabir and Gorus 2019; Sampene et al., 2023), but both found a positive association between BIOOC and ECOPC in the context of South Asian countries.

In the long run, the impact of natural resource extraction (RES) on ECOPC is positive but statistically insignificant. However, in the short run, the effect of RES with time lags (t-1 and t-2) is positive and significant on ECOPC. It demonstrates that a 1% increase in RES in the short run leads to a rise in ECOPC of between 0.052% and 0.047% on average. The findings imply that the effect of RES on ECOPC may not be immediate but may take some time (between 1 and 2 years) to materialise the impact. Additionally, the intuition behind the positive but insignificant long-run effect of RES on ECOPC could be because of a smaller amount of natural resource extraction in Pakistan relative to the size of the economy compared to other South Asian countries. It shows that, in the long run, the extraction of natural resources does

Table 6: Long run and short run coefficients

ECOPC	Coefficient	Std. error	t-statistic	Prob.
Long run coefficients				
Intercept	−43.991	12.762	−3.447	0.003
$GDPPC_t$	11.543	3.642	3.169	0.005
$GDPPC_t^2$	−0.780	0.264	−2.959	0.008
$BIOPC_t$	−0.161	0.027	−5.959	0.000
RES_t	0.033	0.035	0.962	0.347
$PCAT_t$	−0.085	0.019	−4.561	0.000
RE_t	0.406	0.086	4.738	0.000
Short run coefficients				
$\Delta GDPPC_t$	8.613	3.075	2.801	0.011
$\Delta GDPPC_t^2$	−0.582	0.219	−2.655	0.015
$\Delta BIOPC_t$	−0.331	0.114	−2.897	0.009
ΔRES_t	0.014	0.015	0.954	0.352
ΔRES_{t-1}	0.052	0.022	−2.363	0.028
ΔRES_{t-2}	0.047	0.017	2.714	0.013
$\Delta PCAT_t$	−0.014	0.012	−1.188	0.249
$\Delta PCAT_{t-1}$	−0.047	0.026	−1.804	0.086
ΔRE_t	0.027	0.023	1.159	0.260
ΔRE_{t-1}	−0.063	0.024	−2.638	0.016
ΔRE_{t-2}	−0.072	0.026	−2.736	0.013
ECM_{t-1}	−0.746	0.137	−5.431	0.000

not degrade the environment's quality. However, in the short run, RES leads to degraded environmental quality. Our findings are consistent with the study by Sampene et al. (2023). They found a positive and significant association between natural resource extraction and ecological footprint in the case of South Asian countries, including Pakistan.

The impact of green technical innovation (PCAT) on ECOPC is negative and significant in the long and short runs. The outcome demonstrates a critical role for green innovation; it suggests that as green technology advances, it improves environmental quality. The long-run slope coefficient of PCAT shows that a 1% increase in green technological innovation reduces environmental degradation in the long run by an average of 0.08%. On the other hand, the short-term impact of PCAT may not be immediate and may take more than a year to materialize in terms of its effect on environmental quality. The slope coefficient suggests that a 1% increase in PCAT with a year and 2-year lags reduces environmental degradation on average by 0.01% and 0.05%. It may be possible with the help of government policy interventions such as supporting renewable energy, protecting private property rights, creating more opportunities for private investment in green initiatives, and other private businesses that increasingly focus on R&D since it creates environmentally friendly capital goods and boosts production technology efficiency, reducing environmental damage. Our findings are consistent with studies by Chien et al. (2021); Sampene et al. (2023) in the case of South Asian countries; Feng et al. (2009) in the case of China; and Irandoust (2016) in the case of Nordic countries.

More interestingly, the impact of renewable energy consumption (RE) on ECOPC is positive and significant, indicating an adverse impact of RE on ECOPC. It demonstrates that an increase in renewable energy consumption also degrades environmental quality in Pakistan. The linear association reveals that a 1% increase in RE may lead to an increased ECOPC of 0.406% in long run. On the other hand, the short-term impact of RE may not be immediate and may take more than a year to materialize in terms of its positive effect on environmental quality. The slope coefficient suggests that a 1% increase in RE with a year and 2-year lags reduces environmental degradation on average by 0.062% and 0.073%. It may be possible because renewable energy production in Pakistan is highly based on hydro-energy rather than biofuel, geothermal, solar, or wind energy production. Hydro-energy reliance necessitates more water and land, endangering marine life and land allocated for agriculture, resulting in an increasing ecological footprint. Whereas in short run, hydro energy may not be threat directly to marine life, and agriculture land. Our findings are consistent with the study of Al-Mulali et al. (2016) and opposite those of Chien et al. (2021). For instance, Chien et al. (2021) argued that the increase in RE helps to control the amount of CO_2 emissions in the environment. Al-Mulali et al. (2016) argued that renewable energy increases the ecological footprint through inefficient land and water usage and degrades the ecosystem. It is true because, over the past two decades, Pakistan has faced several problems related to climate and air pollution. On the other side, the country also experienced significant energy crises that resulted in a decline in economic activities (Komal and Abbas, 2015). Pakistan has started several hydro based energy projects during the past 5 years to promote renewable energy sources and reduce the use of non-renewable resources, which are the primary causes of CO_2 emissions in the nation (Chien et al., 2021). Although Pakistan has various policies and procedures to address these problems, the energy industry is poorly managed and unable to meet the targeted ratio of clean energy production. In this manner, reaching the goal will require more public and private resources.

Table 7: Diagnostics tests

Diagnostic test		
Serial correlation test	**F-stats**	**Prob**
LM test	0.199	0.660
Heteroscedasticity test		
BPG test	0.458	0.932
Ramsey RESET test	0.199	0.660
Jarque-Bera test	1.216	0.544

*Author's estimates

5.6. Diagnostics Tests

The post-requisition for long-run ARDL estimates and bound test discussion, some diagnostic tests are performed on the above model. Table 7 presents the different diagnostic tests for estimated models. To confirm, there is no autocorrelation, heteroscedasticity, residual non-normality, or bias in functional forms. We employed the LM test for serial autocorrelation, the BPG test for heteroscedasticity, the J-B test for residual normality, and the Ramsey RESET test to detect potential omitted variable bias or misspecification of the functional form of the model.

The null hypothesis of "no-serial autocorrelation" is accepted based on F-statistics corresponding to its P-value at a 5 percent significance level. On the other hand, the null hypothesis that "there is homoscedasticity" is accepted as the F-statistics of the B-P-G test found it statistically insignificant at a 5% significance level. Additionally, the "residuals are normally distributed" is accepted based on insignificant J-B test statistics at a 5% significance level. It suggests that the residuals are normally distributed, and the normality assumption is satisfied. Lastly, we found an unbiased functional form of ecological footprint. Because the F-statistics associated with its P-value found to be statistically insignificant at a 1% level of significance. As a result, it suggests, no evidence of omitted variable bias or misspecification of the functional form of the regression model. After passing all the diagnostic tests, it has concluded that regression-based results are robust and interpretable.

6. CONCLUSION AND POLICY RECOMMENDATIONS

Human activities in material resource consumption are to blame for global warming and climate change. Academicians and policymakers across many developed and developing countries address these issues through various channels. Developing countries are generally more concerned about stressing economic resources to achieve stable growth but ignore environmental quality. However, this leads to serious challenges for human life and the ecosystem. To address these issues, the current study investigated the nexus between Pakistan's environmental sustainability green technological innovation and renewable energy consumption in context of environmental Kuznets framework. The empirical findings provide very interesting insights for the policy practitioners in the case of Pakistan. Using ARDL regression method, the study reveals the existence of EKC framework in case of Pakistan in long run as well as in short run. It is concluded that per capita income growth upsurge ecological footprint at initial stage of economic development, as the economy reaches at a certain stage of development, the increase in per capital income is used for better environment quality. It could be justified that, at higher levels of developments, the government and its residents initiate more environmentally friendly policies by focusing on environmental quality.

Moreover, the findings suggest that an increase in biocapacity per capita leads to a decrease in the per capita ecological footprint, indicating the importance of preserving and increasing biocapacity to maintain environmental quality. On the other hand, the positive and significant short-run effect of natural resource extraction on ecological footprint highlights the negative impact of resource extraction on the environment. However, in the long run, the effect of natural resource extraction on ecological footprint is insignificant, suggesting that the impact may take time to materialize.

Additionally, the green technological innovation negatively and significantly associated with ecological footprint in long run as well as in short run. It demonstrates that green technological innovation is an important factor to mitigate ecological footprint in case of Pakistan. Interestingly the use of renewable energy is positively and significantly associated with ecological footprint in case of Pakistan. This demonstrates that an increase in renewable energy consumption degrades environmental conditions in Pakistan. It is justified as renewable energy production significantly based on hydro-energy rather than biofuel, geothermal, solar power, and wind energy production in Pakistan. Thus, a significant reliance on Hydro-energy necessitates more water and land, endangering marine life and agricultural land and resulting in an increasing ecological footprint in long run. Thus, it is more important to be concerned about environmental reforms to limit the rising trend of carbon emissions, farmland, and forest product footprints.

Based on the study's findings, some policies are suggested. First, the government should increase environmental priority when it comes to fostering economic growth. Second policymakers and researchers should consider promoting sustainable land use practices, ecosystem restoration, and conservation efforts to increase biocapacity per capita and reduce ecological footprints. Third, the latest technology not only helps to reduce CO_2 emissions but also helps in efficient use of natural resources and develops fresh and creative methods to use conventional energy sources effectively, making it crucial to invest in green technology to restore ecological balance. Fourth Innovation in technology also makes it possible to create new RE sources more affordably. Since energy consumption has become a crucial component of the process of economic growth in the modern era, TI not only uses traditional and renewable energy sources effectively but also offers a cost-effective solution. Additionally, Pakistan's current renewable energy output is detrimental to the environment, particularly the marine ecosystem. Since hydro energy may destroy marine life and increase the ecological footprint. Thus, government should expand its roadmap for renewable energy and find acceptable solutions (such as switching to wind and solar bio-fuel energy) for a high percentage of renewable energy in national grades/networks.

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