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Impact of Technological Innovations on CO_2 Emissions: Evidence from Pakistan

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Abstract

In Pakistan, production pattern is increasingly reliant on energy consumption, driven by economic and population growth. The country's industries primarily employ non-renewable technologies which escalate emissions. Nevertheless, there is a growing emphasis on energy efficiency within the production sector, prompting efforts to stimulate technological innovation aimed at producing more efficient technologies for pollution mitigation. The current study investigated the impact of technological innovation on CO_2 emissions within the context of Pakistan. Patents, both residential and non-residential, serve as proxies for technological innovations. Time series data covering the period from 1990-2019 was utilized and the study employed Johansen Cointegration, FMOLS (Fully Modified OLS), and VECM (Vector Error Correction Model) Granger Causality tests. The results from the Johansen Cointegration test indicated the presence of cointegration between CO_2 emissions and technological innovation. FMOLS results revealed that non-residential patents have a significant mitigating effect on CO_2 emissions in the long run, while energy consumption and Foreign Direct Investment (FDI) increase CO_2 emissions in the long run. Interestingly, Gross Domestic Product (GDP) per capita showed no significant effect on mitigating pollution emissions. The VECM Granger Causality results indicate a long-term association between CO_2 emissions, patents, GDP per capita, FDI, and energy consumption. These findings suggest that technological innovation plays a crucial role in reducing CO_2 emissions. Consequently, it is recommended that the government increases investments in Research and Development (R&D) to

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promote cleaner technologies and control pollution emissions. Additionally, policymakers and government should work towards attracting environmentally friendly FDI to country's industries.

Keywords**:** CO_2 emissions, consumption, patents, pollution, technology innovation

Introduction

Over the past few decades, the world has witnessed significant global economic growth and improved human well-being, however, these achievements have been accompanied by the surge in pollution emissions, prompting heightened concern for environmental issues. Economic growth often leads to an increased demand for energy. As countries develop and their economies expand, they require more energy to fuel industries, transportation, and infrastructure (Dorian et al., 2006; Jones, 1991). However, the increasing use of energy, especially if it relies heavily on fossil fuels, may have detrimental environmental effects and drive climate change. The most influencing component of global heating are production activities that depreciate environmental condition by using excessive oil and consuming extra coal. Furthermore, human acts are the main elements that greatly modified environment, strange storms, accidental dehydration, and evaporate iceberg melting (Balsalobre-Lorente et al., 2018; Destek & Sarkodie, 2019). The tradeoff between environmental deterioration and economic development triggers demand for innovation in current production procedures. Therefore, environmental degradation is a major concern which has led to call for transitioning to cleaner and more sustainable energy sources through research and development by requiring the engagement and concentration of experts all over the world.

Currently, Pakistan's economy is expanding and authorities are concerned about alleviating CO_2 emissions. Numerous strategies and plans have been designed to control pollution. Indeed, technological advancements may bring about positive changes. The innovation in energy technologies plays a primary role in the mitigation of CO_2 emissions. Researchers have established that green technology decreases CO_2 emissions. Numerous studies have investigated the connection between technology innovation (TI) and CO_2 emissions (Erdoğan et al., 2020; Bakhsh et al., 2021; Xue et al., 2022; Wang et al., 2023).

Pakistan has begun to transition to a low-carbon economy along with phasing out government support for fossil fuel consumption recently. In 2011, these subsidies were seven times higher than the assistance for renewable energy. The Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) emphasizes that countries need to achieve net-zero emissions sometime between 2050 and 2070 which requires a profound decarbonization of both developed and developing economies.

The development of green ecological system necessitates the progress in technological innovation. Innovative production of technologies has been given considerable attention that may decrease adverse influence of CO_2 emissions. Therefore, the foremost thing is to enhance the skills of manpower, promoting awareness, introducing green applications, and expanded coordination with manufacturers to regulate and advance the innovation mechanism. Innovation exhibits dominance in environment redesign strategy negotiation (Metz et al., 2007). Indeed, it evaluates the solution to overcome the barriers between economic growth and growing atmosphere conditions (Aronsson et al., 2010; Hubler et al., 2012). Therefore, innovations are a fundamental element to attain effective development for nations, especially for developing countries while protecting the environment at the same time. There are various mechanisms through which technological innovation mitigates pollution emissions. Technological innovation can lead to the production, development, and adoption of cleaner and more energy-efficient technologies in various industrial sectors. These technologies may reduce the carbon footprint of production processes and energy consumption, thereby lowering CO_2 emissions. Additionally, technological advancements may result in improved energy efficiency in manufacturing, transportation, and other sectors, leading to reduced energy consumption and, subsequently, lowererd CO_2 emissions. Furthermore, technological innovation can enable the implementation of sustainable practices, such as carbon capture and storage, waste recycling, and emissions monitoring, which can directly impact CO_2 emissions.

The technological innovations are registered in the form of patents. Therefore, patents serve as a source to promote innovation and calculate the return on innovation performance (Popp & Newell, 2012). Patents show the capability of energy technologies' performance and the progress of energy automation. Additionally, patents in fuel-efficient and non-polluting areas require the upgradation of energy technological innovation capacity (Liu & Sun, 2021).

The technological advancement of energy production in manufacturing sector has played an important role in controlling CO_2 emissions. The policies for optimal use of energy have been comparatively stronger and helped mitigating CO_2 emissions in Pakistan. In Pakistan, energy production is mostly dependent on coal, fossil fuels, imported gas, and oil which are the main reasons of emissions. The replacement of these methods of energy production with environmental friendly technologies must be prioritized. Pakistan is nowadays paying attention on fuel efficiency in the production sector on the demand for efficient technologies. Still, there are massive hurdles in designing and implementing green technological energy in Pakistan.

The literature on the relationship between technological innovations and CO_2 emissions is relatively scant especially in the context of Pakistan. Many studies have examined this specific relationship as well. However, some studies report a negative impact of technological innovation on environmental quality (Acemoglu et al., 2012; Çelik & Alola, 2022), while others suggest a positive impact (Cheng et al., 2021; Saleem et al., 2022). These varying findings contribute to the complexity of understanding this relationship. Furthermore, various studies used different methodologies to arrive at their respective conclusions. The current study analyzed the long-run effects by employing Fully Modified OLS (FMOLS) methodology. It is a technique that extends the traditional Ordinary Least Squares (OLS) regression by addressing issues related to nonstationarity and cointegration among variables. Furthermore, this approach incorporates endogeneity concerns where independent variables are correlated with error term. Moreover, it focuses on long-run relationships which is quite relevant with the current study. Additionally, FMOLS technique is efficient as it contains asymptotic properties that enhances its ability to provide consistent estimates even when the sample size is small. Finally, it is robust in handling various forms of heteroscedasticity and autocorrelation which are common issues in time series data. The findings revealed a significant and positive correlation between technological innovation and mitigation of CO_2 emissions in the Pakistani context. Furthermore, no feedback effect was found, that is, CO_2 does not cause patent filing. This contribution not only enhances our understanding of the discourse on environmental pollution, however, it also underscores the importance of technological innovation as a means to address sustainability challenges in Pakistan.

The main objective of the current study was to examine the impact of technological innovations on pollution emissions. Specifically, the sub-objectives of the study are as follows:

- To what extent has technological innovations influenced the reduction of CO_2 emissions in Pakistan in various sectors?
- What lessons can be learned from Pakistan's experience with technological innovations and CO_2 emissions' reduction that can be applied to other developing countries facing similar challenges?

Section 2 of the current study comprises review of literature on the topic. Section 3 presents the data and methodology for estimations. Section 4 reports the results and provides discussions. Section 5 presents the conclusion.

Literature Review

Addressing environmental degradation, climatic changes, global warming, melting of glaciers, unusual and unexpected rains, and emission of gases demand serious and thoughtful discussions at national and global level among environmentalists, policymakers, and donors. If the above mentioned objectives are not met timely, the pursuit of sustainable development and fulfillment of sustainable goals can never become a reality. Numerous studies have investigated the effects of economic factors, such as globalization (Chishti et al., 2020), human capital (Khan et al., 2023), trade openness (Tachie et al., 2020), economic instability (Khan et al., 2022), Foreign Direct Investment (FDI) (Demena & Afesorgbor, 2020; Rana et al., 2022), and renewable energy sources (Chen et al., 2023) on environmental damage. Others have examined the role of institutional and governance factors on environmental degradation (Abid, 2017; Hassan et al., 2020; Khan & Rana, 2021). To achieve sustainable economic development, many countries all over the world have taken financial, institutional, and innovation initiatives to reduce greenhouse gas emissions and protect the quality of environment (Godil et al., 2021; Luo et al., 2021). Recently, the trend shifted towards technological innovation because it is an essential factor for economic growth (Khan et al., 2022) and positively affects the growth of countries as well (Anakpo & Oyenubi, 2022). Robust economic growth results in large scale manufacturing that demands and consumes more energy fuels (Zhang et al., 2022). Thus producing more carbon emissions. The upsurge in greenhouse gas and CO_2 emissions poses a severe threat to the peaceful human coexistence, sustainability of the environment, and ecosystem. Such an endangered environment raises questions about the survival of future generations. The researchers added a new concept of technological innovation to address the issue of environmental degradation in the form of CO_2 emissions and green house effects. For instance, Cheng et al. (2021) highlighted the importance to promote technological innovation as a widely applicable solution in order to address pollution emissions, particularly in developing economies. Technological innovation plays a pivotal role to enhance environmental quality and mitigate various environmental challenges (Saleem et al., 2022). Technological advancements have played a fundamental role in increasing the economic growth while improving environmental quality (Meirun et al., 2020) because modifications in production techniques leads to that overall effectiveness and productivity.

The theory of technological progress explains how and why technology changes over time. It is based on the idea that technological progress is driven by a number of factors including innovation and diffusion. Innovation refers to the development of new technologies and products and diffusion is the adoption of new technologies and products by firms and consumers (Freeman, 1994). The theory of technological progress has a number of implications for environmental sustainability through technological innovation as well as energy efficiency.

These theoretical developments triggered several research studies that investigated the effects of technological innovation on CO_2 emissions (Bakhsh et al. 2021; Erdoğan et al., 2020; Ullah et al., 2021; Xue et al., 2022; Wang et al., 2023). Technological innovation in construction sector intensifies emissions, while technological innovation in industrial sector helps to reduce pollution emissions (Erdoğan et al., 2020).

Technological innovation mitigates CO_2 emissions and enhances the environmental quality (Kumail et al., 2020; Chien et al., 2021; Çakar et al., 2021). Researchers have identified that several variables play a significant role in CO_2 emissions, such as technological innovation and green investment (Luo et al., 2021); use of ICT (Danish, 2019); technological innovation stimulates green initiatives within the G7 nations (Ahmed et al., 2022). Murad et al. (2019) identified that innovation in energy sector optimizes energy consumption and performance. CO_2 emissions had a bidirectional association with energy consumption, structural change, and technological innovation in Malaysia (Ali et al., 2020) which means that advancement in the patent could reduce emissions and promote efficient utilization of energy resources in Malaysia.

Esquivias et al. (2022) conducted a study on emerging Asian economies using the methodology of Panel Quantile Regression for the time period 1990–2019. The results indicated that gross capital formation, human development index, technological innovation, and reduced consumption of both renewable and non-renewable energy sources leads to a decrease in CO_2 emissions. Similarly, Jianguo et al. (2022) conducted research on OECD economies using the methodology of SYS-GMM from the time period 1998-2018. The results indicated that technological innovation and institutional quality decreases CO_2 emissions. Raihan and Voumik (2022) studied the technological innovation in India using the methodology of ARDL, FMOLS, DOLS, and CCR between the time period 1990–2020. The findings showed that renewable energy consumption and technological innovation decrease CO_2 emissions. Similar results were obtained by Liu et al. (2022) on E-7 countries. They used the methodology of panel quantile estimations and FGLS during the time period 1996– 2018. It was determined that the incorporation of renewable energy sources, technological innovations, and institutional quality decrease CO_2 emissions. Obobisa et al. (2022) examined African countries by using the methodology of AMG and CCEMG between the time period 2000–2018. The findings showed that eco-friendly energy usage and technological innovation decrease CO_2 emissions. Abid et al. (2022) found long-run and negative relationship with CO_2 between financial development, FDI, and technological innovation in G8 countries.

Technological innovation could also have adverse impacts on environmental quality as identified by a number of research studies (Acemoglu et al., 2012). Çelik and Alola (2022) assessed that GDP, economic growth, technological innovation, and research and development increase CO_2 emissions. Furthermore, the researchers also identified that innovation in resources, knowledge, and environment negatively affects CO_2 emissions (Samargandi, 2017; Shahbaz et al., 2020). Technological innovation has a negative correlation with environmental quality (Rafique et al., 2020; Raihan & Voumik, 2022); technological innovations increase CO_2 emissions (Jiang et al., 2023). Koondhar et al. (2021) explained that modern technologies demand extensive use of fossil fuels in their operations which results in an increase in CO_2 emissions, hence degrading the environmental quality.

In conclusion, the literature on the impact of technological innovations on CO_2 emissions provided valuable insights into the multifaceted relationship between technology and environment. Over the years, technological advancements have emerged as an important driver in the global efforts to combat climate change. As evidenced by numerous studies, innovations, such as renewable energy technologies, smart grid systems, and sustainable transportation solutions have demonstrated significant potential to reduce CO_2 emissions. However, it is essential to acknowledge that the effectiveness of these innovations is contingent upon various factors including policy support, market adoption, and societal engagement. This is due to the fact that technological innovations may be detrimental for environment. The literature underscored the importance of a holistic approach that integrates technology to achieve reductions in CO_2 emissions while fostering sustainable economic growth.

Therefore, the formulated hypotheses are as follows:

H_1: Technological innovations significantly mitigate pollution emissions.

Indeed, technological innovation was measured by the number of patent filings in this study and they were further distinguished as resident and non-resident patents. Therefore, the following hypotheses were drawn:

H_{1a}: The filing of resident patents significantly mitigates pollution emissions.

H_{1b}: The filing of non-resident patents significantly mitigates pollution emissions.

Data and Methodology

To examine short and long-run association between technological innovation and CO_2 emissions for Pakistan, the data was taken from WDI. The study used time series data, covering the time period 1990-2019. All the data was converted to its natural logarithm.

The dependent variable, that is, CO_2 emissions were measured as metric tons per capita. The numbers of patent applications (residents and non-residents) were considered as technological innovation which is the explanatory variable. Technological innovation refers to the efforts of public and private organizations of a country to search for innovative technology. Finally, for the control variables, the study had GDP per capita (current US$), FDI net inflow (% of GDP), energy use (kg of oil equivalent per capita), and financial development. The definitions and sources of the variables are provided in the appendix. Table 1 shows the descriptive statistics for the variables included in the analysis.

Table 1
Descriptive Statistics (1990-2019)

Variable	Mean	Std. Dev	Min	Max
CO_2	-.1940094	.1655913	-.4844611	.1089135
PATENTS_RES	4.271214	.9199605	2.772589	6.037871
PATENTS_NONRES	6.755653	.3381862	6.2186	7.406711
ENERGYUSE	.7331306	.3484614	.0849655	1.269903
FDI	-.1028136	.5778014	-.9794209	1.299735
GDPPC	6.607853	.4625486	5.918029	7.301354

Given the explanation provided for the variables in question, the foundational theoretical model takes the following shape:

$$CO2 = f(patents_{res}, patents_{nonres}, Energy\ use, GDPPC, FDI) \qquad (1)$$

Time Series Unit Root Tests

Unit root tests are used to determine if data is stationary after being differenced once. Many macroeconomic variables tend to have unit root problems which means that their variance increases over time (Nelson & Plosser, 1982). This may make Granger Causality tests ambiguous. Therefore, it is important to test each time series for unit roots before using Granger Causality analysis. For this purpose, the Augmented Dickey Fuller (ADF) and Phillips-Perron (PP) tests were employed with individual constant and trend for all variables (dependent and independent) to verify the stationarity at first difference.

ADF equation takes the following form:

$$\Delta co2_t = \alpha + \beta_t + \gamma co2_{t-1} + \sum_{j=1}^{p} \delta_j \Delta co2_{t-1} + \varepsilon_t \quad (2)$$

PP equation:

$$\Delta co2_t = \alpha + \theta co2_{t-1} + u_t \quad (3)$$

Time Series Cointegration tests

It is important to determine whether the variables in the model are cointegrated. Cointegration is a statistical concept that refers to the possibility of two or more non-stationary time series having a linear relationship that is stationary. This means that the two series may fluctuate independently in the short-run, however they would return to a long-run equilibrium relationship. The cointegration test proposed by Johansen and Juselius (1990) was used to determine whether two or more non-stationary time series are cointegrated. If the test results are positive, then it can be concluded that the two series have a long-run equilibrium relationship. The presence of cointegration is important because it allows the use of regression analysis to study the long-run relationships between variables. Without cointegration, the results of regression analysis may be spurious.

Long-run Parameter Estimates

To estimate the long-run relationship between technological innovation and pollution emissions in Pakistan, the current study delved into long-term effects using the FMOLS methodology. This method goes beyond conventional OLS regression by addressing challenges related to nonstationarity and cointegration among variables. Additionally, it takes into account endogeneity concerns where independent variables are correlated with the error term. Moreover, it emphasizes long-term relationships which aligns with the focus of the current study. Furthermore, the FMOLS technique is characterized by efficiency due to its asymptotic properties, enabling it to yield consistent estimates even when working with small sample sizes. Lastly, it demonstrates robustness in handling various forms of heteroscedasticity and autocorrelation which are frequently encountered issues in time series data.

The FMOLS method was developed by Phillips and Hansen (1990) to estimate a single cointegrating relationship between a combination of I(1) variables. The FMOLS method is robust to endogeneity and serial correlation.

Short-run Parameter Estimation and Time Series Causality Test

Finally, a Vector Error Correction model (VECM was used to analyze the convergence of variables towards equilibrium and long-run causality between variables. VECM is a multivariate cointegration method developed by Granger (1988) and Engle and Granger (1987). It allows to examine the mutual dependencies between all the variables in the system. It also identifies the direction of causality. VECM is specified with a dynamic error correction representation. Error correction modeling (ECM) is also known as the speed of adjustment of a variable (dependent). ECM postulates that the dependent variable converges towards equilibrium after adjusting for other variables in the system.

Results and Discussion

This section provides main findings from the comprehensive three-step investigations previously detailed, focusing on the sample of the current study for Pakistan. Tables 2 and 3 present the results of ADF and PP unit root tests, respectively at both levels and first differences. The results show that all of the variables are stationary after taking the first difference, that is, they are integrated at order 1 (I(1)) which is consistent with the PP test results.

Table 2
ADF Unit Root Test Results

Variables	Level		First difference	
	Constant	Constant and trend	Constant	Constant and trend
CO_2	-0.07	-2.36	-6.36***	-6.22***
PATENTS_RES	-0.24	-3.29*	-5.58***	-5.54***
PATENTS_NONRES	-1.54	-1.43	-3.95***	-4.34***
ENERGYUSE	-1.20	-2.41	-6.53***	-6.57***
FDI	-2.11	-2.06	-4.71***	-4.65***
GDPPC	-0.92	-1.74	-4.79***	-4.69***

Table 3
PP Unit Root Test Results

Variables	Level	First difference

	Constant	Constant and trend	Constant	Constant and trend
CO_2	0.02	-2.55	-6.25***	-6.13***
PATENTS_RES	0.32	-3.22*	-6.03***	-5.95***
PATENTS_NONRES	-1.71	-1.46	-3.98***	-4.29***
ENERGYUSE	-1.28	-2.44	-6.44***	-6.49***
FDI	-2.38	-2.32	-4.73***	-4.67***
GDPPC	-0.93	-1.72	-4.69***	-4.58***

After the confirmation of stationarity at first differences, we proceed to employ the Johansen cointegration test to assess the presence of cointegration among the variables. The outcomes of the Johansen cointegration tests are outlined in Table 4.

Table 4

Cointegration Test (Johansen)

No. of CEs	Eigen value	Trace statistic	Critical value (95% CI)
Cointegration rank test (trace)			
None	-	115.418	94.15
At most 1	0.813	68.448	68.52*
Cointegration rank test (maximum eigenvalue)			
None	-	46.971	39.37
At most 1	0.813	28.381	33.46*

The results indicated the existence of cointegration in the proposed model. Consequently, the cointegration tests provide evidence of a long-term relationship between CO_2 emissions, patents of residents as well as non-residents, energy consumption, FDI, and GDP. The outcomes of the Johansen-cointegration tests reject the null hypothesis, indicating the absence of a cointegration relationship. The results presented in all the tables demonstrate the presence of at least one cointegration equation.

Following the confirmation of a single cointegration relationship between the variables under study, the next step involved estimating FMOLS regressions to evaluate the presence of a long-term connection among the dependent and independent variables. Table 5 provides an overview of the outcomes of FMOLS estimations, offering insights into the impact of selected variables on CO_2 emissions.

Table 5

Fully Modified OLS (FMOLS) Estimates

Variables	Estimates (*SE*)
GDPPC	0.006(0.017)
ENERGYUSE	0.480***(0.031)
FDI	0.017***(0.003)
PATENTS_RES	-0.004(0.007)
PATENTS_NONRES	-0.0226***(0.007)
Cumulative effects (Resident and Non-resident patents)	-0.026***(0.009)
χ2Normality test	0.96 (0.618)
χ2Heterosced test	0.26 (0.611)
ADF test on Residuals	-5.194 (0.000)
Observations	29
R^2	0.98

Note. *** p<0.01

In the specification, the FMOLS estimation results are reported as in equation 4. Here, the coefficient on the GDP variable is not significant in creating pollution emissions. These results are in line with Bieth (2020) who found insignificant effects of GDP on CO_2 emissions for ASEAN countries and Japan. Indeed, the justification for this result lies in economic structure. The composition of an economy's sectors can significantly impact its CO_2 emissions. Over time, economies shift away from carbon-intensive industries, such as heavy manufacturing, towards less emissions-intensive sectors, such as services. Resultantly, even if GDP grows, emissions may remain stable. The services share to GDP has been increasing over time in Pakistan. It was around 46% in 1999 and jumped to around 54% in 2019. However, the results contradict with Shahbaz et al. (2013) who determined positive effects for Indonesia. Abbassi and Riaz (2016) found significant pollution increasing effects of GDP for Pakistan. Indeed, the results also pertain to the situation of Pakistan, however, the difference between the results may be due to the sample period taken. Their study selected the sample between the time period 1971-2011 and the subsample from 1988-2011. Indeed, the sample ended in 2019 when the services sector was approximately 54% of GDP. The increase in services share, as discussed above, may be the reason for this difference in results.

The variable of inward FDI is found to be positive and highly significant. While, attracting FDI is frequently regarded as crucial for the technology transfer and knowledge in developing nations, such as Pakistan.

It is noteworthy that higher FDI inflows are associated with increased pollution emissions. This is mainly due to the migration of polluting manufacturing industries to these recipient economies, a phenomenon well-documented in studies, such as Blanco et al. (2013) and Leal et al. (2021). Numerous studies have provided support for the idea that FDI has pollution-increasing effects on Asian economies and Pakistan is one of them. For instance, the studies conducted by Abbasi and Riaz (2016) on Pakistan, Kılıçarslana and Dumurul (2017) on Turkey, Salahuddin et al. (2018) on Kuwait. Furthermore, Xie et al. (2020) have recently affirmed the relationship between FDI and CO_2 emissions in 11 emerging economies.

It is worth noting that energy consumption is responsible for heightened pollution emissions in Pakistan. This is evident from the results presented in Table 5. The extant research on energy and environment reiterates that a primary factor influencing CO_2 emissions is the escalating energy demand in countries (see Tamazian & Rao, 2010; Ozturk & Al-Mulali, 2015). Consequently, the variable representing energy consumption consistently maintains its positive and statistically significant association across most empirical studies in this domain.

Finally, the explanatory variables and patents (resident and non-resident) reveal some interesting results. The nonresidential patents have significant impact in decreasing pollution emissions in case of Pakistan. The results indicate that a 10% increase in non-residential patents would decrease CO_2 emissions significantly by 0.22%. Indeed, the technological innovation, measured through patents, focuses on improving energy efficiency in various sectors, such as transportation and manufacturing. Therefore, more energy-efficient processes require less energy input, leading to lower CO_2 emissions. There are patents related to renewable energy technologies, such as solar, wind, and hydroelectric power. They can lead to the adoption of cleaner energy sources. Shifting from fossil fuels to renewable energy reduces CO_2 emissions.

The patents filed by nonresidents represent advanced technologies that may not be available in the country. Furthermore, nonresidential patents often reflect technology transfer and knowledge exchange between developed countries and developing or emerging economies. The introduction of these advanced technologies to a developing country may lead to significant emission reductions as they replace older, more polluting technologies. The findings are consistent with Hussain et al. (2023) who determined significant pollution mitigating effects of innovations for G-20 countries.

The residential patents exhibit that they do not have any effect. The reason for this outcome may be that the residential innovations in Pakistan, protected by patents, do not focus on pollution mitigation or environmental sustainability. For instance, if residential patents predominantly cover consumer goods or services that are not designed with environmental considerations in mind, their impact on pollution may be limited.

The overall cumulative effect, taking into account the joint effect of (1) residential patents, (2) non-residential patents, is negative and significant, indicating that the joint effect of these two patent types substantially mitigates pollution.

The concluding phase of the current empirical study involves examining both the short-term and long-term associations between CO_2 emissions and the independent variables. These findings are presented in Table 6.

Here, a causal relationship is observed in the short-term between CO_2 emissions and residents as well as nonresident patents. The resident patents contribute to a reduction in CO_2 emissions in the short-run. The bidirectional causality with CO_2 emissions is not found for resident and nonresident patents, where an increase in CO_2 emissions does not lead to more patent filing. On the other hand, the long-term analysis reveals a robust link between CO_2 emissions and the variables that were analyzed which encompass both resident and nonresident patents, GDPPC, energy use, and FDI.

Conclusion

The global concern over environmental degradation and its relationship with economic growth has become increasingly evident. As countries' economies expand, the demand for energy increases and if this demand is fulfilled by fossil fuels, it may pose severe environmental threats.

The rapid expansion of Pakistan's economy has drawn attention of government authorities to confront the issue of CO_2 emissions, resulting in the adoption of diverse strategies aimed at mitigating pollution. Technological progress is considered as a critical driver to foster positive change, especially within the domain of energy technology. Numerous research studies have delved into the important relationship between technological innovation and the mitigation of CO_2 emissions, emphasizing the potential of green technology. The patents serve as indicators of technological innovation.

Table 6

VECM Results

Dependent Variables	Short-run						Long-run
	ΔCO_2	ΔPATENTS_RES	ΔPATENTS_NONRES	ΔENERGYUSE	ΔFDI	ΔGDPPC	ECT
ΔCO_2	*NA*	-0.045***	0.093***	0.087	-0.016	0.018	-0.60***
		(0.015)	(0.032)	(0.126)	(0.013)	(0.066)	(0.151)
ΔPATENTS_RES	3.962**	*NA*	0.062	0.544	-0.057	-0.153	3.228
	(1.987)		(0.415)	(1.649)	(0.166)	(0.861)	(1.977)
ΔPATENTS_NONRES	0.562	0.116	*NA*	-0.772	0.060	0.505	-0.903
	(1.063)	(0.103)		(0.883)	(0.089)	(0.460)	(1.058)
ΔENERGYUSE	-0.083	0.000	0.077	*NA*	0.011	0.009	-0.297
	(0.334)	(0.032)	(0.069)	(-0.404)	(0.028)	(0.144)	(0.332)
ΔFDI	-0.323	0.463	0.770	2.559	*NA*	1.181	0.633
	(2.997)	(0.292)	(0.626)	(2.488)	(0.250)	(1.298)	(2.982)
ΔGDPPC	-0.018	-0.051	-0.222	-0.113	0.073	*NA*	-0.170
	(0.497)	(0.049)	(0.104)	(0.413)	(0.042)		(0.495)

Note. Standard errors of estimation results in parentheses and *p*-values are reported in parentheses for diagnostic tests. ECT represents the coefficient of the error correction term. ***, ** and * denote significance at the 1, 5 and 10% levels, respectively.

The current study attempted to investigate the impact of technological innovation on CO_2 emissions in the context of Pakistan. The study utilized time series data spanning from 1990-2019 in the context of Pakistan. The research methodology comprised the application of Johansen cointegration analysis as well as the use of FMOLS and VECM models in order to examine the long-term effects of technological innovation on CO_2 emissions. The findings from the Johansen cointegration analysis indicated the existence of cointegration between the examined variables. The FMOLS results provided evidence that nonresidential patents play a significant role in mitigating pollution emissions, however, this is not the case for residential patents. Conversely, energy use and FDI exhibit positive influences on CO_2 emissions over the long-term. However, it is noteworthy that neither residential patents nor GDP per capita appear to have a significant impact on CO_2 emissions' reduction in the long-run. Moreover, the results of VECM show that long-run causality exists between CO_2 emissions, patents, GDP per capita, FDI, and energy use for Pakistan.

The patent filings by nonresidents signify the introduction of advanced technologies that may not be locally accessible. When these cutting-edge technologies are adopted in a developing country, such as Pakistan, they have the potential to reduce pollution emissions, as they replace obsolete and more environmentally harmful technologies. However, the residential innovations in Pakistan may not take into account the environmental considerations.

The current study has important policy implications. The findings emphasized that government should consider implementing policies that prioritize increased investments in research and development (R&D) to facilitate the transition away from fossil fuel-based energy sources, particularly in the production sectors where the use of gas and oil is prominent. The research should be promoted to undertake green technological projects for the betterment of environment. The Government of Pakistan (GOP) should provide financial grants to firms to invest in the research and production of environment friendly technology.

The study may further be extended by measuring technological innovation through aspects other than patents. Furthermore, technological innovation may also be segregated into different sectors and therefore, the heterogenous effects of innovation in those sectors can be analyzed.

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Appendix

Data Definition and Sources

Symbol	Variable	Definitions	Source
CO_2	Carbon dioxide emissions	CO_2 emissions expressed metric tons per capita	WDI
PATENTS_RES	Patents filed by residents	Patent applications encompass applications for patents that are filed by residents either via the Patent Cooperation Treaty process or through national patent offices.	WDI
PATENTS_NONRES	Patents filed by nonresidents	Patent applications refer to applications for patents that are submitted by nonresidents either internationally through the Patent Cooperation Treaty (PCT) process or to a national patent office.	WDI
ENERGYUSE	Energy consumption	Energy use per capita (measured in kilograms of oil equivalent).	WDI
FDI	Foreign Direct Investment	Net inflows as a %age of GDP	WDI
GDPPC	Real GDP per capita	GDP per capita at constant purchasing power parity (PPP), expressed in 2005 US dollars."	WDI