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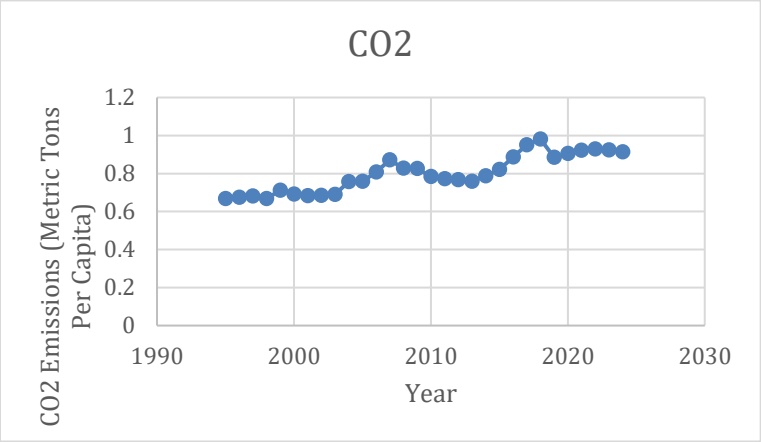
THE EFFECTS OF ECONOMIC, TECHNOLOGICAL, AND INSTITUTIONAL FACTORS ON THE CO2 EMISSIONS IN PAKISTAN USING ARDL APPROACH

Iqra Manzoor
School of Economics, University of the Punjab, Lahore, Pakistan, miqra485@gmail.com
Shabbir Ahmad
School of Economics, University of the Punjab, Lahore, Pakistan, shabbir.eco@pu.edu.pk
Maria Faiq Javaid*
School of Economics, University of the Punjab, Lahore, Pakistan, mariafaiq.eco@pu.edu.pk
Minahil Mir
School of Economics, University of the Punjab, mirminahil585@gmail.com

Abstract
This research examines the relationships among economic, technological, and institutional factors and CO2 emissions in Pakistan. It uses Autoregressive Distributed Lag (ARDL) bounds testing approach to obtain long- and short-run results by using data from from1995 to 2024. The results showed that GDP per capita increases CO2 emissions (consistent with the first half of the Environmental Kuznets Curve (EKC) Hypothesis while trade openness (TO) significantly reduces emissions. Moreover, foreign direct investment (FDI) also increases CO2 emissions which confirming the Pollution Haven Hypothesis (PHH) for Pakistan. Based on these findings, the study proposes trade and FDI should focus on environmentally sustainable, technology-intensive activities, supported by stronger environmental institutions to reduce CO2 emissions in Pakistan.
Keywords: *ARDL, CO2 Emissions, FDI, Environmental Innovation (EI), Trade, Government Effectiveness*

1. Introduction

The high level of CO2 emissions is a serious threat to global sustainability, as it negatively affects the climate (Sadatshojaie & Rahimpour, 2020) and causes global warming (Mohajan, 2011), which, in turn, disrupts the socioeconomic conditions in developing countries like Pakistan. Although developed countries account for the bulk of CO2 emissions, developing countries are the most vulnerable to its consequences (Nath & Behera, 2011). Pakistan is facing multifaceted issues, including overpopulation (Rehman et al., 2022; Mehdi et al., 2025), energy crises (Qudrat-Ullah, 2022), and natural disasters driven by climate change (Hussain et al., 2022; Abbasi et al., 2025). Pakistan is now among the most vulnerable countries to natural disasters, as seen in the 2022 and 2025 floods. According to the Climate Risk Index 2025, Pakistan has emitted only 0.81 metric tons of CO2 per capita, which is far below the world average of 4.76 metric tons in 2023, yet it was ranked among the most vulnerable countries in 2022. In addition, China and India are among the largest CO2-emitting countries, further exacerbating environmental challenges for Pakistan.

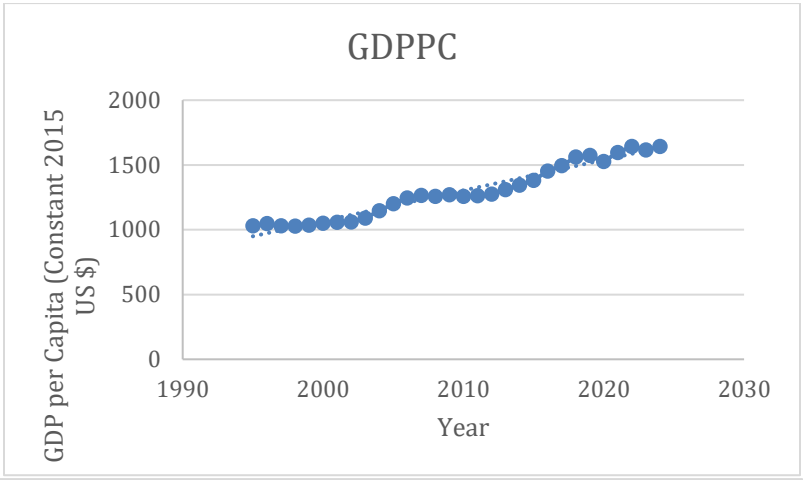


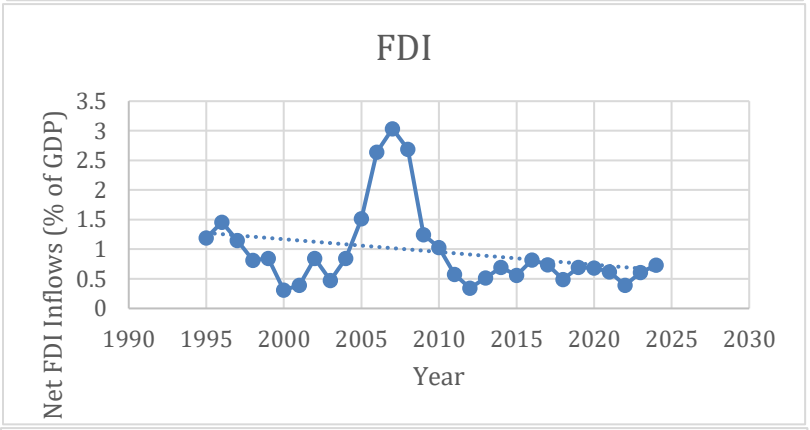
The consequences of CO2 emissions ripple through Pakistan's society and economy in devastating ways. Pakistan faces acute environmental degradation in the forms of severe urban air pollution (Ilyas et al., 2010; Batool et al., 2025), frequent floods (M. H. A. Khan, Arshad, Zahoor, & Khan, 2025), extreme rainfall (Weisheimer et al., 2025), and intense heat waves (Saeed, Almazroui, Islam, & Khan, 2017). As urban cities like Lahore (Arif et al., 2023; Naeem et al., 2025),

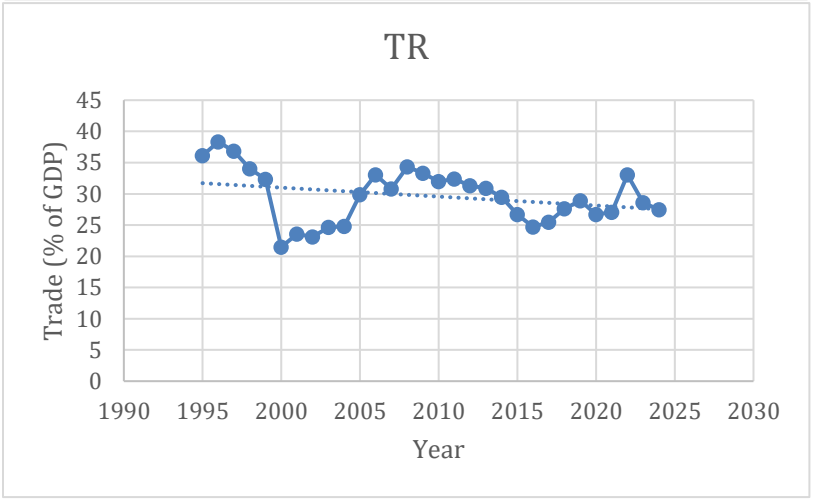
* Corresponding Author,

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Karachi (Moyebi et al., 2023), and Faisalabad (Zeeshan et al., 2024) choke under air pollution with AQI levels exceeding 300, severely impacting human health, the environment (Manisalidis et al., 2020; Ali et al., 2025), and incurring global economic costs due to illness and reduced productivity. On the other hand, Himalayan glaciers are melting rapidly, endangering water supplies for millions of people and causing significant agricultural losses (Singh, 2024; Ali et al., 2025). Moreover, climate change due to CO2 emissions leads to 170,000 premature deaths each year, causes events like the 2022 floods with $30 billion in economic losses, 33 million displaced people, and the 2025 floods with 5.9 million affected people and $2.95 billion in losses.







Various economic, technological, and institutional factors underlie rising CO2 emissions. As far as economic factors are concerned, some scholars argue that economic growth initially leads to environmental degradation at a certain level of income, and thereafter to environmental sustainability, as posited by the EKC (Grossman & Krueger, 1991). Moreover, some studies suggest that investment outside the nation brings cleaner technologies (Zarsky, 1999), while

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others argue that investment is directed toward pollution-intensive industries that cause environmental degradation (Cole & Elliott, 2005). Thus, developing nations strive to achieve the objectives of the Paris Agreement and Goal 13 on climate action of the UN Sustainable Development Goals (UNSDG). Thus, the combined effects of economic growth, FDI, TO, and environmental protection are of great importance for deriving effective economic policies to attain environmental sustainability. In Pakistan, these factors interact amid the post-WTO trade liberalization (Raza & Lin, 2024; Longston et al., 2025) and CPEC FDI (Zubedi, Jianqiu, Ali, Memon, & Zubedi, 2022), rendering their combined impact of critical importance. Meanwhile, TO fuels textile exports but escalates short-term emissions from transport and production (Arshad et al., 2024; Ali et al., 2025).

Institutional factors also contribute significantly to the escalation of CO2 emissions. Research and Development (R&D) increases CO2 emissions (Zhou et al., 2022; Arshad et al., 2025). Pakistan's overall R&D spending is 0.16% of GDP, yielding few green patents and missing gains. Moreover, there is extensive use of fossil fuels, with coal jumping 15% from CPEC plants, trapping industries and the power sector in outdated, emission-intensive cycles. While weak institutions turn potential gains into persistent problems. Moreover, Pakistan is ranked quite low i.e. 27 out of 100 according to Corruption Perception Index of 2024.

Extensive research has been conducted to check the relationships of macroeconomic indicators and environmental issues of Pakistan but still some linkages are need to be defined. As Pakistan emits lower CO_2 than the global average (Naeem et al., 2021; Ali et al., 2025), it is one of the most vulnerable countries in the region due to its CO2 emissions (Lin & Ahmad, 2017). Most papers examine the separate effects of economic growth, trade liberalization, FDI, environmental innovation, and institutional quality, thereby limiting the combined effects of economic, technological, and institutional factors on CO2 emissions in Pakistan. However, common problems include nonlinear patterns, feedback loops between variables, and infrequent use of ARDL methods that handle short- and long-run dynamics well.

This research addresses these deficiencies by investigating the short- and long-run effects of economic, technological, and institutional factors on CO2 emissions in Pakistan for the period 1995-2024 using the ARDL approach. However, the study makes three major contributions: first, it focuses on Pakistan, a developing country with lower CO2 emissions in the region but highly vulnerable to CO2 emissions. Second, it encompasses the effect of three dimensions, including economic, technological, and institutional indicators, to analyze the impacts on the environmental outcomes in Pakistan. Thus, these are the sole features of the current study on Pakistan.

2. Literature Review

Economic, technological, and institutional factors are critical determinants of CO_2 emissions in developing economies such as Pakistan. EKC explains the inverted U-shaped relationship between environmental degradation and economic growth, explaining the rise in emissions during early industrialization, followed by their decline at higher income levels due to technological advancements and policy shifts (Grossman & Krueger, 1991). Numerous empirical studies confirm the positive effect of economic growth on environment in case of Pakistan (Matloub et al., 2012; Mohiuddin et al., 2016; Anus et al., 2025), driven by inefficient energy technologies, fossil fuels (Ur Rehman et al., 2019; Marc et al., 2022; Marc & Ali, 2023), and carbon-intensive industrialization (Abbas et al., 2023; Audi et al., 2025). Pakistan's industrial sector, particularly textiles, construction, fertilizer, and transportation, predominantly consumes oil, natural gas, and coal, thereby intensifying CO_2 emissions (Khan et al., 2020; Marc et al., 2025).

Several studies also show that the growth-emissions relationship is predominantly positive due to weak environmental regulation, heavy fossil-fuel consumption, and urban expansion (Abbas et al., 2023; Ullah & Ali, 2024). Numerous empirical findings support the EKC, but the turning point for Pakistan remains unrealistically high, as it lacks sufficient financial stability and industrial innovation to achieve enhanced economic growth and reduced CO2 emissions (Mohsin et al., 2022; Marc et al., 2024). Thus, given the structural shifts in the Pakistan economy, the economic growth-CO2 emission relationship requires a dynamic ARDL approach to analyze both long-run and short-run adjustments.

FDI is a crucial economic indicator that influences environmental outcomes through mechanisms like the Pollution Haven and Pollution Halo Hypotheses. PHH proposes that foreign firms brings pollution-intensive industries to the countries where taxes on such industries is low and labor is cheap (Cole & Elliott, 2005). Conversely, the Pollution Halo Hypothesis states that FDI brings cleaner technologies (Zarsky, 1999). International results are mixed, and developing countries show evidence of the PHH due to poor institutional quality, low human capital investment, and vague policies (Marc & Ali, 2023; Honglei et al., 2025). For Pakistan, FDI contributes to environmental degradation when environmental regulations are weakly enforced (Sabir et al., 2020; Ali et al., 2021). Other studies depict that FDI reduces emissions when foreign firms transfer advanced, cleaner production technology to Pakistan (Bakhsh et al., 2017). Pakistan's institutional and structural weaknesses limit the potential for FDI to deliver environmental benefits (Ali et al., 2024). The existing literature seldom examines FDI and institutional quality together, where IQ plays a key

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role in determining whether Pakistan is a pollution-halo destination or a pollution haven. Therefore, incorporating both FDI and IQ provides a comprehensive picture of how FDI affects CO2 emissions in Pakistan.

Moreover, trade is also an economic indicator that exacerbates CO2 emissions. Technology affects CO2 emissions through technique, composition, and scale (Antweiler et al., 2001). Globally, TO increases emissions when countries specialize in pollution-intensive goods, and reduces emissions when cleaner production technology is transferred through integration (Grossman & Krueger, 1991). In developing countries, trade liberalization increases emissions because export-led growth depends on energy-intensive industries (Copeland & Taylor, 2001). Empirical studies on Pakistan show that TO generally increases CO2 emissions due to the expansion in manufacturing and transport sectors (Ansari et al., 2020; Ali et al., 2021; Hussain & Khan, 2022). Some literature indicates that long-term benefits are achieved through the import of energy-efficient machinery and the adoption of improved production techniques. Nevertheless, Pakistan's lax environmental regulations lead to an increase in pollution-intensive activities that outweigh technical improvements (Audi & Ali, 2018; Moyebi et al., 2023). However, the research lacks an integrated model that jointly analyzes TO with FDI, environmental innovation, and institutional quality. This gap justifies its comprehensive inclusion in the current ARDL model, where the emissions impact of trade liberalization in Pakistan is conditional on technology adoption, governance, and macroeconomic structure.

The technological dimension includes environmental innovation that is generally recognized as a vital determinant of long-term decarbonization (Udeagha & Ngepah, 2023). Evidence shows a significant reduction in green R&D (Cho & Sohn, 2018), renewable energy technologies (Saber & Venayagamoorthy, 2010), and energy-efficient production processes (Hasanbeigi et al., 2012; Marc & Ali, 2016). However, low innovation capacity, insufficient R&D funding, and challenges in technology adoption limit the impact of environmental innovation in developing countries (Adenle et al., 2015). Pakistan is considerably under-researched in this domain. The literature highlights that Pakistan lags behind in renewable energy technologies (Asghar et al., 2023; Martin, 2025), green patents, and industrial innovation (Raza et al., 2022; Carlo, 2025). Moreover, Pakistan's energy mix comprises oil, gas, and coal, overshadowing any marginal environmental gains from emerging renewable initiatives. As environmental innovation is widely integrated in Pakistan's policy framework and academic literature, analyzing its role in the multivariate emission model is of huge significance. The model allows assessing whether environmental innovation reduces emissions or remains insufficient to incorporate.

Wang et al., (2020) state that financial development can either facilitate green investment or expand credit to pollution-intensive industries. Empirical research finds both effects, depending on capital allocation patterns and regulatory quality (Tamazian & Rao, 2010; Lee & Zhuang, 2025). However, Imamoglu (2019) argued that financial development is directed towards conventional industries rather than the renewable energy sector in developing countries. The same is true for Pakistan, where financial development channels credit to fuel energy demand and expand industrial activity (Ur Rehman et al., 2019). However, recent research indicates that financial inclusion and green finance lead to increased investment in cleaner energy up to a certain level (Hussain et al., 2023). Thus, the inclusion of financial development leads to the comprehensive analysis of the model.

Lastly, the institutional dimension includes Institutional quality (IQ), which plays a key role in determining environmental outcomes as strong institutions enforce regulations, reduce corruption, and improve compliance (Fatima et al., 2022; Qasir & Agha, 2025). In the developing countries, weak institutions lead to higher CO2 emissions due to a lack of enforcement of regulatory frameworks (Anwar et al., 2025; Ahmad & Hu, 2025). However, weak institutions contribute to rising emissions through unchecked industrial expansion and poor enforcement of environmental standards (Shoaib et al., 2025; Chowdhury & Hassan, 2025). Thus, in the multivariate model, institutional quality (IQ), along with environmental innovation and trade liberalization, explains the persistent pattern of CO2 emissions in Pakistan.

Overall, the literature reveals substantial work on global determinants of CO2 emissions, but there is limited evidence for Pakistan. Most Pakistan-focused studies analyze growth, FDI, trade, or finance separately, often using short samples or static models. Critical variables such as environmental innovation and institutional quality are rarely incorporated. Furthermore, the combined dynamic impact of GDP per capita, FDI, TO, environmental innovation, and institutional quality, especially through an ARDL model that accommodates mixed integration orders and captures long- and short-run dynamics, remains unexplored. The ARDL model offers a suitable framework to capture Pakistan's structural shifts and evolving policy landscape, providing more robust insights for environmental and economic policy.

3. Methodology

a. Data

The research employs annual data spanning 1995 to 2024, sourced from multiple databases, including the World Development Indicators (WDI), the World Governance Indicators (WGI), and the OECD website. Table 1 provides details on the variables used in this analysis along with their respective descriptions.

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Table 1: Variables Description

	Parameter	Proxy	Source
Dependent Variable	CO2	CO2 emissions (metric tons per capita)	WDI
		Dimensions	
Economic Dimension	GDPPC	GDP per capita (constant 2015 US $)	WDI
	FDI	Net FDI inflows (% of GDP)	WDI
	Trade	Trade (% of GDP)	WDI
Technological Dimension	EI	Environmental-related technological innovation	OECD website
Institutional Dimension	IQ	Government Effectiveness	WGI)

b. Econometric Model

The economic model developed for the study is;

$$CO_{2t} = \beta_0 + \beta_1 * GDPPC_t + \beta_2 * FDI_t + \beta_3 * EI_t + \beta_4 * TR_t + \beta_5 * IQ_t + \varepsilon_t \quad (1)$$

All β_s are the parameters with their corresponding coefficients and each independent variable' intercepts that needs to be estimated. While ε_t stands for the error term that includes factors not included in the equation.

c. Econometric Methodology

The research employs various methodological methods including pre-estimation (descriptive statistics, unit root tests), estimation, and post estimation techniques.

i. Descriptive Summary

Descriptive statistics are the summary metrics that quantitatively describe a collection of information including central tendency, variation, and distribution shapes of the estimators.

ii. Unit Root Test

The stationarity of the data in the time series analysis is used through the Augmented Dickey Fuller (ADF). The model equation of the ADF technique is as follows;

$$\Delta y_t = \alpha + \beta_t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta i \Delta y_{t-i} + \epsilon_t \quad (2)$$

Where Δy_t is the first difference of time series at time t (i.e $y_t - y_{t-1}$), α is the constant or intercept term (drift), β_t is the deterministic time trend component, γy_{t-1} is the lagged level of the time series; it is the crucial term for the unit root test, and ϵt is the white noise error term (residual). The number of lags, p, is typically selected using information criteria like AIC or BIC.

iii. Lag Selection Criterion

The lag selection criterion is a statistical tool that systematically identifies the optimal number of lagged variables for time-series analysis. In econometric modeling, researchers typically rely on information criteria such as AIC, HQ, and SIC to establish the most suitable lag length. Among these, the AIC is often highlighted as the more precise metric for identifying optimal lags.

$$AIC = 2K - 2\, ln\, ln\, (L) \quad (3)$$

Where k represents the count of parameters (encompassing the intercept and residual variances, L denotes the Maximum Likelihood Function value, and ln indicates the natural logarithm.

iv. Auto Regressive Distributed Lag (ARDL)

ARDL is used econometric modeling technique for testing long- and short-run relationships among variables when they are of mixed orders. However, the key features of ARDL are the flexibility to use variables at levels and in first differences, to estimate long-run and short-run results, and to conduct bounds testing (Pesaran & Shin, 1995). The equation for ARDL is;

$$Y_t = \beta_0 + \beta_1 Y_{t-1} + \cdots + \beta_\rho Y_{t-m} + \alpha_0 X_t + \alpha_1 X_{t-1} + \alpha_2 X_{t-2} + \cdots + \alpha_q X_{t-n} + \varepsilon_t \quad (4)$$

Where, Y_t denotes the dependent variable and X_t represents the explanatory variables, β and α are the corresponding coefficients. $\varepsilon_t$is the ARDL estimation equation takes the following form:

$$\Delta CO2_t = \beta_0 + \beta_1 CO2_{t-1} + \beta_2 GDPPC_{t-1} + \beta_3 FDI_{t-1} + \beta_4 TR_{t-1} + \beta_5 EI_{t-1} + \beta_6 IQ_{t-1} + \sum_{i=1}^{p} \beta_{7i} \Delta CO2_{t-i} + \sum_{i=1}^{p} \beta_{8i} \Delta GDPPC_{t-i} + \sum_{i=1}^{p} \beta_{9i} \Delta FDI_{t-i} + \sum_{i=1}^{p} \beta_{10i} \Delta TR_{t-i} + \sum_{i=1}^{p} \beta_{11i} \Delta EI_{t-i} + \sum_{i=1}^{p} \beta_{12i} \Delta IQ_{t-i} + \epsilon_t \quad (5)$$

v. Error Correction Method (ECM)

The ECM plays a crucial role in identifying short-run effects and evaluating the model's ability to revert to the long-run equilibrium following the deviations. Specifically, the coefficient of the error correction term (ECT) quantifies the pace of this adjustment mechanism.

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The equation for ECM is as follow;

$\Delta CO2t = \beta 0 + \sum \beta 1i\Delta CO2t{-}I + \sum \beta 2i\Delta GDPPCt{-}i + \sum \beta 3i\Delta FDIt{-}i + \sum \beta 4i\Delta EIt{-}i + \sum \beta 5i\Delta TRt{-}i + \sum \beta 4i\Delta IQt{-}I + \varepsilon t$

$$\Delta CO2_t = \beta_0 + \sum_{i=1}^{p} \beta_{1i}\, \Delta CO2_{t-i} + \sum_{i=1}^{p} \beta_{2i}\, \Delta GDPPC_{t-i} + \sum_{i=1}^{p} \beta_{3i}\, \Delta FDI_{t-i} + \sum_{i=1}^{p} \beta_{4i}\, \Delta EI_{t-i} + \sum_{i=1}^{p} \beta_{5i}\, \Delta TR_{t-i} + \sum_{i=1}^{p} \beta_{6i}\, \Delta IQ_{t-i} + \epsilon_t \quad (6)$$

d. Diagnostic Tests

Breusch-Pagan-Godfrey, Breusch-Godfrey, and Jarque-Bera (JB) tests are used to test for heteroscedasticity, Serial Correlation, and normality, respectively. Moreover, Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) Tests are used for stability analysis that help identify structural breaks or shifts in time series data. These diagnostics are significant, as unstable coefficients can yield inconsistent and unreliable model outcomes.

4. Results and Discussion

a. Descriptive Statistics

Descriptive measures are based on 30 data points and shown in Table 2. Mean measures the average values of the variables in the data set. TR shows the overall maximum average of 29.63154, and lnCO2 shows the overall minimum mean of .2306996. While TR displays the overall maximum value of 38.33013, lnCO2 shows the overall minimum value of -.4028979 among all variables.

Table 2: Descriptive Statistics

Variables	Mean	St. Deviation	Max	Min
lnCO2	-.2306996	.1224944	-.0183472	-.4028979
lnGDPPC	7.150572	.1632811	7.404695	6.93391
FDI	.9642789	.6926665	3.035719	.309595
EI	.9596098	.5331815	2.646516	.176125
TR	29.63154	4.331431	38.33013	21.45996
IQ	-.6198873	.120777	-.3838154	-.8337232

The deviation of values of a variable from its mean point is checked through the standard deviation. TR exhibits a high overall standard deviation of 4.331431, and IQ has the lowest standard deviation of .120777.

b. Unit Root Test

Augmented Dickey Fuller (ADF) Test is applied on all the variables of the study and results are shown in Table 3. The results of the unit root test are presented in Table 3. With the exception of one variable, Environmental Innovation, all the variables become stationary at first differences; Environmental Innovation is level-stationary.

Table 3: Unit Root Test

Variables	Level (Test Statistic (p-value))	Stationary (Test Statistic (p-value)	Order of Integration)
CO2	0.186 (0.9715)	-3.840 (0.0025)	I(1)
GDPPC	-1.140 (0.6989)	-4.730 (0.0001)	I(1)
FDI	-1.775 (0.3930)	-3.706 (0.0040)	I(1)
EI	-3.341 (0.0131)*	-7.604 (0.0000)	I(0)
TR	-2.340 (0.1594)	-5.425 (0.0000)	I(1)
IQ	-2.043 (0.2680)	-4.969 (0.0000)	I(1)

p-value < significance level (0.05) → *Reject H₀ → Series is stationary.*

Table 4: Bounds Test Results

T Statistics	Value
F-Statistics	7.333
t-Statistics	-5.628
Critical Value Bounds	
Significance	I(0) Lower Bounds
10%	2.26
5%	2.62
1%	3.41

Source: Authors' Calculations

Note: If F-statistic > upper bound → Reject H₀ (cointegration exists).

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Length Selection

AIC automatically selected the most efficient ARDL configuration (1, 2, 2, 0, 0, 1), balancing model complexity and goodness of fit by evaluating potential models within the predefined maximum lag bounds (maxlags = 5 2 2 2 2 1). This rigorous selection technique ensures that the final model is both parsimonious and statistically robust, capturing the underlying data dynamics.

a. ARDL Bound Testing Approach

Table 4 shows the bound test results.

b. LR Results

Table 5 shows the long-run results of the study.

Table 5: Long run Results of ARDL

lnCO2 as Dependent Variable	
Variable	**Coefficient (p-values)**
lnGDPPC	0.8093 (0.000)
FDI	0.0923 (0.000)
EI	0.0231 (0.160)
TR	-0.009 (0.005)
IQ	0.0555 (0.460)

Source: Authors' Calculations

Note: p-value ≤ 0.05 → Reject H₀ (significant long-run effect)

Note: p-values are in parentheses.

The results show that 1 % increase in the GDP per capita results in increase in CO2 emission by 0.8093%. Xuan (2025) found the similar results for Australia by using data from 1990 to 2023. Likewise, Chaabouni and Saidi (2017) reported a positive effect of CO2 emissions on the economic growth across 51 nations of varying income levels. In the case of Pakistan, the positive and significant association between CO2 and GDPPC reported in the current research confirms earlier studies (M. U. Ali, Gong, Ali, Wu, & Yao, 2021; Matloub Hussain et al., 2012). However, the findings are contradictory to EKC hypothesis as Pakistan is not using energy efficiently.

FDI shows a significant, positive association with CO2 emissions in Pakistan, with a 1% increase in FDI leading to a 0.0923 increase in emissions in the long run. The results of this study are aligned with the studies of M. Khan, Rana, and Ghardallou (2023) and Musah et al. (2022) where these studies are proved PHH, which attributes the rise in emissions to investments by developed countries in energy-intensive, fuel-based industries, such as the CPEC coal projects. Additionally, time-series study Naeem et al. (2021) confirm that Pakistan's lax environmental regulations and emphasis on economic growth over environmental quality further support the PHH.

The results also show TO has a significant and negative effect on CO2 emissions. A 1% increase in TO is associated with a 0.0095% decrease in CO2 emissions. The current research aligns with earlier studies (Zhang, Liu, & Bae, 2017) as TO leads to the import of cleaner technologies such as Chinese solar panels (>13GW in early 2024), electric buses, Chinese-funded wind and hydropower technology, and zig-zag brick kiln technology, all contributing to improved environmental quality. This finding also supports the EKC hypothesis that as countries reach a certain level of income and trade integration, environmental quality improves. In Pakistan, previous studies have shown a significant negative association between CO2 and TO (Khawaja, Ali, Bhatti, & Khan, 2025), further supporting our findings.

c. Short Run ARDL Estimates

Table 6 estimates the SR results retrieved from the ARDL model.

Table 7: ARDL SR Coefficients

	Dependent Variable: lnCO2		
Variable	Coefficient	Variable	Coefficient
D.ln_GDPPC	0.5249 (0.040)*	LD.ln_GDPPC	0.6023 (0.020)*
D.FDI	-0.0376 (0.024)*	LD.FDI	-0.0278 (0.055)**
D.EI	0.02308 (0.160)	D.TR	-0.0095 (0.005)*
D.IQ	0.15489 (0.021)*	_cons	-5.0437 (0.000)*
ECT (L1.ln_CO2)	-0.8626 (0.000)*		
R-squared	0.9058		

Source: Authors' Calculations

Note: p-value ≤ 0.05 → Reject H₀ (significant short-run effect)

ECT is statistically significant at the 1% level and negative, with a value of -0.8627%, confirming stable cointegration among the variables. A negative ECM value predicts the annual speed of adjustment of the dependent variable toward

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its equilibrium. The R-squared value of 0.9058% indicates that the model explains 90.58% of the variation in the dependent variable.

d. Diagnostic Tests

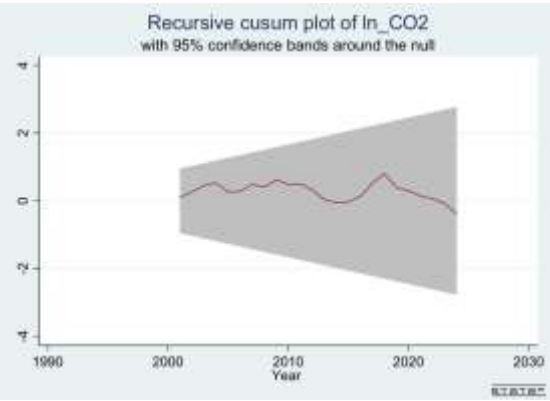
Various diagnostic tests included tests for heteroskedasticity, autocorrelation, and test for normal distribution of residuals are carried out to check whether the regression model is robust and meets the key assumptions. Based on the results, there is no evidence of heteroskedasticity and serial correlation while there is normal distribution of errors.

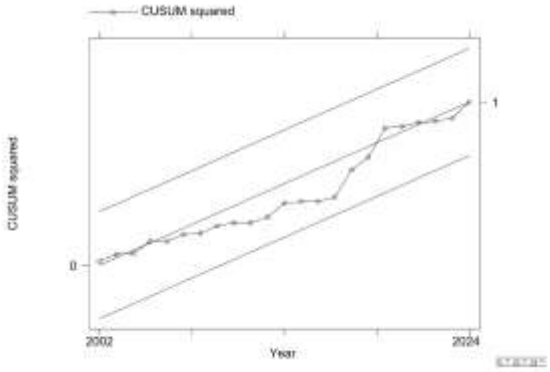
Table 8: Diagnostic Tests

Test	F Statistics	Conclusion
Breusch-Godfrey Test	0.903, p-value: 0.3421	No serial correlation
Breusch-Pagan-Godfrey Test	0.02, p-value: 0.8772	No Heteroskedasticity
Jarque-Bera Normality Test	2.655, p-value: 0.2652	Residuals are normally distributed
Mean VIF	2.08	No severe multicollinearity

e. CUSUM and CUSUMSQ Test

The recursive CUSUM plot shows that the test statistic stays within the 95% confidence bands while CUSUM of squares statistic stays within the 5% critical bounds. This indicates no structural breaks or parameter instability in the ln_CO2 model over time. These results show that the model parameters are stable over time and that the results can be interpreted with confidence, as there is no evidence of structural instability affecting the model's validity**.**





5. Conclusion

The current research aims to assess the effects of GDP per capita, FDI, Environmental Innovation (EI), TO, and Institutional Quality (IQ) on CO2 emissions in Pakistan for the period 1995-2024. Various pre-estimation, estimation, and post-estimation techniques are employed to establish the robust relationship among the variables. ADF unit root test for stationarity posits mixed order of integration of I (0) and I (1) for variables. So, the ARDL Bounds Test is carried out, which is well-suited to variables with mixed orders of integration. The optimal lag length is selected through the Akaike Information Criterion (AIC). However, the long-run coefficients are estimated through the ARDL Bounds Test, while the short-run results are predicted through the VECM method. After that, diagnostic tests were conducted to assess the model's robustness. Thus, the results of the long-run model show that GDP per capita, FDI, and TR are statistically significant and positively affect CO2 emissions in Pakistan, while EI and IQ have no significant effect. Moreover, the ECM term is statistically significant and indicates a significant annual speed of adjustment for the dependent variable toward its equilibrium. Also, CUSUM and CUSUMQ tests are used to assess the model's stability by detecting structural breaks across the time periods under study.

a. Policy Recommendations

The grave consequences of CO2, driven by various economic factors, are impacting Pakistan's socioeconomic conditions in many ways. Based on the ARDL long- and short-run estimates, policymakers should adopt effective and comprehensive policies to bring Pakistan's socioeconomic trajectory back onto its potential track. As economic growth significantly increases CO2 emissions in the long run, policymakers need to prioritize green growth strategies by implementing environmental rules and regulations into development projects, promoting energy-efficient technologies, expanding renewable energy, and, furthermore, introducing carbon pricing instruments to the market. In the case of FDI in Pakistan, it increases CO2 emissions in the long run, suggesting that FDI is concentrated in energy-intensive sectors (Pollution Haven Hypothesis). Thus, policymakers redirect FDI spending toward environmental sustainability sectors under strict regulations, incentives for clean and green investments (such as renewable energy projects), and effective impact assessments. In terms of trade that reduces CO2 emissions in the long run in Pakistan, this is a clear indication

of access to cleaner technologies and more efficient production methods. Therefore, Pakistan should focus more on trade liberalization, export diversification, and incorporating environmental regulations into trade agreements.

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