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CO_2 EMISSIONS AND STATIONARITY IN PAKISTAN: A TIME-SERIES ANALYSIS OF SOCIOECONOMIC, ENERGY, ENVIRONMENTAL AND TECHNOLOGICAL INDICATORS

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CO_2 emissions; time-series analysis; Augmented Dickey–Fuller; stationarity; energy consumption; urbanization; technological innovation; Pakistan.

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Abstract
Over the past 30 years, Pakistan has seen significant economic development, urbanization, energy needs, and environmental shifts. The study investigates the trends and stationarity of the carbon dioxide (CO_2) emissions and selected socioeconomic, energy, environmental, technological, financial, demographic, and natural-resource indicators across Pakistan over the time period 1990–2023. Secondary data was used annually from world recognized data sources such as the World Bank, International Energy Agency, Global Carbon Project, Our World in Data, International Monetary Fund, and Financial Development Database. Descriptive time-series trend analysis and Augmented Dickey–Fuller (ADF) unit-root test were performed on 13 variables. A significant long-term trend of increasing CO_2 emissions was found, with emissions around 66 Mt CO_2e in 1990, reaching 236 Mt CO_2e in 2022 and decreasing in 2023. In general, energy consumption, GDP, urbanization and technological development had positive trends while forest area had a negative one. The ADF test indicates that three of the variables, namely GDP growth, urban population and fossil-fuel energy consumption, were stationary at level while ten were non-stationary. Persistent trends were much less prominent after first-order differencing and the fluctuations around zero were more stable. The findings highlight the importance of stationarity testing and sustainable energy and technological policies for improving Pakistan's environmental sustainability.

1. INTRODUCTION

The energy demand for urbanization and economic development has grown rapidly around the globe, along with the environmental pressure. Cities consume a significant portion of the world's energy and are responsible for a significant share of anthropogenic greenhouse gas emissions (GHGs) (IEA, 2021; IPCC, 2022). Pakistan is undergoing the same process and its urban population is growing steadily as are its infrastructure, industry, transport and services. These processes can lead to higher energy consumption, increased waste production, air pollution and pressure on natural resources, but with the support of good planning and clean

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technologies, their impacts can be mitigated (Ali et al., 2019; Khalid et al., 2021).

Tanveer et al. (2025) used the ARDL model to study Pakistan's data (1990–2017) and demonstrated the impact of urban expansion on methane and nitrous oxide emissions. (Riaz et al. 2017; Zeb et al. 2025) used panel quantile regression to study the relationship between technological innovation and the ecological footprint in South Asia, which found that the impact of technological innovation is initially on the environmental quality, but gradually has a positive impact on it. Javed et al. (2025) and Sajid et al. (2025) conducted studies on Pakistan using ARDL and nonlinear ARDL model, which found that technological innovation has impactful effect to alleviate the pressures of ecological footprint and improve environmental quality. Anas et al. (2023) applied Cross-section ARDL approach for the period of 2000 to 2018 for emerging economies with green innovation and forest cover enables environmental sustainability. Danish and Hassan (2023), using a Dynamic ARDL approach with Pakistani data, found that natural resource rent, especially in urbanization, remains a driver of carbon emissions, The dynamic relationship between natural resources, TI and environmental sustainability was studied by Chen et al. (2022) based on annual data for the newly industrialized countries from 1990 to 2019. The long-run outcomes revealed that natural resource rent was a constraint for environmental sustainability.

The major aim of this study is (1) Presentation and analysis of urbanization and environmental scenario of Pakistan over the time (2) to examine the impacts of urbanization and other key macroeconomic variables on CO2 emissions in Pakistan in the short and long run (3) to identify the causal relationship among the variables of interest.

2. Materials and Methods

2.1. Study Area

The area of Pakistan is 796,096 km^2. It lies between 23.35°–37.05° North and 60.50°–77° East. To the east the country borders with India, to the south with the Arabian Sea, and to the north with China, with Afghanistan and Iran to the West (Pakistan Bureau of Statistics, 2017). The national population of 241,499,431, according to the digital census of 2023. The average density is about 261 people per square kilometer (Asian Development Bank, 2022; Pakistan Bureau of Statistics, 2017). The Himalayan, Karakoram and Hindu Kush Mountains in the north. (Seto et al., 2012; IPCC, 2022). Indus Plain in Punjab and Sindh. (Hasan & Raza, 2015; Cervero, 1998). Baluchistan Plateau in Baluchistan province. Asian Development Bank, 2022; World Bank, 2021; Khan, 2022). Coastal Belt is the belt along the Arabian sea, where Karachi and Gwadar are located. (Revi, 2008; World Bank, 2021; IPCC, 2022). The clime of Pakistan is dry and semi-dry (IPCC, 2022).

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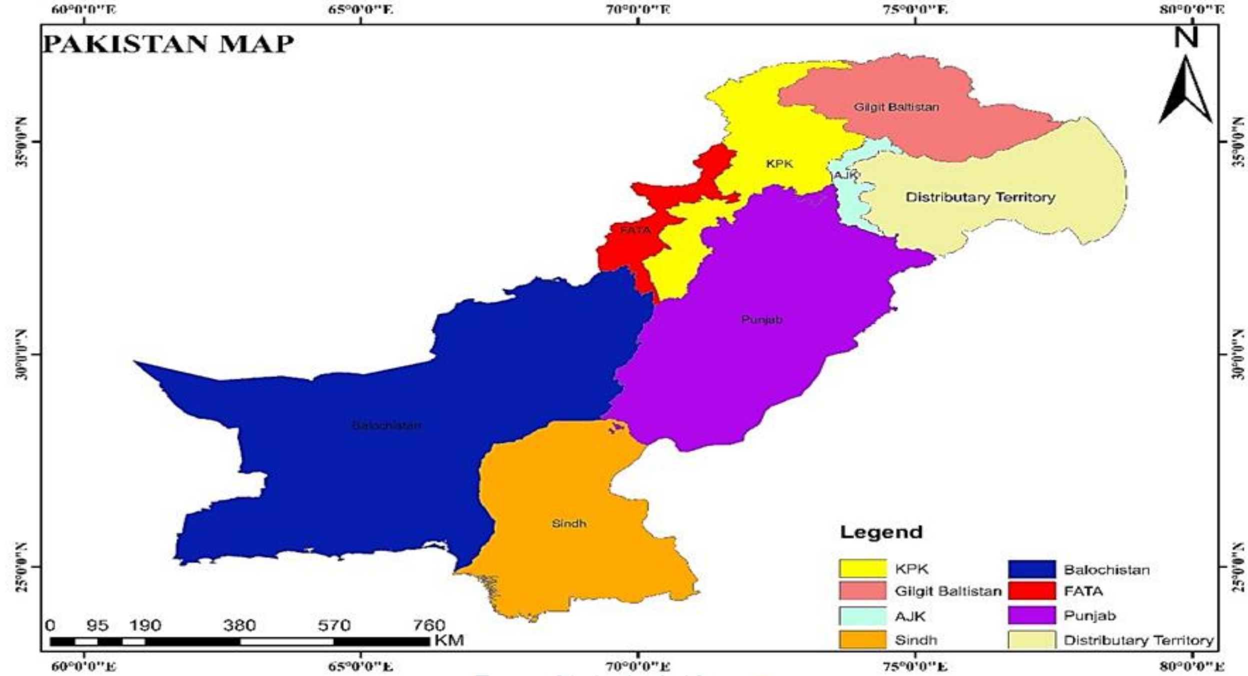

2.2. Data Source

In this study, secondary annual time-series data ranging from 1990 to 2023 for Pakistan is used. Data were obtained from internationally recognized and reliable databases. These are mainly the World Bank's World Development Indicators (WDI), International Energy Agency (IEA), Global Carbon Project (GCP), Our World in Data (OWID), International Monetary Fund (IMF) and Financial Development Database. These databases contain uniform data on environmental and economic indicators, energy, demographic, technological, financial and natural-resource indicators. CO_2 emission data were taken from internationally recognized carbon-emission datasets, and GDP, GDP growth, urban population, forest area, natural-resource rents and energy-related indicators were mostly taken from the World Bank and other international databases (Table 1). Technological innovation was captured by the number of patent applications filed by residents of the country and by non-residents (counted as domestic) and financial development by the Financial Development Index. The use of internationally recognized secondary data adds credibility and replicability to the research since the data collection, validation, estimation and reporting procedures are uniform at these institutions. A time series data set with consistent observations was prepared for 1990 – 2023. The obtained data was then subjected to time-series trend analysis and Augmented Dickey–Fuller (ADF) unit-root test to examine for time-series trends and stationarity.

Table 1: The analysis includes thirteen variables representing environmental, economic, energy, technological, demographic, financial, and natural-resource dimensions.

Category	Variable
Environmental	CO_2 emissions
Economic	GDP
Economic	GDP growth
Energy	Energy use

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Energy	Fossil-fuel energy consumption
Energy	Renewable-energy consumption
Environment	Forest area
Natural resources	Natural-resource rents
Financial	Financial Development Index
Demographic	Urban population
Technology	Resident patent applications
Technology	Non-resident patent applications
Technology	Technological innovation

2.3. Data Analysis

2.3.1. Time-Series Analysis

The study utilizes annual time-series analysis to decipher the temporal evolution of CO_2 emissions and the selected socioeconomic, energy, environmental, technological, financial and demographic indicators in Pakistan, 1990-2023. Long-term trends, short-term fluctuations, growth and decline are detected with the time-series analysis, as well as patterns of individual variables' behavior over the course of the study (Gazi et al., 2022). Every variable was organized on a chronological basis (year) and analyzed graphically and descriptively. To get a sense of the variables' annual movements and to determine if there are consistent upward and downward trends, line graphs were used. The temporal analysis offers a basic knowledge about the historical development of the chosen indicators. CO_2 emissions, GDP, energy consumption, renewable energy consumption, urban population, technological innovation, forest area, natural-resource rents and financial development were specifically analyzed to see their general direction and variability over time (Makur, 2024). GDP growth and fossil-fuel energy consumption were also analyzed individually since they are growth rates or shares and not absolute levels. The time-series analysis is descriptive (not causal). Thus, when two variables go up or down at the same time, the change in one variable is not said to cause the change in the other (Prasetyani et al., 2021). Rather, the analysis offers an historical description of the evolution of each indicator over 1990-2023 and sets the stage for the subsequent testing of stationarity.

2.3.2. Unit Root Test: Augmented Dickey–Fuller (ADF)

The temporal trends have been examined and the Augmented Dickey–Fuller (ADF) unit-root test was conducted to ascertain the stationarity at level of the time series selected. The stationarity of the time-series is important because if a time-series is stationary then the statistical characteristics of the series remain relatively constant with time, while if it is not stationary, then there may exist a persistent trend or a unit root (Ishioro, 2022). The ADF test was chosen because it tests the null hypothesis that a time series is non-stationary (has a unit root) against the alternative hypothesis that the series is stationary (Roza et al., 2022; Vasilopoulos et al., 2022; Yang et al., 2023). The general ADF regression is Eq (1):

$$\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \sum_{i-1}^{p} \delta_i \Delta Y_{t-i} + \varepsilon_t$$

where:

- Y_t = observed variable,
- ΔY_t = first difference of the variable,
- α = intercept,
- βt = deterministic trend,
- γ = coefficient of the lagged variable,
- p = number of lagged differences,
- ε_t = random error term.

The hypotheses of the ADF test are:

Null Hypothesis (H_0):

The time series contains a unit root (non-stationary).

$$H_0 : \delta = 0$$

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Alternative Hypothesis (H_1):
The time series is stationary.

$$H_1 : \delta < 0$$

The decision rule adopted in this study was based on the p-value obtained from the ADF test:

- p-value < 0.05: Reject the null hypothesis; the variable is stationary.
- p-value ≥ 0.05: Fail to reject the null hypothesis; the variable is non-stationary.

The Python implementation used the *adfuller()* function from the Stats models package with automatic lag selection based on the Akaike Information Criterion (AIC). Automatic lag selection helps eliminate serial correlation in the residuals while avoiding over-parameterization. All thirteen variables (CO_2 emissions, GDP, GDP growth, non-resident patent applications, resident patent applications, technological innovation, energy use, renewable-energy consumption, forest area, natural-resource rents, financial development, urban population and fossil-fuel energy consumption) were tested separately using the ADF method. Variables found to be non-stationary at level were taken to be candidates for first-order differencing for subsequent time-series applications:

$$\Delta Y_t = Y_t - Y_{t-1}$$

where:

- ΔY_t = first-differenced series,
- Y_t = current observation,
- Y_{t-1} = previous observation.

In the Python implementation, first-order differencing was performed using the *diff()* function provided by the Pandas library. Since differencing creates one missing observation at the beginning of the series, the resulting missing value was removed using the *dropna()* function. The present study, however, does not use other econometric techniques. It is important to note that the analysis is limited to time-series trend analysis and the ADF unit-root test, and first differencing is only discussed as an implication of the stationarity tests. This method allows separating statistical characteristics of variables from those that are permanently non-stationary for the period 1990-2023.

3. Results

3.1. Time series Analysis

The annual trends of CO_2 emissions and selected socioeconomic, energy, environmental and technological indicators are analyzed annually in Pakistan from 1990 to 2023 using the time-series analysis. The analysis is made using 13 variables observed annually and the emphasis is on the long-term movements, fluctuations and changes of the variables during the study period. This way, one can gain a general understanding of the variables' change over time and serves as a foundation for the next analysis using econometric approach. The trend is clear and with time CO_2 emissions are increasing: from the ~66 Mt CO_2e in 1990, to over 200 Mt CO_2e from 2015 onwards, to ~236 Mt CO_2e in 2022 (Figure). There was a short-term shift in emissions dynamics in 2023, with a decrease. The overall rise is consistent with the growth of industrialization, urbanization, economic activity and the reliance on fossil fuel energy.

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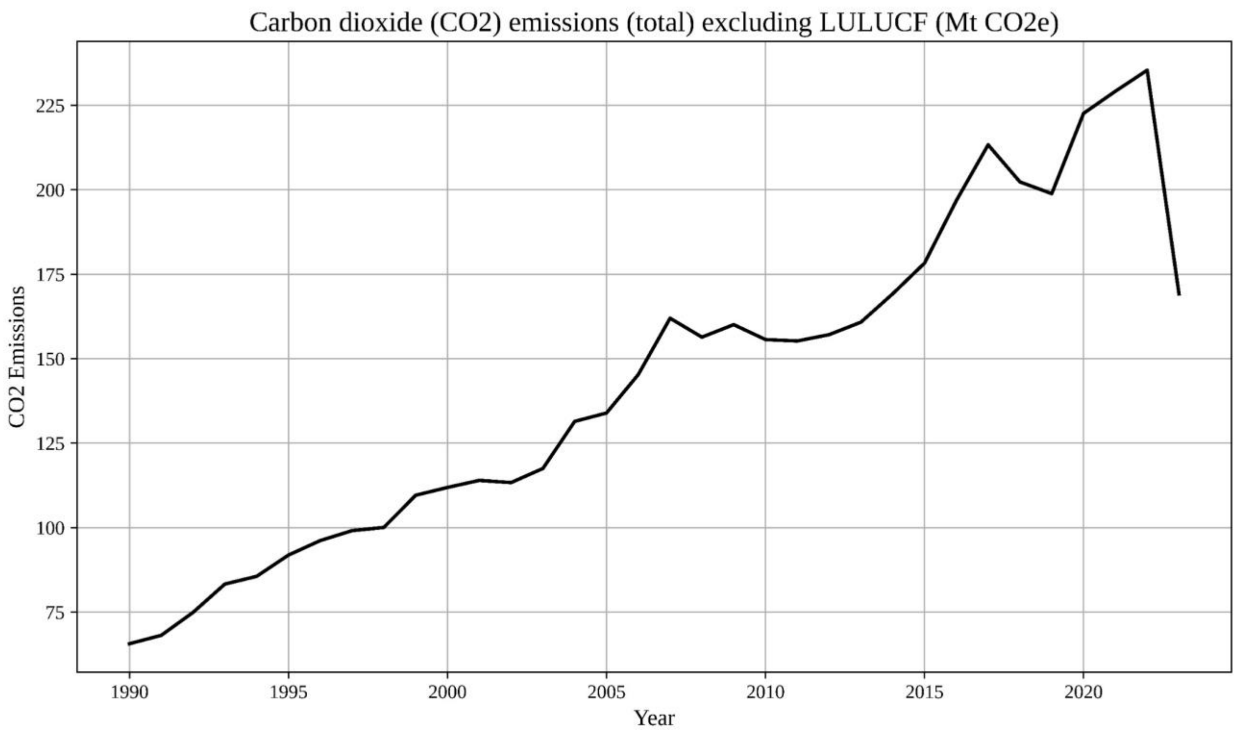

Figure 2: Trend of carbon dioxide (CO_2) emissions (total) excluding land-use, land-use change, and forestry (LULUCF) in Pakistan from 1990–2023.

The per-capita energy consumption also shows a general trend of increasing. The energy use rose from around 370 kg of oil equivalent per capita in 1990 to almost 457 kg in 2007 and about 470 kg in 2022 (Figure 3). Consumption fell from 2008-2012 but has bounced back since then. This trend reflects the growing demand for energy with the development of the economy, industry, infrastructure and urbanization. The Financial Development Index showed significant fluctuations and was not of a continuous trend. It rose from around 0.12-0.13 in the early 1990s to around 0.37 in 2007, and decreased significantly in 2008-2010. Financial development has been relatively stable since 2011 and picked up slightly in 2023 before dipping slightly in 2024. The movements reflect shifts in financial-sector development, credit conditions, financial markets and overall economic conditions. In the study period, fossil-fuel energy use was still predominant. In 1990, it accounted for about 52.5% and in 2007, it accounted for about 62%. However, fossil fuels remained a significant part of Pakistan's energy mix even after dropping to around the 45% in 2015. This long-standing reliance is crucial in understanding the trend of growing CO_2 emissions. GDP also shows a robust long-term growth trend, although dips in the trend are linked to economic and world-shock events. From the early 1990s GDP was under US$50 billion, but has increased to about US$375 billion in 2021–2022, before dropping in 2023. The use of renewable energy grew slowly and moderately, while the number of urban populations grew steadily during the period. The overall findings of the time-series analysis show that Pakistan had significant economic, energy, financial and urban transformation between 1990 and 2023. Before performing further econometric analysis, the stationarity properties of these variables must be examined, as a result of their simultaneous

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growth, in terms of GDP, energy consumption, urbanization and CO_2 emissions.

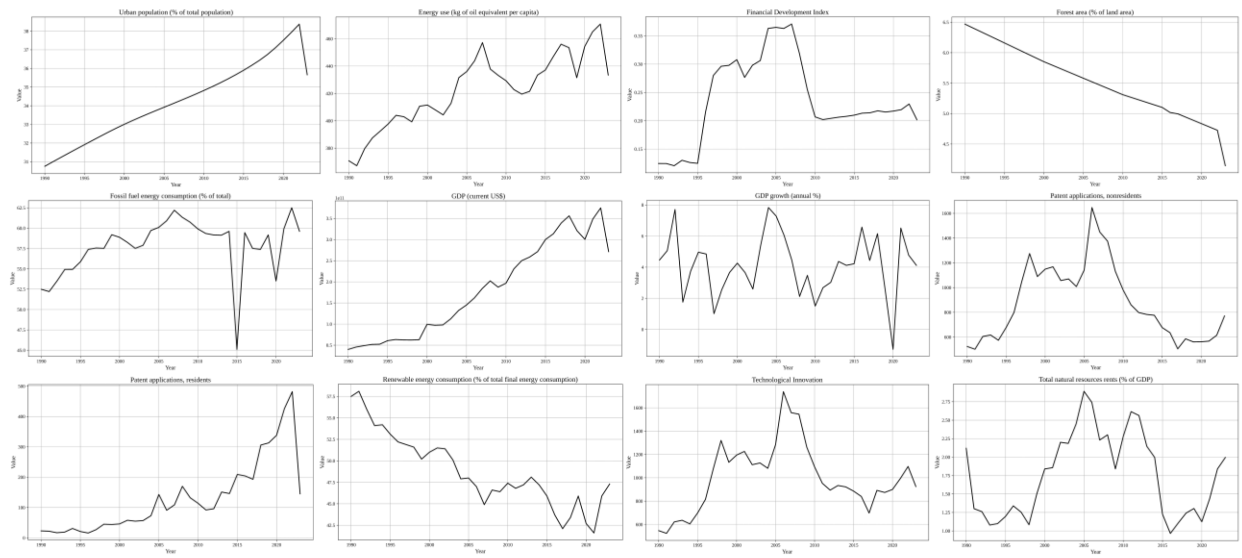

Figure 3: Time series analysis of socio-economics factors from 1990-2023.

3.2. Unit Root Test: Augmented Dickey–Fuller (ADF)

A unit root test is a statistical test that can be applied to a time-series variable to test whether it is a stationary or non-stationary process. Stationarity means there are no persistent changes in the statistical characteristics of a series such as its mean, variance, and auto covariance. Stationarity test is one of the key tests in time series analysis, as regression models with non-stationary variables might be misleading and lead to spurious relationships. For this reason, determining the order of integration of each variable is a significant first step before doing any more econometric analysis. In this study, the Augmented Dickey–Fuller (ADF) test is used to study stationarity properties of the 13 variables used in the analysis. The ADF test tests the null hypothesis that a time series has a unit root, which means that the series is non-stationary. The alternative hypothesis is the stationarity of the series. The level of significance is 0.05. Thus, a p-value < 0.05 is considered to be statistically significant and the data is stationary, and a p-value > 0.05 is statistically non-significant and the data is not stationary. The result of the ADF test for all variables in level form is presented in Table 2. The results show that out of thirteen variables, only 3 variables are stationary at level while 10 variables are non-stationary. The p-values for GDP growth (annual %), urban population (% of total population) and fossil-fuel energy consumption (% of total energy consumption) are 0.0060, 0.0426, and 0.0004, respectively. All three values are less than 0.05, so the null hypothesis of a unit root is rejected, and these variables are stationary at level, which means that they can be used without first differencing. CO_2 emissions, on the other hand, are highly non-stationary at level with an ADF p value of 0.9874. Similarly, GDP (current US$) is also non-stationary (p-value: 0.2861). The p-values of the non-resident patent applications, resident patent applications, and technological innovation variables are not enough to reject the unit-root null hypothesis (0.4823, 0.3720, and 0.3075, respectively). The results suggest that there were the persistent trends in these variables during the study period. The stationarity properties of the energy-related variables also turn out to be mixed. The results of the non-stationarity test show that energy use is non-stationary at level with a p-value of 0.2549 and renewable energy use is also non-stationary at level with a p-value of 0.0657. The p-value for the renewable energy is quite close to 0.05 but still greater than the significance level. Likewise, the p-values of the variables forest area, natural-resource rents and Financial Development Index are 0.9846, 0.2884 and 0.2011 respectively, which are also non-stationary. The overall results of the ADF indicates that three variables are stationary at level and ten are non-stationary. Hence, it is necessary to apply first-order differencing to the non-stationary variables to check if they are stationary for further econometric analysis.

Table 2: Results of the Augmented Dickey–Fuller (ADF) Unit Root Test.

Variable	ADF Statistic	P-value	Result
Carbon dioxide (CO2) emissions (total) excluding LULUCF (Mt CO2e)	0.592	0.9874	Non-Stationary
GDP (current US$)	-2.0012	0.2861	Non-Stationary
GDP growth (annual %)	-3.5875	0.006	Stationary
Urban population (% of total population)	-2.9246	0.0426	Stationary
Patent applications, nonresidents	-1.6026	0.4823	Non-Stationary
Patent applications, residents	-1.817	0.372	Non-Stationary
Fossil fuel energy consumption (% of total)	-4.329	0.0004	Stationary
Energy use (kg of oil equivalent per capita)	-2.0744	0.2549	Non-Stationary
Renewable energy consumption (% of total final energy consumption)	-2.7503	0.0657	Non-Stationary
Forest area (% of land area)	0.4926	0.9846	Non-Stationary
Total natural resources rents (% of GDP)	-1.9959	0.2884	Non-Stationary
Financial Development Index	-2.2144	0.2011	Non-Stationary
Technological Innovation	-1.9532	0.3075	Non-Stationary

3.3. First Order Difference

The long-term trends in the non-stationary variables were significantly decreased by the first difference transformation and yielded relatively stable series which are mainly affected by the annual changes. CO_2 fluxes were quite variable but mostly small, with some positive fluxes in the 2003-2007 period, near 0 in 2008-2010, and higher variability around 2018-2021. First differencing a similar pattern, removing the strong upward trend in GDP, but with annual changes in the range around zero with larger moves during periods of economic expansion, contraction and during the COVID-19 period. The transformed growth rate for GDP, which is already expressed as an annual growth rate, also bounced around the zero. Innovation indicators were obtained by first differencing to eliminate the long-term trends in non-resident patent applications, resident patent applications and technological innovation measured by patents. A positive change was observed in non-resident patent applications, notably large in 2006, but which fell in 2007, after which there was a more even pattern. Also, following differencing, there were some more significant fluctuations in energy use around 1999, 2004, and 2008-2011. Annual changes in renewable energy use had also been positive and negative, reflecting the slow and steady growth in this energy use, but without an overall trend. Very small differences in forest area was observed as small changes in forest-cover was taking place but relatively large change in area was observed during 2016-2018. The use of fossil-fuel energy showed little annual fluctuation with a clear downward trend around 2015 and an upturn in 2016. Natural-resource rents began to reflect changes related to the economic and market situation rather than long-term changes. The Financial Development Index remained in the vicinity of zero and was rather stable after 2011. Finally, urban population had relatively smooth annual changes, which reflect the slow pace of urbanization. Overall, the first differencing had a significant effect on stabilizing the non-stationary variables, and delivered suitable transformed series for time-series analysis.

4. Discussion

The findings demonstrate substantial temporal changes in Pakistan's environmental, economic, energy, technological, financial, and demographic indicators during 1990–2023. The most important result is that 10 of the 13 variables were non-stationary at level, while only GDP growth, urban population, and fossil-fuel energy consumption were stationary. This indicates that most variables followed persistent long-term trends rather than fluctuating around constant statistical means. The importance of distinguishing stationary and non-stationary processes was established by Dickey and Fuller (1979), who developed the statistical framework for testing unit roots in autoregressive time series. The strong non-stationarity of CO_2 emissions is consistent with their substantial long-term increase from approximately 66 Mt CO_2e in 1990 to around 236 Mt CO_2e in 2022. The ADF p-value of 0.9874 provides strong evidence of a unit root. Similarly, GDP and energy use were non-stationary, reflecting Pakistan's long-term economic expansion and increasing energy requirements. Previous research on Pakistan has also applied ADF tests to CO_2 emissions, GDP, energy consumption, and electricity-related variables and found that several variables were non-stationary at level but became stationary after first differencing (Khan et al., 2022). The non-stationarity of renewable-energy consumption, technological innovation, resident and non-resident patent applications, natural-resource rents, and financial development indicates that these indicators also experienced persistent changes during the study period. Such findings are consistent with the broader literature showing that environmental and energy-related indicators in Pakistan often possess different orders of integration and therefore require stationarity testing before further econometric analysis (Khan et al., 2022; Ullah et al., 2019). The first-order difference results demonstrate that differencing substantially reduced the persistent trends in the non-stationary variables. The differenced series generally fluctuated around zero, indicating greater temporal stability. This is consistent with the theoretical basis of unit-root analysis, in which a non-stationary series can become stationary after differencing when it is integrated of order one (Dickey & Fuller, 1979, 1981). Previous Pakistan-focused research has similarly reported that variables that were non-stationary at level became stationary at first difference (Khan et al., 2022). Overall, the findings emphasize the importance of testing stationarity before undertaking further time-series analysis. The results also demonstrate that visual trends alone cannot determine stationarity. The ADF test therefore provides an essential statistical basis for distinguishing persistent trends from stationary fluctuations in Pakistan's environmental and socioeconomic time series. The extended ADF framework developed by Dickey and Fuller (1981) further strengthened the statistical testing of unit-root processes.

5. Conclusion

The current study focused on the temporal dynamics and stationarity of CO_2 emissions and twelve socioeconomic, energy, environmental, technological, financial, demographic and natural-resource indicators within the time frame 1990-2023 in Pakistan. The time-series analysis revealed that there was significant structural differences

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throughout the study period. The CO_2 emissions rose significantly from around 66 Mt CO_2e in 1990 to around 236 Mt CO_2e in 2022, before dropping in 2023. There was also strong long-term growth in energy use and GDP which are indicative of economic activity and industrialization, urbanization and energy demand. Forest area showed a consistent decline, renewable energy and technological innovation grew at a slower pace. The ADF unit root test is important as a piece of evidence about the statistical properties of these indicators. The results showed that only 3 out of 13 variables were stationary at level with p values of 0.0060, 0.0426 and 0.0004 for GDP growth, urban population and fossil-fuel energy consumption, respectively. Ten other variables such as CO_2 emissions, GDP, energy use, renewable energy use, forest area, natural-resource rents, financial development, technological innovation and patent applications were non-stationary at level. Persistent trends in the non-stationary series were significantly decreased by first-order differencing, and most of the transformed series were seen to be closer to zero and more temporally stable. These results highlight that looking at visual trends is not enough to decide stationarity and the need for unit-root testing prior to further time-series modelling. In total, Pakistan's growing carbon emissions, growing energy demand, reliance on fossil fuels and reducing forest cover are all indicative of the need for better environmental management. Increased investment in renewable energy sources, energy efficiency, technological innovations, forest protection and sustainable development in cities can contribute to the economic development and decrease the environmental pressure. Future research could extend this study by using causal and long run econometric analysis to explore the relationships descriptively reported here.

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