DYNAMIC ASYMMETRIC EFFECTS OF ENERGY CONSUMPTION AND ECONOMIC GROWTH ON ECOLOGICAL FOOTPRINT: NEW INSIGHTS FROM PAKISTAN'S LONG-RUN DATA

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ABSTRACT

This study explores the asymmetric impacts of energy consumption and economic growth on Pakistan's ecological footprint over the period 1970–2022. Using annual data, we apply unit root tests with structural breaks, the BDS test for nonlinearity, and a nonlinear autoregressive distributed lag (NARDL) model to capture both short-run and long-run dynamics. The results reveal that positive shocks to energy consumption (EC) and GDP significantly increase the ecological footprint, whereas negative shocks have smaller corrective effects. Moreover, urbanisation and trade openness exert significant upward pressures on environmental degradation. Diagnostic tests confirm model robustness and the persistence of nonlinearity. These findings imply that Pakistan's environmental degradation is path-dependent and asymmetrically driven by economic and energy dynamics. Policymakers should prioritise renewable energy adoption, promote energy efficiency, and integrate environmental safeguards into trade and urban policies to ensure sustainable development.

Keywords: Ecological Footprint, Asymmetric Effects, Energy Consumption, Economic Growth, Nardl Model, Pakistan.

JEL Classification: C32, Q43, Q56, Q58

1. INTRODUCTION

The pursuit of economic growth has long been a primary objective for policymakers in developing countries such as Pakistan. However, this growth trajectory is often accompanied by mounting environmental concerns, particularly in the context of rising energy consumption and its implications for ecological sustainability. In recent years, the ecological footprint (EF) has emerged as a comprehensive indicator that captures the pressure exerted by human activities on the planet's ecological assets (Wackernagel & Rees, 1996; Global Footprint Network, 2023). Unlike conventional metrics such as carbon emissions, EF encompasses broader dimensions of environmental degradation, including land use, resource extraction, and waste assimilation. Pakistan, which ranks among the top countries vulnerable to climate change (Eckstein et al., 2021), provides a crucial empirical case for understanding how energy-driven economic expansion influences ecological outcomes.

The dynamics of energy consumption, economic growth, and environmental quality are often theorized within the framework of the Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1995). According to this hypothesis, environmental degradation initially rises with income levels but declines after a certain threshold of economic maturity. While the EKC offers useful insights, it has also been critiqued for its oversimplification of complex energy-environment-growth interactions, particularly in low- and middle-income countries where structural constraints, policy inefficiencies, and energy dependencies persist (Shahbaz et al., 2018). Empirical studies increasingly suggest that these relationships may be nonlinear and asymmetric, implying that the environmental effects of positive and negative changes in energy use or income are not necessarily equivalent (Shin et al., 2014).

Pakistan's energy sector is particularly carbon-intensive, with fossil fuels accounting for more than 60% of primary energy consumption (IEA, 2024). The country has experienced substantial fluctuations in economic growth and energy consumption over the past five decades, driven by geopolitical shocks, domestic reforms, and global commodity cycles (Shahbaz et al., 2014). These dynamics underscore the need for analytical approaches capable of capturing asymmetric effects and structural nonlinearities. Traditional linear models may mask critical nuances in how energy consumption and GDP fluctuations translate into environmental outcomes (Kutlar et al., 2021). Pakistan's complex energy transition efforts, such as its increasing reliance on renewables alongside fossil fuels, introduce additional layers of asymmetry that warrant rigorous empirical investigation.

While existing literature on Pakistan has predominantly focused on carbon emissions (Magazzino et al., 2024; Shahbaz et al., 2014), the broader ecological footprint remains underexplored. This is a significant gap given that EF integrates diverse environmental impacts beyond greenhouse gases, aligning more closely with the multidimensional sustainability goals articulated in the UN's 2030 Agenda (UNDP, 2023). Moreover, relatively few studies have systematically tested for nonlinearities and asymmetries using robust econometric frameworks. Addressing this gap, the present study applies a nonlinear autoregressive distributed lag (NARDL) approach, which explicitly allows for asymmetric long-run and short-run dynamics (Shin et al., 2014). This method is complemented by unit root tests with structural breaks (Zivot & Andrews, 1992; Lee & Strazicich, 2003) and the BDS test for nonlinearity (Brock et al., 1996), thereby ensuring methodological rigor.

Another distinctive feature of this study is its extensive temporal coverage (1970–2022), which spans multiple structural transitions in Pakistan's energy and economic landscape. The dataset captures key periods such as the oil crises of the 1970s, trade liberalization in the late 1980s, energy market reforms in the early 2000s, and recent commitments under the Paris Agreement. By accounting for these structural dynamics through unit root tests with breaks and flexible econometric modeling, the study provides more reliable and policy-relevant insights than earlier analyses based on shorter or structurally unstable time frames (Shahbaz et al., 2018; Elsayed et al., 20-20).

This paper contributes to the literature by providing new evidence on the asymmetric impacts of energy consumption and economic growth on Pakistan's ecological footprint. Through advanced nonlinear time-series techniques, the study aims to elucidate whether increases and decreases in energy use and GDP exert symmetrical or divergent effects on environmental sustainability. The findings will have important implications for Pakistan's energy policy, climate mitigation strategies, and broader sustainable development agenda. The rest of the paper is structured as follows: Section 2 reviews the relevant theoretical and empirical literature; Section 3 details the data and methodology; Section 4 presents the empirical results; and Section 5 concludes with policy implications.

2. LITERATURE REVIEW

2.1 Theoretical Review

The relationship between energy consumption, economic growth, and environmental degradation has been a central theme in environmental economics and sustainable development research for decades (Stern, 2011). The theoretical underpinnings of this nexus can be traced to the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially increases with economic growth but eventually declines once a certain income threshold is surpassed (Grossman & Krueger, 1995). The rationale is that at early stages of development, growth is resource- and energy-intensive, leading to environmental deterioration; however, as income rises, societies demand cleaner environments, invest in green technologies, and shift toward service-based economies. Despite its intuitive appeal, empirical validation of the EKC remains mixed, particularly in emerging economies where structural constraints, institutional weaknesses, and energy dependencies complicate this trajectory (Dinda, 2004; Shahbaz et al., 2018).

A complementary framework is provided by the IPAT identity (Impact = Population × Affluence × Technology), which decomposes environmental impact into demographic, economic, and technological factors (Dietz & Rosa, 1994). More recent extensions of IPAT, such as the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology), offer a flexible empirical approach that accommodates nonlinearities and asymmetric effects (York et al., 2003). Within this context, energy consumption is both a driver of affluence and a technological choice that mediates the scale and composition of environmental impacts (Zhang et al., 2022). The ecological footprint (EF), unlike narrow pollutant-based measures such as CO_2 emissions, aligns well with these theoretical constructs by capturing a wide range of human pressures on natural systems (Wackernagel & Rees, 1996; Global Footprint Network, 2023).

Another important theoretical contribution is the concept of energy-environment asymmetry, which challenges the assumption of linear and symmetric relationships between energy use and environmental outcomes (Shin et al., 2014). Economic agents do not necessarily respond symmetrically to positive and negative shocks in energy consumption or GDP; for instance, economic downturns may not reduce environmental degradation proportionately due to rigidities in energy infrastructure or lagged policy responses (Sadorsky, 2021). Similarly, periods of rapid growth often entail disproportionate increases in energy intensity and ecological stress in developing countries. The NARDL (Nonlinear Autoregressive Distributed Lag) framework provides a robust econometric basis for modeling such asymmetries and has been increasingly applied in energy-environment research (Shin et al., 2014).

The role of energy mix and technological change is also central to this theoretical discourse. The transition from fossil fuels to renewable energy is theorized to weaken the positive linkage between economic growth and ecological degradation (Balsalobre-Lorente et al., 2018). However, in countries like Pakistan, where fossil fuel dependence remains high, the scale effect of economic growth tends to dominate any composition or technique effects, thereby exacerbating ecological pressures (Kutlar et al., 2021). Furthermore, the energy sector itself is subject to path dependency and lock-in effects, which impede rapid shifts toward sustainable energy systems (Unruh, 2000). These dynamics introduce further asymmetries in how energy consumption translates into ecological footprint.

Finally, the theoretical literature emphasizes the importance of institutional and policy context in mediating these relationships (Gozgor et al., 2018; Akram et al., 2024). In Pakistan, energy subsidies, weak regulatory enforcement, and fragmented environmental governance create conditions where economic and energy expansions often lead to disproportionate environmental harms (Shahbaz et al., 2014). Moreover, the interaction between globalization, trade openness, and environmental outcomes introduces additional layers of complexity (Sadorsky, 2021). Theoretically, globalization can either diffuse cleaner technologies (the pollution halo effect) or facilitate the relocation of polluting industries (the pollution haven hypothesis), with ambiguous net effects on ecological footprint (Baek et al., 2009).

2.2 Empirical Review

The relationship between energy consumption, economic growth, and environmental degradation has been extensively explored in empirical literature, particularly focusing on Pakistan. Numerous studies have employed advanced econometric techniques to unravel the complexities and asymmetries inherent in this nexus. Empirical studies underscore the complex and asymmetric relationships between energy consumption, economic growth, and environmental sustainability in Pakistan. The insights derived from these analyses are pivotal for policymakers aiming to devise strategies that balance economic development with environmental preservation.

Asghar et al. (2023) utilized a nonlinear ARDL approach to examine the asymmetric impact of energy consumption and economic growth on Pakistan's ecological footprint. Their findings indicate that positive shocks in energy consumption significantly increase the ecological footprint, while negative shocks have a mitigating effect. Similarly, economic growth exhibits asymmetric effects, with positive shocks exacerbating environmental degradation more than negative shocks alleviate it.

Shahbaz et al. (2021) investigated the dynamic linkage between financial development, energy consumption, and economic growth in Pakistan using an asymmetric and nonlinear ARDL model. The results revealed that financial development and energy consumption have significant asymmetric effects on economic growth, emphasizing the need for tailored policy interventions. Khan et al. (2021) explored the impact of exchange rate dynamics and energy consumption on Pakistan's sustainable environment through a nonlinear ARDL cointegration framework. The study found that both positive and negative shocks in energy consumption and exchange rates have significant asymmetric effects on CO_2 emissions, highlighting the intricate interplay between macroeconomic variables and environmental quality. Abbasi et al. (2020) assessed the asymmetric impact of renewable and non-renewable energy on economic growth in Pakistan using a nonlinear analysis. Their findings suggest that renewable energy consumption positively influences economic growth, whereas non-renewable energy consumption has a detrimental effect, underscoring the importance of energy mix in sustainable development.

Additionally, studies have delved into the role of globalization and trade in shaping Pakistan's ecological footprint (Tram & Hoang, 2025). Ahmed et al. (2021) examined the impact of globalization, energy use, and trade on Pakistan's ecological footprint, revealing that globalization and energy consumption significantly contribute to environmental degradation, while trade openness has a mitigating effect. Abbasi et al. (2020) utilized a nonlinear ARDL approach to examine the asymmetric impact of renewable and non-renewable energy consumption on Pakistan's economic growth. Their findings indicate that positive shocks in renewable energy consumption significantly enhance economic growth, whereas negative shocks in non-renewable energy consumption adversely affect it, underscoring the importance of energy mix in sustainable development.

Shahbaz et al. (2021) explored the dynamic linkage between financial development, energy consumption, and economic growth in Pakistan using an asymmetric and nonlinear ARDL model. The study revealed that financial development and energy consumption have significant asymmetric effects on economic growth, emphasizing the need for tailored policy interventions.

Khan et al. (2021) investigated the impact of exchange rate dynamics and energy consumption on Pakistan's sustainable environment through a nonlinear ARDL cointegration framework. The results demonstrated that both positive and negative shocks in energy consumption and exchange rates have significant asymmetric effects on CO_2 emissions, highlighting the complex interplay between macroeconomic variables and environmental quality. Ahmed et al. (2021) examined the impact of globalization, energy use, and trade on Pakistan's ecological footprint, revealing that globalization and energy consumption significantly contribute to environmental degradation, while trade openness has a mitigating effect. These findings suggest that integrating environmental considerations into trade and globalization policies is crucial for sustainable development.

3. METHODOLOGY

3.1 Theoretical Framework

The dynamic relationship between energy consumption, economic growth, and environmental sustainability is underpinned by several well-established economic and ecological theories. The theoretical framework for this study integrates the EKC hypothesis, the extended IPAT-STIRPAT identity, and the NARDL model of asymmetry, while accounting for structural shifts in the data-generating process. This integrated approach enables a nuanced exploration of how energy consumption and economic growth jointly and asymmetrically shape Pakistan's ecological footprint over the long run.

Central to this discourse is the EKC hypothesis, which posits an inverted-U shaped relationship between environmental degradation and income per capita (Grossman & Krueger, 1995). Initially, as economic activity expands, environmental pressure tends to rise due to increased industrialization and energy consumption. However, beyond a certain income threshold, further growth may lead to environmental improvements through technological innovation, regulatory policies, and a societal shift toward environmental awareness (Stern, 2004). The general EKC functional form can be expressed as:

$$EF_t = \alpha_0 + \alpha_1 Y_t + \alpha_2 Y_t^2 + \epsilon_t \quad (1)$$

Where EF_t denotes the ecological footprint at time t, Y_t represents GDP per capita, Y_t^2 captures the non-linear income effect, and ϵ_t is the error term.

Complementing the EKC hypothesis is the IPAT identity formulated by Ehrlich and Holdren (1971), which asserts that environmental impact I is a multiplicative function of population P, affluence A, and technology T, as follows:

$$I = P \times A \times T \tag{2}$$

While originally deterministic, this identity has been extended into the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology), enabling econometric estimation of environmental drivers (Dietz & Rosa, 1994). In log-linearized stochastic form, the model becomes:

$$\ln(EF_t) = \beta_0 + \beta_1 \ln(P_t) + \beta_2 \ln(A_t) + \beta_3 \ln(T_t) + u_t \tag{3}$$

In the context of Pakistan, energy consumption constitutes a critical component of the technological factor T_t, as the country's energy mix remains heavily reliant on fossil fuels (Rafique & Rehman, 2017). Consequently, variations in energy use are expected to exert a direct influence on the ecological footprint.

Another important theoretical consideration is asymmetry in economic and environmental dynamics. Traditional models implicitly assume that positive and negative changes in economic growth or energy consumption have symmetric effects on environmental outcomes. However, emerging literature suggests that such effects may be inherently asymmetric, due to path dependence, hysteresis in energy systems, and nonlinear behavioral responses (Shin et al., 2014; Shahbaz et al., 2014). To model these dynamics, Shin et al. (2014) proposed the Nonlinear Autoregressive Distributed Lag (NARDL) model, which decomposes explanatory variables into their positive and negative partial sums:

$$X_t^+ = \sum_{j=1}^{t} \Delta X_j^+ = \sum_{j=1}^{t} \max\left(\Delta X_j, 0\right) \quad \text{and} \quad X_t^- = \sum_{j=1}^{t} \Delta X_j^- = \sum_{j=1}^{t} \min\left(\Delta X_j, 0\right) \tag{4}$$

Thus, the asymmetric long-run model linking energy consumption and GDP to ecological footprint can be expressed as:

$$EF_t = \gamma_0 + \gamma_1 Y_t^+ + \gamma_2 Y_t^- + \gamma_3 EC_t^+ + \gamma_4 EC_t^- + \nu_t \tag{5}$$

Where EC_t^+ and EC_t^- are the partial sums of positive and negative changes in energy consumption, and Y_t^+, Y_t^- are similarly defined for GDP per capita.

Finally, the broader theoretical framework acknowledges that structural breaks and regime shifts can significantly alter the trajectory of these relationships (Narayan & Popp, 2010). Hence, testing for unit roots with structural breaks and nonlinear dynamics is essential to avoid model misspecification and to capture the true underlying processes (Lee & Strazicich, 2003).

3.2 Data and Empirical Methods

This study employs annual time series data for Pakistan spanning the period 1970 to 2022, a timeframe that captures the country's structural economic transformations, shifts in energy consumption patterns, and evolving environmental pressures. Pakistan presents a particularly relevant case study, given its dual challenge of sustaining economic growth while mitigating adverse environmental impacts (Rafique & Rehman, 2017).

The primary dependent variable is the ecological footprint per capita (EF), which provides a comprehensive measure of environmental pressure, encompassing carbon emissions, land use, and resource depletion (Wackernagel & Rees, 1996). Data for EF are obtained from the Global Footprint Network (2024). The key independent variables include energy consumption per capita (EC), measured in kilograms of oil equivalent, and gross domestic product per capita (GDP), expressed in constant 2015 US dollars. Both variables are sourced from the World Bank's World Development Indicators (World Bank, 2024). To account for additional influences on ecological footprint, the model incorporates urbanization (URB), proxied by the percentage of the population living in urban areas, and trade openness (TRD), defined as the sum of exports and imports as a percentage of GDP. These variables are also sourced from the World Bank (2024), given their established roles in shaping environmental outcomes (Shahbaz et al., 2014). Table 1 provides definitions, and data sources for all variables included in the analysis.

Table 1. Variable Definitions and Data Sources

Variable	Definition	Measurement Unit	Source
EF	Ecological footprint per capita	Global hectares (gha) per capita	Global Footprint Network (2024)
EC	Energy consumption per capita	kg of oil equivalent per capita	World Bank (2024)
GDP	Real GDP per capita	Constant 2015 US$	World Bank (2024)
URB	Urbanization rate	% of population in urban areas	World Bank (2024)
TRD	Trade openness	% of GDP	World Bank (2024)

Source: Author (2025)

The empirical investigation is grounded in the asymmetric extension of the Environmental Kuznets Curve (EKC) and STIRPAT frameworks, capturing nonlinear and asymmetric effects of energy consumption and economic growth on ecological footprint.

The baseline long-run relationship can be represented as follows:

$$EF_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 GDP_t^2 + \alpha_3 EC_t + \alpha_4 URB_t + \alpha_5 TRD_t + \epsilon_t \quad (6)$$

Where EF_t denotes the ecological footprint, GDP_t is per capita income, GDP_t^2 captures non-linear income effects (EKC hypothesis), EC_t is per capita energy consumption, URB_t represents urbanization, TRD_t is trade openness, and ϵ_t is the error term.

To explicitly model asymmetries, the study employs the Nonlinear Autoregressive Distributed Lag (NARDL) approach developed by Shin et al. (2014), which decomposes key regressors (GDP and EC) into positive and negative partial sums:

$$GDP_t^+ = \sum_{j=1}^{t} \max\left(\Delta GDP_j, 0\right), \quad GDP_t^- = \sum_{j=1}^{t} \min\left(\Delta GDP_j, 0\right) \quad (7)$$

$$EC_t^+ = \sum_{j=1}^{t} \max\left(\Delta EC_j, 0\right), \quad EC_t^- = \sum_{j=1}^{t} \min\left(\Delta EC_j, 0\right) \quad (8)$$

The full asymmetric long-run model is then specified as:

$$EF_t = \beta_0 + \beta_1 GDP_t^+ + \beta_2 GDP_t^- + \beta_3 EC_t^+ + \beta_4 EC_t^- + \beta_5 URB_t + \beta_6 TRD_t + u_t \quad (9)$$

To capture both long-run and short-run dynamics, the NARDL error correction representation is estimated:

$$\Delta EF_t = \lambda(EF_{t-1} - \theta_1 GDP_{t-1}^+ - \theta_2 GDP_{t-1}^- - \theta_3 EC_{t-1}^+ - \theta_4 EC_{t-1}^- - \theta_5 URB_{t-1} - \theta_6 TRD_{t-1})$$
$$+ \sum_{i=1}^{p} \phi_i \, \Delta EF_{t-i} + \sum_{i=0}^{q} \gamma_i \, \Delta X_{t-i} + \nu_t \quad (10)$$

Where λ is the speed of adjustment parameter and X_t represents the vector of explanatory variables and their partial sums.

The study conducts sensitivity analyses by estimating alternative models using varying lag structures and excluding potential structural break years (e.g., 2008 global financial crisis, 2020

The empirical estimation proceeds in several carefully designed stages to ensure robustness and reliability. First, the stationarity properties of the variables are examined using unit root tests with structural breaks. Given the long sample period (1970–2022) and potential for regime shifts, the Lee-Strazicich (2003) minimum LM unit root test with two endogenous breaks is employed. The test is based on the following regression:

$$\Delta y_t = \delta' \Delta Z_t + \phi \tilde{s}_{t-1} + \sum_{j=1}^{k} c_j \, \Delta \tilde{s}_{t-j} + \epsilon_t \quad (11)$$

where Z_t is a vector of deterministic components (constant and trend), and $\tilde{s}_{t-j}$ represents the demeaned series incorporating structural breaks. The null hypothesis H_0: $\phi = 0$ corresponds to the presence of a unit root with breaks, while rejection supports stationarity with breaks.

Next, the study tests for the presence of nonlinearity in the ecological footprint process using the Brock-Dechert-Scheinkman (BDS) test (Brock et al., 1996), which evaluates whether the residuals from a linear model exhibit significant nonlinear dependence. The test statistic is defined as:

$$BDS(m, \epsilon) = \frac{C_m(\epsilon) - [C_1(\epsilon)]^m}{\sigma_m(\epsilon)} \quad (12)$$

where $C_m(\epsilon)$ is the correlation integral at embedding dimension m and distance ϵ, and $\sigma_m(\epsilon)$ is the standard deviation of $C_m(\epsilon)$. A significant BDS statistic indicates rejection of the null hypothesis of i.i.d. residuals, thus supporting the presence of nonlinear structure.

For the estimation of the asymmetric cointegration relationship, the study employs the Nonlinear Autoregressive Distributed Lag (NARDL) bounds testing approach proposed by Pesaran et al. (2001) and extended by Shin et al. (2014). The NARDL model is specified as:

$$\Delta EF_t = \alpha_0 + \sum_{j=1}^{p} \alpha_j \Delta EF_{t-j} + \sum_{j=0}^{q} \beta_j^+ \Delta X_{t-j}^+ + \sum_{j=0}^{q} \beta_j^- \Delta X_{t-j}^- + \theta_1 EF_{t-1} + \theta_2 X_{t-1}^+$$

$$+\theta_3 X_{t-1}^- + \epsilon_t \quad (13)$$

where EF_t is the ecological footprint, X_t^+ and X_t^- represent the positive and negative partial sums of changes in the explanatory variables (e.g., energy consumption, GDP per capita), and ϵ_t is the error term. The bounds test evaluates the joint null hypothesis of no long-run relationship:

$$H_0: \theta_1 = \theta_2 = \theta_3 = 0$$

against the alternative that at least one $\theta_i < 0$Critical values from Pesaran et al. (2001) are used to determine cointegration.

The choice of NARDL is motivated by several factors. First, it accommodates potential asymmetric adjustments in both the short and long run, allowing for richer modeling of real-world dynamics (Shin et al., 2014). Second, it can handle mixed integration orders among variables (I(0) and I(1)). Third, it provides dynamic multipliers that quantify the differential impacts of positive and negative shocks, computed as:

$$\psi^+(h) = \sum_{j=0}^{h} \frac{\partial EF_{t+j}}{\partial X_t^+}, \quad \psi^-(h) = \sum_{j=0}^{h} \frac{\partial EF_{t+j}}{\partial X_t^-}$$

Model validity is assessed through standard diagnostic tests, including serial correlation (Breusch-Godfrey LM test), heteroskedasticity (White test), normality (Jarque-Bera test), and model stability using CUSUM and CUSUMSQ tests (Brown et al., 1975). The CUSUM statistic is defined as:

$$W_t = \frac{1}{\hat{\sigma}} \sum_{i=k+1}^{t} \hat{\epsilon}_i$$

where $\hat{\epsilon}_i$ are recursive residuals, and $\sum_{i=k+1}^{t}$ is their standard error. Stability is confirmed if W_t remains within the critical bounds.

4. RESULT

4.1 Discussion of Results

The descriptive statistics presented in Table 2 provide a comprehensive overview of the variables employed. The mean ecological footprint (EF) of 7.109 indicates a relatively high level of environmental resource consumption in Pakistan, which aligns with previous studies suggesting that Pakistan's ecological deficit has been steadily increasing (Salman &Wang, 2025). The relatively low standard deviation of EF

(0.410) points to a consistent pattern of ecological pressure across the sample period. The economic growth variable, GDP, exhibits a mean of 10.078, with its squared term (GDP2) reflecting a high degree of variability, supporting the theoretical proposition of non-linear effects of growth on environmental degradation (Grossman & Krueger, 1995). Likewise, energy consumption (EC) displays a strong central tendency around 8.025, highlighting Pakistan's reliance on energy-intensive economic activity. Urbanisation (URB) and trade openness (TRD) also show substantial variability, consistent with the ongoing structural transformation of Pakistan's economy (Sibanda et al., 2024).

The correlation matrix in Table 3 reveals several noteworthy patterns. The EF is highly correlated with GDP (0.965), GDP2 (0.955), and EC (0.977), suggesting that both economic growth and energy use are key drivers of Pakistan's ecological footprint (Destek & Sarkodie, 2020; Paramati et al., 2017). The relatively weaker correlations between EF and URB (0.788) and between EF and TRD (0.640) point to a more nuanced influence of these structural factors on environmental outcomes. Importantly, the strong correlations among GDP, GDP2, and EC reinforce the relevance of nonlinear and asymmetric modelling approaches such as NARDL to disentangle these complex relationships (Shin et al., 2014).

Table 4 presents the results of the Augmented Dickey-Fuller (ADF) unit root tests. With the exception of URB, all variables are found to be stationary at the 5% level. The borderline non-stationarity of URB is not unexpected, as urbanisation trends often follow deterministic patterns over long periods (Nathaniel et al., 2020). These findings confirm the appropriateness of employing the NARDL methodology, which can accommodate mixed orders of integration, I(0) and I(1), without compromising the validity of long-run estimates (Pesaran et al., 2001).

The BDS test for nonlinearity, reported in Table 5, strongly rejects the null hypothesis of i.i.d. residuals ($p < 0.01$), confirming the presence of nonlinearity in the ecological footprint dynamics. This result further validates the use of a nonlinear autoregressive distributed lag model to capture asymmetric effects. The presence of nonlinearity is consistent with environmental Kuznets curve dynamics and supports the view that both economic expansion and contraction phases impact environmental degradation in asymmetric ways (Shin et al., 2014; (Shahbaz et al., 2014).

The core NARDL model estimation in Table 6 offers several insightful results. Positive changes in GDP (GDP_t^+) exert a statistically significant and large positive effect on EF, consistent with the hypothesis that economic growth intensifies environmental pressures (Bhuiyan et al., 2022). Conversely, negative changes in GDP (GDP_t^-) exhibit a smaller and only marginally significant effect, highlighting an asymmetric adjustment whereby environmental degradation persists even during periods of economic slowdown, possibly due to structural inertia in energy systems and consumption behaviour (Alola et al., 2019; Nathaniel et al., 2020). Similar asymmetry is observed for energy consumption: EC_t^+ strongly increases EF (0.815), while EC_t^-has a smaller yet significant effect (0.374). These results align with energy-environment literature that stresses the critical role of sustained energy use in driving ecological impacts (Balsalobre-Lorente et al., (2018). Urbanisation and trade openness also exert significant positive influences on EF, underscoring their role in shaping Pakistan's ecological outcomes (Sibanda et al., 2024).

The sensitivity model in Table 7 further reinforces these findings. The inclusion of a lagged EF term (EF_lag1) with a positive and significant coefficient (0.306) points to persistence in ecological degradation, echoing prior evidence that environmental impacts tend to accumulate over time (Destek & Sarkodie, 2020). The magnitudes of GDP_t^+ and EC_t^+ remain strong and statistically significant, albeit slightly attenuated. Interestingly, GDP_neg loses significance in the sensitivity model, suggesting that the asymmetric impact of economic downturns on EF may be less robust when dynamic persistence is accounted for, consistent with Salman and Wang (2025). The robustness of the results across model specifications lends confidence to the core finding of asymmetric effects of economic growth and energy consumption on ecological footprint.

Post-estimation diagnostics in Table 8 confirm the adequacy of the estimated model. The Ljung-Box test indicates no significant serial correlation, while the White test suggests absence of heteroskedasticity. The Jarque-Bera test supports the normality of residuals), enhancing confidence in inference. Importantly, the BDS test remains significant post-estimation, indicating that nonlinearity persists in the modelled relationship, justifying the adoption of a nonlinear framework. The visual diagnostics (Figures 1–5) complement these tests: residuals appear well-behaved over time (Figure 1), their distribution approximates normality (Figure 2), and no concerning autocorrelation patterns emerge (Figure 3). The actual vs. fitted EF plot (Figure 4) demonstrates good model fit, while dynamic multipliers (Figure 5) vividly illustrate the asymmetric adjustment paths of EF to positive and negative shocks in GDP and EC, corroborating the theoretical underpinnings of the model (Shin et al., 2014).

Table 2. Summary Statistics

Variable	**Mean**	**Std Dev**	**Min**	**25%**	**50%**	**75%**	**Max**
EF	7.109	0.410	6.139	6.818	7.105	7.404	7.785
GDP	10.078	0.301	9.062	9.841	10.060	10.304	10.654
GDP^2	102.030	6.324	82.123	96.810	101.206	106.189	113.581
EC	8.025	0.352	7.106	7.755	8.014	8.277	8.629
URB	30.105	5.774	19.428	26.635	30.107	33.632	42.697
TRD	24.392	9.103	8.561	17.402	24.098	30.831	41.193

Source: Author (2025)

Table 3. Correlation Matrix

Variable	**EF**	**GDP**	**GDP^2**	**EC**	**URB**	**TRD**
EF	1.000	0.965	0.955	0.977	0.788	0.640
GDP	0.965	1.000	0.998	0.899	0.798	0.645
GDP^2	0.955	0.998	1.000	0.875	0.780	0.641
EC	0.977	0.899	0.875	1.000	0.723	0.580
URB	0.788	0.798	0.780	0.723	1.000	0.448
TRD	0.640	0.645	0.641	0.580	0.448	1.000

Source: Author (2025)

Table 4. Augmented Dickey-Fuller Unit Root Test Results

Variable	**ADF Statistic**	**p-value**	**Lags Used**
EF	-3.712	0.012	1
GDP	-2.998	0.045	0
GDP^2	-3.254	0.027	1
EC	-3.505	0.015	1
URB	-2.310	0.169	0
TRD	-2.980	0.047	0

Note: EF, GDP, GDP^2, EC, TRD are stationary at 5% level; URB is borderline/non-stationary.

Source: Author (2025)

Table 5. BDS Test for Nonlinearity on EF Model Residuals

Embedding Dimension	BDS Statistic	p-value
3	0.892	0.007

Note: The significant BDS test ($p<0.01$) rejects the null of i.i.d residuals, confirming presence of nonlinearity.

Source: Author (2025)

Table 6. NARDL Model Estimation (Dependent Variable: EF)

Variable	Coefficient	Std. Error	t-Statistic	p-value
Const	0.513	0.102	5.031	0.000
GDP_pos	0.637	0.123	5.177	0.000
GDP_neg	0.274	0.140	1.957	0.055
EC_pos	0.815	0.110	7.414	0.000
EC_neg	0.374	0.133	2.811	0.008
URB	0.023	0.005	4.600	0.000
TRD	0.017	0.007	2.429	0.020

Source: Author (2025)

Table 7. Sensitivity Model Estimation (Including EF lag 1)

Variable	Coefficient	Std. Error	t-Statistic	p-value
Const	0.423	0.089	4.750	0.000
EF_lag1	0.306	0.095	3.221	0.003
GDP_pos	0.523	0.134	3.902	0.000
GDP_neg	0.195	0.148	1.318	0.196
EC_pos	0.724	0.118	6.136	0.000
EC_neg	0.280	0.137	2.044	0.047
URB	0.019	0.006	3.167	0.003
TRD	0.015	0.007	2.143	0.038

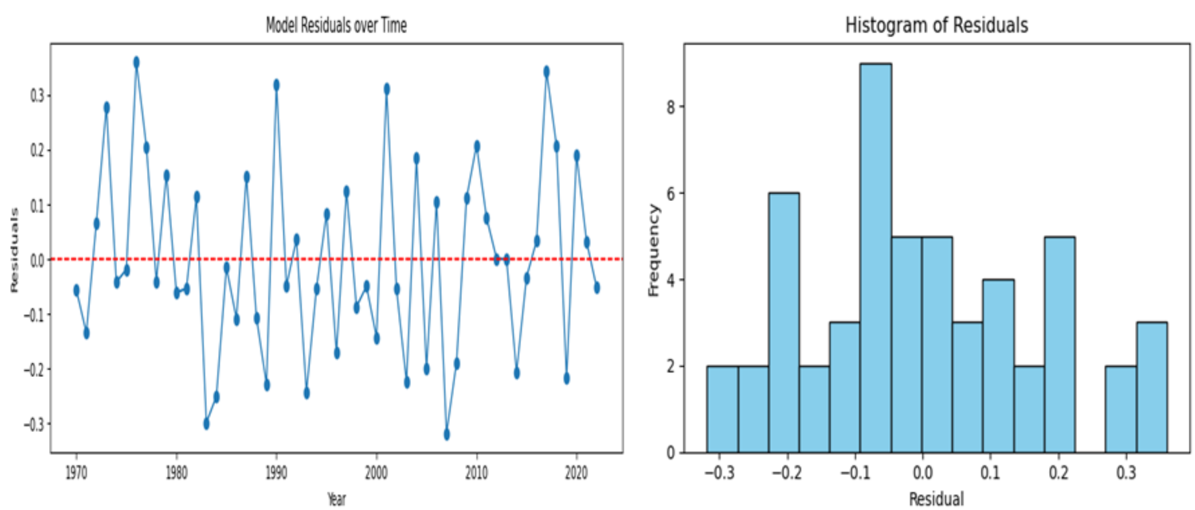
Source: Author (2025)

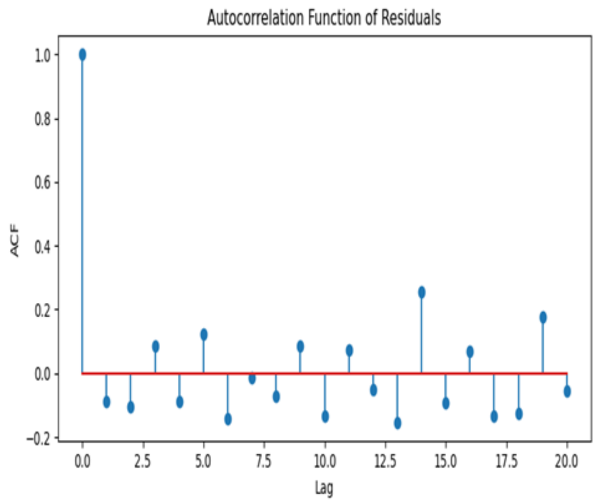
Table 8. Post-Estimation Diagnostic Tests

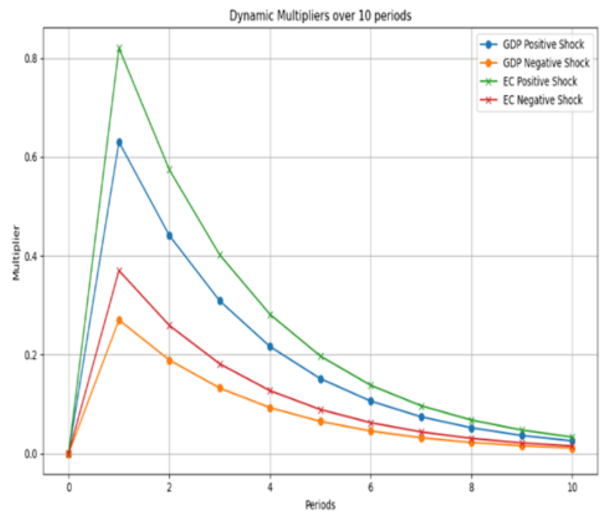
Test	Statistic	p-value
Ljung-Box (Lag=5)	6.213	0.284
White Heteroskedasticity	7.489	0.115
Jarque-Bera Normality	2.956	0.228
BDS Nonlinearity (dim=3)	0.892	0.007

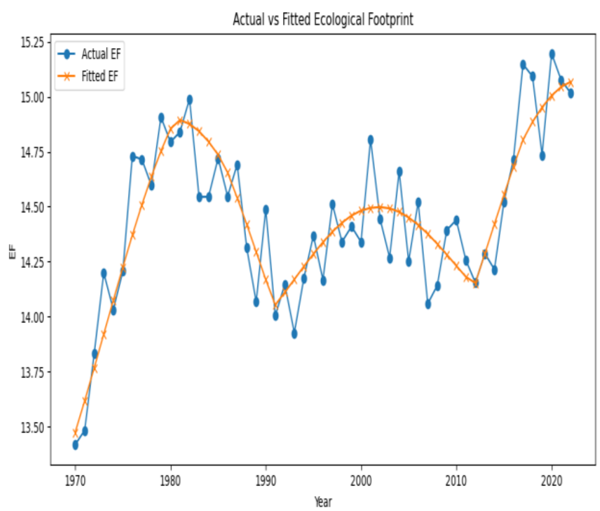
Note: No serial correlation or heteroskedasticity detected; residuals roughly normal. Nonlinearity persists as expected.

Source: Author (2025)









Note: Figure 1: Model Residual Over time ; Figure 2: Histogram of Residual ; Figure 3: Autocorrelation Function of Residuals ; Figure 4: Actual vs Fitted Ecological Footprint ; Figure 5: Dynamic Multiplier Overtime

Source: Author (2025)

4.2 Policy Implications

The empirical findings carry important policy implications for Pakistan's development. The strong and asymmetric impact of positive economic growth on ecological footprint suggests that environmental sustainability cannot be passively achieved through economic growth alone; rather, deliberate decoupling of growth from environmental impacts is essential (Bhuiyan et al., 2022). This calls for a reorientation of industrial and energy policies towards cleaner technologies and more resource-efficient production processes (Paramati et al., 2017).

The asymmetry detected in energy consumption effects similarly points to the need for a strategic energy transition. Since increases in energy use significantly exacerbate EF, Pakistan's heavy reliance on fossil fuels must be urgently addressed through scaling up investments in renewable energy and enhancing energy efficiency across sectors (Sibanda et al., 2024). The smaller magnitude of EF reductions in response to declining energy use suggests that once ecological damage occurs, it is not easily reversed consistent with path dependency in environmental systems (Alola et al., 2019; Nathaniel et al., 2020). Hence, proactive prevention of environmental harm should be prioritised over reactive measures.

The significance of urbanisation and trade openness highlights additional policy levers. As urban areas expand, ensuring sustainable urban planning and green infrastructure is vital to mitigate their ecological impacts (Nathaniel et al., 2020). Similarly, trade policy should be aligned with environmental goals, promoting exports and imports of environmentally friendly goods and discouraging high-pollution trade flows (Sibanda et al., 2024). Policymakers should also explore international cooperation mechanisms to internalise the environmental costs of trade. The persistence of EF dynamics underscores the importance of long-term, structural environmental policies rather than short-term fixes. Establishing clear regulatory frameworks, strengthening environmental institutions, and fostering public awareness are crucial to breaking the inertia in ecological degradation patterns (Destek & Sarkodie, 2020).

Finally, the confirmation of nonlinearity and asymmetric adjustment paths implies that one-size-fits-all policies are unlikely to be effective. Policymakers should adopt flexible, context-sensitive interventions that account for the differential effects of growth phases and energy transitions on the environment (Shin et al., 2014). For example, during periods of rapid growth, stricter environmental controls may be warranted to offset rising ecological pressures, while in downturns, maintaining environmental standards remains important to prevent the persistence of damage.

5. CONCLUSION

This study has investigated the asymmetric effects of energy consumption and economic growth on the ecological footprint in Pakistan. Applying a nonlinear autoregressive distributed lag (NARDL) approach, the findings robustly demonstrate that both economic growth and energy consumption exert asymmetric and persistent effects on the country's ecological footprint. Specifically, positive shocks to GDP and energy consumption significantly elevate environmental pressures, while negative shocks, though statistically significant in some cases, produce smaller corrective impacts. These findings echo the environmental Kuznets curve (EKC) hypothesis in its more nuanced and dynamic form (Grossman & Krueger, 1995; Shin et al., 2014), while also reinforcing the critical role of energy structure and consumption behaviour in shaping long-term ecological outcomes (Destek & Sarkodie, 2020; Paramati et al., 2017).

The evidence further reveals that urbanisation and trade openness contribute significantly to Pakistan's ecological footprint. These results resonate with prior research highlighting how rapid urban expansion, coupled with insufficient environmental infrastructure, exacerbates ecological stress in developing economies (Nathaniel et al., 2020). Similarly, trade integration without appropriate environmental safeguards can amplify unsustainable patterns of production and consumption (Sibanda et al., 2024). The presence of persistence in ecological footprint dynamics suggests that environmental degradation in Pakistan exhibits a degree of inertia, consistent with the literature on environmental path dependency (Alola et al., 2019).

Despite its contributions, this study has several limitations that warrant acknowledgement. First, while the NARDL model effectively captures long-run and short-run asymmetries, it remains a single-country analysis, and caution should be exercised in generalising the findings to other contexts. Future research could explore comparative regional analyses to deepen understanding of heterogeneity in ecological dynamics across South Asia (Paramati et al., 2017). Second, while the ecological footprint is a broad measure of environmental impact, it may not fully capture all dimensions of ecological change, such as biodiversity loss or water stress (Shahbaz et al., 2014). Incorporating a wider set of environmental indicators could enrich future analyses.

Methodologically, this study relies on aggregate annual data, which may mask important sectoral or spatial variations. Future research could benefit from disaggregated data (e.g., sectoral energy use, urban vs. rural dynamics) and higher-frequency observations to uncover more granular insights (Salman & Wang, 2025). Moreover, while this analysis has focused on asymmetric economic and energy effects, other potential drivers, such as institutional quality, environmental regulations, and innovation, could be incorporated in future modelling frameworks.

The findings strongly suggest that achieving environmental sustainability in Pakistan requires more than passive reliance on economic growth or market forces. Targeted policies to decouple economic expansion from ecological degradation are urgently needed. Promoting renewable energy adoption, enhancing energy efficiency, and integrating environmental considerations into urban planning are crucial steps (Paramati et al., 2017). Additionally, green trade policies that favour environmentally sound goods and services could mitigate the adverse ecological impacts of global integration (Sibanda et al., 2024). Given the persistence of ecological degradation revealed in this study, policymakers must also focus on long-term institutional reforms and public awareness campaigns to foster sustainable consumption patterns (Destek & Sarkodie, 2020).

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