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Threshold Effects of Institutional Quality on the Relationship Between the Sustainable Energy Policy Index and Socioeconomic Development with Ecological Footprint in Selected Developing and Developed Countries

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A B S T R A C T

This study examines the threshold effects of institutional quality on the relationship between the Sustainable Energy Policy Index and socioeconomic development with the ecological footprint in selected developing (D8) and developed (G7) countries over the period 2000–2023. The research model is estimated using panel data and the Panel Smooth Transition Regression (PSTR) approach to analyze the nonlinear effects of the Sustainable Energy Policy Index and socioeconomic development on the ecological footprint under the influence of institutional quality. The ecological footprint is calculated based on greenhouse gas emissions, including CO_2, CH_4, and N_2O. The variables URB, FDI, SD, L, NRS, RENE, GOV, and CAP are considered as explanatory variables in the model. The results of the unit root and cointegration tests indicate that all variables are stationary and that a long-run relationship exists among them. Diagnostic tests for model selection also confirm the appropriateness of the panel data approach. The analysis of the linearity hypothesis reveals that the relationship among variables is nonlinear, and a single transition function is sufficient for the PSTR model. The estimation results for developing countries show that urban population and foreign direct investment have a positive and significant effect on increasing the ecological footprint, while socioeconomic development and the Sustainable Energy Policy Index have a negative and mitigating effect on it. Additionally, natural resource abundance and labor force participation rate exhibit a positive and significant impact on increasing the ecological footprint. These findings highlight the critical role of institutional quality in moderating the effects of sustainable energy policies and socioeconomic development on the environment, suggesting that effective policies for reducing the ecological footprint require careful consideration of institutional structures and an appropriate balance between economic development and sustainable energy.

Keywords: *Institutional Quality, Sustainable Energy Policy Index, Socioeconomic Development, Ecological Footprint, Environment*

1. Introduction

The accelerating pace of environmental degradation and the intensification of climate-related risks have elevated the importance of understanding the complex interactions among energy systems, institutional structures, and socioeconomic development. In recent decades, the ecological footprint has emerged as a comprehensive indicator for assessing environmental pressure, capturing the aggregate impact of human activities on natural ecosystems through resource consumption and waste generation. The growing reliance on fossil fuels, coupled with rapid urbanization and industrial expansion, has significantly increased greenhouse gas emissions, thereby intensifying ecological imbalances and threatening sustainable development pathways (Yang et al., 2025; Zhao et al., 2024). Within this context, policymakers and researchers have increasingly focused on identifying the determinants of ecological footprint dynamics and exploring mechanisms to mitigate environmental degradation while maintaining economic growth.

One of the central drivers of environmental change is the structure of energy consumption, particularly the transition from non-renewable to renewable energy sources. Renewable energy has been widely recognized as a critical component in reducing environmental pressure, improving ecological sustainability, and supporting long-term economic resilience. Empirical evidence suggests that the expansion of clean energy consumption contributes to lowering ecological footprints and mitigating carbon emissions, especially in regions undergoing structural transformation in their energy sectors (Ahmed & Khan, 2024; Ali & Khan, 2024). However, the effectiveness of renewable energy policies is not uniform across countries, as it depends on multiple contextual factors, including institutional capacity, regulatory quality, and economic structure. Consequently, the relationship between sustainable energy policy and environmental outcomes cannot be adequately captured through linear analytical frameworks.

Institutional quality plays a pivotal role in shaping environmental performance and mediating the impact of energy policies. Institutions influence governance effectiveness, regulatory enforcement, transparency, and the allocation of resources, all of which are essential for implementing sustainable development strategies. High-quality institutions facilitate the adoption of environmentally friendly technologies, enhance compliance with environmental regulations, and promote efficient resource management. Conversely, weak institutional frameworks may lead to regulatory inefficiencies, misallocation of investments, and increased environmental degradation (Mansouri, 2025; Sun et al., 2025). Recent studies emphasize that institutional quality not only directly affects environmental outcomes but also interacts with other determinants such as financial development, human capital, and energy consumption, thereby creating nonlinear and threshold-dependent effects (Salari & Shahraki, 2024; Sayyadi et al., 2023).

The concept of threshold effects has gained increasing attention in environmental economics, particularly in analyzing how the impact of explanatory variables changes across different levels of a conditioning factor. In the context of ecological footprint analysis, threshold models allow for the identification of regime shifts, where the influence of energy policies or socioeconomic development varies depending on the level of institutional quality. This approach provides a more nuanced understanding of the energy–environment nexus, highlighting that policy effectiveness may differ significantly between low- and high-institutional-quality regimes. For instance, in countries with stronger institutional frameworks, renewable energy policies are more likely to translate into tangible environmental improvements due to better governance and enforcement mechanisms (Torkaman et al., 2025; Wang & Li, 2025). In contrast, in countries with weaker institutions, similar policies may yield limited or even adverse outcomes.

Socioeconomic development constitutes another critical dimension influencing environmental sustainability. While economic growth is often associated with increased resource consumption and environmental pressure, it can also enable investments in cleaner technologies and infrastructure, leading to improved environmental performance in the long run. This dual effect is consistent with the environmental Kuznets curve (EKC) hypothesis, which suggests that environmental degradation initially increases with economic growth but eventually declines after reaching a certain income threshold. However, empirical findings on this relationship remain mixed, with some studies reporting persistent positive associations between economic growth and ecological footprint, particularly in developing countries (Esfahani et al., 2024; Mohammadi & Rezaei, 2024). These inconsistencies highlight the need for more sophisticated modeling approaches that account for heterogeneity and nonlinearities.

Urbanization, foreign direct investment (FDI), and natural resource endowments are additional factors that significantly influence ecological footprint dynamics. Rapid urbanization often leads to increased energy consumption, transportation demand, and industrial activities, thereby exacerbating environmental pressures. At the same time, urban areas can serve as hubs for technological innovation and efficiency improvements, potentially offsetting some of these negative effects. Similarly, FDI can have both positive and negative environmental impacts, depending on the nature of investments and the regulatory environment. While some studies suggest that FDI contributes to environmental degradation through the "pollution haven" effect, others argue that it facilitates technology transfer and promotes cleaner production processes (Tabrizi & Zadeh, 2025; Tu et al., 2024). Natural resource abundance, on the other hand, is often associated with increased ecological pressure, particularly in resource-dependent economies where extraction activities dominate economic structures.

Recent advancements in econometric modeling have enabled researchers to better capture the complex and dynamic relationships among these variables. Panel data techniques, particularly the Panel Smooth Transition Regression (PSTR) model, provide a flexible framework for analyzing nonlinear relationships and identifying threshold effects in cross-country studies. Unlike traditional linear models, the PSTR approach allows coefficients to vary smoothly across regimes, reflecting the gradual transition between different states of the system. This feature is particularly relevant for studying the energy–environment nexus, where the impact of policies and economic variables may evolve over time and across different institutional contexts (Lima Campos & Cysne, 2025; Tuoku & Men, 2023). Moreover, the integration of spatial and temporal dimensions in recent studies has further enriched the analysis of environmental dynamics, revealing significant heterogeneity across regions and time periods (Wu et al., 2024; Zhang et al., 2024).

In addition to methodological advancements, the growing body of empirical literature underscores the importance of adopting a multidimensional perspective in environmental analysis. The ecological footprint, as a composite indicator, captures various aspects of environmental pressure, including carbon emissions, land use, and resource consumption. Studies focusing on specific components of the ecological footprint, such as carbon footprint or water footprint, provide valuable insights into particular dimensions of environmental sustainability but may overlook the broader systemic interactions (Mostafa, 2024; Shadastanjin & Saffarzadeh, 2024). Therefore, a comprehensive approach that integrates multiple indicators and considers their interdependencies is essential for developing effective policy interventions.

Furthermore, the role of green finance and sustainable investment has gained prominence in recent years as a mechanism for promoting environmental sustainability. Financial instruments aimed at supporting renewable energy projects and environmentally friendly technologies can significantly reduce ecological footprints and enhance economic resilience. However, the effectiveness of such instruments depends heavily on institutional quality and governance structures, which determine the allocation and utilization of financial resources (Sun et al., 2025; Wang & Li, 2025). This interplay between financial development, institutional quality, and environmental outcomes further reinforces the need for integrated analytical frameworks.

Despite the extensive literature on the determinants of ecological footprint, several gaps remain. First, most existing studies focus on either developing or developed countries, with limited comparative analysis between these two groups. Given the substantial differences in economic structures, institutional capacities, and energy systems, a comparative approach can provide valuable insights into the heterogeneity of environmental dynamics. Second, many studies rely on linear modeling techniques that may not adequately capture the complexity of the relationships among variables. Third, the interaction effects between institutional quality and key determinants such as energy policy and socioeconomic development have not been fully explored, particularly within a nonlinear framework.

Addressing these gaps is crucial for enhancing our understanding of the energy–environment nexus and informing policy design. By incorporating threshold effects and nonlinear dynamics, researchers can identify critical points at which policy interventions become more or less effective, thereby enabling more targeted and efficient strategies. Moreover, comparative analyses between developing and developed countries can highlight best practices and facilitate knowledge transfer, contributing to global efforts toward sustainable development.

In light of these considerations, this study aims to examine the threshold effects of institutional quality on the relationship between the Sustainable Energy Policy Index and socioeconomic development with the ecological footprint in selected developing and developed countries using a PSTR framework.

2. Methods and Materials

This study investigates the comparative threshold effects of institutional quality on the relationship between the Sustainable Energy Policy Index and socioeconomic development with the ecological footprint in selected developing and developed countries. The research model is estimated using panel data for selected developing (D8) and developed (G7) countries over the period 2000–2023, employing the Panel Smooth Transition Regression (PSTR) approach.

Considering the theoretical foundations and empirical studies by Ji et al. (2023), Sarwar et al. (2024), and Georgescu et al. (2024) regarding the threshold effects of institutional quality on the relationship between the Sustainable Energy Policy Index and socioeconomic development with the ecological footprint, the regression model of the study is specified as follows:

$$(1) COE_{i,t} = \alpha_0 + \beta_1 URB_{i,t} + \beta_2 FDI_{i,t} + \beta_3 SD_{i,t} + \beta_4 L_{i,t} + \beta_5 NRS_{i,t} + \beta_6 RENE_{i,t} + \beta_7 GOV_{i,t} + \beta_8 CAP_{i,t} + (\theta_1 URB_{i,t} + \theta_2 FDI_{i,t} + \theta_3 SD_{i,t} + \theta_4 URB_{i,t} + \theta_5 NRS_{i,t} + \theta_6 RENE_{i,t} + \theta_7 GOV_{i,t} + \theta_8 CAP_{i,t}) F(s_t, \gamma, c) + u_{i,t}$$

where the transition function $F$is defined as:

$$F(\gamma, s_t, c) = \left(1 + e^{-\gamma(s_t - c)}\right)^{-1}, \gamma > 0$$

In this model, the variables are defined as follows:

COE: Ecological footprint, calculated following Georgescu et al. (2024) and Sarwar et al. (2024) as the total greenhouse gas emissions of CO_2, CH_4, and N_2O. These emissions are derived from the product of energy consumption and emission coefficients for each gas, equal to 1, 21, and 310 per joule of energy consumption, respectively. Given the different global warming potentials (GWP) of CH_4 and N_2O, total emissions are converted into CO_2-equivalent units. Specifically, one kilogram of CH_4 and N_2O corresponds to 21 and 310 kilograms of CO_2-equivalent emissions, respectively. After calculating total GWP, the ecological footprint is expressed per unit area (kg CO_2/ha), per unit weight (kg CO_2/ton), per unit input energy (kg CO_2/GJ), and per unit output energy (kg CO_2/GJ).

After calculating Equation (2), it is substituted into the main equation as the ecological footprint index.

$NRSOURCES$: Natural resource abundance, calculated following the literature as:

$$RA_t = \frac{\alpha_1 \cdot Coal + \alpha_2 \cdot Oil + \alpha_3 \cdot Gas}{Population}$$

$RENE$: Sustainable energy policy index, measured as the share of renewable (clean) energy consumption in total energy consumption, based on World Bank data.

GOV: Institutional quality, measured as the average of five dimensions: (1) size of government, (2) legal system and property rights, (3) accountability and transparency, (4) freedom to trade internationally, and (5) regulation of credit, labor, and business. Each component consists of sub-indices aggregated into a composite index. The Fraser Institute provides scores for each dimension, and their average constitutes the institutional quality index for each country. The index ranges from 0 (lowest institutional quality) to 5 (highest institutional quality).

URB: Urban population growth rate (World Bank).

CAP: Gross fixed capital formation per capita (in USD, expressed as a growth rate percentage).

SD_t: Socioeconomic development index, measured using the sustainable development index provided by the World Bank. This index captures multiple dimensions such as poverty, health, hunger, global warming, gender inequality, water scarcity, energy, and environmental degradation. It ranges from 0 to 1, where higher values indicate higher levels of sustainable development (World Bank, 2020).

L: Labor force participation rate, expressed as a percentage of the total population.

3. Findings and Results

First, the stationarity of the variables is examined. Prior to conducting panel cointegration tests to determine long-run relationships among the main variables, the Levin, Lin, and Chu (LLC) unit root test is applied.

Table 1

Results of Unit Root Test for Variables in Developing Countries (D8)

Variable	LLC W-stat	Probability	Order of Integration
CAP	-5.83733	0.0000	I(0)
COE	-4.25117	0.0000	I(0)
FDI	-12.5887	0.0000	I(0)
GOV	-3.42619	0.0003	I(0)
L	-2.67528	0.0037	I(0)
NRS	-9.61361	0.0000	I(0)
RENE	-3.14515	0.0008	I(0)
SD	-6.05078	0.0000	I(0)
URB	-10.7448	0.0000	I(0)

Table 2

Results of Unit Root Test for Variables in Developed Countries (G7)

Variable	LLC W-stat	Probability	Order of Integration
CAP	-2.77226	0.0028	I(0)
COE	-2.84476	0.0022	I(0)
FDI	-2.80673	0.0025	I(0)
GOV	-4.36636	0.0000	I(0)
L	-3.95702	0.0000	I(0)
NRS	-6.08492	0.0000	I(0)
RENE	-1.83466	0.0333	I(0)
SD	-6.31024	0.0000	I(0)
URB	-2.81081	0.0025	I(0)

The results in Tables 1 and 2, based on the calculated statistics and associated probabilities, indicate that all research variables in both developing and developed countries are stationary at level, i.e., integrated of order zero $I(0)$.

Most economic theories express long-run relationships among variables in level form. To confirm the existence of a long-run equilibrium relationship among variables, it is necessary to examine their stationarity or, in the case of non-stationarity, ensure they share the same order of integration. If the residuals from estimated regressions are stationary $I(0)$, a long-run relationship among variables is confirmed. In this study, the Kao panel cointegration test is used to verify the existence of long-run equilibrium relationships.

Table 3

Kao Cointegration Test Results for Developing Countries

Test Statistic	Value	Probability
ADF	-6.272487	0.0000

Table 4

Kao Cointegration Test Results for Developed Countries

Test Statistic	Value	Probability
ADF	-7.118398	0.0000

As shown in the above tables, the panel cointegration test confirms the existence of a long-run relationship among the estimated variables in both developing and developed countries. The hypotheses of the test are defined as follows:

H_0: No cointegration exists.

H_1: Cointegration exists among variables.

Given that the probability values are less than 0.05, the null hypothesis is rejected, indicating that the variables are cointegrated and have a long-run equilibrium relationship.

To determine the optimal model type in panel data estimation, several tests are employed. One of the most common is the Chow (or Limer) test, which evaluates the appropriateness of panel data models versus pooled data estimation. The results of the Limer test are presented below.

Table 5

Model Selection Test Results for Developing Countries

Test Type	Test Statistic	Degrees of Freedom	Probability	Model Selection
Limer Test	6.469992	(7,176)	0.0000	Panel Data
	43.966044	7	0.0000	

Table 6

Model Selection Test Results for Developed Countries

Test Type	Test Statistic	Degrees of Freedom	Probability	Model Selection
Limer Test	4.150380	(6,153)	0.0007	Panel Data
	25.333810	6	0.0003	

Based on the above tables, since the probability values are less than 0.05, the null hypothesis of pooled data estimation is rejected. Therefore, the appropriate model for both groups of selected developing and developed countries is the panel data model.

To examine whether a linear or nonlinear relationship exists among the model variables, it is necessary to determine whether m(the number of regime parameters) equals one or not. It should be noted that in the following tests, the null hypothesis assumes a linear model, while the alternative hypothesis corresponds to a logistic PSTR model $(m = 1)$or an exponential PSTR model $(m = 2)$. The results of the diagnostic test presented in Table (7) indicate that the null hypothesis of linearity is rejected. Therefore, a nonlinear relationship exists between sustainable energy, socioeconomic development, and the ecological footprint in the countries under study, and consequently, the PSTR approach must be employed to estimate the model parameters.

Table 7

Results of Linearity Hypothesis Test (BBC Test)

Null Hypothesis	F-statistic	Significance Level
Wald Test	5.128	0.0000
Fisher Test	4.200	0.0000
LRT Test	4.395	0.0000

As observed in Table (7), the hypothesis of a linear relationship between variables is rejected; therefore, the possibility of a linear relationship is ruled out. It should also be noted that the proposed PSTR model, based on the selected transition variable, is chosen as the optimal model for estimation in the selected countries. For this purpose, following González et al. (2005) and Colletaz and Hurlin (2006), the null hypothesis of a PSTR model with a single transition function is tested against the alternative of a PSTR model with at least two transition functions. The results are presented in Table (8). The findings indicate that the null hypothesis, which assumes that a single transition function is sufficient in both cases of one and two threshold values, cannot be rejected. Therefore, a single transition function adequately captures the nonlinear behavior between sustainable energy, socioeconomic development, and the ecological footprint in the studied countries.

Table 8

Test of Nonlinear Relationship in Residuals

Case	LR	LMf	LMw
$\boldsymbol{M} = \mathbf{2}$(two thresholds)	1.328 (0.489)	1.118 (0.421)	1.258 (0.521)
$\boldsymbol{M} = \mathbf{1}$(one threshold)	1.392 (0.704)	1.608 (0.701)	1.915 (0.614)

$H_0: r = 1, H_1: r = 2$

After confirming the existence of a nonlinear relationship among the variables and the adequacy of a single transition function, the optimal specification between one-threshold and two-threshold transition functions must be determined. For this purpose, PSTR models corresponding to each case are estimated, and based on criteria such as the residual sum of squares, Schwarz criterion, and Akaike information criterion, the PSTR model with one threshold is selected as the optimal specification. Therefore, a PSTR model with a single transition function and one threshold is employed to analyze the nonlinear behavior among the study variables.

Using a PSTR model in which institutional quality is the transition variable, the ecological footprint function is modeled for the group of selected developing countries. Given the confirmation of nonlinearity, the results of the nonlinear component of the model are analyzed.

According to the estimation results, the coefficient of the urban population variable in the nonlinear regime is 0.26, which is statistically significant. This indicates that urbanization has a direct and positive effect on the ecological footprint in the selected developing countries, leading to greater environmental degradation. This phenomenon may be attributed to industrial structures and the lack of proper urban planning and infrastructure in pollution-intensive sectors.

The coefficient of foreign direct investment (FDI) in this group of countries is positive and equal to 0.07, and it is statistically significant. This suggests that FDI inflows contribute directly to environmental degradation, possibly due to inadequate technology transfer and the concentration of investments in pollution-intensive industries such as oil, gas, and petrochemicals.

The coefficient of socioeconomic development on the ecological footprint in these countries is negative and statistically significant, indicating its mitigating effect on environmental degradation.

The coefficient of natural resource abundance is 0.19, which is statistically significant, indicating a direct positive effect on the ecological footprint.

The coefficient of the sustainable energy policy index is negative and statistically significant, confirming its role in reducing the ecological footprint.

Table 9

Estimation Results Using the PSTR Model (Ecological Footprint Model)

Linear Component

Variable	Coefficient	Std. Error	t-Statistic	Probability
CONSTANT	0.521556	0.300193	1.737401	0.0823
URB	0.047188	0.007428	6.352493	0.0000
FDI	0.038076	0.004899	7.771932	0.0000
SD	-0.029633	0.003810	-7.778481	0.0000
L	0.007565	0.001745	4.335478	0.0000
NRS	0.139694	0.048299	2.892296	0.0038
RENE	0.289560	0.208206	1.390750	0.1664
GOV	-0.325879	0.177539	-1.835536	0.0683
CAP	0.134509	0.025286	5.319560	0.0000

Nonlinear Component

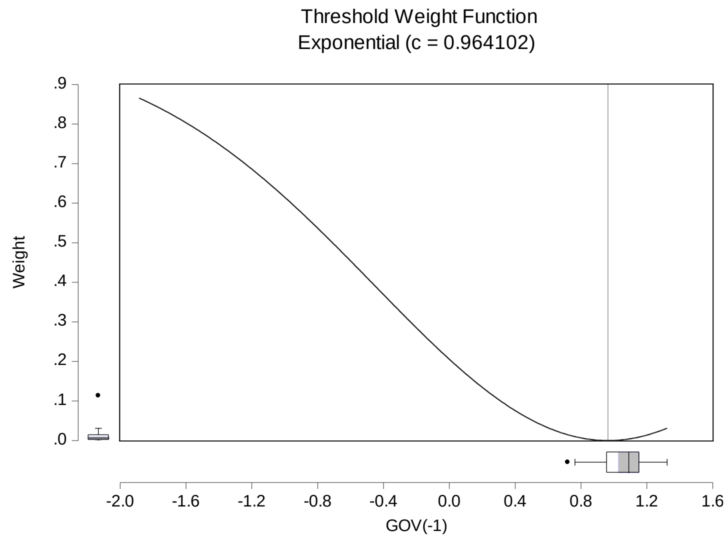
Variable	Coefficient	Std. Error	t-Statistic	Probability
CONSTANT	0.454951	0.260162	1.748721	0.0937
URB	0.265979	0.021786	12.208750	0.0000
FDI	0.077482	0.009537	8.124038	0.0000
SD	-0.164212	0.061974	-2.649681	0.0092
L	0.237879	0.061631	3.859691	0.0001
NRS	0.199451	0.024551	8.124038	0.0000
RENE	-0.533757	0.307849	-1.733825	0.0829
GOV	-0.978563	0.294953	-3.317570	0.0011
CAP	0.177326	0.070478	2.516070	0.0126
Threshold (C)	0.964102	0.158623	6.077495	0.0000
Slope (γ)	6.675325	2.934622	2.274678	0.0284

Adjusted $R^2 = 0.89$

The comparison of coefficients across the two regimes is based on the transition variable and its values, which determine the transition function and the governing regime. In this estimation, institutional quality is the transition variable, and the estimated threshold value is 0.964102. Depending on the distance of institutional quality from this threshold, the model follows two distinct regimes. By comparing the coefficients across regimes, it is observed that once institutional quality surpasses the threshold (i.e., transition from the linear to the nonlinear regime), the responsiveness of the ecological footprint to changes in variables increases significantly. This suggests that environmental policymakers have adopted more effective responses to control and mitigate the ecological footprint.

Figure 1

Relationship Between the Transition Function and Institutional Quality



In this study, the Durbin–Watson test is used to examine autocorrelation.

Table 10

Autocorrelation Test Results

F-Statistic	Prob	Durbin–Watson
1.458	0.48	2.398

As shown in Table (10), the Durbin–Watson test results indicate no autocorrelation among the error terms; therefore, the classical assumption of no serial correlation is not violated, and the estimators are efficient and have minimum variance.

Another classical assumption is homoscedasticity, which is tested using the Breusch–Pagan–Godfrey test.

Table 11

Heteroskedasticity Test Results

F-Statistic	Prob	Breusch–Pagan–Godfrey
0.698	0.812	1.139

As observed, the results indicate no evidence of heteroskedasticity.

Another important measure for evaluating the quality of the estimated model is the stability of coefficients across regimes. If the model is appropriately specified, coefficients are expected to remain stable across regime changes.

Table 12

Results of Smooth Transition Parameter Stability Test

Null Hypothesis	F-Statistic	Prob
$b_1 = b_2 = b_3 = b_4 = 0$	1.236	0.748
$b_1 = b_2 = b_3 = 0$	1.110	0.508
$b_1 = b_2 = 0$	1.348	0.512
$b_1 = 0$	1.147	0.397

As shown in Table (12), the stability test indicates that the coefficients do not change across regimes.

To examine whether a linear or nonlinear relationship exists among the model variables, it must be determined whether m(the number of regime parameters) is equal to one or not. It should be noted that, in the following tests, the null hypothesis assumes that the model is linear, whereas the alternative hypothesis is either a logistic PSTR model $(m = 1)$or an exponential PSTR model $(m = 2)$. The results of the diagnostic test reported in Table 13 indicate that the null hypothesis of model linearity is rejected. Therefore, a nonlinear relationship exists among sustainable energy, socioeconomic development, and the ecological footprint in the countries under study, and accordingly, the PSTR method should be used to estimate the model parameters.

Table 13

Results of the Model Linearity Hypothesis Test (BBC Test)

Null hypothesis	F-statistic	Significance level
Wald test	3.859	0.000
Fisher test	3.987	0.000
LRT test	3.369	0.000

As is also evident from the results of the test reported in Table 13, the hypothesis of a linear relationship among the variables is rejected; therefore, the possibility of a linear relationship among the variables is ruled out. It should also be noted that the proposed PSTR model, based on the selected transition variable, is chosen as the optimal model for estimation in the selected developed countries. For this purpose, following González et al. (2005) and Colletaz and Hurlin (2006), the null hypothesis of the existence of a PSTR specification with one transition function is tested against the alternative hypothesis of a PSTR specification with at least two transition functions, and the results are presented in Table 14. The findings show that the null hypothesis regarding the sufficiency of a single transition function is not rejected in either the one-threshold or two-threshold case. Therefore, one transition function is capable of specifying the nonlinear behavior of sustainable energy, socioeconomic development, and the ecological footprint in the selected developed countries.

Table 14

Test of Residual Nonlinearity

Case	LR (p-value)	LMf (p-value)	LMw (p-value)
(M = 2) (two thresholds)	1.337 (0.423)	1.489 (0.396)	1.268 (0.559)
(M = 1) (one threshold)	1.569 (0.356)	1.378 (0.403)	1.236 (0.512)

$H_0: r = 1, H_1: r = 2$

After confirming the existence of a nonlinear relationship among the variables and the adequacy of one transition function to specify nonlinear behavior, the optimal specification between a transition function with one threshold and one with two thresholds must be selected. For this purpose, the PSTR model corresponding to each of these cases is estimated, and based on the criteria of the residual sum of squares, Schwarz criterion, and Akaike criterion, the PSTR model with one threshold is selected as the optimal specification. Therefore, a PSTR model with one transition function and one threshold is selected to examine the nonlinear behavior among the variables under study.

Using a PSTR model in which institutional quality is the transition variable, the ecological footprint function is modeled for the selected developed countries. Given the confirmation of the nonlinear model, the results of the nonlinear component of the model are analyzed below.

According to the model estimation results, the coefficient of the urban population variable in the nonlinear component of the model is not statistically significant. Compared with the selected developing countries, where this variable had a positive and significant effect on the ecological footprint, this finding indicates that, in this group of countries, the urbanization structure does not cause statistically significant environmental damage at the 95% confidence level.

The coefficient of foreign direct investment in this group of countries has a negative and significant effect on the ecological footprint. Again, in comparison with the selected developing countries, where this effect was positive and significant, this finding suggests that foreign investment in these countries is directed toward industries that do not harm the environment and, on the contrary, help prevent environmental damage. A clear example of this is the transfer of modern technologies aimed at improving environmental quality in this group of countries.

The coefficient of the sustainable energy policy variable in the model is equal to 0.1, and its calculated probability is 0.0002, indicating a negative and significant effect of this variable on the ecological footprint in the selected developed countries.

In this group of countries, the effects of capital and labor variables on the ecological footprint are negative and statistically significant.

Likewise, the effect of institutional quality on the ecological footprint in this group of countries is negative and significant.

Finally, as expected, the coefficient of the socioeconomic development index on the ecological footprint is negative and significant at the 5% error level.

Table 15

Estimation of the Model Using the PSTR Model

Model: Ecological Footprint

Estimation of the Linear Component of the Model

Variable	Coefficient	Standard error	t-statistic	Probability
CONSTANT	0.606596	0.052468	11.56128	0.0000
URB	0.022701	0.054364	0.417576	0.6766
FDI	-0.105587	0.049589	-2.129247	0.0345
SD	-0.083179	0.038798	-2.143912	0.0331
L	-0.068757	0.014853	-4.62912	0.0000
NRS	0.073317	0.058397	1.255494	0.2107
RENE	-0.092592	0.039749	-2.329430	0.0207
GOV	-0.102195	0.043170	-2.367280	0.0267
CAP	-0.499005	0.268939	-1.855461	0.0764

Estimation of the Nonlinear Component of the Model

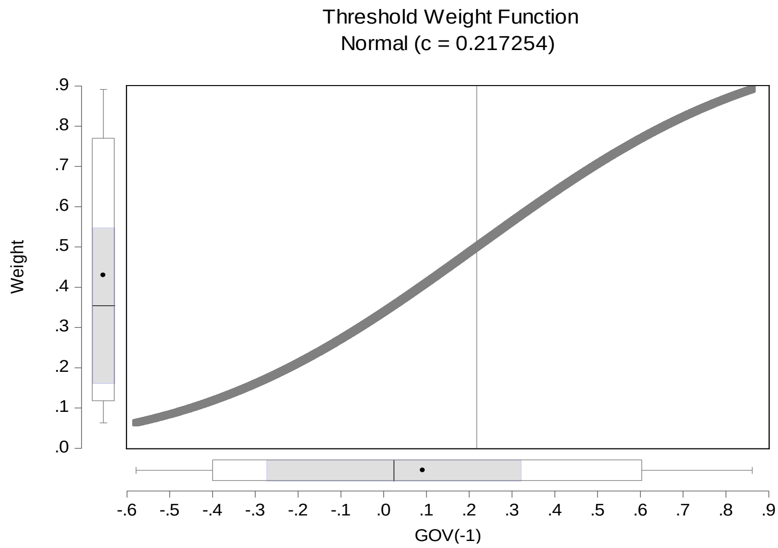
Variable	Coefficient	Standard error	t-statistic	Probability
CONSTANT	0.530693	0.136269	3.894459	0.0001
URB	0.075066	0.052281	1.435819	0.1527
FDI	-0.265475	0.078286	-3.391090	0.0008
SD	-0.175549	0.071785	-2.445475	0.0153
L	-0.110433	0.028554	-3.867560	0.0001
NRS	0.104390	0.041223	2.532328	0.0121
RENE	-0.144645	0.037615	-3.84538	0.0002
GOV	-0.423817	0.183618	-2.308149	0.0331
CAP	-0.642607	0.230948	-2.782475	0.0200
Threshold ($\boldsymbol{C}$)	0.217254	0.009450	22.98900	0.0000
Slope parameter ($\boldsymbol{\gamma}$)	0.618469	0.056286	10.98804	0.0000

Adjusted $R^2 = 0.91$

The comparison of coefficients across the two different regimes is made based on the transition variable and its values, and the value of the transition variable can determine the transition function and, consequently, the governing regime. In the above estimation, the transition variable is institutional quality, and the estimated threshold value for this variable is 0.21. Based on the distance of institutional quality from this threshold value, the model follows two different limiting regimes. By comparing the model coefficients across the two regimes, it can be observed that once institutional quality passes the threshold of 0.21(that is, when moving from the linear to the nonlinear component), the response of the ecological footprint to changes in this variable increases sharply.

Figure 2

Relationship Between the Transition Function and the Institutional Quality Transition Variable



In the present study, the Durbin–Watson test was used to examine autocorrelation.

Table 16

Results of the Autocorrelation Test

F-statistic	Prob	Durbin–Watson
1.228	0.54	2.105

As is evident from the above table, the results of the Durbin–Watson autocorrelation test indicate that there is no correlation among the disturbance terms. Therefore, the third classical standard assumption regarding the absence of autocorrelation among the error terms is not violated. Accordingly, the estimators possess the required properties, namely minimum variance and efficiency. Another classical standard assumption is homoscedasticity, for which the Breusch–Pagan–Godfrey test was used in the present study.

Table 17

Results of the Heteroskedasticity Test

F-statistic	Prob	Breusch–Pagan–Godfrey
0.896	0.789	1.265

As can be seen from the table, the test results indicate the absence of heteroskedasticity.

Another suitable measure for evaluating the quality of the estimated model is the examination of coefficient changes across the two regimes. If the estimated model provides an appropriate fit, the coefficients are expected to remain constant and unchanged as the regime changes.

Table 18

Results of the Smooth Transition Parameter Stability Test

Null hypothesis	F-statistic	Prob
$b_1 = b_2 = b_3 = b_4 = 0$	1.126	0.563
$b_1 = b_2 = b_3 = 0$	1.187	0.512
$b_1 = b_2 = 0$	1.214	0.478
$b_1 = 0$	1.236	0.452

As is also evident from the table, the test of coefficient stability across the two regimes indicates that the coefficients do not change as a result of regime shifts.

4. Discussion and Conclusion

The findings of this study provide robust empirical evidence on the nonlinear and regime-dependent relationships among institutional quality, sustainable energy policy, socioeconomic development, and the ecological footprint across selected developing and developed countries. The rejection of the linearity hypothesis and the confirmation of a smooth transition structure underscore the importance of adopting nonlinear modeling frameworks to capture the complexity of environmental dynamics. In both groups of countries, the results reveal that institutional quality acts as a critical transition variable that governs the intensity and direction of the relationship between key explanatory variables and environmental outcomes. This implies that environmental policies and economic structures do not exert uniform effects across different institutional regimes; rather, their impacts vary depending on the level of institutional development, reinforcing the argument that governance quality is a fundamental determinant of environmental sustainability (Mansouri, 2025; Sun et al., 2025).

In the group of developing countries, the empirical results indicate that urbanization exerts a positive and statistically significant effect on the ecological footprint, particularly in the nonlinear regime. This suggests that rapid urban expansion, often accompanied by insufficient infrastructure and weak regulatory enforcement, contributes to increased environmental degradation. These findings are consistent with previous studies highlighting that urbanization in developing economies tends to intensify energy consumption and emissions due to inefficient urban planning and reliance on fossil fuels (Yang et al., 2025; Zhang et al., 2024). Furthermore, the positive and significant impact of foreign direct investment (FDI) on the ecological footprint in developing countries supports the "pollution haven" hypothesis, which posits that environmentally harmful industries are more likely to be located in countries with weaker environmental regulations. This aligns with the findings of Tabrizi (2025) and Tu (2024), who emphasize that the environmental consequences of FDI depend largely on the regulatory environment and technological capacity of host countries (Tabrizi & Zadeh, 2025; Tu et al., 2024).

In contrast, the results for developed countries reveal a markedly different pattern. The effect of urbanization on the ecological footprint is statistically insignificant, suggesting that advanced economies have achieved a level of urban efficiency that mitigates environmental pressures. This can be attributed to the adoption of sustainable urban planning practices, advanced technologies, and stricter environmental regulations. Similarly, the negative and significant effect of FDI on the ecological footprint in developed countries indicates that foreign investments in these economies are directed toward cleaner and more efficient industries, facilitating technology transfer and environmental improvements. This finding is consistent with the "pollution halo" hypothesis and aligns with the evidence presented by Wang (2025) and Wu (2024), who highlight the role of technological innovation and institutional strength in enhancing environmental performance (Wang & Li, 2025; Wu et al., 2024).

Another key finding of this study is the differential impact of sustainable energy policy across regimes and country groups. In both developing and developed countries, the sustainable energy policy index exhibits a negative and significant effect on the ecological footprint, particularly in higher institutional quality regimes. This confirms the effectiveness of renewable energy adoption in reducing environmental pressure and aligns with previous empirical studies demonstrating the environmental benefits of clean energy transitions (Ahmed & Khan, 2024; Ali & Khan, 2024). However, the magnitude and significance of this effect vary depending on institutional quality, suggesting that policy effectiveness is contingent upon governance structures. In countries with stronger institutions, renewable energy policies are more effectively implemented, leading to greater environmental benefits. This finding is consistent with the literature emphasizing the moderating role of institutional quality in the energy–environment nexus (Hassanzadeh & Rahimi, 2024; Kazemi & Mahmoudi, 2024).

The role of socioeconomic development also emerges as a critical determinant of environmental outcomes. The negative and significant coefficient of the socioeconomic development index in both country groups indicates that higher levels of development are associated with reduced ecological footprints. This supports the argument that economic progress, when accompanied by improvements in technology and institutional capacity, can lead to more efficient resource use and lower environmental impact. These findings are in line with the studies of Esfahani (2024) and Mohammadi (2024), which highlight the potential for sustainable development to mitigate environmental degradation through structural transformation and technological advancement (Esfahani et al., 2024; Mohammadi & Rezaei, 2024). However, the nonlinear nature of this relationship suggests that the benefits of development are not realized uniformly and depend on the interaction with institutional quality.

Natural resource abundance and labor force participation exhibit positive effects on the ecological footprint in developing countries, indicating that resource-dependent economic structures and labor-intensive activities contribute to environmental degradation. This finding is consistent with the resource curse literature, which argues that excessive reliance on natural resources can lead to unsustainable exploitation and environmental harm. In contrast, in developed countries, the effects of capital and labor are negative and significant, reflecting the role of advanced technologies and efficient production systems in reducing environmental pressure. These contrasting results highlight the importance of structural differences between developing and developed economies and underscore the need for context-specific policy interventions (Mostafa, 2024; Salari & Shahraki, 2024).

Institutional quality itself has a negative and significant effect on the ecological footprint, particularly in the nonlinear regime, indicating that improvements in governance can lead to substantial environmental benefits. This finding reinforces the central role of institutions in shaping environmental outcomes and is consistent with the growing body of literature emphasizing the importance of governance in sustainable development. Studies by Sun (2025) and Sayyadi (2023) demonstrate that strong institutions enhance the effectiveness of environmental policies, promote transparency, and facilitate the adoption of sustainable practices (Sayyadi et al., 2023; Sun et al., 2025). Moreover, the presence of a threshold effect suggests that the impact of institutional quality becomes more pronounced beyond a certain level, highlighting the importance of achieving a minimum standard of governance to realize environmental gains.

The identification of a single transition function and a specific threshold level for institutional quality further enriches the analysis by providing insights into the dynamics of regime shifts. The results indicate that once institutional quality surpasses the estimated threshold, the responsiveness of the ecological footprint to changes in explanatory variables increases significantly. This implies that policy interventions become more effective in higher institutional regimes, emphasizing the need for strengthening governance structures as a prerequisite for successful environmental policies. This finding is consistent with the theoretical framework proposed by Mansouri (2025), which highlights the transition from structural to functional institutional effectiveness in achieving sustainable development outcomes (Mansouri, 2025).

Overall, the results of this study contribute to the literature by providing a comprehensive and nuanced understanding of the energy–environment nexus, incorporating nonlinear dynamics and threshold effects. The findings underscore the importance of considering institutional quality as a key determinant of environmental performance and highlight the need for integrated policy approaches that simultaneously address energy, economic, and governance dimensions. By comparing developing and developed countries, this study also provides valuable insights into the heterogeneity of environmental dynamics and the role of structural differences in shaping policy outcomes.

The limitations of this study should be acknowledged. First, the analysis is based on aggregated national-level data, which may mask regional heterogeneity and local-level dynamics within countries. Second, the measurement of institutional quality relies on composite indices that may not fully capture all dimensions of governance and may be subject to measurement errors. Third, the study focuses on a specific set of variables and does not account for other potentially important factors such as technological innovation, cultural differences, and political stability. Finally, the use of the PSTR model, while advantageous in capturing nonlinear relationships, may be sensitive to model specification and parameter selection.

Future research can build on the findings of this study by incorporating additional variables and exploring alternative modeling approaches to further enhance the robustness of the analysis. In particular, the integration of spatial econometric techniques can provide deeper insights into the geographical distribution of environmental impacts and the spillover effects of policies. Moreover, future studies can examine the role of technological innovation and digitalization in shaping the energy–environment nexus, as well as the interaction between environmental policies and social factors such as inequality and public awareness. Expanding the scope of analysis to include more countries and longer time periods can also improve the generalizability of the findings.

From a practical perspective, the results of this study highlight the importance of strengthening institutional frameworks as a key strategy for achieving environmental sustainability. Policymakers should prioritize governance reforms that enhance transparency, accountability, and regulatory effectiveness, thereby creating an enabling environment for the successful implementation of sustainable energy policies. In developing countries, efforts should be directed toward improving infrastructure, promoting cleaner technologies, and ensuring that foreign investments are aligned with environmental objectives. In developed countries, the focus should be on further advancing technological innovation and maintaining high standards of environmental regulation. Overall, a balanced and integrated approach that combines economic development, energy transition, and institutional strengthening is essential for reducing the ecological footprint and achieving sustainable development goals.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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