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Revisiting the growth–environment nexus in China: The role of institutions, energy use, and ecological stress

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Abstract

This study investigates the dynamic relationship between income level and key environmental and institutional drivers in China, focusing on energy use, ecological footprint, trade openness, and rule of law over the period 1990–2023. The purpose is to assess how these factors jointly influence China's growth trajectory under increasing sustainability challenges. The analysis employs the Autoregressive Distributed Lag (ARDL) model, which captures both short-run adjustments and long-run equilibrium dynamics while accommodating variables with mixed integration orders. The empirical results show that ecological footprint, trade openness, and institutional quality exert statistically significant short-run effects on GDP, whereas energy use is not significant in the short run. The highly significant error correction term confirms rapid adjustment toward equilibrium, reflecting the economy's sensitivity to shocks. In contrast, the long-run effects of energy, environmental, and institutional variables are statistically insignificant, suggesting that China's growth path cannot rely on current structures to achieve sustainable outcomes. These findings contribute to the debate on the compatibility of economic expansion with environmental sustainability by providing new evidence from the Chinese context. Practical implications emphasize the need for structural reforms, including reducing coal dependence, accelerating the transition to renewable energy, embedding environmental standards into trade policy, and strengthening institutional enforcement mechanisms. The results also offer policy guidance aligned with China's carbon neutrality objectives and Sustainable Development Goals.

Keywords: Ecological footprint, Energy use, Institutional quality, SDGs, ARDL model, China.

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Contents

Contribution of this paper to the literature

This study contributes to the existing literature by integrating energy use, ecological footprint, trade openness, and the rule of law into a single ARDL framework for China (1990–2023). The primary contribution of this research is the identification of significant short-term effects, while the long-term linkages appear to be weak. This study provides novel evidence on China's growth–environment–institution nexus, offering valuable insights for policymakers and researchers interested in sustainable development and institutional reforms.

1. Introduction

The escalating threat of climate change has prompted unprecedented global awareness and policy attention toward sustainable development. Scientific research widely agrees that anthropogenic activities are the primary drivers of global warming and environmental degradation (Furtuna & Atis, 2024; Idroes, Rahman, Uddin, Hardi, & Falcone, 2024; Kirikkaleli & Adebayo, 2021). As climate risks intensify, both developed and developing economies are pressed to adopt strategies that mitigate environmental harm while maintaining economic stability (Adebayo, Alola, Ullah, & Abbas, 2023). Among the factors shaping this transition, energy consumption patterns, institutional quality, and trade policies have emerged as critical determinants in the debate on sustainable growth.

Environmental challenges stemming from industrial activities, such as air and water pollution, pose profound threats to human health, food security, and ecosystem integrity (Eweade, Uzuner, Akadiri, & Lasisi, 2024). These adverse effects are closely tied to the scale and composition of energy use. Fossil fuels, while sustaining industrial output, emit substantial greenhouse gases and pollutants, creating long-term ecological strain. Consequently, accelerating the transition to clean energy sources and strengthening environmental governance have become key priorities for major economies (Udemba, Tosun, & Matasane, 2021).

China offers a particularly relevant context for this inquiry. Since economic liberalization in 1978, the country has achieved extraordinary growth, averaging over 9% annually, and has lifted more than 800 million people out of poverty (Cai, 2023). However, this rapid expansion has been accompanied by extensive industrialization, surging energy demand, and significant environmental costs. Although the Chinese government has increased investments in renewable energy and enacted environmental legislation, fossil fuels, especially coal, continue to dominate the national energy mix (Ivanovski, Hailemariam, & Smyth, 2021).

The share of coal in China's energy mix declined from 68.5% in 2000 to 60.6% in 2017, while oil consumption dropped slightly from 22.2% to 18.9%. Despite these changes, coal still constitutes around two-thirds of total energy consumption, and CO_2 emissions have been rising steadily since 2013. Meanwhile, per capita GDP rose from RMB 7,912 in 2000 to RMB 59,855 in 2017 (China Statistical Yearbook (CSY), 2018), intensifying pressure on natural systems and exposing the limits of China's environmental carrying capacity.

Accordingly, China has set forth a series of long-term sustainability goals. As reiterated in the 2019 "China–EU Joint Statement on Climate Change," the country aims to attain carbon neutrality by 2060 (Dong, Sun, & Dong, 2018). These objectives are incorporated into China's 14th Five-Year Plan, which emphasizes increasing non-fossil energy sources and strengthening the enforcement of environmental regulations (Organisation for Economic Co-operation and Development (OECD), 2011).

Institutionally, China's environmental governance has undergone significant evolution. Although no unified legal code governs resource protection, a growing body of national and sub-national regulations now covers air, water, soil, waste, and ecosystem conservation (Liu, 2023; Zhao, Taghizadeh-Hesary, Dong, & Dong, 2023). The revised Environmental Protection Law and sector-specific acts have contributed to building a more coherent legal framework for ecological sustainability. Despite these reforms, several structural challenges persist. The tension between economic expansion and environmental conservation, coupled with fragmented enforcement capacity and uneven institutional development, raises important questions about the sustainability of China's growth model (Jiang, Zhu, & Wang, 2022). In particular, the interrelated effects of energy consumption, ecological pressure, trade liberalization, and institutional quality on economic growth remain underexplored.

This study is grounded in the theoretical framework of the Environmental Kuznets Curve (EKC), which suggests an inverted U-shaped relationship between income level and environmental degradation (Grossman & Krueger, 1991). The EKC has been extensively examined in the context of China, with studies providing mixed evidence depending on the pollutants, time periods, and policy regimes considered (Wang, Zhang, Nathwani, Yang, & Shao, 2022). While some analyses confirm the presence of a turning point as income levels rise (Kostakis, Armaos, Abeliotis, & Theodoropoulou, 2023), others argue that the structural dominance of coal, industrial expansion, and delayed enforcement of environmental regulations have postponed or prevented the expected decline in environmental pressure (Gu, Shen, Zhong, Wu, & Rahim, 2023).

Similarly, this study draws upon the institutional theory of development (North, 1990), which highlights the central role of institutional quality, particularly legal frameworks, regulatory effectiveness, and governance, in shaping sustainable economic outcomes. In the Chinese context, institutional reforms have been found to influence both environmental policy enforcement and green technology adoption (Jiang et al., 2022; Zhao et al., 2023). Empirical evidence suggests that stronger institutions enhance the effectiveness of environmental regulations, facilitate investment in renewable energy, and improve the alignment of income levels with environmental objectives (Ozturk, Farooq, Majeed, & Skare, 2024).

This study contributes to the literature by employing the dynamic relationship between GDP and four structural factors: energy use, ecological footprint, trade openness, and the rule of law in China. While each of these variables has been individually explored in prior research, there is a lack of integrated frameworks that examine their combined influence within a single econometric model. By bringing these dimensions together, the study enhances understanding of how environmental and institutional forces jointly shape economic performance in a rapidly developing economy.

By employing the Autoregressive Distributed Lag (ARDL) model using annual data from 1990 to 2023, this study bridges a critical gap in the literature. The ARDL approach accommodates variables with different integration orders and distinguishes between short-run adjustments and long-run equilibrium dynamics. The expected policy relevance of this study lies in its potential to inform evidence-based strategies that align China's economic growth objectives with environmental sustainability commitments, particularly under the Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and Production), and 13 (Climate Action).

2. Data and Methodology

This study utilizes annual time-series data for China spanning the period 1990–2023 to investigate the relationship between income level and key environmental, institutional, and trade-related factors. The analysis adopts the ARDL framework to capture both short-run dynamics and long-run equilibrium relationships.

Table 1 presents the variables used in this study, their abbreviations, detailed descriptions, and data sources. The dependent variable is real GDP at constant 2015 US dollars (*LNGDP*), serving as a proxy for income level, obtained from the World Bank's World Development Indicators (WDI). Energy consumption (*LNEC*) is measured as total primary energy use in kilograms of oil equivalent, with data sourced from the International Energy Agency (IEA).

The ecological footprint (*LNECF*), retrieved from the Global Footprint Network, provides an aggregate measure of environmental pressure. Trade openness (*LNTO*), expressed as the ratio of total trade to GDP, is obtained from the WDI. Institutional quality is captured through the rule of law index (*LNRL*) from the World Bank's Worldwide Governance Indicators (WGI), reflecting the effectiveness of legal enforcement and the strength of governance institutions in China.

Table 1. Variables and descriptions.

Variable	Abbreviation	Description	Source
Gross domestic product per capita	LNGDP	Constant 2015 US$	WDI
Energy consumption	LNEC	Energy use (kg of oil equivalent per capita, log-transformed)	WDI
Ecological footprint	LNECF	Ecological footprint (global hectares per capita, log-transformed)	Global footprint network
Trade openness	LNTO	Trade as a percentage of GDP (log-transformed)	WDI
Rule of law	LNRL	Governance indicator (Index, log-transformed))	Worldwide Governance Indicators (WGI)

The ARDL approach, developed by Pesaran, Shin, and Smith (2001), is particularly well-suited for time-series analysis when the regressors exhibit mixed integration orders, i.e., I(0) and I(1), but are not integrated of order two. Before estimation, the order of integration of each variable is examined to confirm the suitability of the ARDL framework. The ARDL bounds testing procedure is then applied to assess the existence of a long-run cointegration relationship among the variables. When cointegration is established, long-run coefficients are obtained from the ARDL model, and the associated short-run dynamics are evaluated through an Error Correction Model (ECM).

The ARDL method offers several advantages that make it particularly suitable for this study. First, it provides flexibility with respect to integration orders, as it can accommodate regressors integrated at I(0), I(1), or a combination of both, without the need for pre-transforming all variables to the same order of integration. Second, it performs efficiently with relatively small sample sizes, which is especially relevant for the annual dataset covering the period 1990–2023. Third, the ARDL framework enables the simultaneous estimation of short-run dynamics and long-run equilibrium relationships, allowing a comprehensive understanding of both immediate and persistent effects. Finally, it supports robust model stability assessment and post-estimation diagnostic testing, ensuring the adequacy and reliability of the model specification.

The baseline long-run relationship can be expressed as:

$$LNGDP_t = \alpha + \beta_1 LNEC_t + \beta_2 LNECF_t + \beta_3 LNTO_t + \beta_4 LNRL_t + \varepsilon_t \quad (1)$$

Where *LNGDP* denotes real GDP (income level), *LNEC* represents energy consumption, *LNECF* indicates the ecological footprint, *LNTO* measures trade openness, *LNRL* captures the rule of law, and ε_t is the error term. The form of the ARDL (p, q_1, q_2, ..., q_k) model is specified as follows:

$$\Delta\ln(GDP_t) = \alpha + \sum_{i=1}^{p} \beta_i \Delta\ln(GDP_{t-i}) + \sum_{j=0}^{q1} \gamma_j \Delta\ln(X_{1t-j}) + \dots + \sum_{j=0}^{qk} \varphi_j \Delta\ln(X_{kt-j}) + \lambda_1 \ln(GDP_{t-1}) + \lambda_2 \ln(X_{1t-1}) + \dots + \lambda_{k+1} \ln(X_{kt-1}) + \varepsilon_t \quad (2)$$

Where Δ denotes the first-difference operator, X_k are the independent variables (such as energy consumption, ecological footprint, trade openness, and rule of law), and ε_t is the white-noise error term.

Table 2. Descriptive statistics and correlation matrix.

Variable	Obs.	Mean	Std. dev.	Min.	Max.	Skewness	Kurtosis
LNGDP	34	7.145	0.945	5.875	7.288	-1.543	4.645
LNEC	34	2.245	0.368	2.865	4.455	-0.764	1.643
LNECF	34	1.863	0.786	0.346	2.765	-0.446	1.344
LNTO	34	1.536	0.135	1.743	1.245	0.878	1.245
LNRL	34	1.045	0.468	0.57	2.342	-1.787	3.875

Variable	LNGDP	LNEC	LNECF	LNTO	LNRL
LNGDP	1.000				
LNEC	0.341*	1.000			
LNECF	0.432	0.833*	1.000		
LNTO	0.233	0.712*	0.422*	1.000	
LNRL	0.032	0.788*	0.345*	0.234*	1.000

Note: * denotes significance at 5% level.

3. Empirical Findings

Table 2 summarizes the descriptive statistics and correlation relationships among the variables. Most variables show skewed distributions, with real GDP (LNGDP) and rule of law (LNRL) notably left-skewed. The correlation matrix indicates that GDP is significantly and positively associated with both energy consumption and ecological footprint, suggesting that growth in China has been accompanied by environmental pressure. Trade openness shows a positive correlation with GDP. The rule of law is significantly related to all other variables, highlighting its broad influence.

Table 3 summarizes the outcomes of the Augmented Dickey-Fuller (ADF) unit root tests applied to assess the stationarity of the variables. While LNGDP, LNTO, and LNRL are found to be stationary at level at the 10% or 5% significance levels, LNEC and LNECF are non-stationary in level form. After first differencing, all variables become stationary at the 1% level, confirming they are integrated of order one, I(1). These findings justify the use of the ARDL bounds testing approach, which is valid when the variables are a mix of I(0) and I(1), but none are I(2).

Table 3. Unit root test.

Variables	Level		First Difference	
	Constant	Constant and trend	Constant	Constant and trend
LNGDP	-2.399**	-2.535**	-4.066***	-4.289***
LNEC	-1.632	-1.309	-3.691***	-3.903***
LNECF	-0.124	-1.474	-4.344 ***	-5.628***
LNTO	-2.027**	-1.397	-4.566***	-6.757***
LNRL	-2.691*	-2.142**	-5.105***	-6.225***

Note: Stationarity at a significance level of *10%, **5%, and ***1%.

Table 4 displays the outcomes of the ARDL bounds test used to determine the long-run cointegration between variables. The calculated F-statistic value of 11.26 exceeds the upper critical bounds at all significance levels. This strongly confirms a cointegration relation between GDP and its regressors: energy use, ecological footprint, trade openness, and rule of law.

Table 4. ARDL bound test.

Model	F- statistic	Lag		Bound test critical value	
Base Model*	11.26	3	1%	3.15	4.43
			5%	2.55	3.68
			10%	2.26	3.34

Note: *LNGDP=f (LNEC, LNECF, LNTO, LNRL).

Table 5 presents the short-run and long-run estimates from the ARDL model. In the short run, changes in ecological footprint (D(LNECF)), trade openness (D(LNTO)), and rule of law (D(LNRL)) are statistically significant at the 10% or 5% levels, whereas changes in energy consumption (D(LNEC)) are not significant. The error correction term (ECM) is negative and highly significant, confirming the presence of a long-run equilibrium relationship, with approximately 70.3% of the short-run disequilibrium adjusted each period.

In the long run, none of the explanatory variables are statistically significant at the 5% level, although the constant term is marginally significant at the 10% level. Energy consumption (LNEC), ecological footprint (LNECF), trade openness (LNTO), and rule of law (LNRL) all show positive or negative coefficients, but their high p-values indicate that these effects are not statistically robust. This suggests that the long-run relationship between these variables and GDP is weak or unstable. The high R^2 value indicates strong explanatory power of the model, while the adjusted R^2 suggests a reasonably good fit after accounting for degrees of freedom.

Table 5. Short and Long-term coefficients.

Short-term estimation				
Variable	**Coeffi.**	**Std. error**	**t-Stat.**	**Prob.**
D (LNEC)	1.238	1.032	0.193	0.848
D (LNECF)	4.422	2.587	1.702	0.099
D (LNTO)	3.039	1.103	-2.229	0.033
D (LNRL)	2.027	0.054	2.092	0.021
ECM (-1)	-0.703	0.079	-4.213	0.000
R^2	0.912	Mean dep. var		7.024
Adjusted R^2	0.669	S.D. dep. var		0.993
Long-term Estimation				
Variable	Coeffi.	Std. error	t-Stat.	Prob.
LNEC	2.183	2.305	0.567	0.577
LNECF	1.280	1.026	0.921	0.364
LNTO	2.902	1.366	0.120	0.905
LNRL	3.037	1.493	-1.393	0.174
C	14.55	13.32	1.902	0.0002

Note: Probability values are evaluated based on 1%, 5%, and 10% significance levels.

The diagnostic tests confirm the adequacy of the ARDL specification. The Ramsey RESET test indicates no functional form misspecification. The Breusch–Godfrey LM test and the Breusch–Pagan–Godfrey heteroskedasticity test fail to reject the null hypotheses, suggesting the absence of serial correlation and heteroskedasticity. The Jarque–Bera statistic confirms normally distributed residuals. Moreover, the VIF value is well below the critical threshold, implying no multicollinearity concerns. Overall, the model satisfies the key econometric assumptions, supporting the reliability of the estimated coefficients for inference.

Table 6. Diagnostic tests.

Tests	LM-test prob.	Chi-squared- test prob.	t-test / F-test prob.
Ramsey RESET			0.1154
Breusch-Godfrey serial correlation LM	0.1882		
Breusch-Pagan-Godfrey Heteroskedasticity	0.4421		
Jarque-Bera normality		0.5282	
Variance inflation factor (VIF)			3.22

The stability of the estimated ARDL parameters is assessed using the CUSUM and CUSUM of Squares (CUSUMSQ) tests. As illustrated in Figure 1, both test statistics remain well within the 5% significance bounds throughout the sample period (1990–2023). This indicates the absence of structural instabilities or parameter drift over time, thereby confirming the robustness of the model specification. The stability of the coefficients further supports the reliability of the long-run relationships and reinforces the suitability of the ARDL framework for drawing policy-relevant conclusions in the context of China's growth–environment–institution nexus.

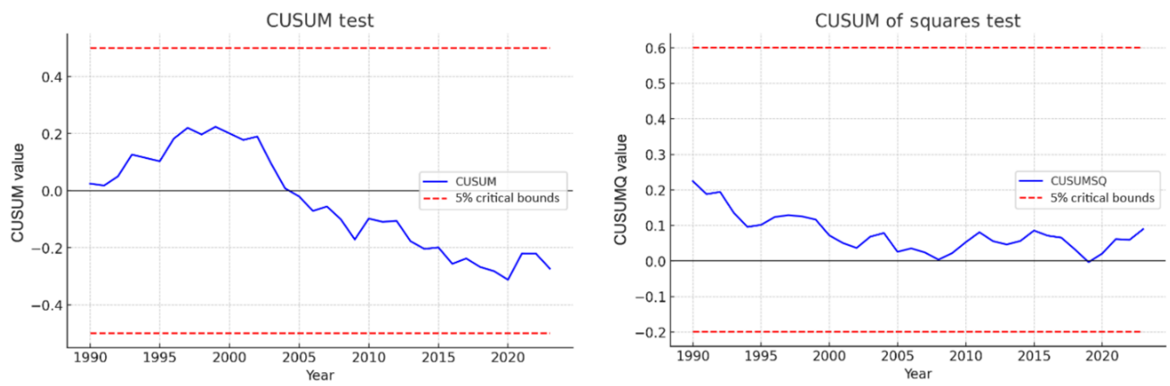

Figure 1. CUSUM and CUSUMQ Test.

4. Discussion

The empirical findings of this study provide important insights into the interaction between environmental, institutional, and trade-related factors and income levels in China, and they align with several strands of the existing literature while also revealing notable divergences.

In the short run, the significant effects of ecological footprint, trade openness, and rule of law on GDP are consistent with prior research emphasizing the immediate economic implications of environmental pressures and institutional interventions. For instance, Dam, Kaya, and Bekun (2024) similarly found that changes in ecological footprint exert short-term impacts on growth, reflecting the sensitivity of production structures to environmental constraints. Likewise, the positive short-run effect of trade openness mirrors the findings of Kim and Lin (2022), who reported that trade liberalization can boost economic performance in the short term, though its environmental effects remain mixed depending on the regulatory framework.

The short-run significance of the rule of law aligns with Mtiraoui, Lazreg, and Chemli (2024) and Shah, Raghoo, and Surroop (2021), who argue that institutional enforcement capacity can produce rapid economic effects by improving policy credibility and investor confidence. However, this study's results suggest that such effects do not persist in the long run, which resonates with Udemba and Yalçıntaş (2021), who noted that institutional quality alone is insufficient to sustain growth without complementary structural reforms.

In the long run, the absence of significant relationships between energy consumption, ecological footprint, trade openness, rule of law, and income level diverges from several studies that reported persistent environmental effects on GDP. For instance, Xia (2022) found a long-run link between fossil fuel consumption and growth, while Wang, Wang, and Li (2024) highlighted the enduring influence of trade openness under China's industrial upgrading. The divergence observed here may be attributable to the inclusion of multiple structural factors in a single model, which could dilute individual long-run effects, or to structural changes in China's economy over the 1990–2023 period that altered the persistence of these relationships.

The insignificance of the long-run institutional variable also contrasts with studies such as North (1990) and Jiang et al. (2022) which emphasizes the foundational role of institutions in sustaining growth. One possible explanation is that the formal institutional framework in China has advanced more rapidly than its enforcement and implementation, resulting in weaker measurable long-term impacts on GDP.

Overall, these findings suggest that the short-run responsiveness of growth to environmental and institutional factors is consistent with the broader literature, while the lack of long-run significance underscores the need to examine threshold effects, sectoral differences, and the role of complementary policies. This study adds to the debate by providing evidence that short-term environmental and institutional changes can generate rapid economic effects in China, but sustained impacts may require deeper structural transformations.

5. Conclusion

This study examined the relationship between income level and key environmental and institutional variables in China, including energy use, ecological footprint, trade openness, and rule of law, over the period 1990–2023 using the ARDL bounds testing approach. Motivated by the ongoing debate on the compatibility of economic expansion with environmental constraints, the analysis considered both short-run dynamics and long-run equilibrium relationships.

The short-run results indicate that changes in ecological footprint, trade openness, and rule of law exert statistically significant effects on GDP, while the effect of energy consumption is positive but not statistically significant. These findings suggest that environmental pressure and institutional dynamics have immediate implications for economic performance, with trade openness also playing a short-term role in shaping growth outcomes. The error correction term (–0.703) is negative and highly significant, confirming rapid adjustment toward the long-run equilibrium following short-run deviations.

In the long run, none of the explanatory variables are statistically significant at conventional levels, implying that the sustained effects of energy consumption, ecological footprint, trade openness, and institutional quality on GDP are weak or unstable over the study period. This result highlights the possibility that China's long-term growth path is influenced by factors beyond the environmental and institutional variables included in this model, or that their effects are conditional on structural and policy changes not captured in the current specification.

The results carry several important policy implications. The significant short-term effect of the ecological footprint suggests that China should accelerate the adoption of clean production processes and enhance environmental efficiency in key industrial sectors. Policies under SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) could be operationalized through stricter ecological footprint reduction targets, technology subsidies for green manufacturing, and more rigorous environmental monitoring. The short-term influence of trade openness on growth highlights the need to integrate environmental standards into trade policy. China can leverage trade agreements to promote green technology transfer, establish environmental quality benchmarks for exports and imports, and avoid pollution haven dynamics. The short-term significance of the rule of law underscores the importance of timely governance interventions. Enhancing enforcement mechanisms, increasing institutional transparency, and ensuring uniform application of environmental laws across provinces will be critical for achieving policy credibility.

The long-term insignificance of environmental and institutional variables points to the necessity of sustained structural reforms. These include reducing coal dependency, expanding the share of renewables (SDG 7), promoting energy efficiency, and embedding environmental sustainability into industrial planning (SDG 8). A gradual shift toward a green growth model will require harmonized energy, industrial, and legal policies. Moreover, the high speed of adjustment toward equilibrium highlights the economy's sensitivity to shocks, supporting the adoption of agile, evidence-based policymaking that responds quickly to environmental and trade fluctuations to maintain macroeconomic stability.

While this study contributes to understanding the growth–environment–institution nexus in China, several avenues remain for future research. Incorporating additional institutional indicators, such as government effectiveness, regulatory quality, and environmental policy stringency, could provide a more nuanced picture of institutional capacity. Expanding the environmental dimension to include renewable energy share, carbon pricing mechanisms, or sector-specific emissions may capture a broader scope of environmental pressures. Future studies could also employ nonlinear or threshold models (e.g., Threshold ARDL, Smooth Transition models) to detect regime shifts that might explain the insignificance of long-run effects. Finally, comparative studies between China and other emerging economies could offer valuable insights into the generalizability of these findings, particularly within the framework of the Sustainable Development Goals.

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