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RESEARCH ARTICLE

Natural Resources, Renewable Energy, and Environmental Sustainability in Central Asian Economies

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Abstract

This study examines the asymmetric effects of natural resource, renewable energy, economic growth, and technology on environmental sustainability in Central Asian (CA) economies. Using panel data for Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, environmental sustainability is measured through ecological footprint (EF) and CO_2 emissions. To capture heterogeneity across different levels of environmental pressure, the study employs the Method of Moments Quantile Regression (MMQR), which allows parameter estimates to vary across the conditional distribution of the dependent variables. The empirical results reveal that natural resource rents significantly exacerbate both EF and CO_2 emissions across all quantiles, with stronger effects observed at higher levels of ecological pressure for EF and at lower quantiles for CO_2 emissions. In contrast, renewable energy consumption contributes to environmental improvement by reducing EF across most quantiles and lowering CO_2 emissions particularly at higher emission levels. Economic growth is found to intensify environmental degradation throughout the distribution, indicating that current growth patterns in CA remain environmentally unsustainable. Technology consistently mitigates environmental pressure across all quantiles, with its impact strengthening as EF and emissions increase. These results underscore the importance of transitioning from resource-dependent growth toward renewable energy deployment and improved resource governance to achieve long-term environmental sustainability in CA economies. The study provides novel quantile-based evidence that supports differentiated and context-specific environmental policies in resource-rich emerging regions.

Keywords: Natural resources; Ecological footprint; Environmental sustainability; Renewable energy; Central Asia; MMQR.

1. Introduction

Environmental sustainability has emerged as one of the most pressing global challenges of the twenty-first century, driven largely by intensified economic activities, rising energy demand, and excessive exploitation of natural resources (Agrawal et al., 2023). While natural resources (NR) constitute a critical foundation for economic growth, particularly in developing and transition economies, their extraction and utilization often impose substantial environmental costs (Dao et al., 2025; Faizi et al., 2025). This trade-off between economic gains from resource exploitation and environmental degradation has reignited scholarly interest in the environmental dimension of the resource curse hypothesis, especially in resource-rich regions where institutional and technological capacities remain relatively weak (Faizi et al., 2024; Hassanein et al., 2025; Ni et al., 2022).

Traditionally, the literature examining the environmental consequences of natural resource abundance has relied predominantly on CO_2 emissions (CO_2) as the primary indicator of environmental degradation (Huang & Ren, 2024). However, CO_2 capture only a limited aspect of environmental pressure and fail to reflect broader ecological stress arising from land use change, energy consumption patterns, and resource overexploitation (Li et al., 2023). In response to this limitation, recent studies have increasingly adopted the ecological footprint (EF) as a more comprehensive measure of environmental sustainability (Faizi et al., 2024; Jahanger et al., 2023; Khan et al., 2021; Zhu et al., 2024). The EF accounts for biologically productive land and water areas required to support human consumption and absorb waste, thereby offering a multidimensional perspective on environmental pressure (Pata, 2021). At the same time, the global shift toward renewable energy has been widely recognized as a key pathway for mitigating environmental degradation and achieving sustainable development. Renewable energy consumption (REC) which includes sources such as solar, hydropower, biofuels, and wind energy, reduces reliance on fossil fuels, lowers greenhouse gas emissions, and improves ecological efficiency (Faizi et al., 2025; Zhang et al., 2024). While the environmental benefits of REC are well documented in the literature, some studies suggest that REC may under certain conditions, contribute to environmental degradation rather than mitigation (Alola et al., 2019; Altıntaş et al., 2024). Nonetheless, the effectiveness of renewable energy in offsetting the environmental consequences of NR dependence remains uncertain, particularly in economies where extractive industries dominate energy structures and export revenues. This uncertainty is especially relevant for Central Asian economies, where abundant natural resources coexist with growing environmental challenges.

Central Asia (CA), comprising Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan, represents a unique and underexplored context for analyzing the interaction between NR, REC, and environmental sustainability. Following the dissolution of the Soviet Union, these countries embarked on economic transition processes characterized by increasing integration into global markets and intensified exploitation of oil, gas, and mineral resources. Natural resource rents constitute a significant share GDP in several CA countries, particularly Turkmenistan, Kazakhstan, and Uzbekistan, making resource extraction a central pillar of fiscal revenues and economic growth. As illustrated in Figure 1(a), Turkmenistan exhibits the highest level of NR rents over time, followed by Kazakhstan and Uzbekistan. Figure 1(b) further shows that the average share of NR rents during 1992–2021 amounts to 34.3% for Turkmenistan, 18.2% for Kazakhstan, and 14.3% for Uzbekistan. However, this heavy reliance on NR has been accompanied by significant environmental degradation, including air pollution, land degradation, water scarcity, and ecological crises. As depicted in Figure 2(a), Kazakhstan and Turkmenistan record the highest levels of ecological footprint in the region, and these countries also exhibit relatively higher CO_2 emissions (Figure 2(b)). Despite the region's vulnerability, empirical evidence on environmental sustainability in CA remains limited and fragmented. Existing studies often focus on individual countries, rely on conventional linear econometric techniques, or employ narrow environmental indicators that fail to capture the multidimensional nature of environmental degradation. Moreover, the assumption of homogeneous environmental effects across countries and over time may be overly restrictive in the CA context, where countries differ markedly in terms of resource endowments, energy structures, and stages of economic development. Ignoring such heterogeneity may lead to biased or incomplete conclusions regarding the environmental impacts of NR and REC. Another important gap in the literature concerns the potential nonlinear and distributional effects of key determinants of environmental sustainability. The environmental impact of NR rents may differ across levels of environmental pressure; for instance, resource extraction may exert limited ecological stress in low-footprint contexts but become highly destructive when ecological capacity is already strained. Similarly, the environmental benefits of REC may be more pronounced at higher levels of environmental degradation, where clean energy substitution plays a critical role. Conventional mean-based estimators, such as fixed effects or generalized method of moments (GMM), are unable to capture such heterogeneous effects across the conditional distribution of environmental indicators.

To address these gaps, this study employs the Method of Moments Quantile Regression (MMQR) proposed by Machado and Silva (2019), which allows slope coefficients to vary across different quantiles of the ecological footprint distribution while controlling unobserved individual effects. The MMQR framework is particularly suitable for panel data settings with cross-country heterogeneity and provides a more nuanced understanding of how natural resources and renewable energy influence environmental sustainability at different levels of environmental pressure. By moving beyond average effects, this approach enables the identification of distribution-dependent relationships that are highly relevant for policy design. Against this background, the objective of this study is to empirically examine the impacts of NR rents and REC on environmental sustainability in CA economies over the period 1992–2021, using ecological footprint as a comprehensive environmental indicator. In addition to NR rents and REC, the analysis controls for key macroeconomic and structural factors, including economic growth, and technology, which are widely recognized as important drivers of environmental outcomes. By focusing on CA, the study provides region-specific insights into the environmental implications of resource dependence and energy transition in post-socialist, resource-rich economies. To achieve these objectives, the study addresses the following research questions:

1. How do natural resource rents affect the ecological footprint in Central Asian countries?
2. Can renewable energy mitigate environmental degradation?
3. Do these effects vary across different levels of environmental pressure?

This study makes several important contributions to the existing literature. First, it extends the environmental resource curse hypothesis to the CA context using ecological footprint rather than conventional emission-based indicators, thereby offering a broader assessment of environmental sustainability. Second, it applies the MMQR approach to uncover heterogeneous effects of NR and REC across different levels of ecological pressure, an aspect that has been largely overlooked in previous studies. Third, by jointly examining NR rents and REC, the study sheds light on whether renewable energy can mitigate the environmental costs associated with resource dependence in transition economies. Finally, the findings offer policy-relevant implications for CA countries seeking to balance economic growth, energy security, and environmental sustainability.

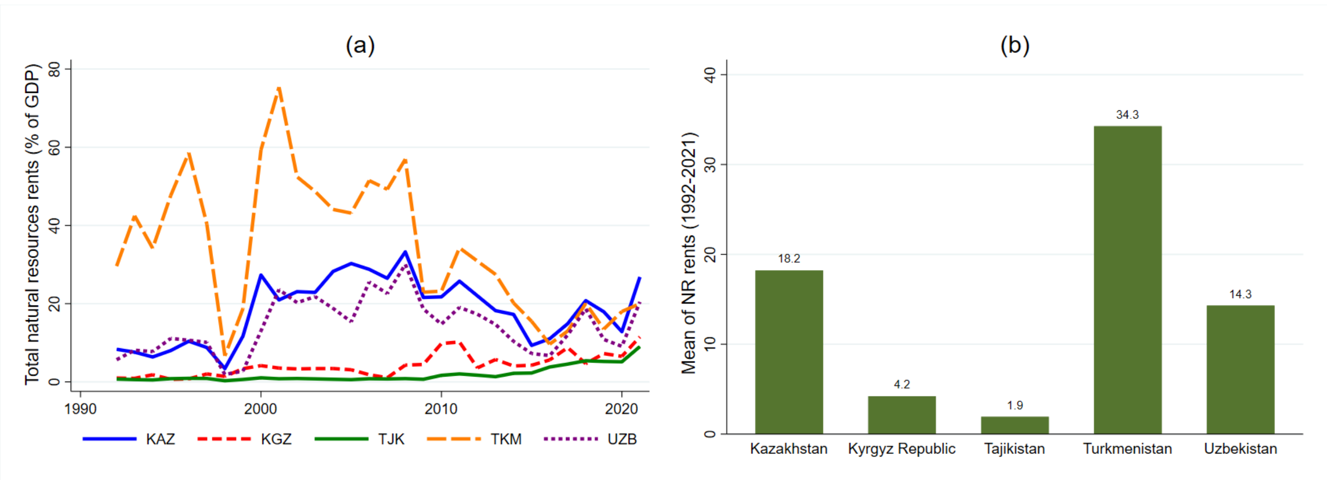

Figure 1: (a) Trends in NR rents and (b) average NR rents (1992–2021) for the five Central Asian countries.

Source: WDI (2025)

The remainder of the paper is structured as follows. Section 2 reviews the relevant literature and hypotheses. Section 3 describes the data sources, variable definitions, and econometric methodology.

Section 4 presents and discusses the empirical results obtained from the analysis. Section 5 concludes the study with policy implications.

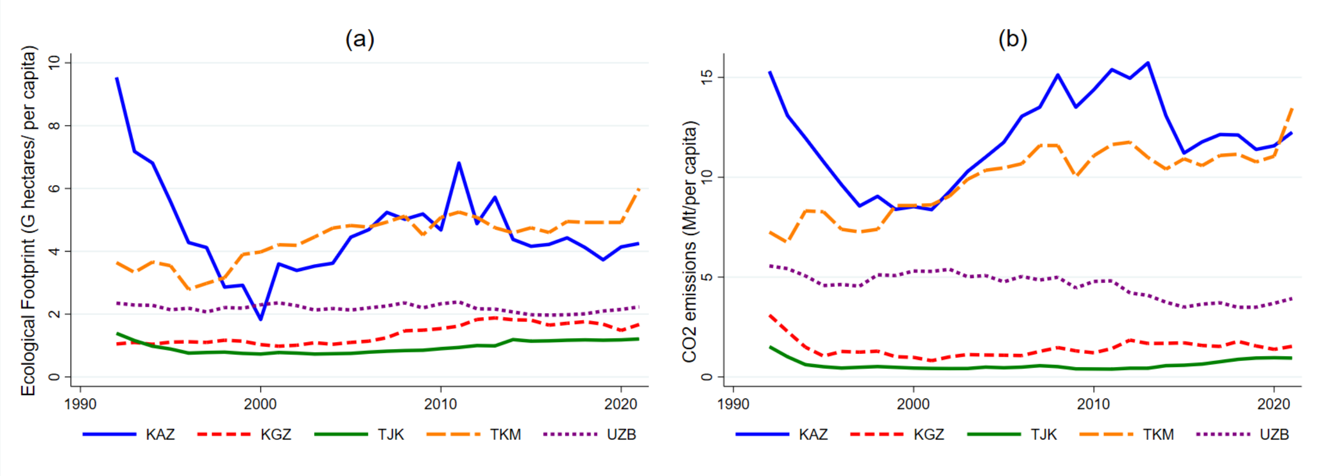

Figure 2: (a) Trends in ecological footprint and (b) CO_2 emissions (1992–2021) for the five Central Asian countries.
Source: GFN (2025)

2. Literature Review

2.1. Natural Resources (NR) and Environmental Sustainability

The relationship between NR abundance and environmental sustainability has been widely debated in economic and environmental literature. While NR provide essential inputs for production and export revenues, their extraction and utilization often generate significant environmental externalities. Early studies on the resource curse hypothesis primarily focused on economic growth outcomes, arguing that resource-rich economies tend to experience slower growth due to rent-seeking behavior, weak institutions, and macroeconomic volatility(Auty, 1993; Sachs & Warner, 1995). More recently, this debate has been extended to environmental dimensions, giving rise to the concept of the environmental resource curse (Hassanein et al., 2025). Empirical studies examining the environmental effects of natural resource rents have produced mixed results. A strand of the literature reports that resource abundance exacerbates environmental degradation by encouraging fossil fuel extraction, energy-intensive industrialization, and lax environmental regulations (Ben-Salha & Zmami, 2023; Erdoğan et al., 2021; Faizi et al., 2024; Satrovic et al., 2024; Sun et al., 2022; Zhou et al., 2024). In this context, natural resource rents are found to increase carbon emissions, ecological footprint, and other measures of environmental pressure, particularly in developing and emerging economies. These findings are often attributed to scale effects and the dominance of extractive industries, which rely heavily on non-renewable energy sources. Conversely, another strand of studies suggests that natural resource wealth may improve environmental quality if resource revenues are invested in cleaner technologies, environmental protection, and institutional development (Khan et al., 2021; Sun et al., 2024; Ullah & Lin, 2024). From this perspective, resource-rich countries may possess greater fiscal capacity to adopt green technologies and enforce environmental regulations. However, this positive channel is often contingent upon strong institutional quality and effective governance, conditions that are frequently absent in transition and developing economies. Importantly, most empirical investigations assume a linear and symmetric relationship between natural resource rents and environmental outcomes. Such an assumption may be overly restrictive, as the environmental impact of resource exploitation is likely to vary across different levels of environmental pressure and stages of economic development. In regions such as Central Asia, where ecological vulnerability and resource dependence coexist, the environmental effects of natural resources may intensify once ecological thresholds are exceeded. This suggests the presence of nonlinear and heterogeneous effects that cannot be captured by conventional mean-based estimators.

Given the heavy reliance of Central Asian economies on oil, gas, and mineral extraction, combined with relatively weak environmental institutions, it is expected that natural resource rents exert a detrimental effect on environmental sustainability. Therefore, the following hypothesis is proposed:

H1: *Natural resource rents increase ecological footprint in Central Asian economies.*

2.2. Renewable Energy and Environmental Sustainability

Renewable energy consumption (REC) has been widely recognized as a key instrument for mitigating environmental degradation and promoting sustainable development. By substituting fossil fuels with cleaner energy sources such as solar, wind, and hydropower, renewable energy reduces greenhouse gas emissions, improves energy efficiency, and alleviates pressure on natural ecosystems. A growing body of empirical literature confirms that renewable energy consumption contributes to environmental improvement by lowering carbon emissions and reducing ecological footprint, particularly in developing and emerging economies. Country-specific and regional studies provide strong support for this relationship. Mohamed et al. (2024) show that REC reduces CO_2 emissions in Malaysia, while Villanthenkodath & Pal (2024) report that REC lowers both CO_2 emissions and EF in India. Similarly, Khan et al. (2024) find a negative association between REC and CO_2 emissions in SAARC countries, especially at higher emission quantiles, and Faizi et al. (2025) confirm the environmental benefits of REC for the OIC countries. Studies by Jahanger et al. (2024), Dogan & Pata (2022), Deng et al. (2024), and Caglar & Yavuz (2023), among others, show that REC increases biocapacity and improves environmental quality across different country groups. These findings suggest that renewable energy adoption plays a crucial role in improving environmental outcomes. Nonetheless, some studies report contrasting results. Alola et al. (2019) and Altıntaş et al. (2024) find that REC may increase ecological pressure under certain conditions, suggesting that the environmental impact of REC depends on structural and institutional factors.

However, the magnitude and effectiveness of REC in improving environmental sustainability may vary across countries and levels of environmental stress. In economies with high environmental pressure and fossil fuel dependence, renewable energy adoption may generate substantial environmental benefits by displacing polluting energy sources. In contrast, in countries with relatively low ecological pressure, the environmental gains from REC may be less pronounced. This heterogeneity underscores the importance of examining the distributional effects of REC rather than focusing solely on average impacts. In the context of Central Asia, renewable energy development remains limited despite the region's significant potential for hydropower, solar, and wind energy. Energy systems in several CA countries are still dominated by fossil fuels, particularly coal and natural gas. Although recent policy initiatives aim to promote renewable energy investment, the environmental effectiveness of these efforts remains uncertain. Empirical evidence on the role of renewable energy in improving environmental sustainability in CA is scarce, creating an important research gap. Given the theoretical and empirical support for the environmental benefits of REC, this study posits that REC contributes to environmental sustainability in Central Asian economies, particularly in contexts of heightened ecological pressure. Accordingly, the following hypothesis is formulated:

H2: *REC reduces ecological footprint in Central Asian economies.*

H3: *The impacts of natural resource rents and renewable energy consumption on ecological footprint vary across different quantiles of the ecological footprint distribution in Central Asian economies.*

3. Methodology and Data

3.1. Data Description and Sources

This study examines the relationship between natural resources (NR), renewable energy consumption (REC), and environmental sustainability in Central Asian economies, namely Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan. The analysis covers the period 1992–2021, subject to data availability, and employs a balanced panel structure. Environmental sustainability is proxied using two alternative indicators to ensure robustness. The primary measure is the ecological footprint (EF), which captures the total biologically productive land and water area required to sustain human consumption and absorb waste. As a robustness indicator, CO_2 emissions are also employed, enabling comparison with the conventional environmental literature. The key explanatory variable is NR, measured as the percentage of GDP. This variable reflects the economic importance of NR extraction and includes rents from oil, natural gas, coal, minerals, and forests. REC is incorporated to capture the role of clean energy in mitigating environmental degradation and is measured as the share of renewable energy in total final energy consumption. Substantial cross-country differences in REC are observed among Central Asian nations. As illustrated in Figure 3(a), which presents the trend of REC over the period 1992–2021, Tajikistan emerges as the leading country in terms of renewable energy adoption, followed by Kyrgyzstan, while the remaining countries exhibit relatively low levels of renewable energy penetration. Figure 3(b) further shows the share of REC in total energy consumption, again highlighting Tajikistan as the frontrunner, with Kyrgyzstan ranking second.

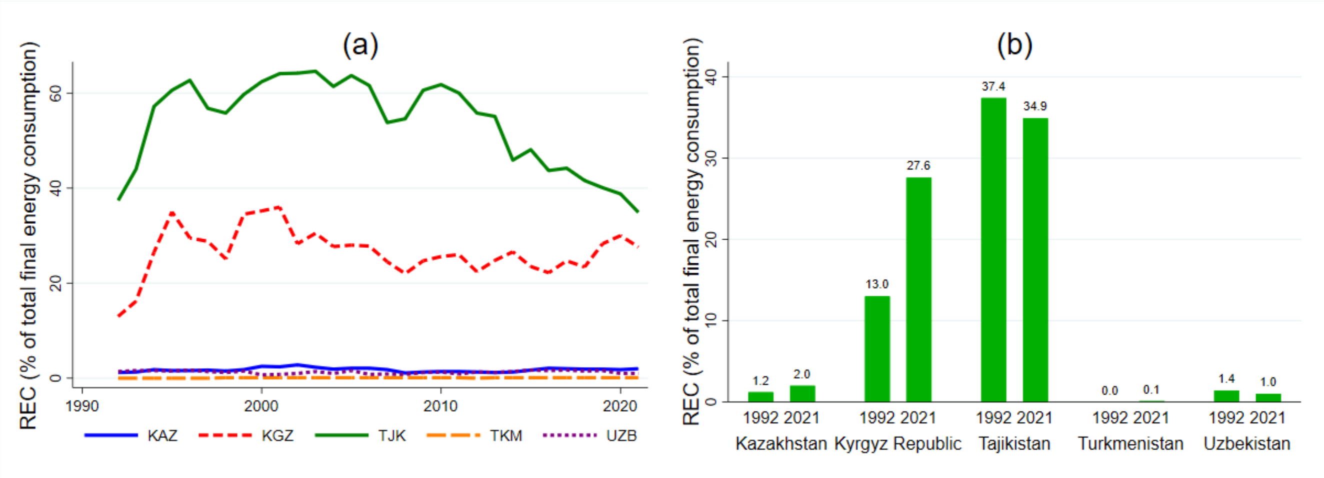

Figure 3: (a) Trends in REC and (b) comparison of REC in 1992 and 2021 across Central Asian countries.
Source: WDI (2025)

Economic growth is controlled by using GDP per capita**,** which accounts for scale effects associated with increased production and consumption. Technology (TEC) is proxied by mobile cellular subscriptions per 100 people, a commonly used indicator in the literature to reflect technological diffusion and digital infrastructure, particularly in developing and transition economies. The EF data are obtained from the Global Footprint Network GFN (2025), while data for the remaining variables are sourced from the World Bank WDI (2025). All variables are transformed into their natural logarithmic form to reduce heteroscedasticity, mitigate potential nonlinearity, and allow the estimated coefficients to be interpreted as elasticities. A detailed description of the variables is presented in Table 1.

Table 1: Description and Sources of Variables

Symbol	Variable	Unit	Source
EF	Ecological Footprint	Global hectares per capita	GFN (2025)
CO_2	CO_2 emissions	Metric tons of CO_2 per capita (excluding LULUCF)	WDI (2025)
NR	Natural resource rents	% of GDP	WDI (2025)
REC	Renewable energy consumption	% of total final energy consumption	WDI (2025)
GDP	GDP per capita	Constant US dollars	WDI (2025)
TEC	Technological innovation	Mobile cellular subscriptions (per 100 people)	WDI (2025)

3.2. Model Specification

To investigate the impact of NR and REC on environmental sustainability, based on research of Faizi et al. (2024), Zhou et al. (2024), and Jahanger et al. (2023), the study specifies two baseline models. The first model employs ecological footprint (EF) as the dependent variable, while the second model uses CO_2 emissions to ensure robustness and comparability with existing studies.

Model 1: EF Model

$$\ln EF_{it} = \alpha_i + \beta_1 \ln NR_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln TEC_{it} + \varepsilon_{it} \quad (1)$$

Model 2: CO_2 Model

$$\ln CO_{2it} = \alpha_i + \beta_1 \ln NR_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln TEC_{it} + \varepsilon_{it} \quad (2)$$

where i denotes country and t represents time. β's are the coefficients of regressors and the term α_i captures unobserved country-specific effects, while ε_{it} is the error term.

Based on theoretical and empirical considerations, natural resource rents and economic growth are expected to exert a positive effect on environmental degradation, while renewable energy consumption is anticipated to improve environmental sustainability. The impact of technology remains ambiguous, as technological progress may either reduce environmental pressure through efficiency gains or increase it through rebound effects.

3.3. Econometric Methodology

Prior to estimation, a series of diagnostic tests commonly employed in panel data analysis are conducted to ensure the reliability of the empirical results. In today's globalized economy, countries are increasingly interconnected through economic, social, and political linkages, implying that shocks in one country may spill over to others. This interdependence raises concerns regarding the presence of cross-sectional dependence (CSD) in panel data, which, if ignored, may lead to biased and inconsistent estimates. To account for potential spillover effects among Central Asian countries, the study first applies the Pesaran (2004) CSD test. The H_0 hypothesis of this test assumes the presence of CSD among panel units. Detecting CSD is particularly relevant in the Central Asian context, given the strong regional linkages through energy markets, trade relations, and shared environmental challenges.

In addition, CA countries differ markedly in terms of economic structure, natural resource endowments, and environmental pressures, which may result in heterogeneous slope coefficients across countries. To examine this issue, slope heterogeneity is tested using the Pesaran & Yamagata (2008) test, which evaluates whether the slope parameters are homogeneous across cross-sectional units. Given the evidence of cross-sectional dependence, the study employs second-generation panel unit root tests to assess the stationarity properties of the variables. Specifically, the Cross-Sectionally Augmented IPS (CIPS) test developed by Pesaran (2007) is applied, as it explicitly accounts for CSD and provides more reliable inference compared to first-generation unit root tests.

Following these preliminary diagnostics, the Method of Moments Quantile Regression (MMQR) estimator proposed by Machado and Silva (2019) is employed to estimate both baseline models. For comparison and robustness purposes, conventional long-run panel estimators, namely Fully Modified

Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), are also applied. To capture potential heterogeneity and nonlinearities in the relationship between environmental sustainability and its determinants, MMQR offers several advantages over conventional mean-based estimators such as fixed effects, random effects, and the generalized method of moments (GMM). Unlike these approaches, MMQR allows slope coefficients to vary across different quantiles of the conditional distribution of the dependent variable while controlling for unobserved individual effects. As illustrated in Figure 4, the scatter plot matrix of the study variables reveals substantial dispersion and the presence of outliers, further justifying the use of a quantile-based estimation framework.

The MMQR framework is particularly suitable for this study for several reasons. First, CA economies exhibit substantial heterogeneity in terms of resource dependence, energy structure, and environmental conditions. Second, the environmental impact of NR and REC is unlikely to be uniform across different levels of environmental pressure. Third, MMQR is robust to outliers and provides consistent estimates in panel data settings with fixed effects (Faizi et al., 2024; Ge & Mehmood, 2024).

The MMQR model can be expressed as:

$$Y_{it} = \alpha_i + X_{it}'\beta(\tau) + u_{it}(\tau). \quad (3)$$

where Y_{it} represents the environmental indicator (EF or CO_2) for country $i$at time t; $\alpha_i$captures unobserved country-specific fixed effects, X_{it} is a vector of explanatory variables including NR, REC, GDP, and TEC; and $\beta(\tau)$ represents the vector of quantile-specific slope coefficients associated with the τ-th conditional quantile of Y_{it}, with $\tau \in (0.1)$. The term $u_{it}(\tau)$ denotes the quantile-specific error term, which satisfies the conditional quantile restriction $Q_{u_{it}}(\tau \mid X_{it}) = 0$. The estimation is conducted for the 10th, 25th, 50th, 75th, and 90th quantiles, corresponding to low, medium, and high levels of environmental pressure.

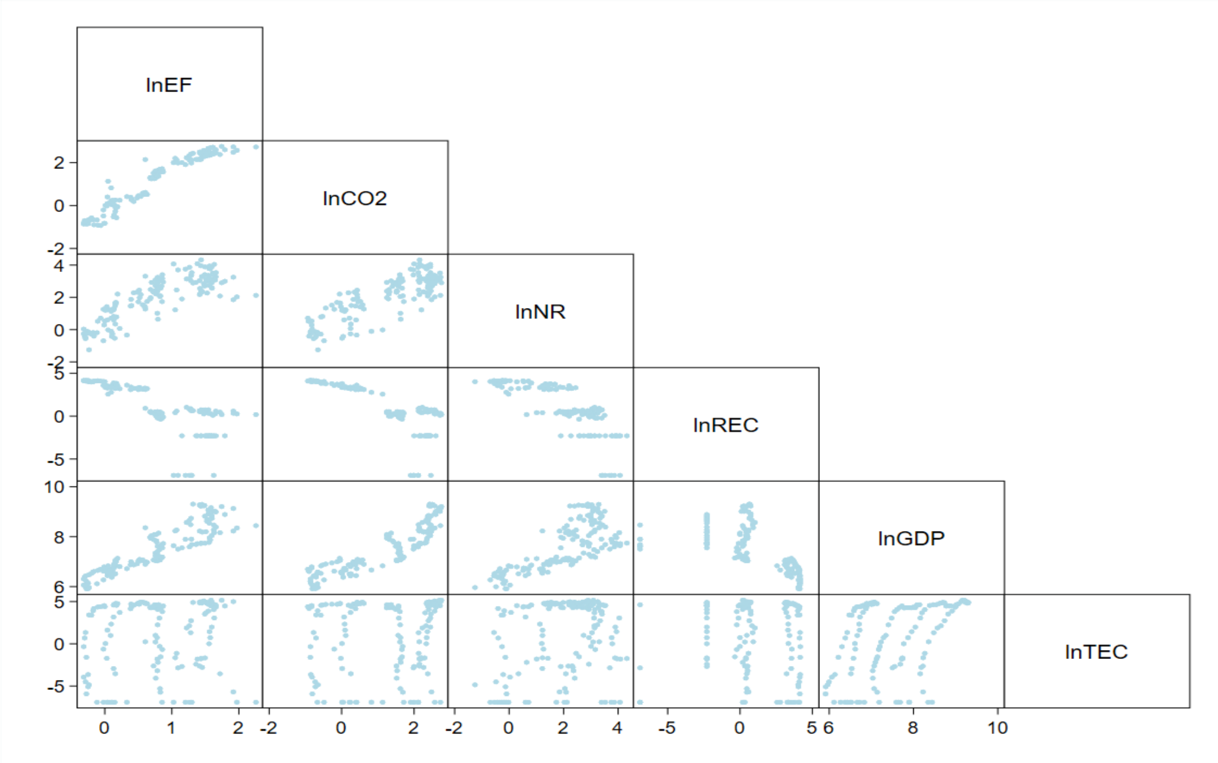

Figure 4: Scatter plot matrix of all variables.

4. Results and discussion

4.1. Descriptive Statistics, Correlation Analysis, and Multicollinearity

Table 2 reports the descriptive statistics of the variables. Both EF and CO_2 exhibit moderate dispersion across Central Asian economies, indicating heterogeneous environmental pressures. The relatively high mean values reflect the region's reliance on resource extraction and fossil fuel–based energy systems. NR shows substantial variation, underscoring differences in resource dependence, while REC displays the highest dispersion, highlighting uneven renewable energy adoption across countries. GDP per capita and TEC also vary considerably, reflecting divergent development paths within the region. The skewness and kurtosis values indicate that most variables deviate from perfect normality, justifying the use of robust estimation techniques such as MMQR. The Jarque–Bera statistics further support this choice, as several variables exhibit non-normal distributions. Table 3 reports the correlation matrix and variance inflation factor (VIF) test results. EF and CO_2 are highly correlated, confirming that both indicators capture environmental pressure, albeit from different perspectives. NR rents and GDP per capita show strong positive correlations with environmental indicators, suggesting that economic growth driven by resource extraction intensifies environmental degradation. In contrast, REC is negatively correlated with both EF and CO_2, indicating its potential role in improving environmental sustainability. Importantly, the mean VIF value of 3.03 is well below the conventional threshold of 10, indicating that multicollinearity is not a concern. This confirms the reliability of the estimated coefficients in the subsequent regression analysis.

Table 2: Descriptive statistics

Variables	**N**	**Mean**	**SD**	**Min**	**Max**	**Skewness**	**Jarque-Bera**	**Kurtosis**
lnEF	150	.79	0.66	-.31	2.26	-.02	2.255	1.8
lnCO_2	150	1.2	1.19	-.93	2.76	-.41	2.755	1.72
lnNR	150	2.02	1.34	-1.25	4.32	-.51	4.322	2.23
lnREC	150	.92	2.76	-6.91	4.17	-.93	4.168	3.77
lnGDP	150	7.55	0.93	5.91	9.3	.28	9.305	2
lnTEC	150	1	4.25	-6.91	5.16	-.74	5.163	2.05

Table 3: Correlation and VIF test results

Variables	lnEF	$lnCO_2$	lnNR	lnREC	lnGDP	lnTEC		**VIF test**	
lnEF	1.00								
$lnCO_2$	0.959	1.00						**VIF**	**1/VIF**
lnNR	0.818	0.832	1.00					4.18	0.239342
lnREC	-0.757	-0.780	-0.781	1.00				3.64	0.275027
lnGDP	0.892	0.885	0.743	-0.599	1.00			2.61	0.383072
lnTEC	0.16	0.09	0.275	0.09	0.400	1.00		1.69	0.592309
							Mean VIF	3.03	

4.2. Results of CSD, Slope heterogeneity, and Unit root tests

Table 4 presents the results of the CSD tests. The null hypothesis of cross-sectional independence is rejected for several variables, including EF, NR, GDP, and TEC. This finding suggests the presence of spillover effects among Central Asian economies, likely driven by shared economic structures, regional energy markets, and common environmental challenges. These results justify the use of second-generation panel techniques that explicitly account for CSD. Table 5 reports the slope heterogeneity test results. The highly significant Delta and adjusted Delta statistics for both Model 1 (EF) and Model 2 (CO_2) reject the null hypothesis of slope homogeneity. This implies that the effects of NR, REC, and other covariates on environmental outcomes differ across countries. Such heterogeneity reinforces the suitability of the MMQR approach, which allows slope coefficients to vary across the conditional distribution of the dependent variable. Table 6 presents the panel unit root test results based on the CIPS methodology. The findings indicate a mixed order of integration, with EF, REC, GDP, and TEC being stationary at levels, while CO_2 and NR become stationary after first differencing. The absence of higher-order integration confirms that the variables are suitable for MMQR estimation, which does not require cointegration but benefits from stationarity properties.

Table 4: CSD tests results

Variable	CD-test	p-value	corr	abs(corr)
lnEF	2.680	0.007	0.155	0.319
$lnCO_2$	1.110	0.267	0.064	0.346
lnNR	5.120	0.000	0.295	0.459
lnREC	1.430	0.153	0.082	0.297
lnGDP	16.360	0.000	0.945	0.945
lnTEC	16.850	0.000	0.973	0.973

Table 5: Slope heterogeneity test results

	Model 1: EF		Model 2: CO_2	
Statistics	Delta	p-value	Delta	p-value
$\tilde{\Delta}$	12.202	0.000	15.606	0.000
$\tilde{\Delta}$ Adjusted	13.642	0.000	17.448	0.000

Table 6: Panel unit root tests results

	CIPS				**Outcome**
Variable	Level		1st difference		Order of integration
	Constant	Constant and trend	Constant	Constant and trend	
lnEF	-2.344**	-3.231***	-	-	I (0)
$lnCO_2$	-1.724	-1.996	-4.772***	-4.748***	I (1)
lnNR	-1.246	-3.290***	-5.747***	-5.817***	I (1)
lnREC	-2.711***	-3.589***	-	-	I (0)
lnGDP	-2.625***	-2.251	-3.936***	-4.170***	I (0)
lnTEC	-2.471**	-2.486	-5.038***	-5.512***	I (0)

Note: ***, **, and * denote the significance level at 1%, 5%, and 10%, respectively.

4.3. MMQR Estimation Results

This study analysis the impact of natural resources (NR), renewable energy consumption (REC), economic performance (GDP), and technology (TEC) on environmental sustainability in Central Asian (CA) countries. Table 7 reports the MMQR estimation results for both environmental indicators (Model 1 and Model 2) across five quantiles (Q10 - Q90), corresponding to low to high levels of environmental pressure. NR rents exert a positive and statistically significant effect on ecological footprint (EF) across all quantiles, with coefficients increasing monotonically from 0.098 at the 10th quantile to 0.141 at the 90th quantile. This pattern indicates that the environmental impact of NR intensifies as ecological pressure rises. In high-footprint contexts, additional resource exploitation leads to disproportionately larger ecological damage. This result provides strong evidence in support of the environmental resource curse hypothesis in CA. It suggests that resource-driven growth amplifies environmental degradation, particularly in countries already operating under high ecological stress. The findings align with the view that weak environmental regulation and fossil fuel dependence magnify the adverse environmental consequences of resource extraction (Faizi et al., 2025; Sun et al., 2022; Zhang et al., 2024; Zhou et al., 2024). For CO_2 emissions, NR rents are also positive and significant across all quantiles; however, the magnitude declines from lower to upper quantiles. This suggests that while resource rents consistently increase emissions, their marginal effect diminishes at higher emission levels, possibly due to capacity constraints or partial adoption of cleaner technologies in highly polluting contexts. These results strongly support Hypothesis H1.

REC exhibits a negative and statistically significant effect on ecological footprint at lower and middle quantiles, although its significance weakens at higher quantiles. This finding suggests that renewable energy is effective in reducing ecological pressure in relatively less environmentally stressed contexts but becomes less effective in high-footprint situations where fossil fuel dominance remains strong. In the CO_2 model, REC shows a stronger and increasingly significant negative effect at higher quantiles, with the largest reductions observed at the 75th and 90th quantiles. This indicates that renewable energy adoption is particularly effective in reducing emissions in high-pollution environments, where substitution away from fossil fuels yields substantial environmental gains. These findings are consistent with Wang et al. (2024), Aydin & Erdem (2024), and Faizi et al. (2024), all of whom report a beneficial impact of REC on environmental sustainability. Overall, these results confirm that REC contributes to environmental sustainability, although its effectiveness varies across environmental conditions. Thus, Hypothesis H2 is partially supported, with stronger evidence at higher emission levels.

Economic performance (GDP) consistently shows a positive and highly significant impact on both EF and CO_2 across all quantiles. Moreover, for EF, the magnitude of the coefficient increases steadily from lower to upper quantiles, indicating that economic growth exacerbates environmental degradation more severely in high-footprint contexts. These findings reflect dominant scale effects in Central Asian economies, where economic expansion is closely tied to energy-intensive industries and natural resource extraction. These findings are consistent with Ni et al. (2022), Işık et al. (2024), and Teng et al. (2024), who conclude that economic expansion deteriorates environmental excellence.

Technology (TEC), proxied by mobile cellular subscriptions, has a negative and statistically significant effect on both environmental indicators across all quantiles. Notably, the magnitude of the coefficient increases at higher quantiles for EF, indicating that technological diffusion plays a more prominent role in mitigating environmental degradation in high-pressure environments. For CO_2 emissions, the effect of technology remains stable and strongly negative across all quantiles, suggesting that digitalization and technological advancement contribute to improved energy efficiency and emissions reduction in Central Asia. The findings align with Lin et al. (2024) and Adebayo et al. (2022), who confirm that TEC improves environmental quality. These results highlight the importance of technology-driven environmental improvements and underscore the role of digital infrastructure in promoting sustainable development.

Taken together, the results reveal strong evidence of heterogeneous and nonlinear environmental effects in Central Asian economies. NR rents intensify environmental degradation, particularly at higher EF levels, confirming the environmental resource curse. REC and TEC play mitigating roles, although their effectiveness varies across environmental conditions. Importantly, the quantile-dependent results validate the use of MMQR and confirm Hypothesis H3, demonstrating that the environmental impacts of NR and REC are not uniform across the distribution of environmental pressure.

Table 7. MMQR estimation results

Variables	***Model 1: EF as Dependent variable***				
	Q10	**Q25**	**Q50**	**Q75**	**Q90**
lnNR	0.0986***	0.106***	0.117***	0.130***	0.141***
	(0.0287)	(0.0253)	(0.0256)	(0.0332)	(0.0434)
lnREC	-0.0344**	-0.0331**	-0.0313**	-0.0290	-0.0271
	(0.0154)	(0.0136)	(0.0137)	(0.0178)	(0.0232)
lnGDP	0.436***	0.461***	0.498***	0.542***	0.580***
	(0.0401)	(0.0354)	(0.0361)	(0.0466)	(0.0610)
lnTEC	-0.0147**	-0.0197***	-0.0269***	-0.0356***	-0.0431***
	(0.00637)	(0.00563)	(0.00575)	(0.00741)	(0.00972)
Constant	-2.892***	-3.006***	-3.173***	-3.373***	-3.546***
	(0.291)	(0.257)	(0.261)	(0.338)	(0.441)
Observations	150	150	150	150	150
	Model 2: CO2 as Dependent variable				
lnNR	0.317***	0.299***	0.274***	0.255***	0.246***
	(0.100)	(0.0766)	(0.0483)	(0.0398)	(0.0429)
lnREC	0.0280	-7.51e-05	-0.0398	-0.0698***	-0.0850***
	(0.0533)	(0.0409)	(0.0262)	(0.0216)	(0.0233)
lnGDP	1.093***	1.016***	0.908***	0.826***	0.784***
	(0.0884)	(0.0686)	(0.0446)	(0.0367)	(0.0398)
lnTEC	-0.0777***	-0.0773***	-0.0767***	-0.0762***	-0.0759***
	(0.0193)	(0.0147)	(0.00927)	(0.00764)	(0.00823)
Constant	-8.074***	-7.249***	-6.083***	-5.202***	-4.756***
	(0.672)	(0.530)	(0.354)	(0.290)	(0.316)
Observations	150	150	150	150	150

Note: *** and **signify significance at the 1% and 5% levels, respectively. Standard errors in parentheses.

4.4 Robustness Checks

Table 8 reports robustness check results using DOLS and FMOLS estimators. The signs and statistical significance of the coefficients are consistent with the MMQR findings for both environmental indicators. NR rents and GDP remain environmentally harmful, while REC and TEC contribute to environmental improvement. The consistency between MMQR and long-run estimators confirms the robustness of the results and strengthens confidence in the main conclusions of the study.

Table 8. Robustness Check Results

	Model 1: EF				Model 2: CO_2			
	DOLS		FMOLS		DOLS		FMOLS	
Variables	Coeff.	t-Stat.	Coeff.	t-Stat.	Coeff.	t-Stat.	Coeff.	t-Stat.
lnNR	0.09*	5.51	0.06*	8.39	0.11*	10.16	0.03*	6.49
lnREC	-0.27	-0.07	-0.20*	-4.04	-0.99*	-22.36	-0.57*	-23.84
lnGDP	0.69*	5.77	0.54*	18.89	0.06*	2.97	0.38*	14.59
lnTEC	-0.03*	-2.55	-0.03*	-7.79	-0.01*	-4.15	-0.02*	-7.85

Note: * indicates P-value at 0.01 (1%).

5. Conclusion

This study investigates the asymmetric and heterogeneous impacts of natural resource rents, renewable energy consumption, economic growth, and technology on environmental sustainability in Central Asian economies over the period 1992-2021. By employing the MMQR, the analysis moves beyond conventional mean-based estimations and captures distributional effects across different levels of ecological footprint and CO_2 emissions. This approach provides a more nuanced understanding of the environmental consequences of development dynamics in resource-dependent emerging economies. The empirical results reveal several key findings. First, natural resource rents significantly intensify both ecological footprint and CO_2 emissions across all quantiles, confirming that resource abundance in Central Asia is associated with environmental degradation rather than sustainability, confirming the environmental resource curse hypothesis. Second, renewable energy consumption plays a mitigating role in environmental degradation. The MMQR estimates show that renewable energy significantly reduces ecological footprint across most quantiles and lowers CO_2 emissions particularly at higher emission levels. Third, economic growth is found to exacerbate environmental pressure, with a consistently positive and significant impact on both ecological footprint and CO_2 emissions across all quantiles. The strengthening impact of income on ecological footprint at higher quantiles indicates that current growth trajectories in Central Asia are environmentally unsustainable and largely driven by energy-intensive and carbon-heavy production structures. Fourth, technology exerts a robust and negative effect on environmental degradation across all quantiles. The increasing magnitude of this effect at higher levels of pollution suggests that technological advancement and digital diffusion serve as critical tools for improving energy efficiency and reducing emissions, even in resource-dependent economies.

In terms of policy recommendation, these findings emphasize the urgent need for Central Asian governments to move beyond resource-dependent growth models by strengthening resource governance frameworks. Specifically, policymakers should: (i) redirect a portion of natural resource rents toward green investment funds, environmental restoration, and climate-resilient infrastructure; (ii) enhance transparency and accountability in extractive industries through compliance with international standards such as the Extractive Industries Transparency Initiative (EITI); and (iii) promote economic diversification into less resource and pollution-intensive sectors -such as agri-processing, services, and green manufacturing- particularly in resource-rich economies like Kazakhstan and Turkmenistan. Without institutional reforms, continued reliance on extractive rents risks locking the region into a resource-environment trap, where short-term growth gains are offset by long-term ecological degradation. In addition, governments should prioritize scaling up renewable energy deployment by: (i) exploiting the region's substantial solar and wind potential, especially in Kazakhstan and Uzbekistan; (ii) introducing stable feed-in tariffs, tax incentives, and long-term power purchase agreements (PPAs) to attract private and foreign investment; and (iii) strengthening regional energy cooperation through cross-border electricity trade and shared renewable infrastructure to reduce dependence on fossil fuels.

Despite its contributions, this study is not without limitations. Future research could incorporate broader measures of technological innovation, institutional quality, and environmental regulation, as well as explore country-specific nonlinear thresholds and dynamic spillover effects. Extending the analysis to include climate policy indicators or sectoral energy data would further enrich understanding of sustainable development pathways in Central Asia.

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