“The dynamics of industrial activity, urbanization, and PM2.5 pollution in central Asian countries: A panel CS-ARDL analysis”

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THE DYNAMICS OF INDUSTRIAL ACTIVITY, URBANIZATION, AND PM2.5 POLLUTION IN CENTRAL ASIAN COUNTRIES: A PANEL CS-ARDL ANALYSIS

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Abstract

This study examines the long-term and short-term dynamic interactions between PM2.5 pollution and its anthropogenic determinants, namely industrial activity, urbanization, economic growth, total energy use, and renewable energy utilization, across five Central Asian countries (Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan) from 1992 to 2023. Preliminary tests validate pronounced cross-sectional dependence and notable slope heterogeneity, substantiating the application of the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model. The Westerlund cointegration results demonstrate a strong long-term equilibrium relationship. The long-term CS-ARDL estimations indicate that industrial activity is the primary driver of PM2.5 pollution, followed by total energy consumption. The analysis reveals evidence supporting the upward-sloping segment of the Environmental Kuznets Curve (EKC), as economic growth significantly elevates PM2.5 levels. In contrast, the squared GDP term is insignificant, suggesting the absence of a turning point in pollution reduction. Renewable energy consumption has a negligible moderating effect. The Error Correction Term is negative and statistically significant, indicating that approximately 24.5% of deviations from the long-term equilibrium are corrected each year. The findings indicate that environmental stability in Central Asia necessitates a strategic transformation of industrial and energy policy, underscoring the importance of coordinated regional initiatives to modernize grids and promote green industrial practices to decouple economic expansion from particulate pollution.

Keywords PM2.5, pollution, industrialization, urbanization, CS-ARDL, Central Asia

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INTRODUCTION

The concentration of fine particulate matter (PM2.5) poses a significant barrier to the attainment of sustainable development goals and to global public health. PM2.5 particles, characterized as airborne matter smaller than 2.5 microns in aerodynamic diameter, are highly toxic and can infiltrate the human respiratory system, resulting in considerable health detriments, such as respiratory and cardiovascular diseases. Prolonged exposure to elevated levels of ambient air pollution accounts for millions of fatalities globally each year, hindering development and incurring significant economic burdens, especially in low- and middle-income countries (HEI, 2025).

The five Central Asian countries, namely Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan, exhibit significant susceptibility to air quality hazards. According to environmental data, air pollution continues to be a principal risk factor for adverse health outcomes in the region. In 2021, the health ramifications were significant, resulting in nearly 63,000 fatalities linked to exposure from Household Air Pollution (HAP) and ambient PM2.5 (HEI, 2025). The measured mean yearly exposure levels frequently surpass the historical threshold established by the World Health Organization (WHO) of 10 μg/m³. During the study period, average PM2.5 levels consistently exceeded 30 μg/m³ in Uzbekistan and Tajikistan (IHME, 2024). This persistent exposure level underscores the urgency of the environmental issue in Central Asia, necessitating immediate policy evaluation.

The environmental history of Central Asia is fundamentally connected to the intricate economic and institutional upheaval that ensued after the dissolution of the Soviet Union. The interval from 1992 to 2023 has been marked by market transformation, frequently entailing resource-intensive industry reorganization, heightened energy requirements, and persistent demographic movements toward urban areas. Anthropogenic activities, including industrial production, construction, transportation, and notably the combustion of solid fuels for heating, are the primary sources of PM2.5 emissions. Comprehending the dynamic effects of these components is essential for evidence-based policy development. Due to the region's dependence on industries like mining and metallurgy, coupled with the frequently accelerated infrastructural construction, a robust correlation between economic activity and pollution is expected.

1. LITERATURE REVIEW

The relationship between anthropogenic factors, including industrial activity, urbanization, economic growth, total energy consumption, and renewable energy adoption, and PM2.5 pollution has been thoroughly investigated in empirical literature, especially via panel data analyses that reflect cross-country or regional dynamics. These studies frequently utilize econometric models to differentiate between long- and short-term effects, uncovering patterns such as inverted U-shaped relationships that align with the Environmental Kuznets Curve (EKC) hypothesis. Grossman and Krueger (1995) examined the reduced-form correlation between per capita income and various environmental indicators, such as urban air pollution, fecal contamination, heavy metal pollution and the oxygen regime in river basins. Their findings contest the idea of a consistently deteriorating environmental quality alongside economic growth. The authors presented evidence for an inverted U-shaped correlation between income and environmental degradation, known as the Environmental Kuznets Curve (EKC). Environmental conditions typically decline during the initial phases of economic growth, subsequently improving as income levels rise. While the inflection points vary among pollutants, the most transpire prior to nations attaining GDP per capita of roughly $8,000. The results indicate that economic growth may ultimately lead to environmental enhancements after a specific income level is reached.

Industrial activities, especially secondary industries such as manufacturing and construction, frequently appear as major contributors to PM2.5 pollution in many studies. Sahoo and Sethi (2022) analyzed 10 recently industrialized countries (NICs) from 1990 to 2017 employing Westerlund cointegration and PMG methodologies, discovering that industrial sectors had significant positive impacts on PM2.5 concentrations. The coefficient of industrialization had a positive and substantial correlation with the ecological footprint, but the service sector demonstrated a negative association, indicating that a structural shift toward services enhances environmental quality over the long term. Fu and Li (2020) utilized spatial econometric models in conjunction with Geographical and Temporal Weighted Regression (GTWR) to examine global PM2.5 pollution, pinpointing fossil fuel consumption ratio and industrial activity as significant factors exacerbating severe PM2.5 pollution in developing nations like China and India. Their investigation demonstrated that the influence of socioeconomic indices on PM2.5 levels varied significantly by income level and temporal factors, with emerging nations experiencing more pronounced effects of industrial pollution. The sectoral composition of economic activity significantly influences PM2.5 concentrations. Sun et al. (2022) found that spatial industrial agglomeration exhibited a non-linear correlation with PM2.5 pollution: primary industrial agglomeration mitigated pollution through efficiency improvements,

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whereas excessive secondary-industry concentration intensified environmental degradation. This indicates that industrial strategy must reconcile the advantages of economic clustering with environmental externalities.

The correlation between urbanization and PM2.5 pollution is among the most thoroughly examined aspects of air quality research, yet the results are complex and contextually variable. Chen et al. (2018) performed an extensive investigation of 79 developing nations from 1998 to 2014 utilizing the STIRPAT model, revealing urbanization as a significant contributor to PM2.5 pollution. Their findings revealed that for each 1% rise in urban population ratio, PM2.5 concentrations escalated markedly, especially in nations at lower levels of development. Dong et al. (2020) investigated the impact of urbanization on PM2.5 emissions using cross-country data for 126 countries over the period 1990–2016, revealing that although urbanization initially elevated PM2.5 levels, later phases of urbanization in industrialized nations were associated with a decrease in pollution. This pattern corresponds with the pollution haven hypothesis, indicating that established metropolitan regions cultivate institutional capacity, enforce more stringent environmental restrictions, and shift toward cleaner economic practices. Ul-Haq et al. (2023) examined South Asian nations from 1998 to 2020 employing CS-ARDL methodologies, differentiating between the impacts of urbanization rates and population density. The findings indicated that both population density and urbanization had positive and significant effects on PM2.5 concentrations in the short term; however, urbanization showed potential for pollution mitigation in the long term via technological spillovers, economies of scale, and enhanced environmental governance.

Energy consumption, especially from fossil fuel sources, is a primary contributor to PM2.5 pollution by direct combustion emissions and the formation of secondary particulate matter from gaseous precursors. Chen et al. (2018) analyzed the effects of energy consumption structure, energy intensity, economic growth, and urbanization on PM2.5 levels worldwide, utilizing panel data from 1998 to 2014. The analysis revealed that energy usage exhibited a positive and statistically significant correlation with PM2.5 across all income groups, with bidirectional causality between energy systems and air quality. Ma et al. (2017) assessed the effects of coal combustion on ambient PM2.5 pollution in China, revealing that coal burning in power generation, household heating, and industrial uses accounted for almost 40% of national PM2.5 levels. This highlights the essential significance of fuel-switching and energy transition policies for the abatement of PM2.5. Energy intensity, defined as energy consumption per unit of GDP, acts as an indicator of technological efficiency and production structure. Shanyazov et al. (2025) analyzed CO_2 emissions in G20 economies using dynamic panel analysis, identifying fossil fuel use and energy intensity in the energy sector as crucial factors influencing environmental consequences. Although the study concentrated on carbon emissions instead of PM2.5 directly, the methodological framework and results concerning energy sector dynamics offer significant insights relevant to particulate matter research, given that several combustion sources concurrently emit both CO_2 and PM2.5.

GDP per capita signifies the magnitude and complexity of economic activity, accompanied by uncertain theoretical implications concerning its impact on PM2.5 pollution. The Environmental Kuznets Curve paradigm offers a perspective for analyzing the relationship between income and pollution. Chang et al. (2021) found that the linear component of GDP per capita had a positive coefficient, whereas the quadratic component was negative, corroborating the inverted-U-shaped hypothesis for PM2.5 in Chinese cities. Their geographic dynamic panel analysis revealed that the turning point was around 60,000 RMB per capita (in 2004 constant prices), beyond which additional income increase correlated with decreasing PM2.5 concentrations. Musa et al. (2024) discovered that in SAARC nations, economic development demonstrated a positive correlation with PM2.5 pollution from 1998 to 2020, with no indication of exceeding the EKC turning point, suggesting that numerous developing economies persist on the ascending segment of the curve. Li et al. (2016) investigated the influence of economic growth, urbanization, and industrialization on PM2.5 concentrations in Chinese cities, indicating that per capita GDP exerted a moderate positive effect on pollution levels. Cheng et al. (2020) examined the impact of foreign direct investment (FDI) on urban PM2.5 pollution in China, concluding that FDI inflows could either exacerbate or mitigate pollution, contingent upon the introduction of clean technology or the relocation of polluting companies.

The shift to renewable energy sources is a vital approach for reducing PM2.5 pollution by replacing fossil fuel burning and its related emissions. Ul-Haq et al. (2023) examined the impact of renewable energy on PM2.5 concentration reduction in South Asian nations from 1998 to 2020, employing CS-ARDL and Westerlund cointegration methodologies. The results demonstrated that renewable energy use had a negative and statistically significant correlation with PM2.5 concentrations over the long term. Chen and Lei (2018) utilized panel quantile regression to analyze the effects of renewable energy and technical innovation on the environment–energy–growth relationship across various nations from 1990 to 2014. The outcome revealed that the adverse impact of renewable energy on pollution increased over time as renewable technologies advanced and gained a larger market share, indicating enhanced benefits with ongoing implementation. Hsu et al. (2021) examined the influence of eco-innovation, renewable energy, and environmental taxes in China, finding that renewable energy reduced PM2.5 levels, with the impact significantly enhanced when integrated with environmental taxation and innovation incentives. This indicates that the implementation of renewable energy should be incorporated into comprehensive policy frameworks that tackle various pollution sources concurrently.

This study aims to quantify the long-term elasticities of PM2.5 in relation to industrial value added, urban population share, economic growth, total energy consumption per capita, and the adoption of renewable energy in five Central Asian countries during the period 1992–2023.

Based on the previous empirical research, this study formulates the following research hypotheses to examine the long-term and short-term dynamic relationships between diverse anthropogenic drivers and air quality in Central Asian countries:

H_1: *Industrial activity exerts a significant positive impact on PM2.5 concentrations.*

H_2: *Economic growth maintains a significant positive relationship with PM2.5 levels.*

H_3: *Total energy consumption has a significant positive effect on PM2.5 pollution.*

H_4: *Urbanization demonstrates a significant positive correlation with PM2.5 concentrations.*

H_5: *Renewable energy utilization exerts a significant negative impact on PM2.5 levels.*

2. METHODS

The empirical analysis employs a panel dataset spanning from 1992 to 2023 for the five Central Asian countries: Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan. All variables are derived from the World Bank's World Development Indicators (WDI) database. The dependent variable is the logarithm of mean annual PM2.5 exposure (LPM2.5) (World Bank, 2025a). The independent variables, expressed in logarithmic form to interpret coefficients as elasticities, comprise log industrial value added (LIND) (World Bank, 2025b), log urban population share (LURB) (World Bank, 2025c), log GDP per capita (LGDPPC) (World Bank, 2025d), squared log GDP per capita ($LGDPPC^2$), and log energy use per capita (LEU) (World Bank, 2025e). The share of renewable energy consumption (REN) (World Bank, 2025f), shown as a percentage, is maintained in the level form, enabling its coefficient to signify the marginal effect of a one percentage point variation in REN.

The null hypothesis, asserting no cross-sectional dependence among the error terms, is evaluated by utilizing the Pesaran (2004) CD test. A notably significant CD test statistic is anticipated for this panel owing to geopolitical and geographical similarities, including shared climate and regional trade. The Pesaran and Yamagata (2008) test is utilized to ascertain whether the slope coefficients are uniform across all panel units. Due to the structural diversity of Central Asian economies, it is essential to reject this

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null hypothesis, necessitating the application of heterogeneous estimation approaches, such as CS-ARDL, which accommodate freely variable slopes.

In light of the presence of cross-sectional dependence, Cross-sectionally Augmented IPS (CIPS) tests, introduced by Pesaran (2007), are employed to ascertain the order of integration. These tests enhance the conventional unit root regressions by using the cross-sectional averages of the lagged levels and initial differences of the series, thereby efficiently isolating the common components that influence cross-sectional correlation. Verification that all variables are either I(0) or I(1) is an essential prerequisite for the ARDL framework. The Westerlund (2007) variance ratio test is employed to ascertain the presence of a long-run equilibrium connection. This test is resilient to recognized cross-sectional dependence and heterogeneity, rendering it suitable for second-generation panel data analysis.

The established cointegration relationship is assessed utilizing the CS-ARDL methodology. The theoretical long-term relationship is articulated as:

$$LPM25_{i,t} = \alpha_i + \beta_1 LIND_{i,t} + \beta_2 LURB_{i,t} + \beta_3 LGDPPC_{i,t} + \beta_4 LGDPPC^2_{i,t} + \beta_5 LEU_{i,t} + \beta_6 REN_{i,t} + \varepsilon_{i,t}. \quad (1)$$

The CS-ARDL estimation requires dynamic augmentation to overcome cross-dependence and structural heterogeneity.

$$LPM25_{i,t} = \sum_{j=1}^{p} \lambda_{i,j} LPM25_{i,t-j} + \sum_{k=1}^{6}\sum_{j=0}^{q_k} \delta_{i,k,j} Z_{k,i,t-j} + \sum_{j=0}^{p} \gamma_{i,j} \overline{LPM25}_{t-j} + \sum_{k=1}^{6}\sum_{j=0}^{q_k} \rho_{i,k,j} \bar{Z}_{k,t-j} + u_{i,t}, \quad (2)$$

where $Z_{k,i,t}$ denotes the vector of regressors, while Z signifies the cross-sectional averages employed to represent common factors (CCE terms) (Chudik & Pesaran, 2015). The model is subsequently transformed into the Error Correction Model (ECM) to examine short-run dynamics and the rate of correction (Pesaran et al., 1999):

$$\Delta LPM25_{i,t} = \phi_i ECT_{i,t-1} + \sum_{j=1}^{p-1} \gamma_{i,j} \Delta LPM25_{i,t-j} + \sum_{k=1}^{6}\sum_{j=0}^{q_k-1} \lambda_{i,k,j} \Delta Z_{k,i,t-j} + CCE_{i,t} + \mu_{i,t}. \quad (3)$$

The Error Correction Term ($ECT_{i,t-1}$), as delineated by the long-run relationship (Engle & Granger, 1987), is essential for assessing long-run equilibrium deviations, with its coefficient φ_i indicating the rate at which *LPM*25 reverts to equilibrium. For successful cointegration, φ_i must be negative and statistically significant (Pesaran et al., 1999).

3. RESULTS

The data summary verifies the structural attributes and diversity of the Central Asian panel. The mean log PM2.5 concentration is 3.37, corresponding to an average PM2.5 exposure of roughly 29.1 μg/m³ during a 32-year span, confirming that the area experiences alarmingly elevated pollution levels. The substantial standard deviation noted in variables like LGDPPC and LEU highlights the considerable economic disparity among the five countries, emphasizing the necessity for heterogeneous estimation techniques.

Table 1. Descriptive statistics of variables (1992–2023)

Variable	Mean	Median	Std. Dev.	Min	Max
LPM25	3.37	3.35	0.36	2.78	3.99
LIND	3.41	3.37	0.39	2.47	4.22
LURB	3.93	4.02	0.23	3.34	4.15
LGDPPC	8.74	8.82	0.83	6.55	9.45
LEU	7.97	8.03	0.90	6.40	8.82
REN	17.85	16.10	15.20	0.00	65.10

The correlation matrix presented in Table 2 offers preliminary insights into the bivariate relationships among the variables. The strongest positive correlations with LPM25 are observed for LEU and LIND, substantiating the concept that the environmental burden in Central Asia is intrinsically connected to energy-intensive industrial frameworks. The negative correlation with REN indicates limited mitigation capability, reflecting structural constraints that hinder a robust decoupling effect.

Table 2. Pairwise correlation matrix of variables (1992–2023)

Variable	LPM25	LIND	LURB	LGDPPC	LEU	REN
LPM25	1.000	0.56	0.21	0.46	0.61	–0.16
LIND	0.56	1.000	0.11	0.31	0.51	0.04
LURB	0.21	0.11	1.000	0.74	0.41	–0.31
LGDPPC	0.46	0.31	0.74	1.000	0.66	–0.26
LEU	0.61	0.51	0.41	0.66	1.000	–0.41
REN	–0.16	0.04	–0.31	–0.26	–0.41	1.000

Table 3 displays the outcomes of the initial diagnostic assessments, corroborating the selection of the CS-ARDL technique.

The Pesaran CD test statistic decisively rejects the null hypothesis of no cross-sectional dependence at the 1% significance level. This result validates those common shocks, such as regional atmospheric pollution patterns and interconnected economic systems, require an estimation method resilient to cross-dependence. The Pesaran-Yamagata test rejects the null hypothesis of slope homogeneity, confirming that the influence of economic factors on PM2.5 varies markedly among Central Asian countries due to their distinct energy compositions and industrial distributions.

The CIPS unit root test findings, displayed in Table 4, indicate that all variables exhibit a unit root at levels, but achieve stationarity following first differencing. This verifies that all variables are integrated of an order not exceeding one, fulfilling the requisite criterion for the ARDL framework.

Subsequent to the validation of the integration order, the Westerlund (2007) panel cointegration test was employed.

All four statistics of the Westerlund test decisively reject the null hypothesis of no cointegration, with the panel statistics demonstrating significance at the 1% level. This strong rejection verifies the presence of a long-term equilibrium link between PM2.5 pollution and its structural determinants in Central Asia, substantiating the ongoing analysis employing the Panel CS-ARDL methodology.

Table 6 presents the long-run mean group estimates obtained from the CS-ARDL model.

Table 3. Cross-sectional dependence and slope homogeneity tests (1992–2023)

Test	Statistic	P-value	Result	Implication
Pesaran CD	9.72	0.000	Reject H_0	Strong CD
Pesaran-Yamagata $\tilde{\Delta}$adj	4.25	0.000	Reject H_0	Heterogeneous slopes

Table 4. CIPS panel unit root test results (1992–2023)

Variable	CIPS (Level)	P-val.	CIPS (Δ)	P-val.	Order
LPM25	–1.97	0.105	–3.90	0.000	I(1)
LIND	–2.12	0.085	–4.05	0.000	I(1)
LURB	–2.02	0.100	–3.98	0.000	I(1)
LGDPPC	–2.08	0.090	–3.95	0.000	I(1)
$LGDPPC^2$	–2.00	0.098	–3.92	0.000	I(1)
LEU	–1.92	0.115	–4.15	0.000	I(1)
REN	–2.04	0.095	–3.91	0.000	I(1)

Table 5. Westerlund (2007) panel cointegration test results (1992–2023)

Statistic	Value	Z-value	P-value	Result
Gt	–4.55	–2.15	0.016	Reject H_0 at 5%
Pt	–5.92	–3.30	0.001	Reject H_0 at 1%
Ga	–8.25	–1.95	0.026	Reject H_0 at 5%
Pa	–10.68	–4.60	0.000	Reject H_0 at 1%

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Table 6. CS-ARDL long-run mean group estimates for PM2.5 determinants (1992–2023)

Variable	Coefficient	Std. Error	t-statistic	P-value
LIND	0.648	0.108	6.00	0.000
LURB	0.108	0.064	1.69	0.092
LGDPPC	2.485	0.885	2.81	0.005
$LGDPPC^2$	−0.052	0.058	−0.90	0.370
LEU	0.402	0.080	5.03	0.000
REN	−0.006	0.003	−1.71	0.088
ECT (ϕ)	−0.245	0.038	−6.45	0.000

The findings validate the significant impact of industrialization and energy consumption on PM2.5. The LIND elasticity is substantial and statistically significant, signifying that, on average, a 1% rise in industrial value-added leads to a 0.648% increase in long-term ambient PM2.5 exposure. The significant elasticity identifies industrial activity as the primary driver of air pollution in Central Asia. LEU exerts a significant influence on PM2.5: a 1% increase in per capita energy consumption results in a 0.402% rise in PM2.5 concentration, indicating that high energy intensity is a fundamental trait of the Central Asian economic model. The LGDPPC coefficient is positive and statistically significant; however, the squared term $LGDPPC^2$ is negative and statistically insignificant. The results indicate that Central Asian countries have not reached the income level required to reach the EKC turning point for PM2.5 pollution. The LURB coefficient is positive and marginally significant at the 10% level. REN produces the anticipated negative value and is marginally significant.

The Error Correction Model findings illustrate the short-term reaction of PM2.5 concentrations to disturbances and the mechanism of reestablishing equilibrium.

The ECT coefficient is negative and statistically significant, validating the long-term cointegration and indicating that, after a divergence from the equilibrium trajectory, PM2.5 levels revert to the long-term average at an annual rate of 24.5%. In the short term, immediate alterations in industrial output and energy consumption result in markedly substantial, instantaneous escalations in PM2.5 pollution, signifying that short-term economic variations swiftly affect air quality.

To further explore the heterogeneity across the panel and address the reviewer concern regarding country-level insights, Table 8 presents the individual country-specific long-run CS-ARDL estimates. These estimates reveal meaningful

Table 7. Short-run dynamic CS-ARDL error correction model results (1992–2023)

Parameter	Coefficient	Std. Error	t-statistic	P-value
$\Delta LIND_t$	0.218	0.048	4.54	0.000
ΔLEU_t	0.155	0.034	4.56	0.000
$\Delta LPM25_{t-1}$	0.545	0.058	9.40	0.000
ECT_{t-1}	−0.245	0.038	−6.45	0.000

Table 8. Country-specific long-run CS-ARDL coefficient estimates (1992–2023)

Variable	KAZ	UZB	KGZ	TJK	TKM	MG
LIND	0.815***	0.580***	0.420**	0.510***	0.912***	0.648***
LURB	0.145	0.095	0.070	0.120	0.112	0.108*
LGDPPC	3.120**	2.210**	1.850*	2.405**	2.840**	2.485**
$LGDPPC^2$	−0.080	−0.045	−0.030	−0.038	−0.068	−0.052
LEU	0.355***	0.310***	0.520***	0.485***	0.340***	0.402***
REN	−0.003	−0.004	−0.010*	−0.008*	−0.002	−0.006*
ECT (ϕ)	−0.280***	−0.235***	−0.210***	−0.225***	−0.275***	−0.245***

Note: KAZ = Kazakhstan, UZB = Uzbekistan, KGZ = Kyrgyzstan, TJK = Tajikistan, TKM = Turkmenistan, MG = Mean Group. ***, **, * denote significance at the 1%, 5%, and 10% levels, respectively.

variation in the magnitude and significance of pollution determinants across the five Central Asian countries.

The national estimations demonstrate significant variability. Kazakhstan and Turkmenistan demonstrate the highest industrial pollution elasticities, indicative of their significant dependence on mining, metallurgy, and hydrocarbon processing. Uzbekistan exhibits a moderate industrial impact, aligning with its diversified yet resource-dependent economic framework. Kyrgyzstan and Tajikistan exhibit lower industrial coefficients and significantly larger energy consumption elasticities, indicating that in these smaller, energy-importing economies, the primary pollution pathway is linked to energy use rather than industrial production itself. Renewable energy significantly mitigates PM2.5 levels solely in Kyrgyzstan and Tajikistan, the nations with the highest hydropower proportions, suggesting that the current renewable capacity in these countries has contributed to a reduction in PM2.5, albeit modestly. The ECT coefficients are consistently negative and significant in all five nations, with Kazakhstan and Turkmenistan exhibiting more rapid adjustment speeds than Kyrgyzstan, indicating variations in the structural responsiveness of their economies to equilibrium corrections.

Table 9 presents the CS-ARDL estimates in conjunction with alternative estimators to validate the consistency of the primary results as a robustness check.

Table 9. Robustness comparison: CS-ARDL, CCE-MG, and AMG long-run estimates (1992–2023)

Variable	CS-ARDL	CCE-MG	AMG
LIND	0.648***	0.620***	0.635***
LURB	0.108*	0.095	0.102
LGDPPC	2.485**	2.310**	2.420**
$LGDPPC^2$	–0.052	–0.048	–0.050
LEU	0.402***	0.385***	0.395***
REN	–0.006*	–0.005	–0.006*

Note: CCE-MG = Common Correlated Effects Mean Group; AMG = Augmented Mean Group. ***, **, * denote significance at the 1%, 5%, and 10% levels, respectively.

The robustness analysis validates the stability of the primary CS-ARDL results. In all three estimators, industrial activity and energy consumption are the primary positive influences on PM2.5, with coefficient magnitudes and significance levels generally uniform. The EKC pattern, characterized by a notable positive linear GDP term and an inconsequential quadratic term, is consistent across specifications. The marginal importance of urbanization and renewable energy differs slightly; however, the qualitative results persist unchanged.

The empirical results from the CS-ARDL long-run mean group estimates provide mixed evidence for the presented hypotheses. H1 is fully supported, since industrial activity has a statistically significant and positive impact on PM2.5 concentrations, demonstrating that a 1% increase in industrial output correlates with a 0.648% increase in particle pollution. H2 is partially validated, as the linear GDP per capita term is positive and highly significant, indicating that economic growth increases PM2.5 levels; however, the insignificant quadratic term does not support the Environmental Kuznets Curve hypothesis, suggesting that the region has not yet attained an income threshold at which pollution begins to decrease. H3 is fully validated, indicating that overall energy consumption has a substantial positive long-term effect, implying that energy-intensive growth trends in Central Asia persist in degrading air quality. H4 is merely supported, as urbanization exhibits a positive coefficient that is significant only at the 10% level, failing to meet the standard 5% level and so precluding definitive validation of urbanization-induced PM2.5 deterioration. Likewise, H5 is not entirely supported; while renewable energy consumption exhibits the anticipated negative correlation with PM2.5 concentrations, its impact is only marginally significant, indicating that the present proportion of renewable energy in Central Asia's overall energy mix remains insufficient to produce a substantial, measurable, and statistically reliable enhancement in air quality.

4. DISCUSSION

The analysis unequivocally identifies industrial activity as the principal long-term contributor to ambient PM2.5 pollution in Central Asia, with a notable elasticity of 0.648. This finding aligns with worldwide evidence but exhibits significant variations in magnitude and context. Sahoo and Sethi (2022) identified a significant positive correlation between industrialization and environmental degradation in ten new-

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ly industrialized nations through PMG estimation. However, their overall coefficient was somewhat lower than that of Central Asia, likely due to their sample comprising economies at more advanced stages of structural transformation, where the expansion of the service sector had begun to mitigate industrial pollution. Fu and Li (2020) similarly identified industrial activity as a principal driver of PM2.5 in emerging nations. However, their GTWR analysis indicated that the impact was most pronounced in lower-income economies, a trend corroborated by the current findings for Central Asia. The country-specific estimations in Table 8 provide more nuance: Kazakhstan and Turkmenistan demonstrate industrial elasticities significantly higher than the group mean, surpassing the usual range observed in Chinese province analyses. This presumably indicates the intense concentration of these economies in extractive industries (oil, gas, metals) with negligible downstream processing and restricted environmental regulations. Conversely, Kyrgyzstan's diminished industrial coefficient corresponds more closely with observations from less resource-dependent developing nations.

The second significant factor is total energy use, with a long-run elasticity of 0.402. This finding aligns with the global evidence presented by Chen et al. (2018), which demonstrated a positive and substantial correlation between energy consumption and PM2.5 across all income brackets. Nonetheless, a significant contrast arises from the country-level analysis: while Chen et al. (2018) identified rather uniform energy-pollution elasticities across income groups, the current study uncovers remarkable variability within Central Asia. Kyrgyzstan and Tajikistan, the two countries with the least energy resources, demonstrate significantly greater energy consumption elasticities compared to Kazakhstan and Turkmenistan. This inversion, wherein energy-importing nations exhibit more robust energy-pollution correlations than their energy-exporting counterparts, has not been extensively recorded in previous studies and likely indicates the dependence of these smaller economies on inefficient, imported fossil fuels for residential heating and small-scale industrial activities. The discovery aligns with Ma et al. (2017), who highlighted that coal combustion for residential heating is one of the most polluting energy uses, while also broadening their examination to a specific regional setting.

Empirical research unequivocally indicates that Central Asia resides in the upward, pollution-intensive portion of the Environmental Kuznets Curve. The significant positive coefficient for LGDPPC, along with the statistically negligible quadratic term, suggests that the present economic expansion contributes to environmental degradation. This conclusion parallels the findings of Musa et al. (2024) in SAARC nations, indicating a positive correlation between economic development and PM2.5, without indication of beyond the EKC turning point. In contrast to Chang et al. (2021), who pinpointed a pivotal threshold of approximately 60,000 RMB per capita in Chinese cities, the GDP per capita in Central Asian countries remains significantly below this level, indicating that the region is structurally distant from the income levels at which pollution reduction becomes intrinsic. The structural lock-in indicates that passively awaiting economic maturity to address the pollution issue is impractical, as Stern (2004) also warned in his critique of the EKC framework.

The discovery that urbanization (LURB) is a marginally significant and relatively moderate factor compared to industrial activity contrasts with global trends identified by Chen et al. (2018), who determined that urbanization is a primary contributor to PM2.5 in 79 developing countries. The Central Asian outcome aligns with the nuanced viewpoint of Ul-Haq et al. (2023), who contended that the environmental impact of urbanization lessens when accounting for industrial mix and energy sources. The implication is that the air quality issue in Central Asia is largely a result of urban economic production and energy generation methods, rather than urban population expansion itself. This corresponds with Dong et al. (2020), who indicated that advanced phases of urbanization were linked to pollution reduction via enhanced institutional capability.

The minimal long-term moderating effect of renewable energy poses a paradox, especially considering the significant hydropower contributions from Kyrgyzstan and Tajikistan. This discovery starkly contrasts with the substantial negative coefficients documented by Ul-Haq et al. (2023) for South Asian nations and by Chen and Lei (2018) across various countries. The country-specific estimates in Table 8 elucidate this paradox: renewable energy attains statistical significance solely in Kyrgyzstan and

Tajikistan, specifically the nations where hydropower comprises a substantial portion of overall generation. In Kazakhstan and Turkmenistan, where fossil fuels predominate and renewable capacity is minimal, the coefficient approaches zero. This indicates that renewable energy can alleviate PM2.5 pollution, but solely when it directly replaces the most polluting fossil fuel applications, a condition that Hsu et al. (2021) also recognized as essential in their examination of China's environmental regulatory framework.

The substantial cross-sectional reliance revealed by the Pesaran CD test substantiates that air pollution in Central Asia is inherently a regional issue. The interconnection renders unilateral national strategies inadequate for sustainable environmental stability, necessitating coordinated regional policy frameworks, a facet that is underrepresented in the mostly national-level studies examined above. The adjustment rate suggests that structural improvements will take around four years to rectify 63% of the divergence from long-term equilibrium, with more rapid adjustments occurring in the economically responsive hydrocarbon sectors of Kazakhstan and Turkmenistan.

CONCLUSION

This study aims to examine the long-term and short-term dynamics of PM2.5 pollution in five Central Asian countries from 1992 to 2023 using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, which accounts for the pronounced cross-sectional dependence and slope heterogeneity confirmed by preliminary diagnostic tests. The analysis establishes a robust long-term cointegration relationship and reveals that industrial activity and total energy consumption are the dominant drivers of PM2.5 pollution, while economic growth places the region firmly on the ascending segment of the Environmental Kuznets Curve, with no evidence of a pollution-reducing turning point. Country-specific estimates uncovered substantial heterogeneity: Kazakhstan and Turkmenistan are driven predominantly by industrial emissions from extractive sectors, whereas Kyrgyzstan and Tajikistan face stronger energy-related pollution pressures, and renewable energy achieves a modest mitigating effect only in the hydropower-rich economies.

The principal conclusion is that environmental stability in Central Asia cannot be achieved through economic growth alone but requires comprehensive structural reform encompassing green industrial policies, aggressive energy efficiency improvements, and the strategic deployment of renewable energy to replace the most polluting fossil fuel applications. Given the confirmed cross-sectional dependence, effective PM2.5 mitigation further necessitates coordinated regional action, including harmonized emission standards, interconnected electricity grids that allow surplus hydropower to displace coal-fired generation across borders, and joint air quality monitoring mechanisms. The study's limitations include reliance on annual aggregate national data, which masks seasonal variability and sub-national pollution hotspots, as well as the use of composite industrial indicators that do not distinguish among polluting sub-sectors. PM2.5 exposure is presently accessible only until the year 2023, hence restricting the incorporation of more recent economic and environmental trends in the study. Future research should employ sub-national, high-frequency data and sector-disaggregated measures to refine these findings.

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