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Industrial Growth and Air Pollution in Uzbekistan: Testing the Environmental Kuznets Curve Hypothesis

Xamdamov Isakjan Mamasaliyevich
Tashkent State University of Economics, Tashkent, Uzbekistan
Professor of the Department of Econometrics
E-mail: khamdamov.isakjan@gmail.com
Abdullayeva Diloro Kuysunovna
Associate Professor of the Department of Econometrics
E-mail: dilora57@yandex.com

Abstract

This paper tests the environmental Kuznets curve (EKC) hypothesis for Uzbekistan using official annual data on pollutant emissions from stationary sources and real GDP per capita for 2011–2025. Nominal series published by the National Statistics Committee are converted to constant 2011 prices by chain-linking official volume indices. Quadratic and cubic log–log specifications are estimated, the inverted-U shape is assessed with the Lind–Mehlum test, and the analysis is complemented by Tapio decoupling elasticities and a regional decomposition of emissions. A specification in nominal terms proves unreliable owing to severe multicollinearity (variance inflation factors of 91–401). In the full sample, an inverted U is not statistically supported ($p = 0.44$). Once two localized emission spikes (2014 and 2025) are controlled for, a significant inverted U emerges ($p = 0.006$), with a turning point of 5.33 million soums per capita at 2011 prices, which corresponds to the income level of 2016–2017. Between 2016 and 2024, emissions declined by 14.0% while real industrial output grew by 60.2%, indicating strong decoupling. In 2025, however, emissions rose by 37.1%, and virtually the entire increase occurred in the Tashkent, Samarkand and Fergana regions. The results suggest that environmental improvement in Uzbekistan is not an automatic by-product of growth but depends on technology and enforcement policies targeted at regional pollution hotspots.

Keywords

environmental Kuznets curve; air pollution; industrial growth; decoupling; Lind–Mehlum test; regional concentration; Uzbekistan

1. Introduction

Air quality has become one of the most sensitive indicators of the environmental cost of economic development. According to the World Health Organization (WHO), 99% of the world's population lived in 2019 in places where the WHO air quality guideline levels were not met, and ambient air pollution caused an estimated 4.2 million premature deaths in that year [1]. Quantifying how economic growth affects air quality is therefore a pressing policy task, particularly in rapidly industrializing economies.

Uzbekistan is a telling case. Between 2011 and 2025, real industrial output increased 2.25-fold and real GDP per capita 1.88-fold. Over the same period, emissions of pollutants from stationary sources rose from 788.2 to 1,188.2 thousand tonnes, the highest level in the observation window, according to the National Statistics Committee of the Republic of Uzbekistan (NSC) [2]. Environmental quality is also an explicit policy objective: the Strategy for the Transition to a Green Economy for 2019–2030 (Presidential Resolution No. PQ-4477 of 4 October 2019) and the "Uzbekistan–2030" Strategy (Presidential Decree No. PF-158 of 11 September 2023) both aim to reduce environmental pressure while sustaining high growth.

The main theoretical lens for the growth–pollution nexus is the EKC hypothesis, according to which pollution rises in the early stages of development and declines once income passes a turning point [3]. If the EKC holds for Uzbekistan, environmental pressure will partly ease as incomes rise; if it does not, growth without active environmental policy will continue to degrade air quality. Most econometric evidence for Uzbekistan concerns CO_2 emissions (see, e.g., [4]), whereas official data on emissions of local air pollutants from stationary sources, and their regional composition, have received much less attention; a notable exception is the study by Muminova et al. [5].

This paper tests the EKC hypothesis for stationary-source emissions in Uzbekistan using official data for 2011–2025 and assesses the extent to which industrial growth has decoupled from air pollution. It makes three contributions. First, it shows that measuring income in nominal terms in a high-inflation setting produces spurious results, and it re-

estimates the EKC in real terms using chain-linked official volume indices. Second, it tests the shape of the relationship formally with the Lind–Mehlum procedure rather than relying on the sign of the quadratic term. Third, it combines the EKC estimates with Tapio decoupling elasticities and a regional decomposition, which reveals that the aggregate trajectory is driven by a small number of regional hotspots.

2. Literature review

Grossman and Krueger [3] showed that concentrations of several urban air and water pollutants first increase and then decrease with per capita income, a pattern that became known as the EKC. The relationship is usually explained by three proximate effects: a scale effect, whereby a larger economy generates more pollution; a composition effect, as economic activity shifts towards less pollution-intensive sectors; and a technique effect, as cleaner technologies and stricter regulation reduce emissions per unit of output [6]. An inverted U arises only if the composition and technique effects eventually outweigh the scale effect. The existence and location of a turning point therefore depend on a country's production structure, energy mix and institutions rather than on income alone.

The empirical robustness of the EKC has been widely questioned. Stern [6] showed that estimates are highly sensitive to the choice of pollutant, sample and estimation method, and that many studies suffer from omitted-variable bias and spurious regressions between trending series. Dinda [7] documented that estimated turning points vary widely across studies and pollutants. Two methodological issues are particularly relevant here. First, a negative quadratic coefficient is not sufficient evidence of an inverted U: the slope must be positive at the lower bound and negative at the upper bound of the observed income range, a condition that Lind and Mehlum [8] test formally. Second, regressions that include powers of an integrated income series do not obey standard cointegration theory, so estimates obtained from short samples must be interpreted with caution [9].

Evidence for Central Asia is mixed. Caporin et al. [10] concluded that a linear specification describes the region better than an N-shaped one, suggesting that Central Asian economies remain on the rising segment of the curve. For Uzbekistan, Muminova

et al. [5] examined emissions of pollutants into the atmosphere together with GDP per capita and coal consumption and reported a negative relationship beyond a certain income level, while Nuriddinova and Ahmad [4] found tentative support for an inverted U in CO_2 emissions using quarterly data for 1996–2022 in a vector autoregressive framework. None of these studies, however, distinguishes between nominal and real income, tests the turning point formally or examines the regional concentration of emissions. The present paper addresses these gaps.

3. Data and methods

3.1. Data

The analysis uses annual official data for 2011–2025 published by the NSC [2]. The dependent variable is the volume of pollutants emitted into the atmosphere from stationary sources (E, thousand tonnes). The indicator is compiled from statistical reporting form 1-eko, submitted by enterprises that operate stationary emission sources, and does not cover emissions from road transport. Income is measured by GDP per capita and industrial activity by the volume of industrial output. Descriptive statistics are reported in Table 1.

Table 1. Variables and descriptive statistics, 2011–2025 (n = 15)

Symbol	Variable (unit)	Mean	SD	Min	Max	2025/ 2011
E	Emissions of pollutants from stationary sources (thousand t)	921.4	122.5	763.2	1,188.2	×1.51
Y	Real GDP per capita (million soums, 2011 prices)	5.59	1.04	3.94	7.40	×1.88
Q	Real industrial output (trillion soums, 2011 prices)	73.3	18.7	47.6	107.3	×2.25
X_1	Nominal GDP per capita (million soums)	18.84	14.18	3.94	48.82	×12.39
X_3	Nominal industrial output (trillion soums)	346.3	326.7	47.6	1,101.1	×23.14

Source: Authors' calculations based on NSC data [2]. Indicator codes: *E* — 3.02.02.0001; *Y* — 1.01.03.0003 and 1.01.03.0004; *Q* — 1.02.01.0020 and 1.02.01.0022. Real series are computed with Eq. (1); industrial data for 2025 are preliminary.

Unlike nominal series, real indicators remove the effect of price changes. Real GDP per capita was obtained by chain-linking the official volume indices, starting from the nominal value for 2011:

$$Y_t = Y_{t-1} \cdot \frac{I_t^Y}{100} \qquad (1)$$

where I_t^Y is the volume index of GDP per capita (previous year = 100) and Y_{2011} = 3.941 million soums. Real industrial output (Q_t) was computed in the same way from the physical volume index of industrial production (106.8% in 2025, preliminary estimate).

3.2. Model specification

The baseline EKC specification is a quadratic log–log model:

$$ln\, E_t = \beta_0 + \beta_1 x_t + \beta_2 x_t^2 + \varepsilon_t \quad (2)$$

where $x_t = \ln Y_t - \bar{x}$, $\bar{x}$ = 1.7037 is the sample mean of ln Y_t, and ε_t is an error term. Centering does not alter the fit of the model, but it removes the non-essential collinearity between x_t and x_t^2 (the variance inflation factor falls from 340 to 1.04) and allows β_1 to be interpreted as the income elasticity of emissions at the mean income level. The elasticity and the turning point are given by

$$\eta_t = \frac{\partial\, ln\, E_t}{\partial\, ln\, Y_t} = \beta_1 + 2\beta_2 x_t \qquad (3)$$

$$Y^* = exp\left(\bar{x} - \frac{\beta_1}{2\beta_2}\right) \qquad (4)$$

An inverted U requires $\beta_2 < 0$. To test for an N-shape, a cubic term $\beta_3 x_t^3$ is added to Eq. (2). Because the regional data show that the spikes of 2014 and 2025 were concentrated in a few regions (Section 4.2), the model is also extended with dummy variables that control for these localized shocks:

$$ln\, E_t = \beta_0 + \beta_1 x_t + \beta_2 x_t^2 + \delta_1 D_t^{2014} + \delta_2 D_t^{2025} + \varepsilon_t \qquad (5)$$

Real industrial output is not included as a regressor, because the correlation between ln *Y* and ln *Q* is 0.994 and the variance inflation factors reach 166–171 when

both variables enter the model. The link between industrial growth and emissions is instead assessed with decoupling indicators (Section 3.4).

3.3. Estimation and diagnostic tests

The inverted-U shape is tested with the procedure of Lind and Mehlum [8], in which the null hypothesis H_0: $(\beta_1 + 2\beta_2 x_L \leq 0) \cup (\beta_1 + 2\beta_2 x_H \geq 0)$ is tested against the alternative H_1: $(\beta_1 + 2\beta_2 x_L > 0) \cap (\beta_1 + 2\beta_2 x_H < 0)$, where x_L and x_H are the bounds of the observed income range. The 95% confidence interval of the turning point is obtained with the delta method. Stationarity is assessed with the augmented Dickey–Fuller (ADF) and KPSS tests, using finite-sample critical values for the ADF statistic. Model fit is evaluated with R^2, the F-test and the Akaike information criterion (AIC), and the residuals are checked with the Breusch–Godfrey (serial correlation), Breusch–Pagan (heteroskedasticity), Jarque–Bera (normality) and Ramsey RESET (functional form) tests.

3.4. Decoupling analysis

The decoupling of emissions from industrial growth is measured with the elasticity proposed by Tapio [11]:

$$e_t = \frac{\Delta E_t / E_{t-1}}{\Delta Q_t / Q_{t-1}} \qquad (6)$$

When output grows, $e_t < 0$ indicates strong decoupling, $0 \leq e_t < 0.8$ weak decoupling, $0.8 \leq e_t \leq 1.2$ expansive coupling, and $e_t > 1.2$ expansive negative decoupling. In addition, the emission intensity of industrial output (E_t/Q_t) and the Herfindahl–Hirschman index (HHI) of the regional distribution of emissions are computed. All estimations were carried out in Python (NumPy and SciPy); the results of the nominal specification were cross-checked against the regression tool of MS Excel.

4. Results

4.1. Trends in the main indicators

Fig. 1 compares the main indicators, with 2011 as the base year. In nominal terms GDP per capita increased 12.4-fold, but in real terms it grew 1.88-fold (4.6% per year on average), while real industrial output increased 2.25-fold (6.0% per year). In other words, most of the nominal income growth reflects a price factor of 6.6. Emissions, by contrast, did not follow a monotonic path: after the 2014 spike they trended downwards

in 2016–2023, reaching a minimum of 763.2 thousand tonnes in 2023, and then rose sharply over the next two years.

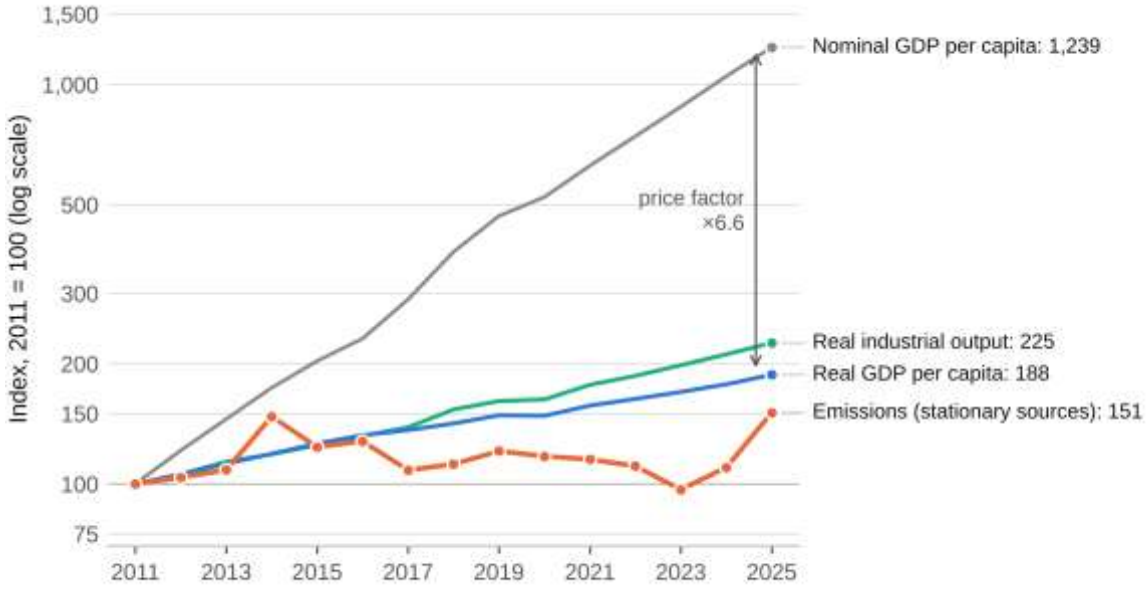

Fig. 1. Indices of emissions, real and nominal income, and real industrial output (2011 = 100, logarithmic scale)

Source: Authors' calculations based on NSC data [2].

This finding has an important methodological implication. Because nominal GDP per capita (X_1) and nominal industrial output (X_3) both rose steadily under the influence of price growth, the correlation between their logarithms reaches 0.998. When a specification with $\ln X_1$, $(\ln X_1)^2$ and $\ln X_3$ is estimated, R^2 is 0.061 and the F-statistic is 0.24 ($p = 0.868$); none of the coefficients is significant ($p > 0.49$), and the variance inflation factors range from 91 to 401. Although the quadratic term is positive (0.006), the implied turning point lies at $\ln X_1 = -43.6$, which is economically meaningless. Conclusions about a U-shape drawn from such a specification are therefore unfounded, and the remainder of the analysis is conducted in real terms.

4.2. Regional composition of emissions

Fig. 2 shows where the fluctuations in emissions originate. The share of the Tashkent region increased from 35.6% in 2011 to 49.4% in 2025, peaking at 56.4% in 2023. The HHI rose from 1,865 to 2,859, indicating a high and increasing degree of concentration. Although emissions fell markedly in the Kashkadarya (−38.9%), Bukhara

(−62.2%) and Syrdarya (−54.3%) regions, these reductions were offset by growth in the Tashkent region.

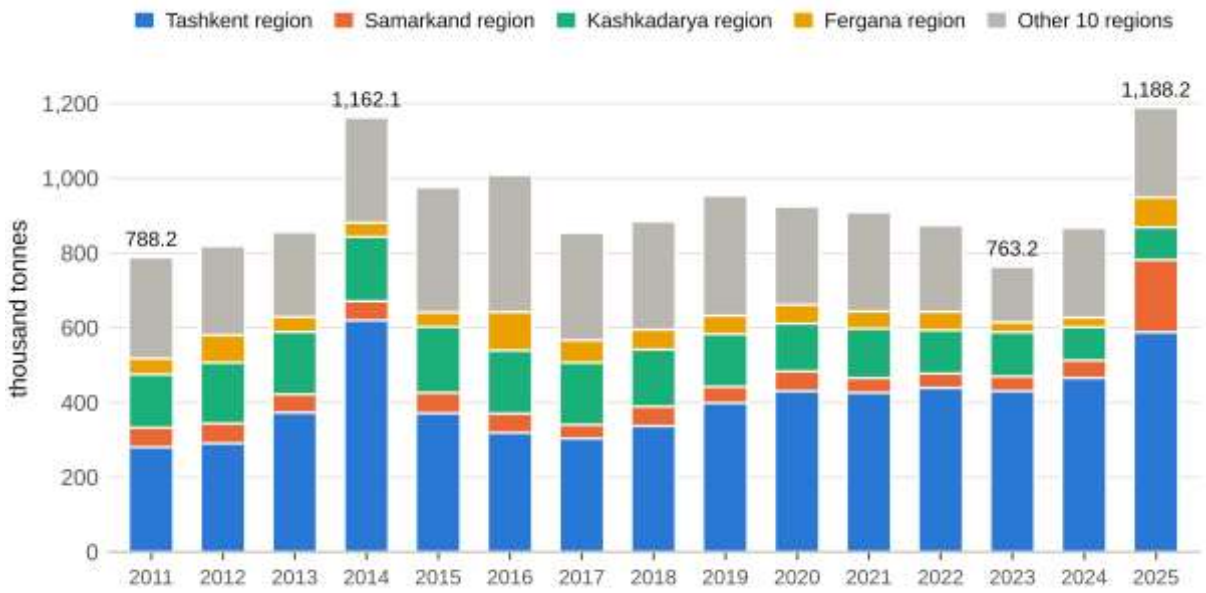

Fig. 2. Regional composition of emissions from stationary sources, thousand tonnes

Source: Compiled by the authors from NSC data [2], indicator 3.02.02.0001.

Both spikes are local in nature. In 2014, the national increase of 306.9 thousand tonnes included 246.9 thousand tonnes (80.4%) in the Tashkent region, whose emissions returned to their previous level in 2015. In 2025, emissions increased by 321.5 thousand tonnes, including 146.4 thousand tonnes in the Samarkand region (a 4.1-fold rise), 122.5 thousand tonnes in the Tashkent region and 53.1 thousand tonnes in the Fergana region. The combined increase in these three regions (322.0 thousand tonnes) exceeds the net national increase. Such spikes cannot be explained by aggregate income or industrial dynamics, since real industrial output grew by only 6.8% in 2025.

4.3. Econometric estimates

Unit root test results are reported in Table 2. Real income (ln *Y*) is non-stationary in levels and stationery in first differences, i.e., integrated of order one. For ln *E*, the ADF and KPSS tests given conflicting results: the ADF test does not reject a unit root, whereas the KPSS test does not reject stationarity. Given the low power of both tests with 15 observations, ln *E* is treated as a series that fluctuates around its mean without a clear trend. This already suggests a weak relationship between trending income and trendless emissions.

Table 2. Unit root tests

Series	Deterministic terms	ADF τ (lags)	ADF 5% critical value	KPSS η	KPSS 5% critical value	Conclusion
ln *E*	constant	−2.42 (0)	−3.10	0.096	0.463	inconclusive
Δ ln *E*	constant	−3.18 (0)	−3.13	0.130	0.463	I(0)
ln *Y*	constant + trend	−2.32 (0)	−3.79	0.130*	0.146	I(1)
Δ ln *Y*	constant	−3.55 (0)	−3.13	0.236	0.463	I(0)

Note: ADF critical values are finite-sample response-surface values; the lag length was selected by the AIC (maximum of one lag). The KPSS test uses a Bartlett kernel with a bandwidth of 2. * Stationarity is rejected at the 10% level (critical value 0.119).

Table 3 summarizes the four models estimated in real terms. In the linear model (Model 1), the income elasticity of emissions is 0.14 but insignificant (p = 0.452). In the standard EKC specification (Model 2), the quadratic term is negative as expected (−0.392) but insignificant (p = 0.708); the model as a whole is not significant (*F* = 0.35; p = 0.709), and the Lind–Mehlum test does not support an inverted U (p = 0.438). Moreover, the RESET test (p = 0.029) points to misspecification.

Table 3. EKC estimation results (dependent variable: ln E_t; 2011–2025, n = 15)

	Model 1 *linear*	**Model 2** *quadratic*	**Model 3** *cubic*	**Model 4** *quadratic + D*
Constant	6.818***	6.831***	6.827***	6.836***
	(0.033)	(0.049)	(0.036)	(0.024)
x_t	0.140	0.126	−0.878**	−0.116
	(0.181)	(0.191)	(0.342)	(0.112)
x_t^2	–	−0.392	0.281	−1.924***
		(1.022)	(0.792)	(0.582)
x_t^3	–	–	15.029***	–
			(4.651)	

	Model 1 *linear*	**Model 2** *quadratic*	**Model 3** *cubic*	**Model 4** *quadratic + D*
D^{2014}	–	–	–	0.252*** (0.065)
D^{2025}	–	–	–	0.449*** (0.086)
R^2	0.044	0.056	0.516	0.836
Adjusted R^2	−0.029	−0.102	0.383	0.770
F-statistic (p)	0.60 (0.452)	0.35 (0.709)	3.90 (0.040)	12.74 (<0.001)
AIC	−17.16	−15.34	−23.35	−37.60
Durbin–Watson	1.37	1.40	2.10	2.37
Breusch–Godfrey LM(1), p	0.410	0.426	0.602	0.393
Breusch–Pagan, p	0.563	0.302	0.567	0.498
Jarque–Bera, p	0.521	0.360	0.633	0.760
Ramsey RESET, p	0.708	0.029	0.020	0.508
VIF (max)	–	1.04	6.25	1.89
Turning point Y^*, million soums	–	6.45	4.75 / 6.28	5.33 [5.03; 5.65]
Lind–Mehlum U-test (inverted U), p	–	0.438	–	0.006

Note: $x_t = \ln Y_t - 1.7037$. Standard errors in parentheses; ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively. Turning points are expressed in 2011 prices; for Model 4, the 95% confidence interval (delta method) is shown in brackets; for Model 3, the local maximum and minimum are reported.

The cubic model (Model 3) is significant (F = 3.90; p = 0.040), and β_3 is positive and significant (15.03; p = 0.008). Its derivative equals zero at about 4.75 million soums per capita (the income level of 2014) and 6.28 million soums (the level of 2021–2022),

so the curve is N-shaped: a rise, a decline and a renewed rise. This shape, however, rests largely on the two extreme observations of 2014 and 2025, and the RESET test (p = 0.020) does not allow it to be accepted as an adequate specification either.

Controlling for the local shocks with dummy variables (Model 4) changes the picture fundamentally. R^2 rises to 0.836 and the F-statistic to 12.74 (p < 0.001), while the quadratic term equals −1.924 and is significant at the 1% level. The residuals show no evidence of serial correlation, heteroskedasticity or non-normality, the RESET test indicates no misspecification (p = 0.508), and the variance inflation factors do not exceed 1.9. The Lind–Mehlum test supports an inverted U (t = 3.06; p = 0.006): the elasticity equals +1.16 at the lower bound of the observed income range and −1.26 at the upper bound. The turning point is 5.33 million soums per capita at 2011 prices (95% CI: 5.03–5.65), which corresponds to the income level of 2016–2017 (Fig. 3). The dummy coefficients imply that emissions in 2014 and 2025 were 28.6% and 56.6% higher, respectively, than the income path would predict.

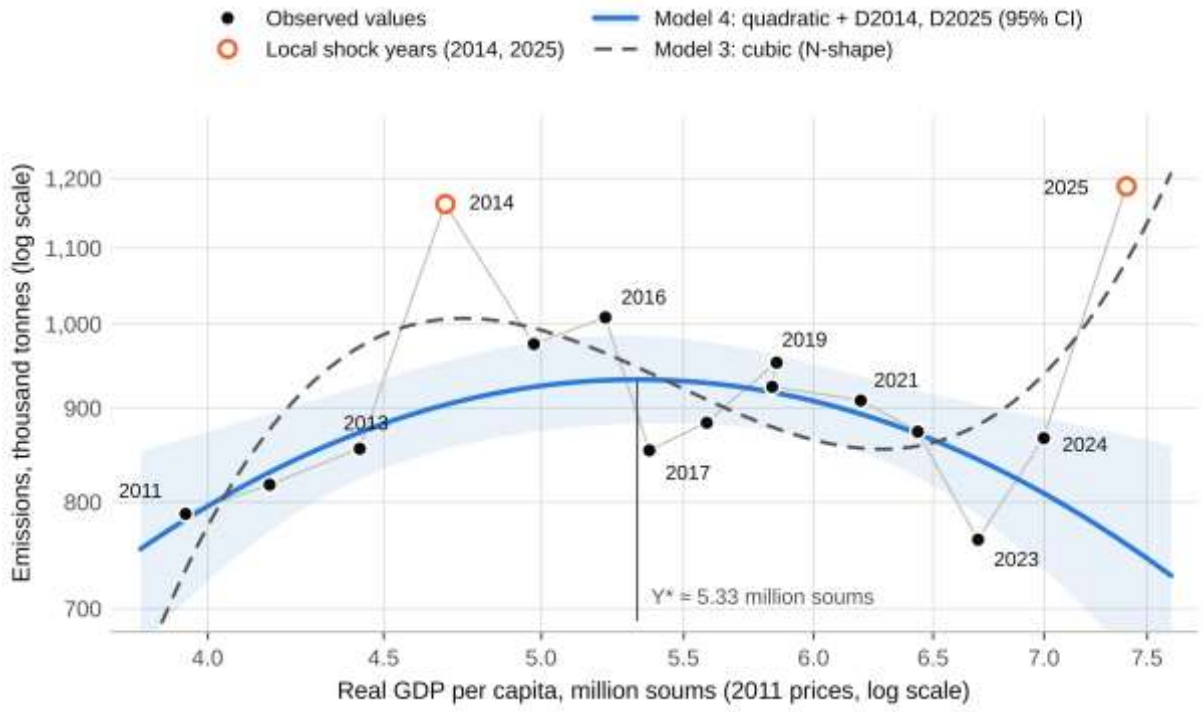

Fig. 3. Real GDP per capita and emissions: observed values and fitted curves

Source: Authors' calculations. The Model 4 curve is drawn for D2014 = D2025 = 0.

Robustness checks refine this conclusion. When 2025 is excluded from the sample (2011–2024), even the quadratic model without dummies yields a significant inverted U (β_2 = −2.30; p = 0.022; U-test p = 0.015; Y^* = 5.22 million soums), whereas adding only

the 2014 dummy leaves the result insignificant (p = 0.872). In a leave-one-out (jackknife) analysis, β_2 is negative in 14 of the 15 estimations but significant only when 2025 is omitted. Hence, the inverted U is stable for 2011–2024, and the main factor that breaks it is the localized spike of 2025.

4.4. Decoupling of emissions from industrial growth

Fig. 4 shows the emission intensity of real industrial output and the annual Tapio elasticities. Emissions per trillion soums of real industrial output fell from 16.6 thousand tonnes in 2011 to 8.1 thousand tonnes in 2023, i.e. by 51.1%, reflecting favorable shifts in industrial structure and technology. In 2024–2025, however, the intensity rose again to 11.1 thousand tonnes.

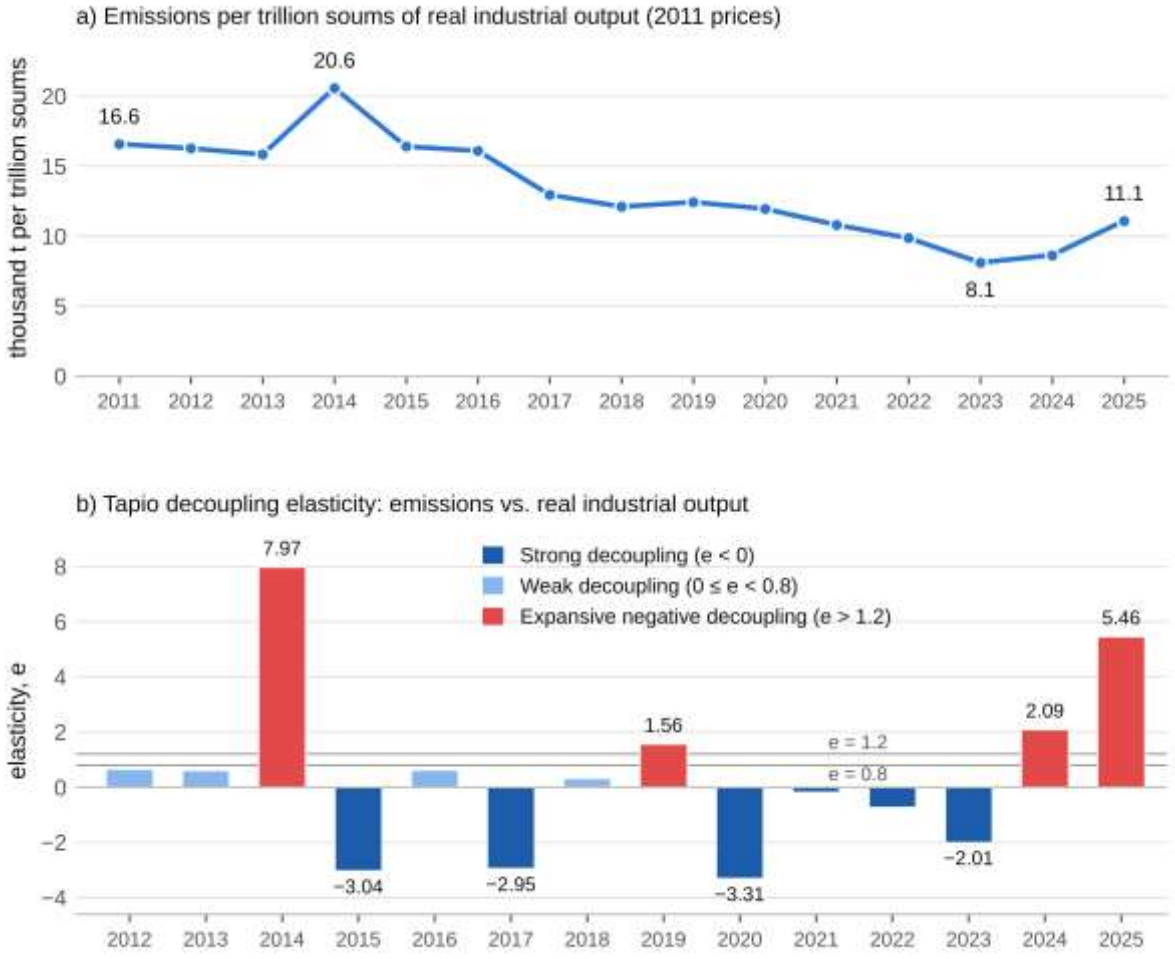

Fig. 4. Emission intensity (a) and Tapio decoupling elasticity (b), 2011–2025

According to the annual estimates, strong decoupling occurred in 6 of the 14 years, weak decoupling in 4, and expansive negative decoupling in 4. The picture becomes clearer at the level of sub-periods. In 2011–2016, the elasticity was 0.88 (expansive

coupling), meaning that emissions grew almost in step with industry. In 2016–2024, emissions fell by 14.0% while real industrial output rose by 60.2% ($e = -0.23$, strong decoupling). In 2025, the elasticity reached 5.46, i.e. expansive negative decoupling. Over the whole period the elasticity is 0.40, so relative (weak) decoupling has been preserved.

5. Discussion

The results indicate that the EKC in Uzbekistan is conditional and fragile rather than "pure". Data for 2011–2024 are consistent with an inverted U whose turning point falls in 2016–2017, and the strong decoupling of 2016–2024 suggests that composition and technique effects began to outweigh the scale effect [6]. The coincidence of the turning point with the period in which economic reforms gained momentum is noteworthy, but establishing a causal link would require plant-level data.

At the same time, the 2025 spike shows that the downward segment of the EKC is not yet secure. The N-shape produced by the cubic model resembles the "re-linking" described in the literature, whereby output growth raises emissions again once the gains from improved technical efficiency are exhausted [12]. In Uzbekistan, this process is unfolding not at the macro level but in specific regions: virtually all of the 2025 increase occurred in three regions. The Tashkent region, which hosts the coal-fired Angren and Novo-Angren thermal power plants and the Almalyk mining and metallurgical complex, largely determines the aggregate dynamics. Part of the 2025 increase may also reflect changes in monitoring and reporting coverage rather than genuine emission growth; disentangling the two again requires plant-level data.

The divergence between the nominal and real results is also methodologically important. In nominal terms, income and industrial output move together, almost linearly, because of price growth; as a result, the model cannot separate their effects, and the sign of the quadratic term becomes arbitrary. EKC studies of high-inflation economies should therefore measure income in constant prices or in purchasing power parity terms, center polynomial terms, and test the turning point formally [6, 8].

These findings are partly consistent with the regional literature. The absence of a robust inverted U in the full sample accords with the evidence for Central Asia [10],

whereas the results for 2011–2024 agree with studies reporting a negative relationship beyond a certain income level in Uzbekistan [4, 5]. The difference is that the 2025 data indicate that this tendency may be reversing.

The study has several limitations. First, a 15-year series limits the power of unit root and cointegration tests; autoregressive distributed lag (ARDL) or polynomial cointegration methods would require longer series [9]. Second, the indicator aggregates different pollutants (SO_2, NO_x, particulate matter and others), for which the shape of the EKC may differ. Third, emissions from road transport are not covered, and the 2025 industrial data are preliminary.

6. Conclusions and policy implications

The analysis leads to four main conclusions.

1. An EKC model based on nominal indicators does not yield reliable results for Uzbekistan: the correlation between the regressors reaches 0.998, the variance inflation factor exceeds 400, and the conclusion of a U-shape has no statistical basis.

2. In real terms, an inverted U is not supported for the full 2011–2025 sample, but it becomes significant once the local shocks of 2014 and 2025 are controlled for; the turning point is 5.33 million soums per capita at 2011 prices, i.e. the income level of 2016–2017.

3. Strong decoupling was observed in 2016–2024: emissions fell by 14.0% while real industrial output rose by 60.2%, and the emission intensity of industrial output halved between 2011 and 2023.

4. The 37.1% increase in emissions in 2025 was concentrated in three regions, and the regional concentration of emissions is rising (the HHI increased from 1,865 to 2,859). The declining phase of the EKC is therefore not self-sustaining.

These findings lead to the following policy recommendations.

1. Environmental policy should be targeted at regional pollution hotspots, in particular by introducing continuous emission monitoring at large category I–II sources in the Tashkent, Samarkand and Fergana regions and publishing the monitoring data.

2. Energy and metallurgical enterprises should be brought gradually in line with best available techniques (BAT), and the modernization of desulfurization and dust-

removal equipment at coal-fired plants should become a mandatory condition of investment programs.

3. Emission statistics should be published by pollutant and by industry, with methodological notes explaining abrupt changes such as that observed in 2025.

4. The emission intensity of industrial output should be included as a target indicator in regional socio-economic development programs.

Future research should estimate the EKC for individual pollutants using a regional panel and apply panel cointegration methods.

Data availability

All data used in this study are publicly available from the statistical database of the National Statistics Committee of the Republic of Uzbekistan (https://siat.stat.uz).

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