

Economic growth and atmospheric pollution in Uzbekistan: A regional test of the environmental kuznets curve

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ABSTRACT

Atmospheric pollution is a growing constraint on sustainable development in rapidly transforming economies, yet subnational evidence for Central Asia remains scarce. This study investigates the regional determinants of directly reported atmospheric pollutant emissions in Uzbekistan using a balanced panel of 14 administrative regions over 2010–2024 (210 region-year observations). The analysis combines atmospheric emissions with gross regional product (GRP) per capita, industrial output, electricity production and heat production from harmonized official statistical datasets. To test the Environmental Kuznets Curve (EKC) while controlling for unobserved heterogeneity, pooled OLS, region fixed effects, year fixed effects and two-way fixed effects are estimated with region-clustered standard errors. The preferred two-way fixed-effects model explains 89.2% of the variation in log emissions (adjusted $R^2 = 0.873$). The centered log of GRP per capita is positive but statistically insignificant (0.487; $p = 0.477$), while its squared term is negative and insignificant (-0.027; $p = 0.661$), providing no robust evidence of an inverted-U EKC. Industrial output and electricity production are also statistically insignificant after region and year effects are absorbed. Heat production remains negatively associated with reported emissions (-0.241; $p = 0.039$), and this result is robust to Driscoll-Kraay inference ($p < 0.001$), exclusion of the income or industrial blocks, and a first-difference specification (-0.174; $p = 0.008$). The findings indicate that regional structural conditions and energy-system characteristics matter more for atmospheric emissions than income growth alone, supporting spatially differentiated industrial, heating and air-quality policies.

Keywords: Air pollution, Economic growth, Energy production, Environmental Kuznets curve, Industrialization, Uzbekistan.

Article type: Research Article.

INTRODUCTION

Air pollution has become an increasingly important constraint on economic development in Uzbekistan, but the relationship between regional income growth and atmospheric emissions is not straightforward. Building on the original Kuznets (1955) development hypothesis, the Environmental Kuznets Curve (EKC) literature offers one possible explanation: environmental pressure may increase during the early stages of economic expansion and decline later as production structures, technologies and regulatory capacity change (Selden & Song 1994; Grossman & Krueger 1995; Stern 2004; Dinda 2004). Whether this pattern holds within a single transition economy, however, is an empirical question rather than an assumption. Recent subnational studies show that the estimated relationship depends strongly on the pollutant considered, industrial composition, spatial dependence and econometric specification. Chang *et al.* (2021) and Bashir (2026) using a spatial dynamic panel for 284 Chinese cities, report an inverted-U relationship for PM_{2.5} after accounting for technological spillovers, whereas Karahasan & Pinar (2022) show that spatial dependence materially changes provincial EKC inference for SO₂ in Turkey. These findings are particularly relevant for Uzbekistan because national averages may conceal substantial differences between heavily industrialized regions and areas with relatively limited stationary-source emissions. Earlier empirical work also shows why income-only EKC specifications can be misleading. Shafik (1994), Holtz-Eakin & Selden (1995) and de Bruyn *et al.* (1998) demonstrated that the income–environment relationship varies across pollutants and samples, while Cole (2004) and Copeland & Taylor (2004) emphasize composition and trade channels. Energy use provides another mechanism: Ang (2007) and Soytaş *et al.* (2007) show that energy consumption can have an independent long-run relationship with emissions, and Narayan & Narayan (2010) reported substantial heterogeneity across developing economies. More recent evidence strengthens the case for including energy transition and regional structure. Mohsin *et al.* (2021) found that the shift toward renewable energy is associated with lower emissions in developing Asian economies, while Saidmamatov *et al.* (2023), Usmonov (2024), Burkhanov (2025), Babakhonov (2026), document interconnections among energy, efficiency of economic activity and environmental degradation in Central Asia. At the subnational level, Xu *et al.* (2019) reported that economic growth, industrialization and urbanization have region-specific effects on SO₂, NO_x and PM_{2.5} in China. These findings motivate the present study's joint treatment of regional income, industrial output and energy production. Income is therefore only one part of the empirical relationship examined here. Industrial structure and the regional energy system can alter emissions independently of income growth. Wang *et al.* (2022), and Imtiaz (2025), documented nonlinear effects of industrial upgrading on haze pollution, while Liu & Guo (2023) show that scale, structural and technological channels may operate in opposite directions. Qi *et al.* (2023) similarly found substantial heterogeneity in PM_{2.5} determinants across Chinese climate zones. Taken together, this literature suggests that the income coefficients in an EKC model should be interpreted alongside variables describing production and energy activity, especially when the unit of analysis is a region rather than a country. Central Asia is a useful setting in which to examine this issue because economic expansion continues to interact with fossil-energy dependence, inherited infrastructure and uneven technological modernization. Existing evidence does not provide a uniform EKC result. Zhang (2019) found that an inverted-U relationship is not consistently supported for the five Central Asian economies and reported a mitigating role for renewable-energy consumption. Caporin *et al.* (2024), using alternative polynomial specifications and long-run panel methods, likewise concluded that a simpler, predominantly linear relationship is more consistent with the regional evidence. These results differ from some city- and province-level findings for China and Turkey and leave open an important question: does the EKC appear when environmental pressure is examined within Uzbekistan rather than across countries? Uzbekistan is an informative case because its regions differ sharply in industrial specialization, electricity and heat infrastructure, urbanization and legacy production assets. This study constructs a balanced panel for the Republic of Karakalpakstan, twelve regions and Tashkent city over 2010–2024. Unlike most Central Asian EKC research, the dependent variable is directly reported atmospheric pollutant emissions rather than national CO₂ emissions. The explanatory structure combines GRP per capita, industrial output, electricity production and heat production. The design therefore connects three strands of Scopus-indexed research: income–pollution nonlinearity, industrial-structure effects and the energy–environment nexus. The contribution of this study follows directly from that question. It moves the analysis below the national level by using 14 first-level administrative units, which makes it possible to control for persistent territorial differences that a country-level time series cannot identify. It also uses directly reported atmospheric pollutant emissions rather than national CO₂ emissions and replaces total regional output with GRP per capita in the income specification. Finally, the empirical

results are evaluated under alternative fixed-effects structures and several diagnostic and robustness procedures. This design is intended not to presume an EKC turning point, but to determine whether the regional data support one once industrial and energy variables and common time shocks are taken into account.

MATERIALS AND METHODS

Conceptual framework and hypotheses

The conceptual model combines EKC logic with the STIRPAT tradition, under which environmental pressure reflects scale, affluence and technology (York *et al.* 2003). The scale channel predicts higher emissions as output and energy demand expand. The composition channel allows pollution to change as regions specialize in different sectors. The technique channel captures cleaner capital, fuel switching, efficiency and abatement. Spatial-panel studies emphasize an additional channel: pollution and abatement technologies can spill across administrative boundaries (Chang *et al.* 2021; Karahasan & Pinar 2022). Since the present dataset does not contain a defensible spatial-weights matrix, the main model controls region and year effects and explicitly tests cross-sectional dependence rather than imposing an unsupported spatial structure. The empirical literature yields no single expected EKC shape. Studies of Chinese cities often identify inverted-U relationships for PM_{2.5}, but also document substantial heterogeneity by industrial structure, climate zone and spatial context (Chang *et al.* 2021; Wang *et al.* 2022; Qi *et al.* 2023). In Central Asia, Zhang (2019), Salahodjaev (2022) and Caporin *et al.* (2024) provided weaker support for the canonical inverted-U form. This divergence motivates a specification in which the income terms are tested rather than presumed, and industrial output, electricity and heat production are entered simultaneously. It also motivates conservative interpretation of null coefficients, since aggregate output variables can mask technology and fuel-mix heterogeneity. H₁: Regional income per capita has a nonlinear association with atmospheric emissions; a conventional EKC requires a positive linear GRP-per-capita term and a negative squared term; H₂: Higher industrial production is associated with higher atmospheric emissions, H_{3a}: Electricity production is positively associated with atmospheric emissions where generation remains combustion-intensive. H_{3b}: The relationship between heat production and emissions is ambiguous *ex ante* because higher measured output may represent either more combustion or greater efficiency and substitution toward centralized heat.

Data

The sample contained 14 first-level administrative units observed annually from 2010 through 2024, yielding 210 observations. The national aggregate row was excluded to avoid double counting. All series come from annual regional workbooks of the National Statistics Committee of the Republic of Uzbekistan (National Statistics Committee of the Republic of Uzbekistan 2025a, 2025b, 2025c, 2025d, 2026). The revised income variable is gross regional product per capita, measured at current prices in thousand soums. According to the dataset metadata, GRP per capita is calculated by dividing gross regional product by the average annual population; the series follows the 2008 SNA framework, incorporates revisions for the non-observed economy, and the 2024 observations are preliminary. Atmospheric emissions are reported in thousand tons, electricity production in million kWh, industrial output in billion soums, while heat production is retained in the official reported unit. Strictly positive variables are transformed using natural logarithms. Electricity and heat contain zero observations, so $\ln(1+x)$ is used to retain them. To reduce nonessential multicollinearity between the linear and quadratic income terms, log GRP per capita is mean-centered before squaring. Since GRP per capita and industrial output are reported at current prices, year fixed effects are included to absorb common nationwide inflation and macroeconomic shocks. However, region-specific price movements may remain; consequently, the EKC estimates are interpreted as conditional associations rather than a definitive constant-price income turning point.

Econometric model and diagnostics

The preferred specification is:

$$\ln(POLL_{it}) = \beta_1 GRPPC_{it} + \beta_2 GRPPC_{it}^2 + \beta_3 \ln(IND_{it}) + \beta_4 \ln(1 + ELEC_{it}) + \beta_5 \ln(1 + HEAT_{it}) + \alpha_i + \lambda_t + \varepsilon_{it}$$

where GRPPCc is mean-centered log GRP per capita, α_i denotes region fixed effects and λ_t denotes year fixed effects. Four nested estimators are compared: pooled OLS, region fixed effects, year fixed effects and two-way fixed effects. Cluster-robust standard errors are computed by region. The robustness analysis further applies a Wooldridge-type serial-correlation diagnostic (Wooldridge 2010), a Pesaran cross-sectional-dependence

test (Pesaran 2021), Driscoll-Kraay covariance estimates (Driscoll & Kraay 1998), alternative specifications excluding potentially collinear variable blocks, and a first-difference model.

Table 1. Variable definitions and transformations.

Variable	Definition	Unit	Transformation	Role/sign
POLL	Pollutants released into atmosphere	thousand tons	ln(POLL)	Dependent
GRPPC	Gross regional product per capita	thousand soums, current prices	mean-centered ln(GRPPC) and square	Nonlinear +/-
IND	Industrial production	billion soums	ln(IND)	+
ELEC	Electricity production	million kWh	ln(1+ELEC)	+
HEAT	Heat production	official source unit	ln(1+HEAT)	Ambiguous

RESULTS

Descriptive evidence

Regional atmospheric emissions vary significantly (mean: 63.63, std. dev.: 98.63, max: 619.2 thousand tons). Total regional emissions rose 18.9% from 729.0 thousand tons in 2010 to 866.7 in 2024. However, mean nominal GRP per capita grew much faster, leading to a notable divergence between the two trends. While this suggests relative decoupling, the use of current prices for GRP per capita prevents its interpretation as a real-output elasticity.

Table 2. Descriptive statistics.

Variable	N	Mean	SD	Min	Median	Max
POLL	210	63.63	98.63	2.90	35.40	619.20
GRPPC	210	14,764.44	16,648.67	1,572.10	9,976.50	120,222.20
IND	210	19,008.70	27,719.35	522.70	8,774.95	171,706.20
ELEC	210	4,499.52	6,286.91	0.00	627.80	20,445.10
HEAT	210	2,021.38	3,240.05	0.00	220.40	13,547.50

The spatial concentration is even more striking. Tashkent and Kashkadarya regions averaged approximately 382.3 and 144.7 thousand tons of emissions, respectively, between 2010 and 2024 (Fig. 2), far above most other regions. Such concentration explains why region fixed effects add substantial explanatory power. Table 3 also indicates that income and industrial activity are correlated, although centering the income term materially improves the conditioning of the quadratic specification.

Table 3. Pairwise correlation matrix.

	lnPOLL	lnGRPPC	lnIND	lnELEC	lnHEAT
lnPOLL	1.000	0.142	0.321	0.405	0.508
lnGRPPC	0.142	1.000	0.885	0.308	0.245
lnIND	0.321	0.885	1.000	0.406	0.405
lnELEC	0.405	0.308	0.406	1.000	0.479
lnHEAT	0.508	0.245	0.405	0.479	1.000

Regression results

Table 4 compares four estimators. Pooled OLS explains 35.0% of log-emission variation, while region fixed effects raise R^2 to 87.2%. The preferred two-way fixed-effects model reaches $R^2 = 0.892$ and adjusted $R^2 = 0.873$. Fig. 3 plots the two-way coefficients with 95% confidence intervals and makes the inferential pattern transparent: most partial effects cross zero, whereas heat production is the only covariate whose interval excludes zero at the 5% level.

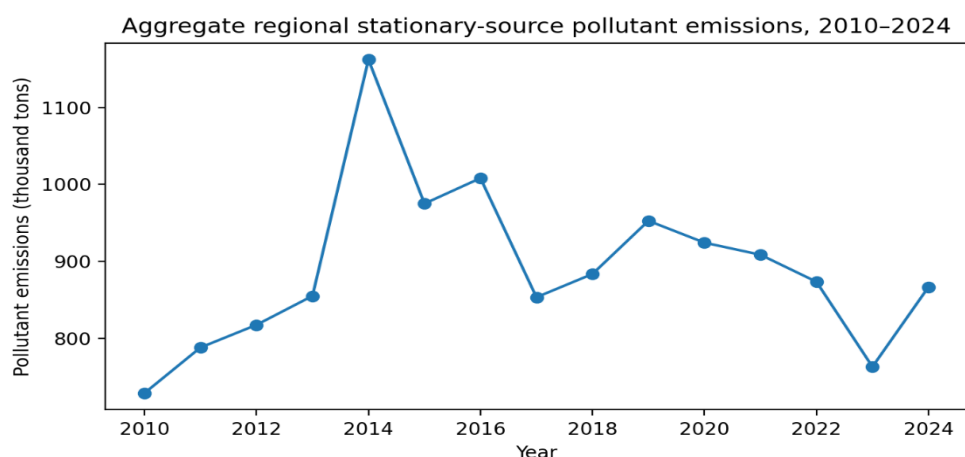


Fig. 1. Aggregate regional atmospheric pollutant emissions in Uzbekistan, 2010–2024 (thousand tons). Source: authors' calculations from National Statistics Committee data.

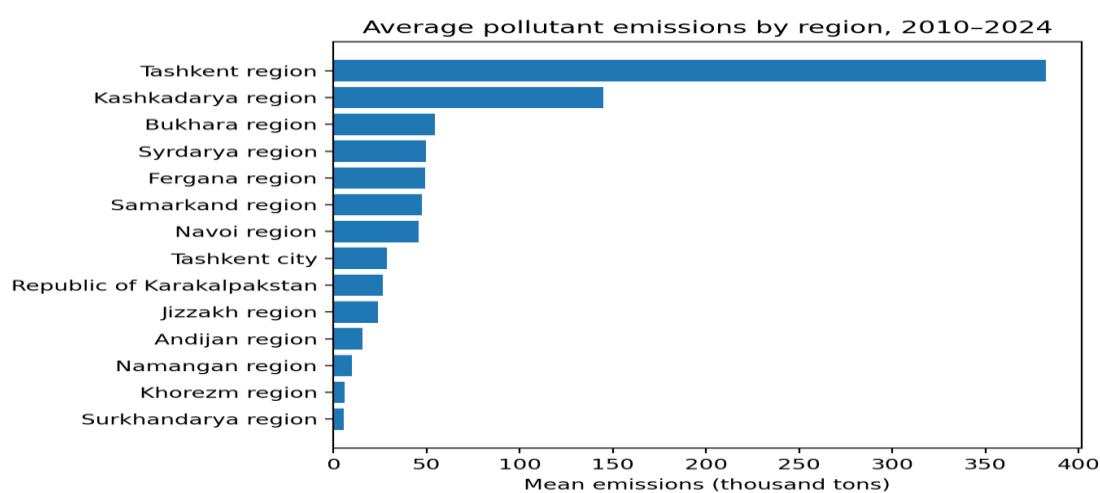


Fig. 2. Average atmospheric pollutant emissions by region, 2010–2024 (thousand tons). Source: authors' calculations from National Statistics Committee data.

Table 4. Panel regression estimates.

Variable	Pooled OLS	Region FE	Year FE	Two-way FE
Centered $\ln(\text{GRPPC})$	-0.574 (0.520)	0.136 (0.243)	-0.043 (0.787)	0.487 (0.686)
Centered $\ln(\text{GRPPC})^2$	-0.136** (0.067)	-0.077* (0.046)	-0.200 (0.148)	-0.027 (0.062)
$\ln(\text{IND})$	0.478 (0.434)	-0.142 (0.185)	0.589 (0.520)	0.050 (0.253)
$\ln(1+\text{ELEC})$	0.071 (0.061)	-0.006 (0.032)	0.080 (0.064)	0.023 (0.031)
$\ln(1+\text{HEAT})$	0.184 (0.113)	-0.177 (0.130)	0.089 (0.165)	-0.241** (0.117)
R ²	0.350	0.872	0.385	0.892
Adjusted R ²	0.334	0.860	0.323	0.873
Observations	210	210	210	210

Notes: Region-clustered robust standard errors in parentheses. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$. Region and year fixed-effect coefficients are omitted for brevity.

For the EKC terms, the centered log-GRP-per-capita coefficient is 0.487 ($p = 0.477$) and its squared term is -0.027 ($p = 0.661$) in the two-way model. The signs are compatible with an inverted-U profile but are statistically imprecise. The region-FE model provides only weak 10% evidence of curvature, which disappears after common year shocks are included. H_1 is therefore not supported robustly. This result is closer to the cautious Central Asian evidence of Zhang (2019) and Caporin *et al.* (2024) than to the robust inverted-U estimates reported for many Chinese and Turkish subnational samples (Chang *et al.* 2021; Karahasan & Pinar 2022; Qi *et al.* 2023).

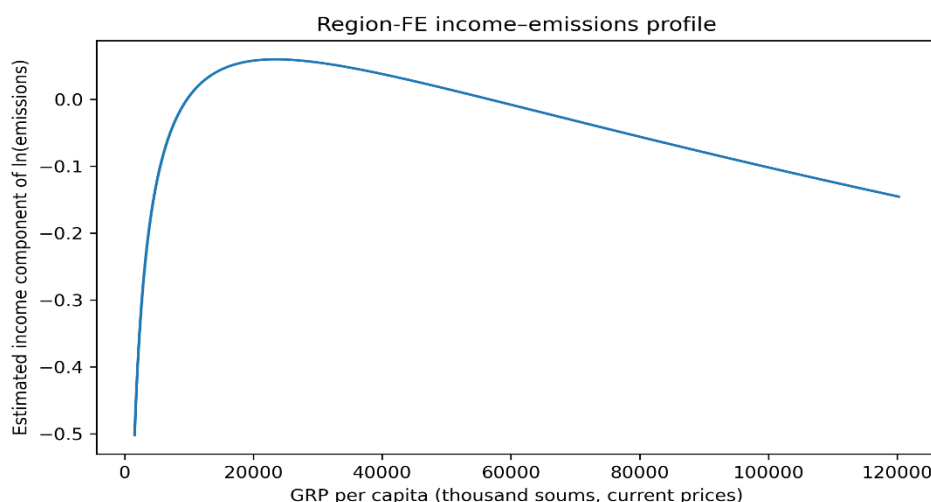


Fig. 3. Estimated income-emissions profile from the region fixed-effects specification using GRP per capita. The curve is descriptive and should not be interpreted as a causal EKC turning point.

Industrial output is positive but insignificant in the preferred model (0.050; $p = 0.844$), and electricity production is similarly small and insignificant (0.023; $p = 0.450$). H_2 and H_{3a} are therefore not confirmed. The null partial coefficients are plausible in a heterogeneous regional system: an identical increase in industrial or electricity output can have very different emission consequences depending on sector, fuel, plant age, control technology and capacity utilization. This interpretation is consistent with recent research showing that industrial restructuring and technology can reverse the pollution effect across development stages (Wang *et al.* 2022; Liu & Guo 2023). Heat production is the only covariate that remains statistically significant in the preferred specification: -0.241 ($p = 0.039$). Conditional on region and year effects, a 1% increase in the transformed heat-production measure is associated with approximately a 0.24% decrease in reported emissions. Table 5 shows that this result survives Driscoll-Kraay inference ($p < 0.001$), exclusion of the industrial block, exclusion of the income block, and a first-difference specification (-0.174; $p = 0.008$). The finding should not be interpreted as evidence that more heat mechanically improves air quality. A more defensible mechanism is that measured centralized heat output may rise alongside efficiency upgrades, fuel switching or substitution away from dirtier decentralized combustion.

Diagnostic and robustness analysis

Mean-centering sharply reduces the artificial VIF generated by the quadratic income term: the VIF is 5.06 for centered log GRP per capita, 1.05 for its square, and 5.74 for industrial output. These values are materially lower than in the total-GRP specification and indicate that using income per capita improves the conditioning of the model. The heat coefficient remains -0.242 ($p = 0.041$) when industrial output is excluded and -0.237 ($p = 0.040$) when the income block is excluded, demonstrating that the principal energy result is not driven by income-industry collinearity.

Table 5. Hypothesis evaluation and empirical interpretation.

Hypothesis	Expected relationship	Preferred-model evidence	Decision
H1	Inverted-U income-emissions relationship	GRPPCc = 0.487 ($p = 0.477$); GRPPCc ² = -0.027 ($p = 0.661$)	Not supported
H2	Industrial production increases emissions	0.050 ($p = 0.844$)	Not supported
H3a	Electricity production increases emissions	0.023 ($p = 0.450$)	Not supported
H3b	Heat effect is ambiguous <i>ex ante</i>	-0.241 ($p = 0.039$); robust in first differences	Negative association supported

Table 6. Diagnostic and robustness checks.

Check	Statistic/coefficient	p-value	Interpretation
Wooldridge-type serial-correlation test	lag coefficient -0.381	0.437	No strong evidence of AR(1)
Pesaran CD	-1.919	0.055	Borderline cross-sectional dependence
VIF: centered $\ln(\text{GRPPC})$	5.06	-	Moderate; improved vs total GRP
VIF: centered $\ln(\text{GRPPC})^2$	1.05	-	No quadratic-term inflation after centering
VIF: $\ln(\text{IND})$	5.74	-	Moderate collinearity with income
Driscoll-Kraay: $\ln(1+\text{HEAT})$	-0.241	0.000	Negative association robust
TWFE excluding industry: $\ln(1+\text{HEAT})$	-0.242	0.041	Robust to income-industry collinearity
TWFE excluding income terms: $\ln(1+\text{HEAT})$	-0.237	0.040	Robust to excluding income block
First differences: Delta $\ln(1+\text{HEAT})$	-0.174	0.008	Robust in annual changes

The Wooldridge-type residual test does not indicate statistically significant first-order serial correlation ($p = 0.437$). The Pesaran CD statistic is -1.919 ($p = 0.055$), indicating borderline cross-sectional dependence and motivating the Driscoll-Kraay robustness check. With a two-period bandwidth, the heat coefficient remains -0.241 and strongly significant ($p < 0.001$). Finally, the first-difference model removes all time-invariant regional factors and again produces a negative heat coefficient (-0.174 ; $p = 0.008$). Together, these checks make the heat-emissions association the most stable empirical result in the study.

DISCUSSION

The first result that stands out is the importance of persistent regional differences. Moving from pooled OLS ($R^2 = 0.350$) to a specification with region fixed effects ($R^2 = 0.872$) produces a much larger improvement in explanatory power than adding the observed economic and energy variables alone. In the Uzbek context, this pattern is plausible because the regional distribution of stationary-source emissions reflects long-lived differences in industrial specialization, resource endowments and energy infrastructure. It also cautions against interpreting a national income-emissions relationship as representative of all regions. This finding is consistent with spatial EKC research showing that location-specific characteristics materially affect pollution estimates (Chang *et al.* 2021; Karahasan & Pinar 2022). The income results provide a second, and more cautious, conclusion. In the preferred two-way fixed-effects model, the linear GRP-per-capita term is positive and the squared term is negative, but neither is statistically distinguishable from zero. The signs alone are therefore insufficient evidence of an inverted-

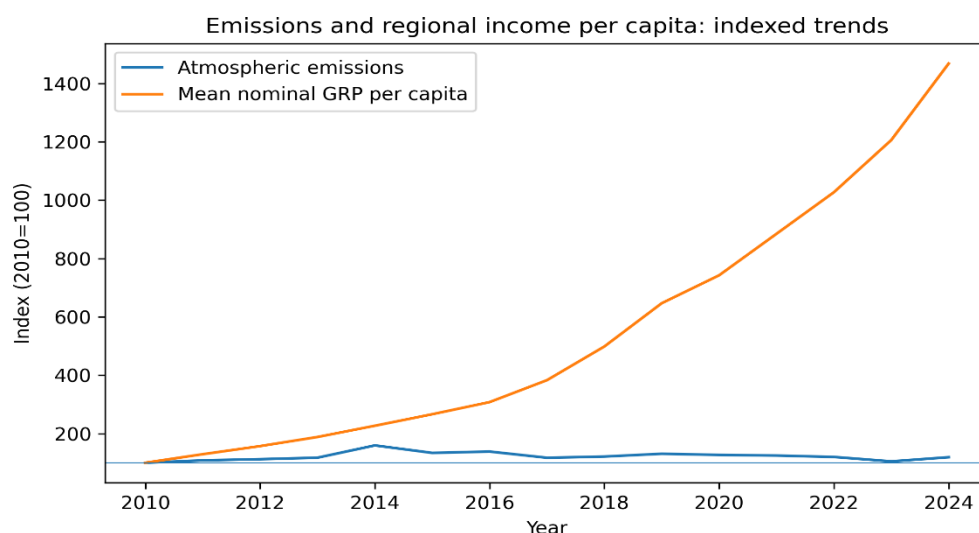


Fig. 4. Indexed trends in aggregate regional atmospheric emissions and mean nominal GRP per capita (2010 = 100). Source: authors' calculations from National Statistics Committee data.

U EKC. Moreover, the weak curvature observed in the region-FE specification disappears after common year shocks are introduced. This instability is substantively informative: over 2010–2024, differences in regional income growth do not provide a robust explanation for changes in reported atmospheric emissions once persistent regional characteristics and nationwide time effects are controlled. The result is closer to the Central Asian evidence reported by Zhang (2019) and Caporin *et al.* (2024) than to studies that identify clear subnational turning points in China. It also supports Stern's (2004) warning that the EKC should be treated as a contingent empirical

relationship rather than a general development law. The insignificant industrial-output coefficient requires similar caution. It does not imply that industrial activity is environmentally irrelevant. The variable measures the value of aggregate industrial production and therefore combines activities with very different emission intensities. Chemicals, metallurgy, construction materials, food processing and cleaner manufacturing can generate very different atmospheric effects even when their output values increase by the same proportion. Research by Wang *et al.* (2022) and Liu & Guo (2023) shows why this aggregation matters: structural upgrading and technological change can offset scale effects. For Uzbekistan, a stronger test would require sectoral production shares, plant-level fuel consumption and pollution-control investment rather than a single aggregate industrial-output series. Heat production produces the most stable coefficient in the analysis, although its interpretation is not mechanical. The negative within-region association remains statistically significant under the preferred model, Driscoll-Kraay inference, alternative variable blocks and first differences. One possible explanation is that increases in measured centralized heat output coincide with efficiency improvements, fuel switching or substitution away from smaller and dirtier combustion sources. This interpretation is consistent with the World Bank's (2024) air-quality assessment for Tashkent, which identifies heating as an important anthropogenic source and highlights cleaner heating and energy-efficiency measures. The available aggregate data cannot identify which of these mechanisms is responsible, so the coefficient should not be interpreted causally. A policy assessment would need information on fuel mix, network losses, useful heat delivered and the heating technologies being displaced. The empirical pattern points toward differentiated rather than uniform environmental policy. Regions with large stationary-source emissions require closer attention to industrial technology and continuous emissions monitoring; regions in which electricity and heating systems are undergoing modernization require information on fuel mix and plant efficiency; and highly urbanized areas require closer integration of heating, transport and air-quality policy. For research purposes, the immediate priority is to combine the existing emissions panel with constant-price GRP per capita, pollutant-specific inventories, urbanization, vehicles, renewable capacity, fuel consumption and green investment. Such data would also make a spatial Durbin specification more defensible if a well-defined contiguity or distance matrix confirms regional spillovers.

CONCLUSION

This paper provides a regional test of the Environmental Kuznets Curve for atmospheric pollution in Uzbekistan using a balanced 14-region panel for 2010–2024 and GRP per capita as the income measure. Reported emissions are strongly concentrated geographically, and persistent regional heterogeneity explains a large share of their variation. The preferred two-way fixed-effects model explains 89.2% of log-emission variation, but the centered GRP-per-capita terms do not provide statistically robust evidence of an inverted-U Environmental Kuznets Curve. Industrial output and electricity production are not significant after region and year effects are absorbed, whereas heat production has a stable negative conditional association with emissions and survives multiple robustness checks. The results show that rising regional income alone cannot be assumed to deliver cleaner air. Environmental improvement is more likely to depend on region-specific industrial modernization, cleaner energy and heating technologies, emissions monitoring and regulatory implementation. Future research should extend the regional EKC framework with constant-price income per capita, pollutant-specific inventories, green investment, renewable-energy indicators and spatial identification strategies.

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Data availability and conflict of interest

Data availability: The study uses annual regional datasets of the National Statistics Committee of the Republic of Uzbekistan, including atmospheric pollutant emissions, GRP per capita, industrial production, electricity production and heat production. Conflict of interest: The authors declare no conflict of interest. Funding.

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- Note: I retained the ellipsis in the Burkhanov et al. author list because the full author information was not supplied. I also kept the original publication details for institutional datasets and book chapters where DOI or publisher information was absent or incomplete.

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