Inverted U Confirmed: Spatial Evidence for the Environmental Kuznets Curve in Polish NUTS-3 Regions

Studia Regionalne i Lokalne
Nr 4(102)/2025

ISSN 1509-4995
E-ISSN 2719-8049
doi: 10.7366/15094995410201

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Abstract

The primary study objective is to verify the environmental Kuznets curve hypothesis for greenhouse gas emissions in Poland at the disaggregated Nomenclature of Territorial Units for Statistics (NUTS)-3 level, accounting for spatial dependencies. The analysis employs a balanced panel of 73 subregions (2005 to 2022) based on the Emissions Database for Global Atmospheric Research and Statistics Poland data. Spatial dependencies were determined using *Moran's* I and Lagrange multiplier tests, justifying the application of a spatial autoregressive panel model with individual fixed effects. The results offer robust evidence of an inverted U-shaped relationship between economic growth and emissions. The estimated turning point is about 73,035 PLN (16,592 USD) at the NUTS-3 level in 2022 prices. Urbanisation exerts a positive, statistically significant influence on per capita emissions, whereas household energy consumption indicates a positive, weakly significant influence ($p < 0.10$). Robustness checks performed at NUTS-2 confirmed the findings, yielding a turning point of 59,704 PLN (13,564 USD), although energy consumption proved statistically insignificant at this aggregated scale. These findings highlight the importance of incorporating spatial spillovers, as neighbouring dynamics shape regional emissions. The results underscore the need for differentiated regional climate policies reflecting spatial and structural disparities across Polish regions.

Keywords

Environmental Kuznets curve (EKC), spatial autoregressive (SAR) model, spatial heterogeneity.

Introduction

The nexus between economic growth and environmental degradation remains a subject of profound academic inquiry in the discourse on environmental economics. The environmental Kuznets curve (EKC) stands as a seminal hypothesis. Drawing inspiration from Simon Kuznets (1955) on income inequality and development, who posited an initial rise in inequality followed by a decline in ongoing growth, this work applies this inverted U-shaped relationship to the environmental domain. This hypothesis was adapted for use in environmental economics in the early 1990s, following the influential contributions of Grossman and Krueger (1991; 1995), and Shafik and Bandyopadhyay (1992).

The theoretical underpinning of this characteristic inverted U-shape suggests that, during the nascent stages of economic development, environmental degradation rapidly intensifies as industrialisation and resource exploitation take precedence, often with rudimentary technology and lax environmental regulations (Li *et al*., 2020; Sharma *et al.*, 2021). As an economy matures and income per capita surpasses a certain threshold or 'turning point', a reversal is observed. Rising affluence engenders greater societal demand for environmental quality, which reduces pollution when combined with structural shifts in the economy from heavy industry to service-oriented sectors, the adoption of cleaner, more energy-efficient technology, and stringent environmental policy (Grossman & Krueger, 1991; Lapinskienė *et al.*, 2017; Andreichyk & Tsvetkov, 2023). This dynamic is often disaggregated into scale, composition, and technology effects (Mahmood *et al.*, 2021; Chen *et al.*, 2022; Wang *et al.*, 2024).

Empirical investigations of the EKC hypothesis have yielded diverse findings, with numerous studies corroborating the inverted U-shaped relationship across geographical scales and economic contexts. For instance, evidence supports an inverted U-shape for the Czech Republic, Slovakia, and Romania concerning per capita carbon dioxide (CO_2) emissions and the gross domestic product (GDP; Piłatowska & Włodarczyk, 2017). Similarly, in a broad assessment of European Union (EU) countries, an inverted U-shaped relationship has been observed between CO_2 emissions and GDP per capita in Denmark, Finland, the Netherlands, Austria, Belgium, France, Germany, Spain, and the United Kingdom (Piłatowska & Włodarczyk, 2018). Concerning Central and Eastern European (CEE) countries, some studies have identified Poland as displaying an inverted U-shaped EKC in relation to CO_2 emissions (Piłatowska *et al.*, 2014).

Beyond the European context, empirical investigations across the OECD, BRICS nations and developing economies have also produced diverse findings. Although some studies have confirmed the EKC hypothesis, others have reported N-shaped or linear patterns, highlighting that the income–emission relationship is highly sensitive to the economic context and developmental stage (Bilgili *et al.*, 2016; Sarkodie & Strezov, 2018; Wang *et al.*, 2019; Golpîra *et al.*, 2023). Some investigations have also reported no conclusive evidence or mixed results (Zoundi, 2017; Ciarlantini *et al.*, 2022).

Despite the rapid expansion of EKC literature since the early 1990s (see the bibliometric overview in Annex 1), most studies have focused on aggregate, national-level analyses. Thus, spatial interactions and regional heterogeneity, which influence environmental outcomes, are often overlooked. As a result, most findings remain inconclusive, reflecting substantial variation across spatial scales, geographical contexts, econometric methods, and environmental indicators. This methodological and contextual diversity has been a principal source of ambiguity in the empirical literature, underscoring the need for more systematic and regionally disaggregated research.

Few EKC studies have examined subnational or regional scales, although spatial differences are critical for understanding the mechanisms behind income–emission relationships. For instance, regional-level investigations of Chinese provinces (Ge *et al.*, 2018), Turkish provinces (Karahasan & Pinar, 2022), Italian regions (Bimonte & Stabile, 2017) and Canadian provinces (Olale *et al.*, 2018) have revealed strong spatial heterogeneity and significant deviations from national patterns. These findings indicate that economic growth and environmental degradation interact via locally specific factors, including the industrial structure, urbanisation and energy mix.

Table 1 summarises regional-level EKC studies meeting the following criteria: (i) analysis of pollutants or close proxies related to greenhouse gases (GHGs), (ii) use of subnational spatial units (e.g., provinces, districts, and Nomenclature of Territorial Units for Statistics (NUTS) regions), and (iii) application of panel or spatial econometric methods. This work excludes studies based solely on national time-series or descriptive approaches.

The reviewed literature indicates that regional-level EKC analyses are most common in China, where employing spatial econometric models has become the standard. Comparable studies in other countries (e.g., Canada, the United States, Brazil, Austria, Italy, and Turkey) remain less common. Thus, the spatial interactions and regional heterogeneity that shape environmental outcomes are often overlooked. This study extends the spatial EKC approach to a CEE country, filling a significant empirical gap.

In Poland, empirical work on the EKC hypothesis has been limited. Crucial contributions include the work by Piłatowska *et al.* (2014), who applied threshold cointegration techniques to determine the CO_2 per capita and real GDP for Poland from 2000 to 2012, finding evidence supporting an inverted-U relationship. Bernaciak (2013) examined multiple pollutants in the transition period from 1980 to 2004 and reported mixed results. However, these studies employed national-level time series or panel methods, without extending the analysis to the regional or spatial dimensions. The scarcity of subnational, spatially disaggregated EKC analyses for Poland represents a gap in the current body of knowledge.

Another critical dimension in spatially disaggregated EKC research concerns the potential for interregional ‘carbon leakage’. Several spatial econometric studies indicate that reductions in emissions observed in one region may partly reflect the relocation of high-emission activities to adjacent, less regulated or lower-income regions. For example, Su *et al.* (2018) documented significant positive spatial spillovers of energy-related CO_2 emissions across Chinese cities, demonstrating that local emission patterns are shaped by domestic economic activity and neighbouring regional dynamics. Similarly, Vagnini *et al.* (2025) demonstrated that, in Europe, industrial decarbonisation processes can displace emissions to peripheral areas, particularly in regions hosting large energy-intensive facilities.

Table 1. Summary of regional-level environmental Kuznets curve (EKC) studies

Ref.	Regions/ Scale	Period	Method	Results
Ahmad *et al.* (2021)	28 Chinese provinces	1998–2016	Dynamic common correlated effects mean group	EKC was confirmed in only 5 out of 28 provinces; no clear link to the development level was found, indicating strong regional heterogeneity and aggregation bias
Aldy (2005)	50 US states	1960–1999	FE panel data model	Results confirm the existence of an inverted Kuznets curve for per capita CO_2 emissions in the US
Bimonte & Stabile (2017)	20 Italian regions (NUTS-2)	1980–2008	FE and FE panel models	Inverted U-shaped EKC confirmed for land consumption per capita
Dong *et al.* (2017)	30 Chinese provinces	1995–2014	Dynamic OLS and fully modified OLS	Inverted U-shaped EKC link between CO_2 emissions and GDP
Fang *et al.* (2019)	Eastern, central, and western China (regional)	1995–2016	FE and RE models	N-shaped EKC relationship for CO_2 emissions for all three regions
Freire *et al.* (2023)	27 Brazilian states	1980–2020	Time-series OLS regressions with robust standard errors	EKC hypothesis confirmed for CO_2 (inverted U) only at the national aggregate level
Getzner & Kadi (2020)	9 Australian federal provinces	1994–2016	Panel regression model with quadratic GDP term and AR(1) error structure	Inverted-U relationship confirmed for per capita land consumption and GDP; partial evidence for EKC
Hao *et al.* (2016)	29 Chinese provinces	1995–2012	Panel SDM	EKC confirmed for coal use per capita; a higher turning point is observed with the spatial model
Kang *et al.* (2016)	30 Chinese provinces	1997–2012	Panel SDM	Inverted N-shaped EKC for CO_2 emissions; spatial spillovers confirmed; emissions driven by urbanisation and coal use
Karahasan & Pinar (2022)	81 Turkish provinces	2004–2019	Spatial FE panel models (SAR, SEM, SAC)	U-shaped relationship between economic development (per capita income) and SO_2 levels
Mosconi *et al.* (2020)	686 local labour systems in Italy	2005	Geographically weighted regression	U-shaped EKC between per capita income and desertification risk; significant spatial heterogeneity of effects
Olale *et al.* (2018)	10 Canadian provinces	1990–2014	Panel pooled and FE regression models	EKC confirmed for Canada; at the provincial level, it was confirmed in all regions under FE, but only in five under pooled OLS

Source: Author's elaboration. AR: autoregressive, EKC: Environmental Kuznets curve, FE: fixed effects, GDP: gross domestic product, NUTS: Nomenclature of Territorial Units for Statistics, OLS: ordinary least squares, RE: random effect, SAC: spatial autoregressive combined, SAR: spatial autoregressive, SDM: spatial Durbin model, SEM: spatial error model.

Poland constitutes a compelling case for such an analysis due to its unique position as a post-transition economy with one of the highest shares of coal in electricity generation among EU members. The country is characterised by pronounced interregional disparities in industrial structure and economic development, creating a distinct divide between the more affluent western regions and developing eastern territories (Gorzelak, 2020, p. 39). Furthermore, Poland's ongoing energy transformation, driven by the EU Green Deal and Fit for 55 initiatives, provides a critical context for examining the link between economic growth and emissions.

Thus, the primary study objective is to verify the EKC hypothesis for GHG emissions at the disaggregated NUTS-3 level, accounting for spatial dependencies. The study employs a spatial panel econometric framework with a balanced panel of 73 subregions (based on the Emissions Database for Global Atmospheric Research (EDGAR) and Statistics Poland data) covering 2005 to 2022. The study aims to determine whether regional emissions follow an inverted-U trajectory relative to economic growth, estimate income turning points for assessing decoupling status, and quantify the magnitude of direct and indirect spatial spillovers.

Materials and Methods

Source data and variables

This study examines GHG emissions in Poland from 2005 to 2022, focusing on those expressed as CO_2 equivalents (CO_2eq). This aggregate includes direct CO_2, methane, nitrous oxide, and fluorinated gases. The analysis was conducted at two spatial scales: NUTS-3 (73 subregions) and NUTS-2 (17 regions). Emissions data were sourced from EDGAR, which provides detailed national and subnational emission estimates for GHGs (in CO_2eq). The underlying EDGAR gridded emission inventories were provided at a fine spatial resolution (0.1° × 0.1°). This study employs EDGAR values reported at NUTS-2 due to the necessity to ensure consistency with socioeconomic covariates available in the NUTS statistical framework and avoid mixing spatial support (grid cells vs administrative units), which could reduce cross-variable comparability.

Given the absence of officially published GHG emission data at the detailed NUTS-3 subregional level in Poland, a novel and robust approach was adopted to disaggregate these emissions spatially from the broader NUTS-2 level down to individual NUTS-3 subregions. The emissions allocated at NUTS-2 were proportionally redistributed using detailed economic and demographic indicators at the NUTS-3 level, including industrial output (for emissions from industry) and population (for other emissions). This approach offers a rigorous proxy for regional emissions.

Table 2 presents the descriptive statistics for GHG emissions, income, urbanisation and household electricity consumption per capita for 73 Polish NUTS-3 subregions from 2005 to 2022 to characterise the empirical distribution of the variables in the NUTS-3 panel model.

Table 2. Descriptive statistics for the Nomenclature of Territorial Units for Statistics (NUTS)-3 model (2005–2022)

Variable	*N*	Mean	*SD*	Min	Q1	Median	Q3	Max
CO_2eq per capita (t/person·year)	1314	10.67	5.21	3.18	6.43	9.30	13.56	32.99
GDP per capita (PLN, 2000 prices)	1314	25,242	10,570	13,669	18,747	22,192	27,387	96,668
Household electricity consumption per capita (kWh/person·year)	1314	754.5	113.8	491.7	681.1	743.3	818.5	1191.0
Urbanisation (%)	1314	57.2	20.1	22.05	43.37	52.48	64.44	100.00

Source: Author's elaboration based on Statistics Poland and EDGAR data.

The descriptive statistics revealed marked regional disparities in all variables. The average GHG emissions were about 10.7 t CO_2eq per person annually, with the highest levels in southern industrialised regions. The GDP per capita varied significantly across subregions, underscoring persistent income inequality. Urbanisation ranged from 22% to 100%, illustrating a divide between metropolitan areas and the surrounding rural areas. Due to the unavailability of the total energy consumption data at the disaggregated level (NUTS-3), household electricity consumption was employed as a proxy. This variable captures residential energy intensity and lifestyle-driven demand, offering insight into the nonindustrial drivers of regional emissions.

All continuous variables (i.e. GDP per capita, its squared term, and electricity consumption) were log-transformed to correct for distributional skewness and allow for an elasticity-based interpretation. Furthermore, variance inflation factors (VIFs) were calculated to assess potential multicollinearity between explanatory variables. The results indicate no serious collinearity problem: VIF (log GDP) = 2.99, VIF (log GDP^2) = 1.62, VIF (urbanisation) = 1.77, and VIF (log electricity per capita) = 1.48. All values fell well below the conventional threshold of 5, confirming that multicollinearity does not distort the estimated parameters. All explanatory variables originate from the Local Data Bank of Statistics Poland at NUTS-3.

Model specifications

The initial diagnostic tests included Lagrange multiplier (LM) tests for spatial autocorrelation, which strongly rejected the null hypothesis of spatial independence. *Moran's I* statistics were computed for residuals from a fixed-effects (FE) panel model without spatial components (significant at $p < 0.001$), justifying the selection of a spatially explicit econometric specification. A simple FE panel model without spatial components demonstrated significant residual clustering, violating the assumptions of spatial independence and potentially biasing the coefficient estimates. Lag and error LM tests were significant ($p < 0.001$). The robust LM-lag and error tests were statistically significant ($p < 0.001$), with diagnostics indicating a dominant spatial lag effect. This statistical evidence supports the application of models incorporating endogenous spatial dependence in the dependent variable.

Several alternative spatial econometric models were considered, including the spatial autoregressive (SAR) model, spatial error model (SEM), and SAR model with autoregressive disturbances (SARAR). The SAR model captures direct spatial spillovers via a dependent variable, whereas the SEM controls for spatially correlated omitted variables via the error term. Combining both effects, the SARAR model addresses the limitations of the two simpler models. This approach ensures the robust treatment of spatial dependencies, consistent with the theoretical rationale for interregional emission spillovers and unobserved heterogeneity. The spatial Durbin model (SDM) was also considered but excluded from the final selection to prioritise model parsimony. Although SDM nests other specifications by including spatially lagged explanatory variables, this added complexity often induces multicollinearity, obscuring the identification of the primary drivers. Given that the theoretical focus of this study is on endogenous emission spillovers, which are captured by models (e.g., SAR or SARAR) via the spatial multiplier, the additional complexity of the SDM was deemed unnecessary for verifying the EKC hypothesis. Therefore, the diagnostic comparison focused on selecting the most appropriate method among the SAR, SEM and SARAR models, benchmarked against the nonspatial FE estimator. Table 3 summarises the model comparison based on the Akaike (AIC), Bayesian (BIC), and log-likelihood information criteria.

Table 3. Comparison of models based on information criteria (NUTS-3, 2005–2022)

Model	Akaike information criterion	Bayesian information criterion	Log-likelihood
Nonspatial fixed effects	–2777.8	–2757.1	1392.9
Spatial autoregressive model	–3296.0	–3264.9	1654.0
Spatial error model	–2762.1	–2731.1	1387.1
SARAR	–2425.4	–2384.0	1220.7

Source: Author's elaboration. SARAR: spatial autoregressive model with autoregressive disturbances, NUTS: Nomenclature of Territorial Units for Statistics.

The SAR model with FE realised the highest log-likelihood (1654.0) and lowest AIC and BIC (–3296.0 and –3264.9) values, outperforming the nonspatial FE, SEM and SARAR alternatives. The results confirm the appropriateness of the SAR model as the baseline for the NUTS-3 analysis. Individual FE models were used in the panel SAR model to control for unobserved, time-invariant regional characteristics that could bias the results. In this study, the SAR model is expressed as follows:

$$\ln\mathrm{CO_2eq}_{it} = \alpha_i + \lambda\sum_{j=1}^{N} w_{ij}\ln\mathrm{CO_2eq}_{jt} + \beta_1\ln GDP_{it} + \beta_2(\ln GDP_{it})^2 + \beta_3\mathrm{Urbanisation}_{it} + \beta_4 ln\mathrm{EnergyConsumption}_{it} + \varepsilon_{it}. \quad (1)$$

In Eq. (1), the terms are defined as follows:

- The term $\ln\mathrm{CO_2eq}_{it}$ denotes the natural logarithm of the per capita GHG emissions $(\mathrm{CO_2eq})$ in region i at time t.
- The terms $\ln GDP_{it}$ and $(\ln GDP_{it})^2$ represent the natural logarithm of the regional GDP per capita and its squared term, respectively, to assess the hypothesised inverted-U EKC relationship.
- $\mathrm{Urbanisation}_{it}$ refers to the population percentage residing in urban areas, capturing structural differences in regional economic and social conditions.
- The term $\ln\mathrm{EnergyConsumption}_{it}$ denotes the natural logarithm of the annual electricity consumption per capita (in kilowatt-hours).
- The estimated regression coefficients β_1 to β_4 quantify the partial effects of each explanatory variable on the regional $\mathrm{CO_2eq}$ emissions.
- The SAR parameter λ indicates the extent to which regional emissions depend on those from neighbouring regions.
- The elements of the spatial weight matrix w_{ij} are defined by the first-order queen contiguity (i.e. regions i and j share at least one boundary point, edge or vertex).
- The term α_i represents a region-specific FE that controls for unobservable time-invariant regional heterogeneity.
- The term ε_{it} is the idiosyncratic, independently distributed error term.

Variables are in logarithmic form (except urbanisation, which is retained as a percentage) to facilitate the interpretation of coefficients as elasticities and mitigate potential heteroscedasticity and skewness. This log-log specification clarifies the income turning point at which regional economic growth transitions from increasing to decreasing emissions per capita. The EKC turning point was computed as follows:

$$\text{Turning point } (\mathrm{GDP\ per\ capita}) = \exp\left(-\frac{\beta_1}{2\beta_2}\right). \quad (2)$$

Additional sensitivity analyses were conducted to verify robustness. First, the model was re-estimated at a higher level of regional aggregation (NUTS-2, covering 17 regions instead of the original 73 subregions), yielding consistent patterns, despite the reduced sample size. Notably, the NUTS-2 analysis relied on the original GHG emission data (expressed in $\mathrm{CO_2eq}$) without requiring further spatial disaggregation, providing strong validation for the method previously applied at the more granular NUTS-3 level.

Results

Results from NUTS-3

Table 4 presents the estimation results of the SAR model for GHG emissions ($\mathrm{CO_2eq}$ per capita) across Poland's 73 NUTS-3 subregions from 2005 to 2022. The specification is estimated using panel data and takes into account spatial links between neighbouring subregions.

The results present robust evidence for the EKC hypothesis. The positive and significant coefficient on the logarithm of GDP per capita (0.046, p = 0.029), combined with the negative and significant squared term (–0.074, p = 0.003), confirms the inverted U-shaped relationship between income and per capita $\mathrm{CO_2}$ emissions. The estimated turning point occurs at about 32,417 PLN per capita (year 2000 prices), corresponding to about 73,035 PLN in 2022 prices (Figure 1), or about 16,592 USD based on the exchange rate at the end of 2022. This level lies well within the empirical income range of Polish subregions, implying that several have reached or exceeded the income stage associated with stabilising emissions.

Table 4. Spatial autoregressive model panel estimation results for the CO_2 equivalent EKC in Poland's NUTS-3 subregions (2005–2022)

Variable	Coefficient (p-value)
ln(GDP per capita)	0.046** (0.0294)
ln(GDP per capita)²	–0.074*** (0.0032)
Urbanisation (%)	0.019*** (<0.001)
ln(energy consumption)	0.076* (0.073)
Spatial lag (λ)	0.597*** (<0.001)
Moran's I (residuals)	0.0076 (0.3927)

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. EKC: environmental Kuznets curve, GDP: gross domestic product, NUTS: Nomenclature of Territorial Units for Statistics.
Source: Author's elaboration.

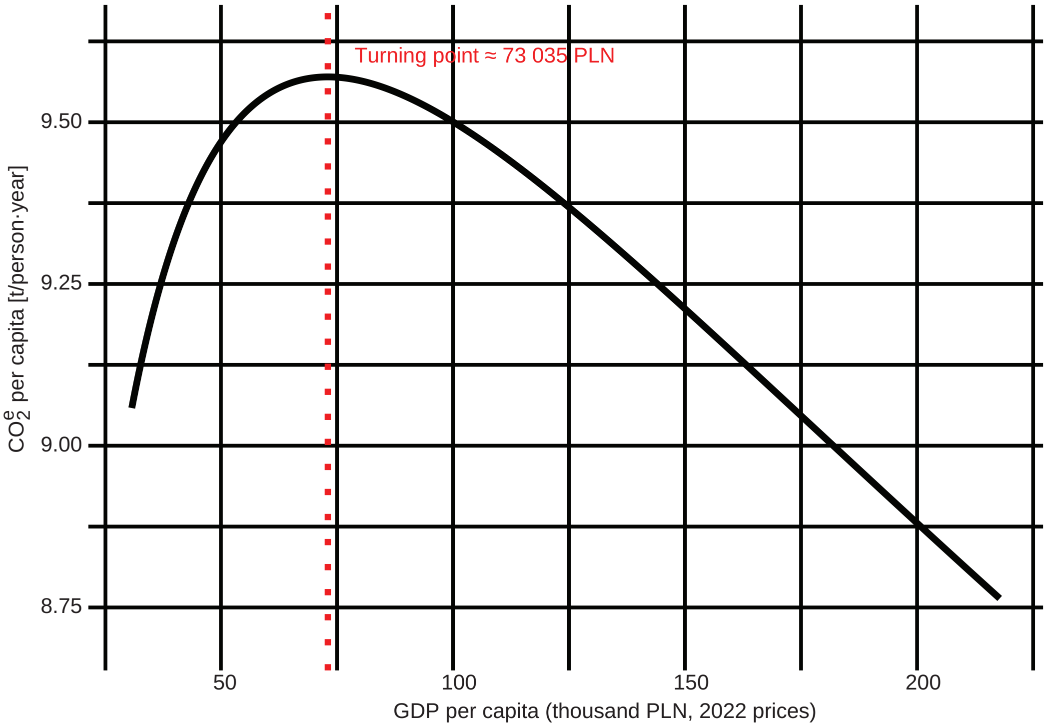

Figure 1. Visual representation of the environmental Kuznets curve with a turning point

Source: Author's elaboration.

This result indicates that many Polish subregions have surpassed this income threshold during the analysed period (2005 to 2022), confirming that economic growth is associated with stabilising or declining emission levels at higher income stages. Below 73,035 PLN per capita (in 2022 prices), regional economic growth is associated with rising CO_2eq emissions driven by scale effects. In contrast, above this income threshold, further economic development is linked to declining emissions due to dominant composition and technique effects.

Urbanisation exhibited a positive and statistically significant association with per capita GHG emissions (coefficient = 0.019, p < 0.001). A percentage-point increase in the urban population is associated with a 1.9% rise in emissions per capita. This finding suggests that greater urban concentration is associated with higher emission intensity in Poland during the analysed period. However, the underlying mechanisms are theoretically ambiguous and may involve scale effects (e.g., higher demand for transport, energy and infrastructure) and efficiency effects related to urban density (Poumanyvong & Kaneko, 2010; Wang *et al.*, 2021).

Energy consumption, proxied by the logarithm of final energy use, displayed a positive coefficient (0.076). The effect is statistically significant at the 10% level (p = 0.073), indicating a weak relationship. The positive coefficient indicates that higher residential electricity consumption contributes marginally to regional emission intensity.

The spatial lag parameter (λ = 0.597, $p < 0.001$) is large and highly significant, underscoring substantial interregional emission spillovers. This finding indicates that regional emission levels are strongly influenced by those of neighbouring subregions, reflecting the spatial diffusion of economic activity, commuting patterns and energy consumption.

Standardised residuals from the SAR model were spatially visualised to illustrate regional deviations from the estimated model (Figure 2). The map highlights subregions where emissions per capita are higher (positive residuals) or lower (negative residuals) than those predicted by the model after accounting for economic output, urbanisation and energy consumption.

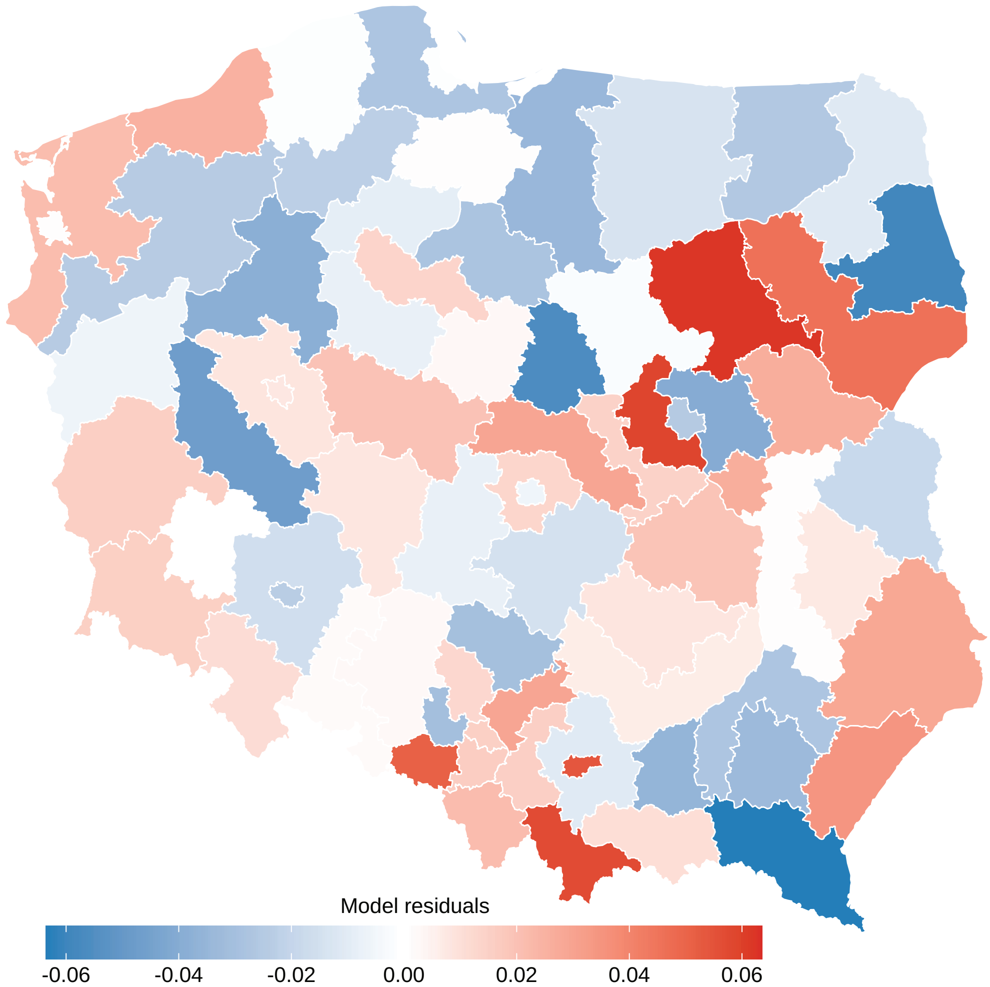

Figure 2. Map of residuals from the spatial autoregressive model at Nomenclature of Territorial Units for Statistics (NUTS)-3 subregions

Source: Author's elaboration.

The post-estimation diagnostics reveal a *Moran's I* statistic for residuals of 0.0076 (p = 0.393), indicating no residual spatial autocorrelation. The absence of significant residual spatial dependence confirms that the SAR model adequately captures spatial interactions in GHG emissions across Polish NUTS-3 subregions. Overall, the results robustly support the EKC hypothesis at the subnational level and underscore the importance of spatial interdependencies that necessitate coordinated regional approaches to emission reduction and sustainable growth.

To assess which regions are positioned on the upward or downward slope of the EKC, regional GDP per capita in 2022 was compared with the estimated turning point of 73,035 PLN (expressed in current prices for the year 2022), at which emissions per capita began to decline with further economic growth. Figure 3 presents this spatial comparison, grouping subregions by the percentage difference between their actual GDP per capita and the estimated threshold.

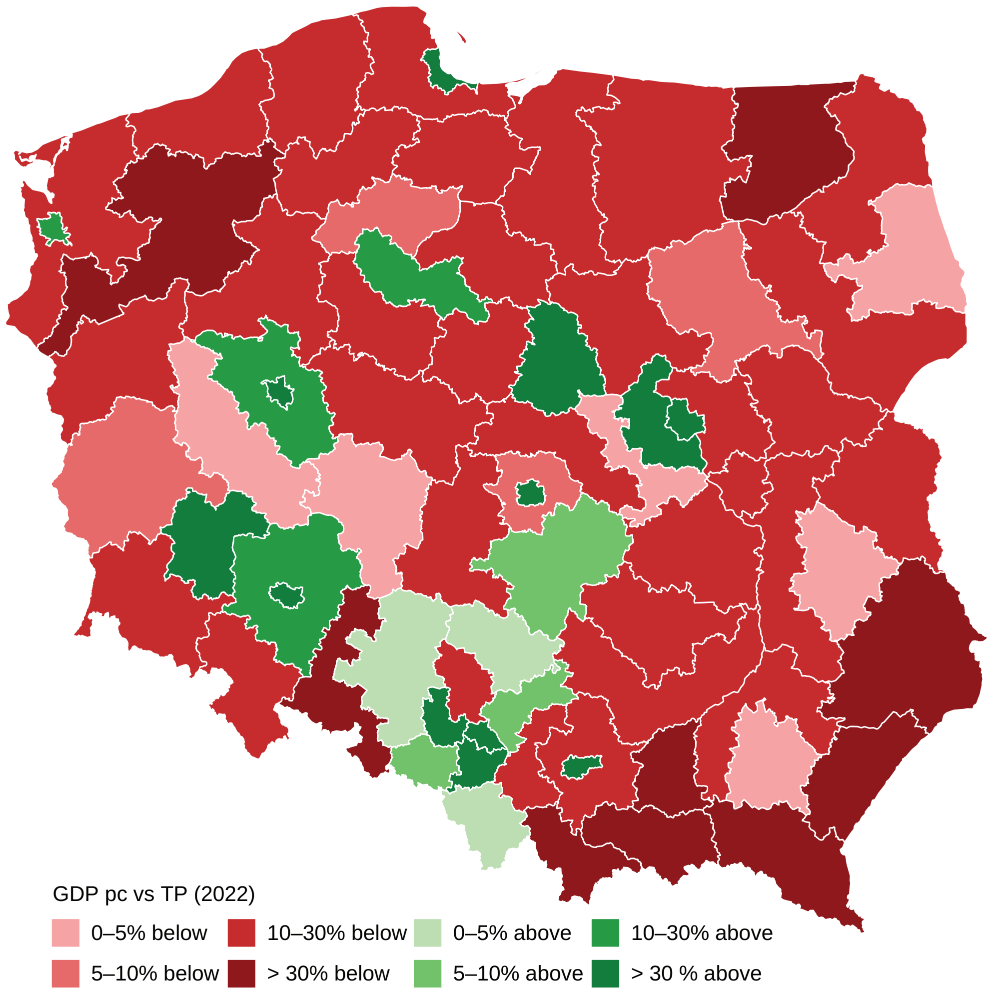

Figure 3. Polish Nomenclature of Territorial Units for Statistics (NUTS)-3 subregions in relation to the environmental Kuznets curve (EKC) turning point in gross domestic product (GDP) per capita (PLN, prices in 2022)

Source: Author's elaboration.

The spatial distribution reveals that most Polish subregions (51/73) remain below the turning point, indicating that most areas are still on the upward slope of the EKC, where economic growth continues to increase emissions. Only a limited number of subregions (22), primarily those in western and southern Poland, have surpassed the income level at which emissions per capita start to decrease. These regions include the more industrialised and economically advanced areas of Dolnośląskie, Wielkopolskie and Śląskie and selected urban centres in Mazowieckie and Pomorskie. In contrast, lagging subregions in the east and northeast, particularly in Podkarpackie, Lubelskie and Warmińsko-Mazurskie, remain significantly below the threshold, often by more than 30%. This pattern highlights a persistent east–west divide in Poland's economic development level and environmental transition.

Decomposition of spatial effects

The application of the SAR model allows for decomposing the marginal effects of explanatory variables into direct (local) and indirect (spillover) components. In Table 5, strong spatial dependence ($\lambda \approx 0.597$) generates a substantial spatial multiplier effect. The estimated indirect effects are about 1.5 times larger than the direct effects, accounting for nearly 60% of the total influence of each variable.

Table 5. Decomposition of spatial effects into direct, indirect and total influences (NUTS-3 level)

Variable	Direct effect	Indirect effect (spillover)	Total effect
ln(GDP per capita)	0.046	0.068	0.114
ln(GDP per capita)²	–0.074	–0.109	–0.183
Urbanisation (%)	0.019	0.029	0.048
ln(energy consumption)	0.076	0.112	0.188

Source: Author's elaboration. GDP: gross domestic product, NUTS: Nomenclature of Territorial Units for Statistics.

Although a 1% increase in the local GDP per capita initially raises local emissions by about 0.046% (direct effect), this increase triggers a broader regional reaction that adds another 0.068% via spatial feedback loops (indirect effect), resulting in a total elasticity of 0.114. A similar multiplier applies to the quadratic term, reinforcing the inverted-U trajectory at the regional system level.

For urbanisation, the direct influence of a percentage-point increase is associated with a 1.9% rise in local emissions, but the total regional influence reaches 4.8% due to strong interregional linkages. This result suggests that urbanisation processes in one subregion exert significant environmental pressure on their neighbours, likely via commuting flows, logistics and shared infrastructure. Household energy consumption, which exhibited marginal significance in the direct estimate ($p < 0.10$), displays a notable total effect (0.188). This result indicates that, although the isolated local influence of residential energy use may appear moderate, its cumulative effect across the spatially interconnected energy system is considerable.

Robustness test at NUTS-2

An additional analysis using a SAR model at a more aggregated level, Poland's 17 NUTS-2 regions, was conducted to ensure that the results at NUTS-3 are robust to various levels of spatial aggregation. Although the panel remains the same length (2005 to 2022), the number of cross-sectional units was significantly reduced to 17, making this analysis more aggregated and less detailed. Nevertheless, the results remained qualitatively consistent with those obtained at NUTS-3 (Table 6).

Table 6. Spatial autoregressive model panel estimation results for CO_2eq EKC in Poland's NUTS-2 regions (2005–2022)

Variable	Coefficient (*p*-value)
ln(GDP per capita)	0.058** (0.0303)
ln(GDP per capita)²	–0.491*** (<0.001)
Urbanisation (%)	0.015** (0.0282)
ln(energy consumption)	0.030 (0.7829)
Spatial lag (λ)	0.2117*** (0.002)
Moran's I (residuals)	-0.045 (0.4548)

Notes: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
EKC: environmental Kuznets curve, NUTS: Nomenclature of Territorial Units for Statistics
Source: Author's elaboration.

At NUTS-2, the SAR model provides a robust confirmation of the presence of an EKC. The significant positive coefficient (0.058, p = 0.0303) of ln(GDP per capita) and the significant negative coefficient of its squared term (-0.491, $p < 0.001$) support the inverted U-shaped relationship at the more detailed NUTS-3 level. At NUTS-2, the turning point was 26,500 PLN per capita in year 2000 constant prices, corresponding to 59,704 PLN in 2022 prices, or about 13,564 USD, using the end-of-year exchange rate.

Urbanisation is positively and significantly associated with emissions per capita (0.015, $p < 0.0282$), suggesting that urban concentration exerts upward pressure on GHG emissions, likely via higher transport and energy demand in metropolitan areas. In contrast, household energy consumption has a small, statistically insignificant effect (β = 0.030, p = 0.7829). Although a weak relationship was observed at NUTS-3, the relationship disappears at the aggregated NUTS-2 scale, implying that local variations in energy consumption may smooth out in larger regions.

The spatial lag parameter (λ = 0.212, $p = 0.002$) confirms moderate spatial dependence, indicating that neighbouring regions partly influence emission levels in one voivodeship (region). Residual spatial autocorrelation is negligible (*Moran's* I = –0.045, $p = 0.4548$), demonstrating that the SAR model at NUTS-2 regions captures the existing spatial structure of the data.

Overall, at NUTS-2, the results align with those at the NUTS-3 scale, confirming the existence and empirical relevance of the EKC in Poland (inverted U-shaped). The location of the turning point in the income range strengthened the reliability of the estimated relationship. These findings offer spatially robust evidence of the nonlinear dynamics between economic growth and environmental outcomes in Polish regions.

Discussion

This study constitutes one of the first applications of the SAR model to validate the EKC hypothesis at a subnational level for an EU member state, filling a gap in the literature on environmental dynamics in Europe. Although EKC studies at the regional level in countries have commonly confirmed the inverted-U pattern using spatial models (Hao *et al.*, 2016; Bimonte & Stabile, 2017; Dong *et al.*, 2017; Getzner & Kadi, 2020; Freire *et al.*, 2023), European evidence remains scarce, particularly for analyses confined to a single country with disaggregated subnational data. In this context, the Polish case offers valuable insight into how regional income dynamics relate to emission intensity in a post-transition economy that has advanced to the high-income group. The current findings are broadly consistent with those of previous EKC studies for Poland based on national-level data (Piłatowska & Włodarczyk, 2017, 2018; Jóźwik *et al.*, 2021), reinforcing the robustness of the inverted-U trajectory.

The results can be contextualised against earlier national-level findings to illustrate the importance of data resolution and methodological approaches. Piłatowska *et al.* (2014) employed threshold cointegration on quarterly data to estimate a turning point for Poland at about 7,219 PLN (in 2005 constant prices). When annualised and adjusted for inflation (about 48,367 PLN in 2022 prices), this threshold is notably lower than the NUTS-3 estimate of 73,035 PLN. Similarly, Jóźwik *et al.* (2021) confirmed the validity of the inverted U-shaped EKC for Poland using an autoregressive distributed lag model bound testing approach. However, they did not calculate a specific income turning point; instead, they focused on long-run elasticities where energy consumption plays a critical role. Nevertheless, unlike these previous contributions, the present analysis employs a SAR model enriched with additional control variables.

The estimated turning points for GHG emissions in Poland, about 16,592 USD at NUTS-3 and 13,564 USD at NUTS-2, fall within the expected range for high-income economies and are well within the empirical income distribution of the dataset. For instance, global estimates place the EKC income threshold at about 11,755 USD for upper-middle-income economies in dynamic models, and 15,859 USD for high-income countries in static settings (Halkos & Gkampoura, 2021). In this study, the NUTS-3 estimate aligns well with this benchmark, confirming that Poland's emission trajectory follows a typical pattern for developed economies.

However, despite this favourable threshold, the drivers in most Polish regions have not yet transitioned from scale to composition and technology environmental dynamics. By the end of 2022, 51 out of 73 NUTS-3 subregions remained below the estimated turning point, indicating that most subregions are still on the upward slope of the EKC. National studies have indicated wider variation, with turning points in Germany ranging from 18,779 to over 36,000 USD and those in Italy ranging from 30,189 to 46,731 USD (Wang *et al.*, 2019). In contrast, the turning points for lower-income countries (e.g., India) were substantially lower, ranging from 2,403 to 3,218 USD (Wang *et al.*, 2019).

Furthermore, the SAR model offers critical insight into the socioeconomic and infrastructural determinants of per capita GHG emissions. The positive and statistically significant effect of urbanisation on CO_2 emissions per capita should be interpreted considering the heterogeneous evidence reported in the literature. The urbanisation–emission relationship is not unidirectional and depends on the economic development stage, urban form, and transport and energy systems. Urbanisation may increase emissions via higher consumption levels, intensified economic activity and infrastructure demand. However, it can also generate efficiency gains associated with dense settlement patterns, such as more viable public transport systems, shorter commuting distances and lower per capita energy consumption in advanced economies. These mechanisms are typically associated with compact city structures, high public transport density and service-based economic profiles.

Empirical studies increasingly document nonlinear or weakening effects of urbanisation on emissions in high-income countries, and in some cases, even a negative long-run relationship once a development threshold is reached (Poumanyvong & Kaneko, 2010; Martínez-Zarzoso & Maruotti, 2011; Wang *et al.*, 2021). In contrast, the estimates for Polish NUTS-3 subregions from 2005 to 2022 indicate that the urbanisation coefficient remains positive and statistically significant, suggesting that the efficiency channel observed in more mature economies has not yet become dominant in Poland during the analysed period, likely due to the relatively high role of private vehicle transport, energy-intensive industries and the spatial structure of Polish cities.

The results for household energy consumption indicate a scale-dependent relationship. At NUTS-3, the coefficient is positive and statistically significant (0.076, $p = 0.073$), suggesting that residential electricity demand is a relevant driver of emissions, albeit less dominant than industrial factors. However, at NUTS-2, this effect vanishes (0.030, $p = 0.783$). This outcome is primarily explained by the scope of the variable, which captures only household electricity consumption rather than the total regional energy consumption. The residential electricity demand represents a small portion of the overall energy consumption; hence, its influence on emissions is indirect and depends on the national energy mix. The fact that significance is observed only at the finer NUTS-3 resolution suggests that local heterogeneity in energy consumption patterns is critical for understanding emission drivers. In contrast, aggregation to NUTS-2 masks these specific effects. This observation also suggests a gradual decoupling between household energy demand and emissions intensity, consistent with the ongoing energy transition in Poland, where renewables accounted for 29% of electricity generation in 2024, and coal use fell to 57% (WysokieNapiecie.pl, 2025).

These findings have implications for the debate on decoupling strategies. The Intergovernmental Panel on Climate Change (IPCC, 2022) framework distinguishes between relative decoupling (where emissions increase more slowly than the GDP), absolute decoupling (where emissions decline while GDP increases), and absolute-plus-sufficient decoupling (where the decline is sufficiently rapid to meet climate targets). The results indicate that reliance on economic growth as the primary driver of decarbonisation is insufficient for the Polish context. Most subregions (51 out of 73) are currently on the ascending slope of the EKC, below the turning point of about 73,035 PLN. Therefore, continued economic growth in these areas is structurally linked to rising per capita emissions, reflecting the persistent legacy of historical structural disparities (Gorzelak, 2019).

Although the 22 most affluent subregions display absolute decoupling (past the turning point), the existence of an inverted-U relationship does not guarantee that emissions will reduce at a pace consistent with the EU's Fit for 55 goals (absolute-plus-sufficient decoupling). Furthermore, although Poland's demographic decline (depopulation) may mechanically lower total nominal emissions, this passive reduction does not reflect a genuine structural transition towards low-carbon efficiency. Hence, active policy interventions, including the acceleration of renewable energy adoption and energy efficiency retrofits, are necessary to force a decoupling trajectory in subregions that have not yet reached the income threshold, rather than waiting for income-driven effects to materialise.

The structural analysis of spatial effects provides deeper insight into the mechanism of emission propagation. The decomposition reveals that the indirect (spillover) effects are substantial, accounting for about 60% of the total influence of the explanatory variables. The large share of indirect effects is driven by the high SAR parameter, which functions as a multiplier of local impulses. For policymakers, this finding implies that the environmental consequences of local economic decisions, such as rapid urbanisation or industrial development, are not confined to the boundaries of a single NUTS-3 subregion. Instead, more than half of the generated environmental pressure was transmitted to neighbouring areas via economic linkages, transport networks and shared energy infrastructure. Thus, mitigation strategies focused solely on isolated administrative units may be ineffective because they fail to address the dominant cross-border component of emissions.

Furthermore, as argued by Gruszecki and Jóźwik (2019), the rising income inequality may weaken the political capacity of local communities to oppose environmentally damaging practices, potentially exacerbating environmental degradation. This dimension, which was not directly addressed in the current model, remains a crucial direction for future spatial research. Considering this dimension, further investigation could include the incorporation of inequality indices (e.g., Gini coefficients or regional income dispersion measures) into extended spatial models to assess whether sociopolitical asymmetries exacerbate environmental pressure.

Moreover, future subnational studies could explore alternative EKC functional forms (e.g., *N* trajectories) and replicate the SAR framework for other CEE countries at the NUTS-2 or 3 levels, where similar post-transition dynamics and institutional heterogeneity may yield critical comparative insight. Cross-country panel models with regional-level disaggregation can explore the role of spatial spillovers, institutional quality and demographic structure in shaping heterogeneous EKC patterns across these countries.

Conclusions

This study presents a robust empirical confirmation of the EKC hypothesis for GHG emissions in an EU country using a spatial panel econometric framework applied to Poland's NUTS-3 subregions and, as a robustness test, NUTS-2 regions. By applying the SAR model, which captures endogenous spatial spillovers, this research represents one of the first applications of this method at a disaggregated subnational scale in the EU context. The inverted U-shaped relationship between GDP per capita and CO_2eq emissions is statistically confirmed across both regional aggregation levels, with estimated turning points well within the observed income distributions.

The turning point was about 73,035 PLN (16,592 USD) at NUTS-3 and 59,704 PLN (13,564 USD) at NUTS-2, suggesting that most Polish regions have not yet entered a phase in which economic growth is associated with stabilising or declining emission intensity. This empirical placement enhances the interpretability and policy relevance of the EKC turning point, affirming that the environment can be improved without sacrificing economic advancement if regions continue to adopt efficient technology and shift from carbon-intensive activities.

In addition to confirming the EKC hypothesis, this study also explains the spatial and socioeconomic dynamics affecting regional GHG emissions. At NUTS-2 and 3, urbanisation exerts a positive and statistically significant influence on CO_2eq emissions per capita, indicating that more urbanised regions tend to generate higher emissions per person. This relationship reflects the energy demand concentration, transport intensity and infrastructure use typical of densely populated urban areas. Regarding energy consumption, the analysis relied on household electricity consumption as a proxy due to the lack of total regional energy consumption data at NUTS-3. The results for this variable present a scale-dependent pattern: a positive, weakly significant effect at NUTS-3 ($p < 0.10$), which vanishes at the aggregated NUTS-2 scale. This outcome suggests that despite residential energy demand contributing to local emission variations, it may be a secondary driver compared with industrial and transport factors. Hence, future research should incorporate total regional energy consumption data to capture the energy–emission nexus fully.

Spatial diagnostics confirm the importance of considering interregional dependencies. The significant spatial autocorrelation in emission levels justifies the application of a SAR model, which captures endogenous spillovers between neighbouring regions. The decomposition of spatial effects demonstrates that indirect spillovers constitute the majority (about 60%) of the total influence of socioeconomic drivers on emissions. This finding challenges the efficacy of disjointed local climate policies. The environmental footprint of a region is more influenced by its interactions with neighbours than by isolated local factors; thus, effective decarbonisation requires supra-regional coordination. Therefore, financial mechanisms must be targeted to support structural transformation in lagging regions (those still on the upward EKC slope) to prevent 'carbon leakage' and ensure that the energy transition costs are distributed equitably.

In summary, this study demonstrates that the EKC hypothesis is a valuable framework for understanding the evolving relationship between income and emissions, but only when analysed through a spatially aware and regionally disaggregated lens. The findings present robust empirical support for differentiated climate policies that reflect local development stages, spatial interdependencies and sociodemographic structures, which are critical factors in designing effective, equitable sustainability transitions.

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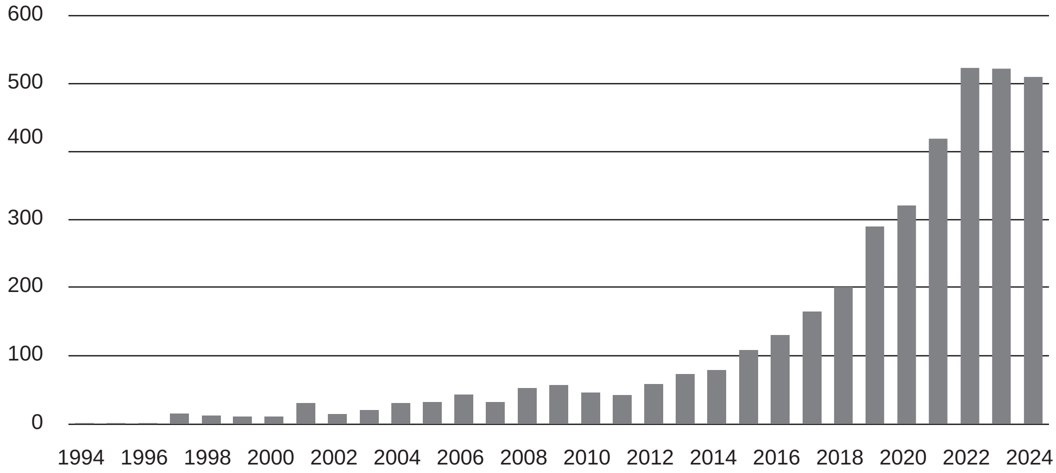

Annex 1. Number of academic articles per year addressing the environmental Kuznets curve indexed in the Scopus database (1994–2025).

Source: Author's elaboration.