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Mismanaged plastic waste and the environmental Kuznets curve: A quantile regression analysis

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Abstract :

The relationship between economic growth, governance, and environmental outcomes, particularly mismanaged plastic waste (MPW) leaking out to the ocean, has been a focal point of policy and academic debates. This study aims to understand the dynamics of income and control of corruption across different levels of MPW. Utilizing Quantile Regression models, we explore the generalized and quantile-specific relationships between the variables. The findings confirm the validity of the Environmental Kuznets Curve (EKC), revealing an initial increase in MPW with economic growth, followed by a decline after surpassing a specific economic threshold. However, the EKC is not validated for all quantiles and the shifting point may vary across the distribution. Moreover, control of corruption emerged as a significant factor in determining MPW levels, emphasizing its moderating role at the highest levels of mismanagement. This study underscores the need for synergizing economic strategies with robust environmental policies, guided by strong governance mechanisms.

Highlights

► The Environmental Kuznets Curve (EKC) is checked for mismanaged plastic waste (MPW). ► A quantile regression shows that the EKC pattern holds only beyond the 40th percentile of MPW. ► The income threshold increases with higher levels of MPW. ► More stringent control of corruption reduces significantly the amount of MPW.

Keywords : Mismanaged plastic waste, Environmental Kuznets Curve, Marine pollution, Economic growth, Governance, Control of corruption, Quantile regression

1. Introduction

The complex relationship between economic development, governance structures, and environmental pollution has long been a subject of intense enquiry and debate. At the core of this discourse lies the question of how nations can achieve economic prosperity without compromising their environmental integrity. Mismanaged plastic waste (MPW), as an illustrative representation of environmental challenges in present-day societies, offers a unique lens through which we can explore this relationship. Between 4.8 and 12.7 million tonnes of MPW leak out annually to the ocean, accumulating in the marine environment (Jambeck et al. 2015). The coastal urban centers located near a river would be responsible for the greatest proportion of MPW leakages, and 1000 rivers would account for 80% of global annual emissions (Meijer et al. 2021). Such quantities have obviously serious implications for marine biodiversity (Lebreton et al. 2017, Beaumont 2019).

Past research has implied at various paths, with some suggesting the Environmental Kuznets Curve (EKC) pattern, an initial rise in environmental degradation with economic growth, followed by a decline after reaching a certain economic threshold (Grossman and Krueger 1991; Dinda 2004; Stern 2004). However, this idea often paints a broad picture, missing out on the detailed differences that might appear at various stages of waste mismanagement. Moreover, while economic parameters are frequently examined, the role of governance, particularly in the realm of corruption control, has not been adequately integrated into the discussion (Abrate et al. 2015). Effective governance can arguably influence sustainable waste management practices, especially as economies evolve and grow (Cordier et al. 2021). Given these considerations, our study aims to delve deeper into the relationship between Gross Domestic Product (GDP) and MPW across a quantile distribution, emphasizing the potential differences that might emerge at different levels of waste mismanagement. Furthermore, we integrate the role of corruption control, to offer a more comprehensive perspective on the determinants of MPW.

Building on the above observations, we hypothesize that: (1) The Environmental Kuznets Curve (EKC) pattern is valid for plastic mismanagement and pollution, but not to the same extent for all levels of mismanaged waste rates. To do so, we employ two primary statistical methods: the Ordinary Least Squares (OLS) and Quantile Regression (QR). (2) Countries with better governance, particularly those with stronger measures to control corruption, will experience a reduced level of MPW even at lower GDP levels, implying that governance can act as a moderating factor in the relationship between economic growth and marine plastic pollution. This study, therefore, seeks not just to confirm or refute these hypotheses, but also to deepen our understanding of the intertwined dynamics of economic growth, governance, and environmental challenges. Establishing a robust relationship between these variables can provide critical insights for framing environmental policies that align with economic strategies.

Following this introduction, the second section covers a literature review, capturing previous studies and theoretical foundations relevant to our research topic. The third section elaborates on the chosen methodology and provides a detailed description of the data utilized. The fourth section presents empirical results, followed in the fifth section by a thorough discussion to interpret and contextualize the findings, drawing out the broader implications of our findings and suggesting potential avenues for future research and policy formulation.

2. Literature review

The Environmental Kuznets Curve (EKC) hypothesis is an important concept in environmental economics. The name derives from the supposed resemblance between the hypothesized relationship between environmental degradation and income per capita, and the Kuznets curve which relates income inequality and per capita income. Initially introduced by Grossman and Krueger in the early 1990s, the EKC postulates an inverted U-shape relationship between environmental degradation and income per capita. Specifically, as a nation's income increases, environmental damages initially escalate until it reaches a turning point, after which it begins to diminish (Grossman and Krueger 1991; 1995). Several theoretical reasons would explain this inverted U-shaped curve. First, a scale effect creates a simultaneous growth between wealth and pollution: by producing and consuming more goods, countries increase their level of waste residuals and emissions to the environment. A second (composition) effect could result from the shifting specialization of countries towards a more dematerialized growth along their development: the domestic economy is increasingly turning to the supply of services and produce fewer manufactured goods. A third factor lies in technical change: beyond a certain degree of development, a growing share of capital is allocated to research activities, fosters greener technologies (De Bruyn et al. 1998) and the demand for green products also increases.

This foundational work has been subject to extensive empirical verification and meta-analyses (Panayotou 1997, Cavlovic et al. 2000, Sarkodie & Strezov 2019, Saqib & Benhmad 2021). The meta-analyses validate the EKC in a significant number of studies, i.e. more than half (57%) in the case of Saqib & Benhmad (2021), nearly two thirds (63%) in the case of Sarkodie & Strezov (2019), but few studies estimate the income level corresponding to the threshold beyond which the pollution level decreases. The average turning point is estimated at USD 8,910 for the studies that validate the EKC (*Ibid.*). Interestingly, the EKC is verified in a majority of studies, irrespective of the data sets, control variables and choice of econometric methods (Saqib & Benhmad, 2021).

While the EKC hypothesis provides an insightful starting point, the nuances and complexities of the relationship between economic growth and environmental pollution or degradation demand a more intricate analysis. Numerous studies have reaffirmed the EKC hypothesis but some challenge its universal applicability by noting distinct turning points for various pollutants and regions (Selden and Song 1994; Dinda 2004) that might be a result of model misspecification or measurement errors (Stern 2004). Moreover, most empirical studies have traditionally focused on the EKC relationship concerning specific pollutants, notably carbon dioxide (CO_2) and sulfur dioxide (SO_2). Specifically, the seminal work of Grossman and Krueger (1991) particularly examined air pollutants, which incorporated both CO_2 and SO_2 among other pollutants, laying the groundwork for subsequent studies in the field (Winslow 2005, Miah et al. 2010, Saqib & Bernhmad 2021). If the EKC hypothesis has been widely studied in relation to various environmental pollutants, its direct relevance to plastic pollution, especially in the context of mismanaged waste, remains an area demanding further exploration (Barnes 2019, Cordier et al. 2021, Kocakaya 2023).

Wagner (2017) notes that as economies grow, plastic production and consumption increase, leading to a rise in plastic waste. Even more worrisome are the long-term trends which do not see any decoupling between growth and marine plastic pollution, nor any “peak waste” before the end of the century (Jambeck et al. 2015, Golden et al. 2017). Barnes (2019) explained the duality of economic development, emphasizing that while it can exacerbate plastic production and pollution, it can also serve as a catalyst for technological research and innovations that counter these challenges. Increasing GDP not only enhances the disposable income per capita in a country, hence the standard of living, but it also improves the waste collection and treatment infrastructures, the level of education and people's awareness of environmental concerns (Cordier et al., 2021). Advanced economies tend to invest more in efficient waste management systems (Dauvergne, 2018) that might drive a decline in MPW, implying a potential EKC relationship. Economic progression not only escalates plastic consumption but also paves the way for innovations aiming at sustainable alternatives and efficient waste management.

Barnes (2019) proposes the first EKC study linking income per capita and MPW, based on a dataset created by Jambeck et al. (2015). However, this study was criticized because some data were missing for many countries (84 over 192) and therefore imputed by models assuming that income level explains the degree of mismanaged waste per capita using a World Bank income classification, hence a circular demonstration (Uehara & Cordier, 2019). This is why we prefer to use MPW data based on recent field observations of macroplastics in rivers and disseminated from land to ocean through a distributed probabilistic model of plastic transport (Meijer et al. 2021). Significant discrepancies can be found between the MPW rates in the two studies for some countries, in particular small island developing states which are particularly vulnerable to plastic waste pollution (Cordier et al. 2021, Guillotreau et al. 2023). For example, the MPW per capita amounted to 44.6 and 50.6 kg in Mauritius and the Seychelles, respectively, in the Jambeck et al. (2015) database, and to 0.2 and 0.3 kg, respectively, in Meijer et al. (2021).

Cordier et al. (2021) extracted a sub-sample of 122 countries from the Jambeck database to test the EKC hypothesis for inadequately managed plastic waste, eliminating the countries having a high proportion of plastic waste not categorized properly as MPW by the World Bank database. Their analysis validates the EKC with this sample and emphasized the need for additional criteria in the relationship, such as governance indicators. Given its multifaceted nature, understanding plastic pollution requires an exhaustive examination of its economic, environmental, and socio-political determinants. Cordier et al. (2021) explored these interactions, revealing that nations characterized by heightened corruption levels tend to struggling with higher levels of MPW. Controlling corruption reduces pollution by preventing illegal activities or the action of lobbies attempting to avoid the enforcement of stringent regulations (Biswas & Farzanegan 2012). This underscores the imperative to concurrently address governance paradigms in the quest to mitigate plastic pollution (Wang et al. 2020).

In light of these findings, our study seeks to advance this discourse further. We incorporate the more recent and refined data on MPW from Meijer et al. (2021). By coupling this MPW data with GDP and other relevant indicators, we aim to understand if a similar trend is evident in the context of plastic pollution. Our empirical approach, based on quantile regression, is different to capture a relation between economic growth and MPW that may vary in intensity according to the level of mismanagement. Furthermore, recognizing that governance plays a pivotal role in environmental management, we link our investigation to the control of corruption.

3. Methods

3.1. The Environmental Kuznets Curve model

The EKC hypothesis postulates that there exists an inverted-U relationship between environmental degradation and economic development. Initially, as economies grow, the level of environmental degradation rises, but after a certain point, further economic growth leads to environmental improvements. The generalized equation with Z covariates can be represented as:

$$ED = \alpha + \beta_1 GDP + \beta_2 GDP^2 + \gamma Z + \varepsilon \qquad (1)$$

Where ED is the environmental degradation; GDP is generally the GDP per capita which represent income; and Z is a vector of covariates. Based on this framework, the EKC hypothesis holds in such that $\beta 1 > 0$ and $\beta 2 < 0$.

Given the data constraints faced during this research attempt, panel data, which would have ideally provided a temporal perspective and facilitated deeper insights into dynamics over time, was unfortunately unavailable for the study. As a result, we employed cross-sectional data as our primary tool to facilitate our examination of the EKC hypothesis.

In the context of cross-sectional data, the Ordinary Least Squares (OLS) method would provide the average relationship between GDP, its squared term, and environmental degradation across the sample. It is essential to ensure that the assumptions of OLS, such as no endogeneity, homoscedasticity, and no perfect multicollinearity, are met. Given the disparities in economic structures, policies, and environmental conditions among countries, the relationship between GDP and environmental degradation might differ substantially across the environmental degradation distribution. While traditional regression analyses offer insights into average relationships, they might not capture these nuanced variations, especially if the relationship between economic development and environmental degradation is non-uniform across different degradation levels. Quantile Regression (QR) becomes a pivotal tool in this context (D'haultfœuille & Givord 2014). By focusing on various quantiles of the environmental degradation distribution, QR allows researchers to unveil the heterogeneous impacts of GDP on environmental degradation at multiple points in its distribution, not just its mean. This QR model in the EKC framework can be expressed as:

$$Q_{ED_{(\tau|\mathrm{GDP,Z})}} = \alpha(\tau) + \beta_1(\tau)\mathrm{GDP} + \beta_2(\tau)\mathrm{GDP}^2 + \gamma(\tau)\mathrm{Z} + \varepsilon(\tau) \qquad (2)$$

where $Q_{ED_{(\tau|\mathrm{GDP,Z})}}$ denotes the conditional quantile of environmental degradation at quantile τ given GDP and Z covariates. τ represents the quantile level (10^{th}, 20^{th}, etc.).

By applying the quantile regression, one may benefit from its various advantages over the traditional OLS by (i) capturing the problem of heterogeneity as QR provides insight into how predictors influence the spread and tails of a response variable's distribution; (ii) it is more robust since it is less sensitive to outliers in the response distribution than OLS; and (iii) it reveals more about the relationship between variables (Koenker 2017). For instance, an explanatory variable might have a more pronounced effect at the lower quantiles of a response variable but a diminished or even opposite effect at higher quantiles. Statistical analyses were performed in R version 2023.03.1+446 (R Core Team, 2024).

3.2. Data

To complement our investigation, we employed the dataset from Meijer et al. (2021), which provides a comprehensive perspective on MPW in the year of 2019. In this study, the quantity of MPW per capita and by country was estimated through a distributed probabilistic model of macroplastic transport from global rivers to the ocean. This model was calibrated with monthly survey data of floating macroplastic emissions coming from 136 field observation data points located in 67 rivers and 14 countries (Meijer et al. 2021). The MPW generated by country in metric tonnes is made publicly available by the authors of the study as supplementary materials and was divided by the population size to obtain MPW in kg per capita. This dataset presents an invaluable snapshot of the current state of marine pollution and offers a potential lens through which one can view the intricate relationships between waste management practices and other factors.

In addition to the plastic waste data, our research also incorporated data on Gross Domestic Product (GDP) and the Control of Corruption indices sourced from the World Bank (2022a; 2022b). These metrics serve as essential economic and socio-political indicators that could shed light on the potential links and interdependencies between economic growth, governance quality, and environmental outcomes. The GDP per capita is measured in PPP constant 2017 international dollars, and the Control of Corruption Estimates were centered and scaled between approximately -2.5 and 2.5, with higher scores indicating better governance (i.e., less corruption). A positive score suggests that a country fares better than average, while a negative score suggests the opposite. The Control of Corruption measures the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as the capture of the state by the elites and private interests (Kaufmann et al. 2010). Indeed, this indicator is one of six governance indicators developed and maintained by the World Bank as part of the Worldwide Governance Indicators (WGI) project. The WGI project has been collecting and reporting governance data since the late 1990s. To produce this indicator, the World Bank aggregates data from a multitude of sources. Each individual data source is standardized to have a mean of zero and a standard deviation of one. All the various sources can be combined into a single aggregate indicator for each governance dimension. The number of observations (countries) where all variables were available for year 2019 is 145.

The descriptive statistics are presented in Table 1. On average, the mismanaged plastic waste value is ~9 kg per person in 2019. The middle value of 6.3 kg, lower than the mean, suggests a right-skewed distribution (skewness = 2.234). We also observed that the distribution of the MPW has heavier tails and a sharper peak than a normal distribution (leptokurtic distribution with the kurtosis of 7.449), indicating a possible application of quantile regression (Koenker 2017). To normalize and simplify the empirical analysis, we express both the MPW per capita and GDP per capita in terms of their natural logarithms. The control of corruption is an exception, as it is already scaled between -2.5 and 2.5.

Table 1: Descriptive statistics (N = 145)

Variable	*Mean*	*Median*	*Min*	*Max*	*SD*	*Skewness*	*Kurtosis*
mpw	9.029	6.268	0.068	69.516	10.782	2.234	7.449
gdp	22324	14852	1060	98455	20271	1.261	1.371
corrupt	0.038	-0.137	-1.560	2.167	0.951	0.523	-0.516
lmpw	1.224	1.836	-2.695	4.242	1.688	-0.407	-1.173
lgdp	9.529	9.606	6.966	11.497	1.084	-0.358	-0.832
lgdp2	91.977	92.273	48.524	132.189	20.279	-0.176	-0.961

4. Results

The EKC model is applied to explain the MPW across economies of varying income levels. Table 2, which showcases the results from an Ordinary Least Squares (OLS) regression with a stepwise method, provides some insights into this relationship. Following the EKC literature on plastic waste (Barnes 2015, Cordier et al. 2021, Kocakaya 2023), we explored a data set with several Z covariates to estimate Eq. (1): *lgdp, lgdp², lgdp³*, *corruption* control (World Bank), *Economic Freedom Index* (www.heritage.org), *% urban population* (WB), *literacy rat*e (WB), *secondary school enrollment*, *number of tourist arrivals* (WB), *islandness* dummy and coastline length (World Population Review). We used the R-package *Leaps* (command *regsubsets*) to perform an exhaustive search for the best subsets of the independent variables for predicting MPW in linear regression, using an efficient algorithm based on several criteria (RSS, adjusted R^2, AIC, BIC, DIC) to return the best model of each size. The best models of the stepwise procedure are presented in Table 2.

Table 2: Ordinary least squares estimates (stepwise)

	(1)	*(2)*	*(3)*
lgdp			5.421***
			(1.598)
lgdp2		-0.030***	-0.325***
		(0.007)	(0.087)
corrupt	-1.171***	-0.724***	-0.541***
	(0.112)	(0.150)	(0.154)
constant	1.269***	-3.973***	-20.519***
	(0.106)	(0.649)	(7.246)
R2	0.435	0.498	0.536
Adjusted R2	0.431	0.491	0.526
AIC	485.589	470.458	461.079
BIC	494.519	482.365	475.962
N	145	145	145

Note: ***, **, and * indicate significant p-values at the 1, 5, and 10% level, respectively. Robust standard errors are presented in the parentheses.

In the initial model, only corruption control is used to explain the variance in MPW. This model alone explains 43.5% of the variance in MPW. A significant negative coefficient of -1.171 suggests that as control of corruption increases (i.e. towards a more stringent governance), MPW decreases. This implies that governance has a substantial role in influencing MPW. The inclusion of the quadratic term of income in the second model increased the R^2 value to 0.498, suggesting that this model explains half of the variance in MPW. Finally, a full EKC model of Eq. (1) is presented in the last model (3) by incorporating the linear term of GDP per capita, improving further the model fit. This model indicates the presence of the EKC relationship since $\beta_1 > 0$ and $\beta_2 < 0$. As GDP increases, MPW first rises, but after a certain point (represented by the peak of the U-shape), it starts to decline. Predictions of MPW by a simple quadratic function follow the U-inverted shape of the model, nonetheless with a larger 95% confidence interval in both extreme quantiles of the distribution (Fig. 1a). A collinearity issue may exist between GDP and corruption control, because the anti-corruption regulations are likely to be enforced with greater stringency in high-income countries, but this problem was checked and rejected with a VIF test (stat = 1.92). We have also checked the functional form of the model by including a cubic term of the income ($lgdp^3$) in the relationship, but the coefficient was not significant and therefore rejected, hence validating the EKC pattern.

While the stepwise OLS results presented in Table 2 provide some interesting insights into the relationship between MPW, GDP, and corruption, the violation of the normality of residuals assumption prompts caution in interpreting the results, as shown by the QQ plot of residuals (Fig. 1b; Shapiro-Wilk test of 0.974 with p-value < 0.05). The MPW density plot in Figure 1c reveals the bimodal nature of the dependent variable and suggests underlying complexities in the data that may interestingly need further exploration, potentially through quantile regression estimated by the "*quantreg*" R-package (Koenker 2017).

a) EKC prediction *b) QQ residuals of model (3)* *b) Density of MPW*

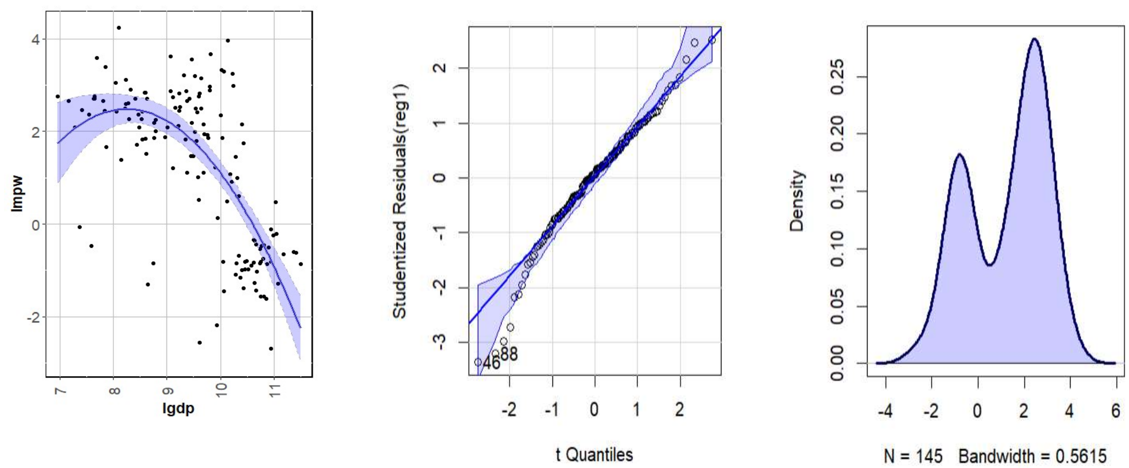

Figure 1: Relationship between GDP and MPW per capita (in logarithms)

Notes: (a) Predictions of *lmpw* as a quadratic function of *lgdp*. Solid lines are the mean predictions with ribbons of 95% confidence intervals. Black dots are observations (countries). (b) quantile-quantile plot checking the normality of the data. (c) Kernel density estimates of log(MPW).

Table 3 both provide a thorough analysis utilizing quantile regression techniques in unravelling the relationship between GDP, control of corruption, and MPW across varying quantiles of plastic waste mismanagement.

Table 3: Quantile regression estimates of MPW

	10th	*20th*	*30th*	*40th*	*50th*	*60th*	*70th*	*80th*	*90th*
lgdp	3.415	2.702	5.167	6.190**	4.906**	4.770**	5.172***	5.838***	7.744***
	(6.127)	(3.465)	(2.608)	(2.048)	(1.569)	(1.783)	(1.464)	(1.017)	(1.333)
lgdp2	-0.233	-0.183	-0.320**	-0.383***	-0.306***	-0.295***	-0.308***	-0.338***	-0.445***
	(0.340)	(0.190)	(0.142)	(0.1125)	(0.087)	(0.098)	(0.083)	(0.057)	(0.074)
corrupt	-0.560	-0.654	-0.539**	-0.299***	-0.375***	-0.430***	-0.532***	-0.596***	-0.500***
	(0.451)	(0.307)	(0.208)	(0.152)	(0.098)	(0.159)	(0.225)	(0.186)	(0.242)
constant	-10.981	-8.498**	-19.053***	-22.688**	-17.267***	-16.823***	-19.158**	-22.357***	-30.355**
	(27.005)	(15.666)	(11.801)	(9.207)	(7.050)	(8.038)	(6.350)	(4.431)	(5.881)

Note: *lmpw* (logarithm of MPW per capita) is the dependent variable. ***, **, and * indicate significant p-values at the 1, 5, and 10% level, respectively. The bootstrapped standard errors are presented in the parentheses.

At the initial quantiles, up to the 40th percentile, the anticipated Environmental Kuznets Curve (EKC) pattern between GDP and mismanaged plastic waste is not discernible. Within these bounds, economic progression does not explicitly manifest in the classic inverted U-shaped curve of the EKC. This suggests that in regions or economies characterized by relatively lower levels of MPW, incremental economic growth might not readily correlate with plastic waste peaks followed by subsequent reductions. Alongside, the efficiency of corruption control mechanisms in influencing plastic waste management remains ambiguous at these quantiles, although significant since the 30^{th} percentile with the expected negative sign. This could be indicative of the overarching influence of other socio-economic or infrastructural factors such as education or urbanization.

Figure 3 shows how the bootstrapped standard errors of the conditional quantile regression are pretty large for every variable included in the model within the first four deciles. Beyond this level, i.e. for greater amounts of MPW, the coefficients become more robust and significant, except for the last quantile where the estimates deviate slightly from the OLS levels, particularly for the corruption control variable.

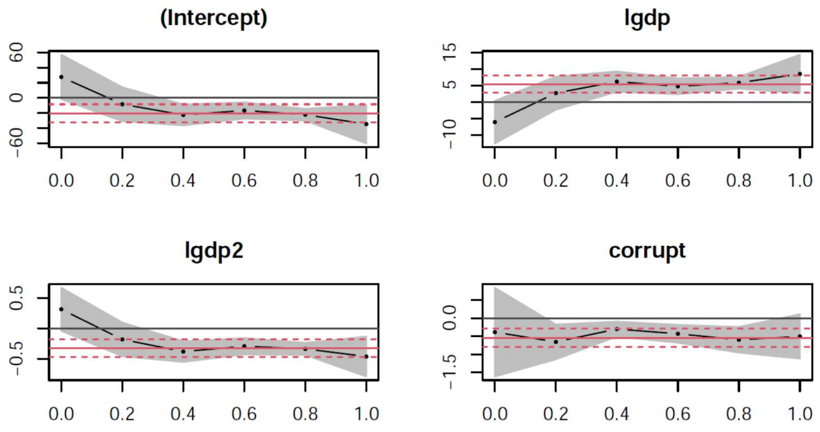

Figure 3: Coefficients of the quantile regression

Note: The x-axis represents the vector of regression quantiles τ, the dashed black line denotes the coefficient of covariates with its grey-shaded confidence band, the solid and dashed red lines indicate the OLS coefficient with its 95% confidence interval, and the solid black line marks the zero value as reference point.

From the 40th quantile upwards, a more pronounced EKC relationship emerges between GDP and MPW. After the 50^{th} percentile, a 1% increase in GDP has a greater marginal impact on MPW per capita. The estimated coefficients for all covariates present the expected signs and coefficients of similar magnitude. As these economies or regions witness escalating levels of MPW, an initial phase of exacerbation linked to economic growth is evident. However, a tipping point arises, beyond which any further economic advancement appears to offset the plastic waste dilemma. On Figure 4, the conditional quantile models validating the EKC pattern show a gradient of smooth quadratic curves rising with the percentile of MPW. Starting from the 40^{th} level, the marginal effect of income per capita on the quantity of MPW becomes heavier, along with an increasing coefficient of the quadratic term (Table 3). A joint Wald test of equality of slopes by Anova method rejected the null of equality (F-value = 2.905, p = 0.001392). In other words, the greater the amount of MPW per capita in the country, the higher the income threshold required before achieving a decline of environmental pollution.

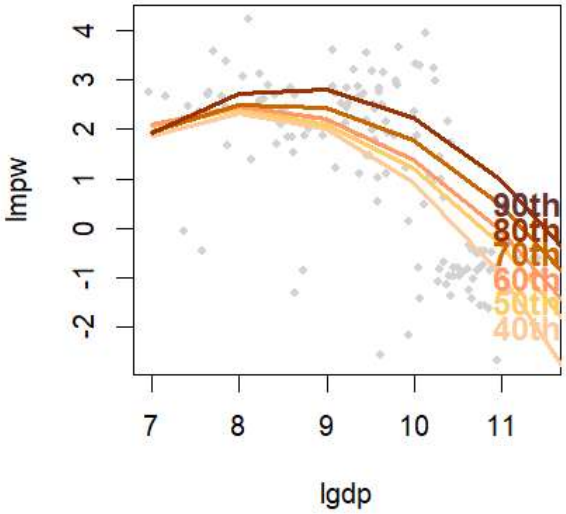

Figure 4. EKC models per quantile

Note: the grey dots represent the 145 observations (countries). The colored lines denote the quantile conditional regressions starting from the 40th percentile (only the significant EKC models are retained).

5. Discussion

The present study extends the pioneer research of Barnes (2019) assuming an EKC pattern for the relationship between income per capita and MPW rates at the worldwide level. Although using a different international dataset for MPW values stemming from the global riverine emissions leaking out to the ocean (Meijer et al. 2021), which seems more accurate, our own results confirm those of previous studies validating the existence of an inverted U-shape relationship between income levels and plastic waste leaking out to the ocean.

Following Koenker (2017), we estimate the conditional quantiles and density function of MPW for the two extreme quantiles of the income distribution, i.e. the 10th (poorest countries) and 90th (richest countries). The average GDP per capita is $2,805 in the former decile and $49,613 in the latter decile. Fig. 5 shows the low amount of MPW for the richest countries (less than 1 kg per capita), while the poorest countries cumulate a mismanaged waste quantity per capita between than 20 and 50 kg (natural logarithm of 3 and 4). We can first conclude that economic growth is a major factor of controlling waste mismanagement, and that poverty is a key driver of marine plastic pollution, especially near urban areas (Meijer et al. 2021). Wealthier countries can afford the logistics, treatment infrastructures, higher investment in education, campaigns for waste sorting behaviour, recycling, and therefore reduce their mismanaged waste (Cordier et al. 2019). This causal relationship has nothing to do with the plastic footprint of nations, because all studies acknowledged that the highest levels of plastic consumption and waste are found in high-income countries (Amadéi et al. 2022, Cabernard et al. 2022, Guillotreau et al. 2023). It simply underscores the link between poverty and plastic waste mismanagement.

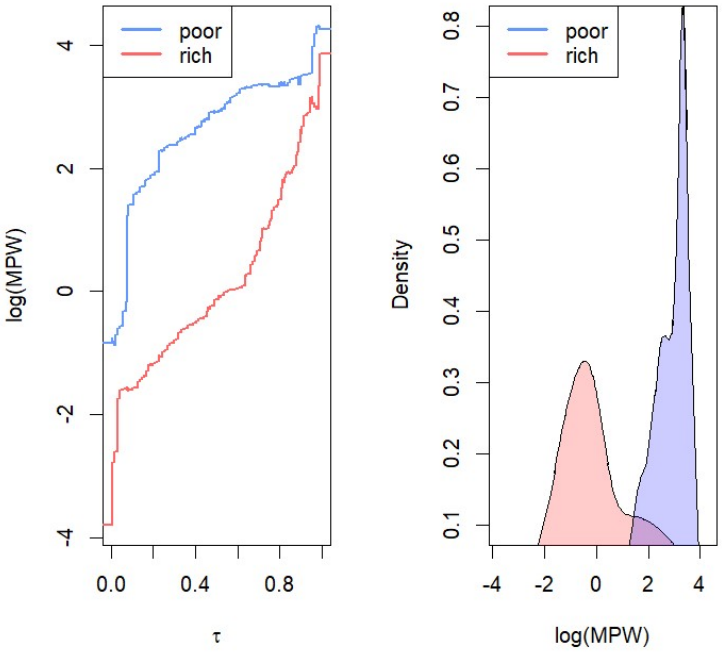

Fig. 5 Estimated conditional quantiles and density functions for MPW.

Note: Estimates are presented for the poorest and richest countries (10th and 90th percentiles of GDP)

Although scarcer for plastic waste than for greenhouse gas emissions and other pollutants, EKC studies on plastics seem to converge and bring evidence of an income point beyond which the MPW per capita decreases (Barnes 2019, Cordier et al. 2021, Kocakaya 2023). The income value above which the MPW per capita declines can be obtained from model (3) by cancelling the derivative of the estimated equation to the logarithm of GDP per capita. This value fetches $4,188 in our case study (Table 4), i.e. less than half of the average value found in a meta-analysis of studies validating the EKC hypothesis for a great number of pollutants (Saqib & Benhmad, 2021). If we compare the value found in our OLS results (third model in Table 2) with the closest studies looking at EKC for MPW, the income threshold is nearly twice the one unveiled in Barnes (2015) based on 2010 data, but far below the value estimated in Cordier et al. (2021) or Kocekaya et al. (2023) (Table 4). One must note that the latter study refers to 29 European (i.e. mostly high income) countries between 2004 and 2019. Moreover, Cordier et al. (2019) removed from the analysis a number of countries for which the inadequately managed plastic waste rate was unclear.

Table 4: Comparison of income levels as shifting points of EKC studies for plastic waste

	GDP per capita (USD)*	*Number of observations*
Barnes (2019)	2,141	151
Cordier (2021)	18,606	149
Kocakaya (2023)	16,507	444
OLS	4,188	145

QR	*40th*	3,232
	50th	3,030
	60th	3,245
	70th	4,430
	80th	5,631
	90th	6,010

However, our study differs from others by the empirical strategy based on quantile regression (Koenker 2017). The non-normality of residuals in the OLS regression and bi-modal distribution of MPW (Fig. 1) demonstrated that the analysis of EKC had to be treated differently. This quantile regression approach allows to estimate the coefficients conditionally to the quantile of the dependent variable. We showed that the EKC was not validated for the first four deciles but appeared more significantly in the last deciles (Table 3 and Fig. 3). Moreover, the slope of the income variables differ from quantile to quantile. From the 60th percentile and upwards, the coefficient of the GDP per capita and the quadratic term increase in absolute values, bending more sharply the EKC model. A consequence is an increasing level of income which is required prior to the decline of MPW pollution (Table 4 and Fig. 4). Starting with the 40th percentile (less than 2 kg of MPW per capita, including some countries as different as Hong Kong, the USA, Colombia, Madagascar, Costa Rica…), a shifting point at $3,232 is estimated, while the maximum MPW rate is found at $4,430 for the 70th percentile (between 9 and 12 kg of MPW p.c., with countries like Nigeria, India, Ukraine, South Africa, Argentina…), and this value increases up to $6,010 for the 90th quantile (between 16 and 23 kg of MPW p.c., including countries like Brazil, Nicaragua, Algeria, Thailand, Turkey, Ghana…). In summary, the marginal cost of shifting to a virtuous EKC descending trajectory for MPW rises as the level of inadequate waste gets higher for a country.

Throughout quantiles, the role of governance, specifically the control of corruption, becomes prominent. Economies with augmented growth, when coupled with effective anti-corruption measures, may experience a synergy that promotes efficient plastic waste management (Cordier et al. 2021). This potentially stems from improved regulatory enforcement, responsible corporate behaviors, and the allocation of resources towards sustainable environmental practices (Biswas et al. 2012, Abrate et al. 2015). In Table 3, interestingly, the absolute value of the estimated parameter of the quantile regression increases between the 40th and 90th quantile, meaning that the impact of governance is stronger to reduce MPW for the last quantiles relatively to those of less polluting countries. For countries facing higher levels of mismanaged waste leaking out to the environment, a greater control of corruption will be very effective to reduce the pollution level and the whole distribution of MPW could be affected positively by such efforts. Superior coefficients for the highest quantiles also mean that the distribution of MPW rates is stretched whenever the control tends towards more stringency. For instance, for the 90th quantile of corruption control, the coefficient of variation for MPW rates is greater than 200%, involving OECD countries (Japan, USA, western Europe), small island developing states (Barbados, Seychelles, Bahamas) and middle-East states (Qatar, United Arab Emirates).

Finally, the present study suffers from certain limits. The scarcity and inaccuracy of international MPW data imposes the use of cross-sectional data for a certain year. This methodological choice carries with it certain inherent limitations, primarily centered around the absence of a temporal dimension, which is crucial when probing into the dynamics between environmental degradation and income. Therefore, the findings derived from this study must be interpreted with caution, recognizing that the insights might not fully capture the complex interplay between environmental factors and economic progress over time. Although improving, the methodology to quantify and trace the origin of marine debris pollution is not an easy task. Global databases of plastic use and waste, either mismanaged or not, are still under construction for a better analysis of drivers and causes in the future.

6. Conclusion

Our investigation into the relationship between economic growth, governance, and mismanaged plastic waste has unveiled a multifaceted interplay that goes beyond traditional understandings. At its core, the findings reinforce the idea that the dynamics between economic prosperity and environmental degradation is not linear, with different quantiles exhibiting unique behaviors in relation to the Environmental Kuznets Curve (EKC).

Our findings indicate that the relationship between economic growth and MPW is not monolithic. Instead, it varies across different levels of waste mismanagement. In the lower quantiles, up to the 40th percentile, economic growth does not manifest the traditional EKC trajectory, highlighting the potential for growth to exacerbate waste problems or remain relatively neutral in its impact. However, as we move towards higher quantiles of MPW, the classical EKC relationship begins to take shape. Beyond a certain economic threshold, greater prosperity appears to lead to improvements in waste management, in which growth begins to show its potential benefits for the environment, hence reducing oceanic pollution.

The role of governance and, more specifically, control of corruption, also stands out as an important driver in influencing this relationship, particularly for the highest quantiles of the distribution. It is evident that as MPW levels rise, robust governance mechanisms can considerably mitigate the negative impacts, highlighting the dual imperative of promoting economic growth while ensuring governance quality, emphasizing the indispensable role of transparent, accountable institutions in environmental conservation.

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