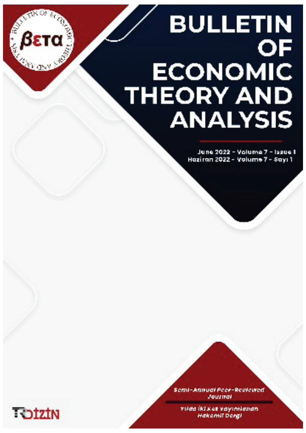

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Unraveling the Nexus of Industrialization, Human Development, Democracy, Trade Openness, and Renewable Energy in EU Environmental Degradation

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ABSTRACT

This study aims to unveil the effects of industrialization, human development, compliance with the rule of law, and renewable energy on CO2 emissions and the ecological footprint of consumption in EU countries over the 1990-2022 period. The empirical findings, based on the MMQR analysis, reveal that the magnitudes of coefficients between factors affecting CO2 emissions and the ecological footprint vary. Industrialization and human development are the main contributors to environmental degradation, while renewable energy use consistently mitigates environmental degradation across all quantiles. Trade openness also mitigates CO2 emissions in all quantiles with a diminishing trend, but the same correlation is only observed in the lowest quantile for the model with ecological footprint. Compliance with the rule of law has a statistically insignificant effect on the ecological footprint; however, in the lowest quantile of CO2 (0.1), the rule of law exacerbates CO2 emissions, whereas in the highest quantile, it has a mitigating effect. While industrialization and human development contribute to both dimensions of environmental degradation, the different impacts of trade openness and the compliance with the rule of law underscore the need for specific strategies in designing policies to mitigate CO2 and ecological footprints from a policy perspective.

Keywords
Ecological Footprint, CO2 Emissions, Industrialization, Human Development, Democracy, Panel Data Analysis

JEL Classification
Q01, Q56, O14, O11

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Sanayileşme, İnsani Gelişme, Demokrasi, Ticari Açıklık ve Yenilenebilir Enerji Bağlamında Avrupa Birliği'nde Çevresel Bozulma

ÖZ

Bu çalışma, 1990-2022 döneminde AB ülkelerinde sanayileşme, insani gelişme, hukukun üstünlüğüne uyum ve yenilenebilir enerjinin kişi başına CO2 emisyonu ve ekolojik ayak izine etkilerini ortaya çıkarmayı amaçlamaktadır. Momentler Kantil Regresyon analizine dayanan ampirik bulgulara göre sanayileşme ve insani gelişme çevresel bozulmayı arttıran başlıca unsurlar olurken, yenilenebilir enerji kullanımı tüm kantil düzeylerinde çevresel bozulmayı tutarlı bir şekilde azaltmaktadır. Ticari açıklık da azalan bir eğilimle tüm kantillerde karbon emisyonlarını azaltmaktadır, ancak aynı korelasyon ekolojik ayak izi modeli için sadece en düşük kantilde (0.1) gözlenmektedir. Hukukun üstünlüğüne uyum ile ekolojik ayak izi arasındaki korelasyon istatistiksel olarak anlamsızdır; ancak, karbon salınımının en düşük kantilinde (0.1), hukukun üstünlüğü karbon emisyonlarını arttırırken, en yüksek kantilde çevresel bozulmayı hafifletmektedir. Sanayileşme ve insani kalkınma çevresel bozulmanın her iki boyutuna da katkıda bulunurken, ticari açıklık ve hukukun üstünlüğüne uyumun farklı etkiler göstermesi, politika üretme perspektifinden bakıldığında, CO2 ve ekolojik ayak izi azaltım politikaları tasarlanırken, spesifik stratejilerin gerekliliğinin altını çizmektedir.

Anahtar Kelimeler
Ekolojik Ayak İzi,
Karbon Emisyonu,
Sanayileşme,
İnsani Gelişme,
Demokrasi,
Panel Veri Analizi

JEL Kodu
Q01, Q56, O14, O11

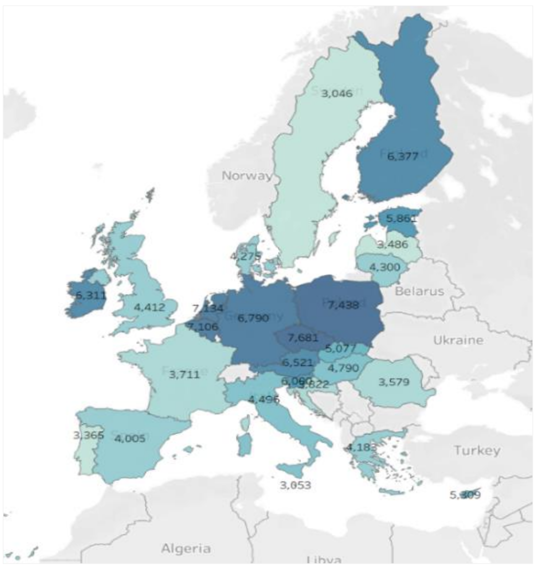
1. Introduction

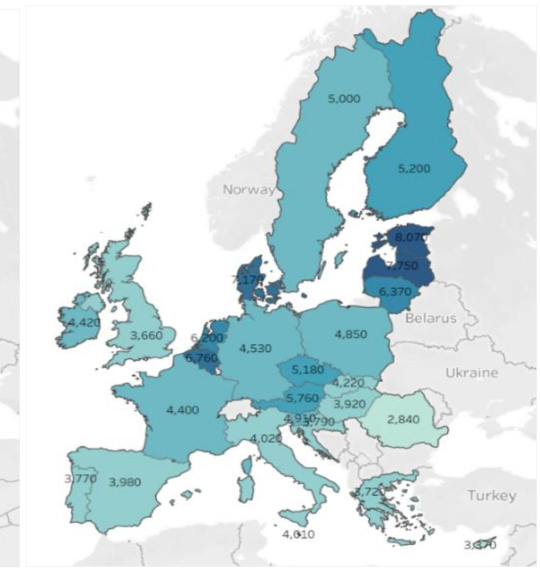
The issue of environmental degradation has been one of the most important topics in academic and public spheres. After the 2012 declaration of a climate emergency, there has been a notable increase in awareness of the global consequences of climate change, with a particularly pronounced rise in Europe. The National Energy and Climate Plans (NECPs) and Long-Term Strategy (LTS) plans of European Union (EU) play a critical role in determining the contributions towards EU's energy and climate targets. These plans, which are overseen by the European Commission (EC), currently represent the primary instruments guiding the decarbonization efforts of the EU. Beyond facilitating the acceleration of greenhouse gas emissions reduction, they encourage the implementation of a circular economy, improve sustainability in resource utilization, and minimize environmental and societal impacts of climate change (Perissi and Jones, 2022). In this context, efforts for understanding the factors affecting environmental degradation in the EU has a great importance for the policy-making process aiming at a zero-carbon economy.

Even there is multitude of theoretical and empirical studies to examine the factors affecting environmental degradation, there are still numerous topics that require further investigation. The earlier research in that area mostly focused on the CO2 emissions as the proxy of environmental degradation. Following the introduction of more comprehensive indicators, such as the Ecological Footprint (EF), research has increasingly focused on the correlation between EF and key economic and policy variables. It is reasonable to conclude that the Environmental Kuznets Curve (EKC) hypothesis, initially proposed by Shafik and Bandyopadhyay (1992) and subsequently developed by Grossman and Krueger (1995), has been a significant contributor to the field of environmental degradation research. These studies demonstrated a non-linear (U-shaped) relationship between income and environmental degradation, thereby establishing the EKC as a well-known concept. Subsequent research has extended this work, examining various dimensions of the topic.

The majority of existing studies focus on fundamental variables such as income and income inequality, as explored by Al-Mulali et al. (2015), Ali (2022), Baloch et al. (2018), Dinda (2005), Kahuthu (2006), Munasinghe (1999), Ongan et al. (2021), Osuntuyi and Lean (2023), Özokcu and Özdemir (2005), and Stern et al. (1996). Other key areas of focus include population growth, examined by Satterthwaite (2009), Shaw (1989), Harte (2007), Rahman et al. (2017), Ray and Ray (2011), and Udemba et al. (2024); foreign direct investment (Acharyya, 2009; Kearsley and Riddel, 2010; Kisswani and Zaitouni, 2023; Viglioni et al., 2024; Ju et al., 2023); energy consumption and transition (Apergis and Payne, 2011; Bélaïd and Youssef, 2017; Kilinc-Ata and Alshami, 2023; Magazzino et al., 2024; Saboori and Sulaiman, 2013; Shahbaz et al., 2014; Wang et al., 2022); and globalization (Ahmed, 2024; Gao et al., 2024; Jorgenson and Kick, 2003; Rahman, 2020; Shahzadi et al., 2019; Warsame et al., 2023). Additionally, there is a growing interest in examining the different roles of industrialization (Destek et al., 2024; Kahouli et al., 2022; Parveen, 2019; Opoku and Boachie, 2020), human development (Jain and Nagpal, 2019; Maccari, 2014; Qing et al., 2024), and democracy (Li and Reuveny, 2006; Lindvall and Karlsson, 2024; Uddin et al., 2024). However, these studies have relatively limited attention to specific country groups, while focusing on individual countries. In addition to the existing literature and the notable efforts being made towards decarbonization strategies in Europe, two important questions arise. The first is whether industrialization, human development, and compliance with the rule of law, trade openness and renewable energy consumption matter for environmental degradation in the EU. The second is that, in the existing literature, there is a significant concern regarding the determinants of CO2 levels and EF. The majority of existing literature perceives these two metrics to be reflective of the same phenomenon. However, Maps 1 and 2 illustrate the variations in CO2 metrics and EF across the

European Union. It can be observed that there are notable differences between the variations in CO2 and EF. This leads to another crucial question: Is there any difference in the role of industrialization, human development, and compliance with the rule of law, trade openness, and renewable energy on CO2 and EF?





Map 1. CO2 Metrics Ton Per Capita

Map 1. Ecological Footprint (Per Capita Gha)

Source. Drawn by authors using World Bank, World Development Indicators, and Global Footprint Network Data.

In this framework, this study will investigate the determinants of CO2 and EF, as proxies of environmental degradation, in EU countries for 1990-2022 period. This study specifically focuses on the effects of industrialization, human development, compliance with the rule of law, renewable energy consumption and trade openness and on environmental degradation. Despite the abundance of literature on the determinants of environmental degradation, this is one of the first studies to comparatively analyze CO2 and EF by controlling for industrialization, human development, and compliance with the rule of law for EU countries.

In the remainder of the study, the following section presents a brief literature review, followed by a description of the data and methodology. Section 4 shows the empirical analysis and section 5 concludes.

2. Literature Review

This section aims to provide a general overview of the relationship between industrialization, human development, democracy, trade openness, and renewable energy use and environmental degradation. Despite historical trends indicating that industrialization has been a primary causal factor in environmental degradation, with roots tracing back to the Industrial Revolution, the empirical literature examining this relationship remains scarce. While a robust positive correlation between these two variables is to be expected, given the relatively limited number of studies that have examined this relationship, there is still much to be discovered. For example, Ahmed et al. (2022) examined the Asia-Pacific region, Al-Mulali and Ozturk (2015) investigated 14 countries in the Middle East and North Africa, Destek (2024) analyzed Turkey, and Phuc Nguyen et al. (2020) assessed 33 emerging economies. All of these studies identified a positive correlation between industrialization and environmental degradation. In contrast, research such as that conducted by Opoku and Boachie (2020) and Kim (2020) has demonstrated that there is no statistically meaningful correlation between the two variables or, conversely, a negative correlation in 36 African countries and South Korea, respectively. The extant literature on this topic remains limited and inconclusive, indicating a need for further research.

The existing literature on the sustainable development dimensions of mitigation policies is still in its infancy, and recent studies have yielded disparate results. For example, Bieth (2021) found that Human Development index (HDI) has no significant impact on CO_2 emissions in ASEAN countries and Japan. By contrast, studies conducted by Balsamo et al. (2023) which encompassed 193 UN member states, and those conducted by Kassouri and Altıntaş (2020), which were focused on 13 countries in the Middle East and North Africa, identified a positive relationship between the variables in question. This suggests a potential trade-off between HDI and environmental degradation. Conversely, Sezgin et al. (2021) indicated a negative correlation between HDI and environmental degradation in the Group of Seven (G7) and BRICS countries, whereas Pata et al. (2021) observed a parallel negative association in the ten countries with the largest ecological footprints. Additionally, Qing et al. (2024) demonstrated that in the context of the Group of twenty (G20), decreased human development leads to reduced ecological footprints. Some studies have concentrated on specific aspects of HDI, including life expectancy at birth. One of the most recent studies by Mughal et al. (2024) posits that higher life expectancy and greater government stability contribute to improved environmental outcomes in the long run for the NEXT Eleven economies.

The role of political institutions in the context of environmental degradation is another important research agenda. The measurement or definition of institutions, democracy and governance can be varied, and this result in a need for further investigation in this area. The institutional capacity of nations can be measured by a variety of factors, including electoral and non-electoral democracy, as well as a range of variables such as liberties, anti-corruption, and compliance with the rule of law. These significant discrepancies in measurement, coupled with methodological differences and country groupings, have yielded a complex picture of the role of governance capacity. Many studies have demonstrated the mitigating effect of institutional capacity, including those by Li and Reuveny (2006) for a larger sample of countries, Adams and Acheampong (2019) for 46 sub-Saharan African countries, and Buitenzorgy and PJ Mol (2011) for 177 countries. Alternatively, the mitigation effects can be observed at a specific level of environmental degradation, as demonstrated by Karimi Alavijeh et al. (2023) in their study of 14 EU countries. Some studies have indicated that an increase in political capacity or democracy may accelerate environmental degradation, as evidenced by the findings of Midlarsky (1998), which examined data from 74 countries. Conversely, other studies have demonstrated that there is no significant relationship between these two variables, as observed by Roberts and Parks (2007) and Sabir et al. (2020) for the sample of South Asian countries.

The investigation of the role of trade openness and renewable energy consumption represents two pivotal domains within the field of environmental research. Two distinct theoretical pathways can be identified through which the relationship between trade openness and environmental degradation can be understood. One perspective posits that environmental degradation, as identified by Jun et al. (2020) for China and Van Tran (2020) for 66 developing countries, may be a consequence of a country's trade structure. Conversely, Porter and Van der Linde (1995) put forth the proposition that trade openness can enhance environmental quality. The argument is made that the implementation of environmentally stringent policies can encourage producers to develop cleaner technologies, thereby mitigating environmental harm. This hypothesis is corroborated by the findings of Khan et al. (2022), who conducted an examination of 176 countries. Another significant area of focus within the literature is the role of renewable energy consumption in environmental degradation. A consensus has emerged in this area, with recent research consistently demonstrating a negative association between renewable energy consumption and indicators of environmental degradation. This is evidenced by studies such as Adebayo and Kirikkaleli (2021) for Japan, Magazzino et al. (2022) for Scandinavian countries, and Sharif et al. (2020) for the ten most polluted countries.

Despite the extensive body of research on environmental degradation, limited attention has been given to the roles of industrialization, human development, and adherence to the rule of law. Additionally, the relationship between renewable energy consumption and trade openness remains underexplored, particularly in the context of the EU. This study seeks to fill these gaps by employing the Method of Moments Quantile Regression (MMQR) approach, which allows for a detailed examination of how different concepts of environmental degradation—proxied by CO2 emissions and ecological footprint—are influenced by various factors. By moving beyond traditional linear estimation techniques, this study provides a more nuanced analysis of these relationships across the distribution of environmental outcomes, thereby offering new insights into the determinants of environmental degradation.

3. Data and Methodology

3.1. Data

In this study, the main aim is to understand the effects of industrialization, human development, trade openness, renewable energy consumption, and democracy on the ecological footprint and CO2 emissions in the EU for the 1990-2022 period. The countries covered in the study include Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom. Bulgaria and Luxembourg are excluded from the sample because of data limitations. Although the UK left the EU in 2020, it is included in the sample as it was an EU member for most of the period under consideration. Environmental degradation, the dependent variable of the study, is measured by two indicators: the traditional proxy of CO2 emissions (measured in metric tons per capita) and the more comprehensive indicator of environmental degradation, the ecological footprint of consumption (measured in Gha per person), as published by the Global Footprint Network.

In this study, a set of explanatory variables is employed. The first independent variable of the study is industrialization, which has been recognized as a main cause of anthropogenic climate change. To control the effects of industrialization and reveal its distinct impacts on EF and CO2, manufacturing value added as a share of GDP is included expecting a positive relationship. The second important variable is the Human Development Index (HDI), included to capture the effects of human-centered development on environmental degradation. The HDI, a well-known and highly credible data published by UNDP, covers three important dimensions of human well-being: standard of living, health, and education. Instead of adding each variable separately into the model, the HDI is included as an aggregate measure of human well-being. According to neoclassical theory, the environment can be accepted as a luxury good. In the theorical and empirical studies is found that when basic needs of the population are met, both individuals and governments may be more inclined to invest in environmental protection, and environmental awareness tends to increase in post-materialistic societies (Abu-Chadi and Kayser, 2017; Erdölek Kozal, 2023; Inglehart, 1977 [1995]; Kayser and Grafstrom, 2016). Therefore, a negative relationship is expected between environmental degradation and HDI. The role of trade openness is also important in explaining differences in environmental degradation across different country groups. Although EU countries share a common trade policy, their incorporation into the world economy through trade varies greatly. Trade openness can either lead to the transfer of green technologies and create a mitigation effect on environmental degradation or make countries havens for polluting products and technologies (Destek and Sinha, 2020). Renewable energy consumption is considered the most important mitigation factor for environmental degradation in the empirical literature. Reflecting the EU's efforts towards a green energy transition in recent years, renewable energy consumption as a share of total energy consumption is also utilized in this study. Incorporating a democracy variable, as a proxy for institutional capacity in a broader manner, into the analysis is essential to capture the impact of varying degrees of institutional capacity on environmental degradation within the European Union, given the significant heterogeneity in the level of democracy across member states. The rule of law index is chosen as the proxy of democracy, ranging from 0 to 1 provided by V-dem Project. The rule of law variable allows for a nuanced examination of how democracy influences environmental outcomes within the EU context measuring how well countries uphold the rule of law, considering factors like legal constraints on the executive, judicial impartiality, protection of rights, and anti-corruption efforts. Analyzing this variable provides insights into a country's legal system effectiveness, judicial autonomy, and overall adherence to legal principles expecting a negative correlation between democracy and environmental degradation. The variables are expressed in their natural logarithmic form. For each variable, a detailed description is provided in Table 1, which also lists the data sources utilized.

Table 1

Variables, Descriptions and Sources

	Variable name	Description	Source
Dependent Variables	EF	Ecological footprint of consumption per person (Gha)	Global Footprint Network
	$CO2$	CO2 emissions (metric tons per capita)	World Bank
Independent Variables	MAN	Manufacturing, value added (% of GDP)	World Bank
	HDI	Human Development Index (ranging from 0-1)	UNDP
	$OPEN$	Trade (% of GDP)	World Bank
	REN	Renewable energy consumption (% of total final energy consumption)	World Bank
	DEM	Rule of law index, v2x_rule, (ranging from 0-1, worst to good)	V-DEM Project

Source. Compiled by Author.

Descriptive statistics (see Table 2) reveal notable deviations from normality, evident in the skewness and kurtosis probability values. Additionally, the Jarque-Bera tests' probability values reject the assumption of normal distribution, further confirming non-normality. It's crucial to consider this heterogeneity as it could introduce bias in parameter estimates, especially in estimation methods using least squares and when handling non-normal data.

Table 2

Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max	Pr(Skewness)	Pr(Kurtosis)	Pr(Jarqua-Bera)
EF	728	1.890	0.373	1.054	2.691	0.045	0.000	0.000
$CO2$	728	1.655	0.263	0.896	2.282	0.010	0.402	0.027
MAN	728	2.687	0.340	1.358	3.637	0.000	0.000	0.000
$OPEN$	728	4.574	0.447	3.614	5.809	0.001	0.001	0.000
REN	728	2.429	1.102	-2.408	4.087	0.000	0.000	0.000
HDI	728	-0.152	0.065	-0.368	-0.049	0.000	0.049	0.000
DEM	728	-0.102	0.152	-1.041	-0.001	0.000	0.000	0.000

Source. Authors calculations.

Table 3

Pairwise Correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) CO2	1.000						
(2) EF		1.000					
(3) MAN	**0.226**	0.038	1.000				
(4) OPEN	0.007	**0.172**	0.061	1.000			
(5) REN	**-0.370**	**-0.228**	0.029	**-0.197**	1.000		
(6) HDI	**0.217**	**0.420**	**-0.182**	**0.154**	**0.173**	1.000	
(7) DEM	**0.341**	**0.586**	**-0.142**	0.030	-0.039	**0.551**	1.000

Source. Authors calculations. Statistically significant correlations are displayed in bold in 0.05 significance level.

Table 3 displays the pairwise correlations among independent variables, with their associated probabilities in parentheses, all of which show acceptable levels of correlation.

3.2. Methodology

In this section, the steps of the empirical strategy followed in the study are presented briefly. Before explaining these steps, it should be noted that all tests and estimation techniques should be chosen with regard to compliance with the N<T panel structure, as the study includes 26 cross-sectional units (N) and covers a time dimension of 28 years (T). Stata 15 is employed for the purpose of econometric analysis.

In the first step, cross-sectional dependency should be investigated. The Breusch-Pagan LM Test (1980) is capable of presenting consistent results in the N<T panel structure (Lee and Robinson, 2016; Pesaran, 2021). Investigating cross-sectional dependency is necessary to determine which type of unit root test should be applied. In the case of cross-sectional dependency, second-generation unit root tests are employed to ascertain the stationarity of variables (Barbieri, 2009). Following this, the Pesaran and Yamagata (2008) method, based on Swamy's (1970) approach, is used to control for the homogeneity of slope coefficients. This step is crucial because there is often a concern that the relationship between the dependent and independent variables may not be uniform across all cross-sectional units. The homogeneity of slope coefficients assumes that these relationships are the same for all units, which may not generally hold. Overlooking the heterogeneity of slope coefficients may lead to biased and inconsistent estimates (Bersvendsen and Ditzen, 2020; Pesaran and Yamagata, 2008). After these tests, the second-generation unit root test, Cross-Sectional Augmented Dickey-Fuller (CADF), will be used. The null hypothesis of this test

is that the variables within panel data are not stationary, while the alternative hypothesis is that at least one individual is not stationary.

For the preliminary empirical analysis, first Fixed Effect (FE) and Random Effect (RE) regression techniques are applied. The OLS estimator is the best linear unbiased estimator (BLUE) only under a set of strict assumptions, such as no autocorrelation, normality, and no cross-sectional dependency. This makes Feasible Generalized Least Squares (FGLS) more efficient and robust for parameter estimation, particularly in panel data analysis where the number of time periods exceeds the number of cross-sections (N<T). Given that the time series dimension is larger than the cross-sectional unit dimension, FGLS, which can handle heterogeneity issues, is also considered to obtain more robust preliminary results compared to FE and RE (Bai et al., 2021). A simple GLS model, adapted to our variables, can be written as follows:

$$CO2_{i,t} = \beta_0 + \beta_1 MAN + \beta_2\, OPEN + \beta_3 REN + \beta_4 HDI + \beta_5 DEM + \alpha_i + \varepsilon_{it} \quad (1)$$

$$EF_{i,t} = \beta_0 + \beta_1 MAN + \beta_2\, OPEN + \beta_3 REN + \beta_4 HDI + \beta_5 DEM + \alpha_i + \varepsilon_{it} \quad (2)$$

In the Equation 1 and 2, $CO2_{i,t}$ and $EF_{i,t}$ represent the two dependent variables in the analysis and the former one represent the CO2 emissions per capita (in natural logarithm) and the latter represent EF of consumption (in natural logarithm) for the individual countries (i), in the 1990-2022 period (t=1990-2022). Here α_i is the unobserved individual-specific random effect. Due to the failure to meet the prerequisites of OLS-type linear regression, this study employs MMQR proposed by the important study of Machado and Silva (2019) with fixed effects, which allows us to assess the impact of several regressors over different quantiles, capturing non-linearity. Despite the robustness of quantile regression to outliers, it does not consider potential unobserved heterogeneity among individuals within a panel. However, MMQR, as discussed by Ike et al. (2020) and Wolde-Rufael and Mulat-Weldemeskel (2022), allows for the identification of conditional heterogeneous covariance effects of CO2 and ecological footprint determinants. Unlike merely shifting means, this method enables individual effects to influence the entire distribution, as outlined in Equation 3 following Machado and Silva (2019: 148), which is reformulated into a panel fixed effect and then transformed into an MMQR specification in Equations 3 and 4.

$$CO2_{i,t} = \beta_0 + \beta_1 MAN + \beta_2\, OPEN + \beta_3 REN + \beta_4 HDI + \beta_5 DEM + \alpha_i + \varepsilon_{it} \quad (3)$$

$$EF_{i,t} = \beta_0 + \beta_1 MAN + \beta_2\ OPEN + \ \beta_3 REN + \beta_4 HDI + \ \beta_5 DEM + \alpha_i + \ \mathcal{E}_{it} \tag{4}$$

$$CO2_{it} = \alpha_i + X'_{it}\beta + (\delta_i + W'_{it}\gamma)U_{it} \tag{5}$$

$$EF_{it} = \alpha_i + X'_{it}\beta + (\delta_i + W'_{it}\gamma)U_{it} \tag{6}$$

X'_{it} (see Equation 5 and 6) covers the matrix of all the explanatory variables, which reflects;

$$X'_{it} = [MAN_{\mathrm{it}}, OPEN_{\mathrm{it}}\ \mathrm{REN}_{\mathrm{it}}\ HDI_{it}\ DEM_{it}]' \tag{7}$$

β is the vector including the coefficients. While α_i is the individual fixed effect, δ_i is the quantile-specific fixed effect. A vector reflecting the differentiable transformations of the explanatory variables satisfying the probability $P\{\delta_i + W'_{it}\gamma > 0\} = 1$ is W_{it}. U_{it} is unobserved random variable independent of X_{it}, normalized to satisfy $E(U_{it}) = 0,\ E(|U_{it}|) = 1$ condition and the parameters α_i, β', δ_i, γ' and $\mathrm{q}(\tau)'$ were estimated based on the first moment conditions. In this framework, quantile representation of the model can be written:

$$Q_Y(\tau|X_{it}) = \big(\alpha_i + \delta_i q(\tau)\big) + X'_{it}\beta + W'_{it}\gamma q(\tau) \tag{8}$$

The first term in the parentheses presents the quantile-τ fixed effect for individual i, or the distributional effect at τ in the above equation (Machado and Silva, 2019).

4. Empirical Results

The results of the Breusch-Pagan LM cross-sectional dependence test indicate that there is cross-sectional dependence by rejecting the null hypothesis of no cross-sectional dependence.

Table 4

Breusch-Pagan LM Cross Sectional Dependency Test

	Chi2	Probability
$CO2$	chi2(325) = 5097.344	0.0000
EF	chi2(325) = 2893.919	0.0000

Source. Authors calculation

Utilizing the slope homogeneity test of Pesaran and Yamagata (2008), Table 3 demonstrates significant country-specific heterogeneity, indicating that regression parameters differ across individual cross-sectional units at a 1% significance level.

Table 5

Testing for Slope Homogeneity, Pesaran and Yamagata (2008)

		Delta	p-value
$CO2$	$\tilde{\Delta}$	22.413	0.0000
	$\tilde{\Delta}_{adj}$	25.881	0.0000
EF	$\tilde{\Delta}$	20.616	0.0000
	$\tilde{\Delta}_{adj}$	23.805	0.0000

Source. Authors calculation.

Both cross-sectional dependency and slope homogeneity tests revealed that second generation unit root test should be applied. CADF developed by Pesaran (2007) is used to analyze the stationary levels of each variable and unit root test results are presented in Table 6. $CO2$, MAN, $OPEN$, HDI and DEM is stationary at the first level and integrated in I(1), EF and REN are stationary at level, which indicates integrated in I(0).

Table 6

Pesaran (2007) CIPS Panel Unit Root Test Results

	Level (with intercept)	Level (intercept and trend)	First difference (with intercept)	First difference (with intercept and trend)
$CO2$	-1.878	-2.091	-4.612***	-4.907***
EF	-2.176 **	-3.227***	-	-
MAN	-2.040	-2.280***	-4.283***	-4.486***
$OPEN$	-1.688	-1.672	-3.918***	-4.142***
REN	-2.259	-2.851	-	-
HDI	-1.755	-2.609*	-4.855***	-4.614***
DEM	-1.465	-2.647*	-4.268***	-4.501***

Note. *** p<.01, ** p<.05, * p<.1. Critical values are -2.07, -2.15, -2.3 for 10%, 5% and 1% significance level, respectively for the test with intercept. Critical values are -2.58, -2.66, -2.81 for 10%, 5% and 1% significance level, respectively, for the test with intercept and trend.

Table 7 presents the baseline analysis using FE, RE and FGLS estimation techniques. The estimations with CO2 as the dependent variable show that industrialization, trade openness, and human development have positive impact on environmental degradation. Conversely, renewable energy usage has a mitigating effect on CO2 emissions. Compliance with the rule of law also mitigates CO2 emissions, but only in the FGLS estimation. In contrast, the estimations with the EF as the dependent variable reveal slightly different results. Industrialization is statistically insignificant in the EF estimation, while trade openness is statistically significant in the FGLS estimation. Additionally, democracy has a mitigating effect on the EF in the linear regression analysis.

Table 7

Baseline Analysis: FE, RE and FGLS Estimations

	Estimations with CO2			Estimations with EF		
	FGLS	FE	RE	FGLS	FE	RE
MAN	.082**	.129***	.111**	.028	-.112	-.112
	(.036)	(.049)	(.049)	(.041)	(.09)	(.091)
$OPEN$	.082***	.083**	.078**	.179***	.077	.074
	(.029)	(.037)	(.037)	(.029)	(.069)	(.069)
REN	-.007***	-.026***	-.006***	-.115***	-.138***	-.135***
	(.002)	(.004)	(.002)	(.014)	(.008)	(.007)
HDI	2.246***	1.459***	2.249***	1.736***	-2.928***	-2.858***
	(.35)	(.453)	(.422)	(.432)	(.838)	(.844)
DEM	-.097*	-.09	-.059	-.117*	-.232*	-.234*
	(.055)	(.066)	(.065)	(.063)	(.122)	(.123)
$\_cons$	-.012**	.038***	-.016**	1.899***	2.008***	2***
	(.006)	(.011)	(.007)	(.037)	(.021)	(.046)
Number of Obs.	702	702	702	702	702	702

Notes. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1

While fixed effects and random effects regression models provide important tools for analyzing panel data and controlling for unobserved heterogeneity, these methods rely on several key assumptions such as linear relationship between the independent variables and dependent variable, homoscedastic and normally distributed error terms. When these assumptions are violated, such as in the presence of outliers or heteroscedasticity, the estimates from fixed and random effects models may be biased or inefficient. To address these issues, FGLS techniques can be used to relax the homoscedasticity assumption. However, FGLS still maintains the linearity assumption. An alternative approach that is more robust to non-linear relationships, outliers, and heteroscedasticity is the MMQR. Beyond technical advantages, MMQR offers a detailed view of the correlation between independent and dependent variables by estimating effects at different points (here it can be said as “quantiles”) of the dependent variable's distribution. This approach allows researchers to understand how effects vary across the entire distribution, not just at the mean. Moreover, MMQR provides flexibility in modeling relationships between variables, as it does not impose a single functional form across the entire distribution (Koengkan et al., 2021; Machado and Silva, 2019). Our primary empirical strategy is based on MMQR and aims to ascertain whether the effects of determinants on CO_2 emissions and the EF may vary across their conditional distributions, reflecting the varying levels of environmental degradation among EU countries.

Table 8

MMQR Regression Results (Dependent variable: CO2)

	Quantiles				
	0.1	**0.25**	**0.5**	**0.75**	**0.9**
MAN	.0631	.132*	.1854***	.2386***	.2741***
	(.1006)	(.068)	(.0539)	(.0581)	(.0701)
$OPEN$	-.2807**	-.26***	-.2439***	-.2279***	-.2172**
	(.1231)	(.0832)	(.0659)	(.0712)	(.086)
REN	-.1905***	-.1858***	-.1821***	-.1785***	-.1761***
	(.0331)	(.0224)	(.0177)	(.0192)	(.0231)
HDI	.2703	.5156	.7062**	.8956***	1.0222***
	(.5347)	(.3615)	(.2864)	(.3091)	(.3731)
DEM	.2192*	.093	-.0052	-.1027	-.1678*
	(.1311)	(.0885)	(.0702)	(.0755)	(.0911)
$\_cons$	3.3587***	3.1928***	3.064***	2.9359***	2.8503***
	(.5476)	(.3703)	(.2933)	(.3168)	(.3823)
Number of Obs.	728	728	728	728	728

Notes. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1
Source. Authors calculations.

Table 9

MMQR Regression Results (Dependent Variable: EF)

	Quantiles				
	0.1	**0.25**	**0.5**	**0.75**	**0.9**
MAN	.108*	.124**	.1423***	.1604***	.1734***
	(.0598)	(.0486)	(.0426)	(.0465)	(.0544)
$OPEN$	-.1313*	-.1023*	-.0691	-.0362	-.0127
	(.0676)	(.0549)	(.0482)	(.0526)	(.0615)
REN	-.1773***	-.1765***	-.1757***	-.1748***	-.1741***
	(.0162)	(.0132)	(.0115)	(.0126)	(.0148)
HDI	1.676***	1.6665***	1.6556***	1.6448***	1.637***
	(.3094)	(.2512)	(.2203)	(.2407)	(.2815)
DEM	.0689	.0278	-.0191	-.0658	-.0991
	(.07)	(.0569)	(.0499)	(.0544)	(.0637)
$\_cons$	2.5212***	2.4018***	2.2655***	2.1301***	2.0332***
	(.3206)	(.2604)	(.2285)	(.2493)	(.2916)
Number of Obs.	728	728	728	728	728

Notes. Standard errors are in parentheses. *** p<.01, ** p<.05, * p<.1
Source. Authors calculation.

Table 8 and Table 9 present the results of the MMQR regression analysis with CO2 emissions and the EF as dependent variables, respectively. The relationship between industrialization and CO2 emissions is positive across all quantiles, with the magnitude of the coefficients increasing at higher quantiles. The results for EF, which can be considered a more comprehensive indicator of environmental degradation, are presented in Table 9. The results demonstrate that industrialization consistently contributes to EF across all quantiles, in a manner similar to that observed in the CO2 case. This indicates that industrialization contributes more significantly to CO2 levels, in line with the existing literature, including the studies by Ahmed et al. (2022), Al-Mulali and Ozturk (2015), and Destek (2024). It is widely acknowledged that industrialization has constituted a significant historical contributor to climate change. This recognition is not fortuitous. Notwithstanding the efforts of EU member states to decouple industrialization and environmental outcomes, this study demonstrates that both CO2 and EF exhibit an increase with the expansion of the manufacturing sector within the EU's GDP. These findings indicate that the pursuit of climate-neutral reindustrialization strategies and the decoupling efforts of environmental degradation from industrial production have not yet resulted in a net reduction in environmental degradation. It is evident that the establishment of a manufacturing sector capable of generating higher value-added products has been identified as a pivotal objective for EU countries seeking to enhance their global competitiveness and integration into the global system. Nevertheless, in the absence of effective measures to mitigate the environmental impact of industrial activities within the EU, there is a considerable risk of exceeding planetary boundaries. Such an outcome would inevitably compromise the ecological sustainability of the planet in a complex and multifaceted manner. Consequently, it is of paramount importance that these countries implement measures to reduce their environmental impact, with the objective of ensuring the long-term ecological sustainability. HDI has a positive impact on CO2 emissions and the EF aligns with the study of Balsamo et al. (2023). In the estimation models with EF, the HDI exhibits the largest coefficient among the independent variables, indicating a positive effect on EF. In this regard, the aggregate measurement of the three dimensions of well-being captured in the HDI—income, education, and health—does not appear to mitigate environmental degradation. It can be proposed that an increase in material well-being may lead to an enhancement in environmental awareness and a rise in government expenditure on environmentally friendly systems. This is particularly relevant in the context of the post-materialistic stage of development, where there is a correlation between environmental concerns and the pursuit of a higher level of well-being. However, contrary to expectations, there is no tendency to decrease the environmental impact of humans in the EU case. In conclusion, it can be stated that an increase in material well-being does not necessarily guarantee environmental sustainability.

Empirical findings revealed that compliance with the rule of law has no statistically impact on EF. However, it shows a polarized effect on CO_2 emissions: it has a positive effect at the lowest quantile of CO_2 but a mitigating effect at higher levels of CO_2 emissions. In this regard, it is challenging to demonstrate a robust correlation between democracy and environmental degradation indicators in accordance with the findings of Roberts and Parks (2007) and Sabir et al. (2020). On the other hand, trade openness has a mitigating effect on CO_2 in all quantiles. The study's sample includes EU countries, which are more incorporated into the world economy compared to other regions. This suggests that trade can be seen as a means of importing green technologies rather than becoming pollution havens for other countries. In contrast to the analysis with CO_2 emissions, trade globalization has a decreasing effect on EF only in the lowest quantiles, indicating a statistically insignificant relationship in most of the quantiles. These two different results may indicate important points: This highlights the potential for trade to facilitate the transfer of knowledge, thereby facilitating the diffusion of green technologies. This, in turn, can result in a mitigation effect on CO_2. However, this effect is not confirmed by EF, which suggests that trade openness may not necessarily create a mitigation effect. The reason behind this difference is that CO_2 emissions result from industrial activities, energy production, and transportation. Trade openness can lead to cleaner technologies and more efficient production methods, potentially reducing CO_2emissions. EF, on the other hand, is a broader measure that accounts for the total environmental impact of consumed goods and services, including land use, water use, and the overall sustainability of resources. It encompasses a wider array of environmental pressures, not just carbon emissions. The benefits of trade openness in reducing CO_2 emissions might not be as effective in mitigating other environmental impacts, such as deforestation, water use, and biodiversity loss (Mahmoodi and Dahmardeh, 2022; Olanrewaju et al., 2022). That is why further investigation is required to reveal the reasons behind the differences between the observed decrease in CO_2 levels and the lack of a statistically significant effect on EF. This can be achieved by utilizing more detailed trade variables. Furthermore, renewable energy has a mitigating effect across all quantiles, in accordance with existing literature. This suggests that an increase in renewable energy investments in the EU could be a key instrument in combating environmental degradation.

5. Conclusion

This study examines the impact of industrialization, human development, compliance with the rule of law, and renewable energy use on environmental degradation, using per capita CO2 emissions and the EF of consumption as proxies in EU countries over the period from 1990 to 2022. The empirical findings, derived from the MMQR analysis, demonstrate varying magnitudes of coefficients between the factors affecting CO2 emissions and EF. Industrialization and human development emerge as the primary contributors to environmental degradation in both models. Increasing share of renewable energy consumption in total energy consumption consistently mitigates both CO2 emissions and EF across all quantiles, underscoring the importance of countries' energy transition in promoting environmental sustainability. Trade openness has negatively correlated with CO2 across all quantiles, albeit with a diminishing trend, and the same effect is observed only in the lowest quantile for the model estimated with EF. Statistical analysis indicates that compliance with the rule of law has not a significant effect on EF, whereas rule of law has a statistically meaningful impact on CO2 emissions only in the two extreme quantiles, namely the lowest and highest. In the former case, it has an adverse effect, while in the latter, it has a mitigating effect on CO2 emissions.

These findings suggest several policy implications. The consistent mitigation effects of renewable energy use on both CO2 emissions and the EF highlight the need for policies that promote renewable energy investments in EU for a green transition. EU countries should increase incentives for renewable energy projects to foster the transition to cleaner energy sources. Given the significant contribution of industrialization to environmental degradation, it is essential to adopt sustainable industrial practices. In the reindustrialization phase of the EU, it is crucial that implementing stricter environmental regulations and standards to ensure that industrial growth does not come at the expense of environmental sustainability. The finding that trade openness mitigates CO2 emissions can be accepted as the signal as benefitting from the import of green technologies in EU. The positive impact of the Human Development Index onenvironmental degradation indicates that higher material well-being does not automatically lead to better environmental outcomes. Policies should focus on integrating environmental education and awareness into the broader development agenda. Promoting sustainable lifestyles and consumption patterns can help align human development with environmental sustainability. While the rule of law shows mixed effects on CO_2 emissions, it is crucial to strengthen institutional frameworks to enhance environmental governance. Policies aimed at improving regulatory enforcement, reducing corruption, and ensuring accountability can contribute to more effective environmental protection measures. The differentiated impact of various factors across quantiles suggests the need for targeted policy interventions. For instance, addressing environmental degradation in the most affected regions or sectors may require specific strategies tailored to regional conditions and challenges. Policymakers should consider country characteristics regarding environmental degradation address the diverse impacts of economic activities on the environment.

It should be noted that the study has certain limitations. In this study, industrialization and human development are proxied by aggregate measurements. The structure of industry and the production patterns of EU countries are not fully accounted for in this study. Furthermore, human development is represented by the human development index, which is an aggregate measurement of income, education, and health. However, focusing on human development requires further and more detailed analysis to cover both materialistic and non-materialistic aspects of human development. Further research could be conducted to examine the variations in the manufacturing sector within the EU and identify a more comprehensive proxy to reflect the variations in the HDI.

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