

The Impact of Financial Development on Carbon Emissions: Evidence from Quantile Panel Regression for EU Countries and Türkiye

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Abstract: *This study examines the dynamic impact of financial development on carbon emissions in European Union nations and Türkiye from 2010 to 2023. The research utilises panel quantile regression methods to tackle the intrinsic variability in the link between financial development and environmental consequences, offering a more thorough insight than conventional mean-based econometric techniques. The analytical approach facilitates the examination of unique repercussions at various levels of carbon emissions, revealing insights into the distinct effects of financial mechanisms in different environmental circumstances. The findings offer empirical evidence for an N-shaped Environmental Kuznets Curve, indicating a non-linear correlation between economic development and environmental quality. This research significantly enhances the literature by including financial development into the discourse on environmental policy. It underscores the necessity of tailoring financial policies to achieve sustainable development goals. The findings offer critical policy implications, emphasising the role of targeted financial interventions in mitigating environmental harm and aligning economic activities with sustainability objectives. The findings have crucial policy implications, stressing the need for targeted financial measures in minimising environmental impact. To boost empirical credibility, robustness checks utilising Driscoll-Kraay standard errors were undertaken, verifying the consistency of the results across estimation methodologies.*

Keywords: Climate change; Financial development; Carbon emission; Environmental Kuznets curve; Panel quantile distribution

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1. Introduction

Climate change and global warming represent two of the most critical environmental challenges of the contemporary era, primarily driven by the excessive accumulation of carbon dioxide (CO₂) and other greenhouse gases (GHGs) in the atmosphere, originating from anthropogenic activities such as fossil fuel combustion, industrial processes, deforestation, and unsustainable land-use practices (IPCC, 2007). In addition to CO₂, potent greenhouse gases such as methane (CH₄) and nitrous oxide (N₂O), emitted from agricultural activities, waste management, and certain industrial sectors, significantly exacerbate the greenhouse effect by trapping heat within the Earth's atmosphere and leading to a progressive rise in global temperatures (Feng et al., 2024). This phenomenon disrupts climatic equilibrium, intensifying the frequency, duration, and severity of extreme weather events, including heatwaves, droughts, hurricanes, and heavy precipitation (IPCC, 2021).

The far-reaching consequences of climate change extend beyond meteorological anomalies, severely impacting both natural ecosystems and human societies. Alterations in temperature and precipitation patterns lead to habitat destruction, shifts in species distribution, and biodiversity loss, thereby weakening ecological resilience and ecosystem services that are essential for sustaining life on Earth (Rockström et al., 2009). Moreover, rising sea levels, primarily caused by the melting of polar ice caps and glaciers, as well as the thermal expansion of seawater, endanger coastal communities by increasing the frequency and magnitude of coastal flooding, land erosion, and saltwater intrusion into freshwater resources (Nicholls & Cazenave, 2010). Such disruptions threaten food security, as erratic weather conditions and shifting climatic zones negatively affect agricultural productivity, crop yields, and water availability, leading to economic instability, forced migration, and social conflicts in vulnerable regions (Porter et al., 2014).

Furthermore, climate change has profound implications for public health, as rising temperatures contribute to the proliferation of vector-borne diseases, such as malaria and dengue fever, while exacerbating respiratory illnesses and cardiovascular diseases due to increased air pollution and heat stress (Haines & Patz, 2004). In parallel, disruptions in oceanic currents, linked to global warming, intensify marine ecosystem degradation, coral bleaching, and declining fish stocks, further endangering the livelihoods of populations dependent on fisheries and marine resources (Hoegh-Guldberg

et al., 2007). In light of these complex and interconnected challenges, urgent and comprehensive mitigation and adaptation strategies are required at local, national, and global scales to curb emissions, promote sustainable development, and enhance climate resilience (Bulut and Tunç, 2025).

Addressing these global issues require effective international collaboration and the smart deployment of financial tools to alleviate the harmful consequences of climate change and promote a sustainable future. In this light, the 2024 COP29 summit held in Azerbaijan stands out as a milestone event, playing a vital role in furthering efforts to cut carbon emissions and battle climate change (Sattar vd., 2024). COP29, planned in 2024 in Azerbaijan, is a key time in the global effort to battle climate change and cut carbon emissions. Central to its relevance is the introduction of a New Common Quantified Goal of Climate Finance (NCQG), intending to amplify the yearly financial commitment from rich to poor nations above the previous \$100 billion benchmark (O’Callaghan, 2024). This endeavour emphasises the need to link global financial institutions with the 1.5°C objective of the Paris Agreement to avert catastrophic climate risks. By supporting fair investment in renewable energy, adaptation measures, and loss and damage funds, COP29 closes significant gaps in climate finance (Adun vd., 2024). Additionally, it highlights the economic benefits of green transitions, understanding that such expenditures are not only charitable gestures but also strategic imperatives to preserve global stability and avert growing climatic calamities.

In recent decades, carbon dioxide (CO₂) emissions have grown dramatically, as illustrated by BP’s statistics (BP, 2024). Emissions grew from 11.2 million tons in 1965 to a startling 37.4 million tons in 2019, showing the fast rise of industrialisation and fossil fuel usage globally. This essential surge brings greater attention to the environmental concerns connected with rising CO₂ emissions. In response, the global community has increasingly realised the necessity of tackling these concerns, pushing various governments to enact policies targeted at reducing climate change. Efforts vary from the adoption of renewable energy technology and energy efficiency improvements to the formation of international accords and national laws targeting reductions in emissions (Dong et al., 2020; Ma et al., 2020; Ren et al., 2021; Wei et al., 2021; Dong et al., 2024).

Following the financial crisis in the world, the association between financial growth and CO₂ emissions has drawn substantial attention from

policymakers and academia (Acheampong et al., 2020). Certain scholars claim that financial development is useful in lowering CO₂ emissions (Khan et al., 2021; Shahbaz et al., 2018; Zhao et al., 2021). Proponents of this perspective believe that financial development increases local governments' abilities to optimise resource allocation and grasp regional variability in pollution and economic development (Mu, 2018). Furthermore, it fosters technological innovation and the adoption of advanced low-carbon technology by firms. These innovations may boost energy efficiency and encourage low-carbon economic development, thereby assisting in the lowering of CO₂ emissions (Zhang, 2011).

Conversely, other researchers question these reasons (Acheampong, 2019; Yin et al., 2019), stating that financial growth may lead to higher CO₂ emissions. They claim that financial development generally draws foreign direct investment (FDI), which, although encouraging economic expansion, tends to worsen CO₂ emissions. Additionally, an efficient and flourishing financial intermediation system provides customer access to loans for purchasing high-value commodities, thereby creating bigger CO₂ emissions (Zhang, 2011). Consequently, the relationship between financial growth and CO₂ emissions stands uncertain. Further investigation into this dynamic is crucial, not merely to counteract global warming, but also to drive growth within the financial sector.

The European Union's ambitious climate ambitions are hindered by the disparate degrees of financial development among its member states and candidate nations such as Turkey, complicating the attainment of consistent carbon reduction results. This paper investigates the percentile-specific impacts of financial development on emissions in the EU and Turkey, providing a novel viewpoint on the unequal influence of financial systems on sustainability outcomes throughout the emissions spectrum.

This study is especially critical in light of the COP29 pledges and the evolving function of financial institutions in influencing environmental outcomes. This work innovatively uses panel quantile regression to reveal the concealed distributional impacts of financial development on CO₂ emissions, in contrast to prior studies that predominantly utilised mean-based estimators to examine the Environmental Kuznets Curve (EKC). The result offers a more thorough comprehension of both marginal and severe environmental impacts, rendering this study both methodologically and contextually relevant.

2. Literature Review

To produce empirical evidence on the link between financial development and carbon emissions, researchers have done many studies using diverse models and datasets. However, this study has failed to establish a consensus. Broadly, empirical research gives three broad perspectives: some studies establish that financial development decreases carbon emissions, others conclude that it increases carbon emissions, while a third group finds no substantial relationship between financial development and carbon emissions.

Empirical research has extensively explored the association between financial development and carbon emissions. Al-Mulali et al. (2015) evaluated the influence of financial development on CO₂ emissions in 129 countries grouped by income levels. The study employed panel data from 1980 to 2011, including crucial factors like urbanisation, GDP growth, trade openness, oil consumption, and financial development variables into the model. The Pedroni cointegration test confirmed the existence of cointegration among the variables. Moreover, evidence from dynamic OLS and Granger causality studies revealed that financial expansion may benefit environmental quality in both the short and long term by cutting CO₂ emissions. Sy et al. (2016) assessed the connection between financial development, carbon emissions, and trade openness in 40 European countries using panel data and OLS models for the period 1985–2014. Their analysis discovered data confirming the neutrality theory, demonstrating no major link between financial development and CO₂ in the EU.

Doğan and Şeker (2016) explored the long-term dynamic link between financial development and carbon emissions by evaluating panel data from 23 prominent renewable energy-producing nations during the period 1985–2011. Their empirical results demonstrated the presence of cointegration among the variables, suggesting a robust long-term link. This study shows that financial development may play a key role in lowering carbon emissions. The authors stated that the progress of financial markets may promote investments in environmentally friendly technology and offer money for sustainable energy projects, hence aiding environmental sustainability.

Acheampong et al. (2020) investigated the impacts of the growth of financial markets on the extent of carbon emissions across 83 countries from 1980 to 2015 using an instrumental variable GMM approach. Their results

suggest that financial expansion, as judged by criteria such as market depth and efficiency, decreases carbon emission intensity in industrialised and emerging countries but enhances it in frontier economies. No appreciable effect was seen in independent economies. Furthermore, they identified the nonlinear and moderating impact of financial development, which vary according to a country's stage of financial development, giving significant insights for policy design.

Tao et al. (2023) evaluated the influence of financial development on carbon emission intensity in OECD countries using an enhanced STIRPAT methodology. Their results demonstrate that financial depth, size, and efficiency contribute to lowering carbon emission intensity, although nonlinear impacts are impacted by information and communication technology (ICT). The analysis also found diversity in these impacts according to institutional quality, economic development, and resource endowments. Sunday Adebayo et al. (2023) investigated the connection between financial development and CO₂ emissions in MINT nations (Mexico, Indonesia, Nigeria, and Turkey) from 1969 to 2019. Using full-sample and rolling-window bootstrap causality tests, they identified time-varying causal links between financial development and CO₂ emissions. The findings indicated that financial development had both emission-increasing and emission-reducing impacts across various eras and countries. The research proposes reallocating financial resources from emission-intensive organisations to emission-reducing institutions or sectors to promote sustainable development.

The existing literature highlights a lack of consensus regarding the impact of financial development on carbon emissions. While some researchers argue that financial development increases carbon emissions, others have presented evidence of its mitigating effects, and a few studies report no significant relationship. This divergence underscores a critical gap in the literature, emphasising the need for further empirical investigation. Exploring this relationship remains essential, particularly in the context of evolving economic and environmental dynamics, to provide a more comprehensive understanding and to inform the design of effective policies for sustainable development.

3. Methodological Framework

Compared to mean-based estimators such as fixed effects or pooled OLS, quantile panel regression captures the diverse effects of regressors at different places in the CO₂ distribution. For example, the financial development variable may have minimal impacts in the lower quantiles but strong positive or negative effects in the upper quantiles, which is critical for policy formulation for high-emission nations. This property makes QPR particularly significant for climate-finance interactions when distributional disparities are predicted.

Binder and Coad (2011) claimed that the panel quantile technique gives more trustworthy findings compared to other coefficient estimation methodologies, since it does not ignore average effects. Quantile analysis provides a major advantage over standard regression techniques as it enables conditional quantile estimation and predicts the behaviour of every single point in the conditional distribution (Alharthi et al., 2021). This approach allows for the analysis of variables impacting income differences over different quantiles.

As a suitable approach for estimating conditional quantile functions, quantile regression doesn't require significant assumptions about error terms, unlike the OLS method, and therefore gives more robust estimate results (Koenker and Bassett, 1978). Moreover, regression coefficients usually fluctuate across quantiles, showing that the influences of explanatory factors on the outcome variable vary between quantiles (Yan et al., 2019). Finally, quantile regression is an analytical technique that does not depend on distributional assumptions (Koenker, 2004; Sherwood and Wang, 2016).

The quantile regression method is a generalisation of median regression analysis to other quantiles. Given x_i , the conditional quantile of y_i is expressed as follows:

$$Q_{y_i}(\tau | x_i) = x_i^T \beta_\tau \quad (1)$$

The fixed-effects panel quantile regression model used in this analysis can be expressed as follows:

$$Q_{y_i}(\tau_k | \alpha_i, x_{it}) = \alpha_i + x_{it}' \beta(\tau_k) \quad (2)$$

A key hurdle in fixed-effects panel quantile regression is the incidental parameters issue, which occurs from including a large number of fixed effects into the model (Lancaster, 2000; Neyman and Scott, 1948). This problem becomes especially obvious when the number of cross-sectional units increases toward infinity, but the number of observations per unit stays constant, resulting in inconsistent and biased parameter estimators. The core of this difficulty arises in the overparameterization generated by estimating several unit-specific effects, which inflates the variance of the estimators and weakens their reliability in limited samples.

The sparse amount of research on fixed-effects panel quantile regression may primarily be attributable to the inherent limitations involved with adapting traditional approaches to properly adjust for unobserved heterogeneity within the quantile regression framework. Traditional fixed-effects estimating strategies often depend on the assumption that expectations work linearly, simplifying the removal of unobserved effects by data transformation or differencing. However, this linearity trait does not extend to conditional quantiles, making it impossible to directly employ these approaches in quantile regression models (Canay, 2011).

Moreover, quantile regression concentrates on modelling the conditional distribution of the dependent variable, capturing heterogeneous effects across various points of the result distribution. This complexity exacerbates the incidental parameters issue, since the effect of unobserved heterogeneity may change across quantiles, further confounding the estimation process. Addressing this difficulty demands creative methodological techniques that can account for nonlinearity and heterogeneity while minimising the bias produced by high-dimensional fixed effects. Thus, advancing robust and efficient methods of estimation for fixed-effects panel quantile regression remains a critical area for future research, with significant consequences for empirical research that aims to uncover distributional effects in the presence of unobserved heterogeneity (Lancaster, 2000).

Koenker (2004) proposes an effective technique for handling these challenges by treating the unobserved fixed effects as parameters to be examined simultaneously with the covariate effects over various quantiles. A basic component of this approach is the insertion of a penalty term during the estimating process, aimed at decreasing the computing cost associated with forecasting a large number of parameters. The estimation of these parameters is achieved as follows:

$$\min_{(\alpha, \beta)} \sum_{k=1}^K \sum_{t=1}^T \sum_{i=1}^N w_k \rho_{\tau_k}(y_{it} - \alpha_{it} - x_{it}^T \beta(\tau_k)) + \lambda \sum_i^N |\alpha_i| \quad (3)$$

In the given formula, i indexes the countries (N), T indexes the number of observations per country, and K indexes the quantiles. α represents the matrix of explanatory variables, while $\rho_{\tau k}$ denotes the quantile loss function. Additionally, w_k represents the relative weight assigned to the k -th quantile, which controls its contribution to the estimation of the fixed effect for the k -th quantile.

The measurements and sources for the variables presented in Equation (1) are detailed in Table 1.

Table 1: Definition of variables

Variable	Measurement Units	Sources
CO ₂	CO ₂ emissions (metric tons per capita)	Our World in Data
DCP	Domestic credit to the private sector (% of GDP)	World Bank
M3/M1	The ratio of aggregate money supply to narrow money (M3/M1)	Eurostat and Trading economics
FDI	Financial Development Index	IMF
GDP	GDP per capita (Constant 2015 US\$)	World Bank

Source: Research findings

In the study, the conditional quantile function for a given quantile τ is defined as follows:

$$Q_{y_{it}}(\tau | \alpha_i, \xi_i, x_{it}) = \alpha_i + \xi_i + \beta_{1\tau} DCP_{it} + \beta_{2\tau} M3 / M1_{it} + \beta_{3\tau} FDI_{it} + \beta_{4\tau} GDP_{it} + \beta_{\tau} \quad (4)$$

The study used a panel of 26 European Union countries and Türkiye. Türkiye was included in the analysis as its carbon emissions are, on average, equivalent to those of European Union countries. The time series data spans the period from 2010 to 2023 and is sourced from datasets provided by the World Bank, Our World in Data, Eurostat, Trading Economics, and the International Monetary Fund (IMF).

Moreover, the study considers the EKC hypothesis, whereby the shape of the EKC may vary depending on the signs of the different β parameters associated with GDP. This approach aligns with the framework proposed by Lorente and Álvarez-Herranz (2016).

The relationship between environmental degradation and income can take various forms depending on the coefficients of a regression model. If all coefficients (β_4 , β_5 , β_6) are zero, no relationship or a flat pattern exists. A monotonic increasing relationship arises if $\beta_4 > 0$ while β_5 and β_6 are zero, indicating that environmental degradation rises with economic growth. Conversely, a monotonic decreasing relationship emerges when $\beta_4 < 0$ and β_5 , β_6 remain zero. The classical EKC with an inverted U-shape appears when $\beta_4 > 0$ and $\beta_5 < 0$, with $\beta_6 = 0$. A U-shaped relationship occurs if $\beta_4 < 0$ and $\beta_5 > 0$, holding $\beta_6 = 0$. A cubic or N-shaped relationship arises when $\beta_4 > 0$, $\beta_5 < 0$, and $\beta_6 > 0$, whereas an inverted N-shaped pattern appears if $\beta_4 < 0$, $\beta_5 > 0$, and $\beta_6 < 0$.

4. Empirical Results and Analysis

In this research, the influence of financial development on carbon emissions was investigated for the European Union nations and Türkiye using yearly data. By applying a panel quantile regression approach, the diverse impacts of financial development across various levels of carbon emissions were revealed. The data reveal that the association between financial development and carbon emissions varies across quantile levels, indicating that this impact is not homogenous. The findings seek to add to the academic literature and make major policy suggestions to improve environmental sustainability via financial policies. The specifics of the results are reported in Table 2 and the ensuing sections.

Table 2 gives descriptive data for the variables considered in the research. The mean CO₂ emissions per capita is 4.038, with a standard deviation of 1.366, ranging from 0.311 to 6.701. The Jarque-Bera test findings defy the normality assumption for all variables, showing the necessity for non-parametric approaches. Other crucial metrics, such as domestic credit to the private sector (DCP), indicate an average of 4.262%, while the M3/M1 ratio and financial development index (FDI) average 1.671 and 0.570, respectively. These statistics emphasise the variability of the dataset and support the use of panel quantile regression for analysis.

Table 2: Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max	Jarque-Bera
CO ₂	4.038	1.366	0.311	6.701	3.100
DCP	4.262	0.453	3.137	5.263	9.560
M3/M1	1.671	0.351	0.183	2.180	148.970
FDI	0.570	0.191	0.197	0.901	106.320
GDPP	10.123	0.651	8.769	11.612	14.580

Source: Research findings

The correlations between all variables are presented in Table 3. The correlation coefficients between the explanatory variables are all below the commonly used threshold of 0.7, indicating no significant multicollinearity concerns. However, the correlation between the GDPP and the FDI is relatively higher, at 0.69, which could potentially pose multicollinearity issues if both variables are included in the same model. Nonetheless, excluding one of these variables could result in omitted variable bias. For the remaining variables, the correlations are sufficiently low, and thus they do not raise any concerns for the analysis.

Table 3: Pearson correlations

Variable	CO ₂	DCP	M3/M1	FDI	GDPP
CO ₂	1.000	-	-	-	-
DCP	0.124	1.000	-	-	-
M3/M1	0.121	-0.072	1.000	-	-
FDI	0.401	0.675	0.209	1.000	-
GDPP	0.010	0.537	0.091	0.563	1.000

Source: Research findings

Additionally, cross-sectional dependency, as suggested by Pesaran (2007), is explored. The statistical results from the Pesaran test are shown in Table 4, illustrating that cross-sectional dependency should be accounted for during unit root testing. Table 5 presents the results of the panel unit root testing. These findings suggest that the null hypothesis of unit root existence cannot be rejected for all variables at their levels. However, for the initial differences of all variables, the null hypothesis is virtually totally rejected

at the 1% significance level. Therefore, an empirical analysis employing the first-difference series is necessary.

Table 4: Result of CD test

Variable	CD Test
CO ₂	36.127***
DCP	12.139***
M3/M1	34.582***
FDI	11.668***
GDPP	55.927***

Source: Research findings

Table 5 summarises the panel unit root test results. According to the LLC estimates, all variables except M3/M1 exhibit stationarity at their levels. Similarly, the IPS test results indicate that CO₂ and FDI are level stationary, while the other variables are stationary at their first differences. The Fisher-ADF test confirms that all variables are stationary at their first differences, whereas CO₂, M3/M1, and FDI are also stationary at their levels. These findings indicate that all variables are difference-stationary. Consequently, conducting the quantile panel analysis using difference-stationary variables is appropriate.

Table 5: Panel unit root summary

Variable	LLC	IPS	Fisher-ADF
CO ₂	-14.767***	-5.169***	4.300***
DCP	-8.530***	1.896	-4.090
M3/M1	-9.285	6.310	2.499*
FDI	-13.189***	-5.447***	-6.382*
GDPP	-8.880***	0.591	-2.942
First Difference			
CO ₂	-15.205***	-5.278***	4.357***
DCP	-9.693***	0.827*	-5.928***
M3/M1	-7.776*	7.655*	5.029**
FDI	-13.318***	-5.287***	-4.312***
GDPP	-10.663***	-5.632**	-4.145**

Source: Research findings

Table 6 displays the findings of the pooled OLS and fixed-effects models evaluating the determinants of CO₂ emissions. The Pooled OLS model suggests a considerable negative influence of domestic lending to the private sector on CO₂ emissions, while the FE model finds no significant link. The ratio of aggregate money supply to narrow money has a considerable beneficial influence on the FE model but not in the pooled OLS model. Financial development consistently demonstrates a favourable effect on CO₂ emissions across both models. The cubic terms of GDP demonstrate a non-linear relationship, validating the EKC theory, with an inverted N-shaped pattern observed in the FE model. The adjusted R² values demonstrate that the pooled OLS explains 51% of the variation, whereas the FE model explains 40%, underlining the importance of accounting for unobserved heterogeneity. These findings underscore the requirement for fixed effects to capture country-specific elements in the research.

Table 6: Results from pooled OLS and FEM estimations

Variable	(1) Pooled OLS	(2) Fixed Effects
DCP	-0.885*** (0.197)	-0.058 (0.042)
M3/M1	0.048 (0.172)	0.253*** (0.061)
FDI	2.351*** (0.253)	0.361*** (0.086)
GDP	-107.281** (49.829)	40.366*** (13.468)
GDP ²	11.242** (4.875)	-3.924*** (1.329)
GDP ³	-0.391** (0.158)	0.126** (0.044)
Intercept	349.443** (169.098)	-133.671*** (45.249)
R ²	0.518	0.419
Adjusted R ²	0.507	0.402
Hausman	-	24.20***
Observations	378	378

Source: Research findings

The findings produced from the quantile regression analysis demonstrate a consistent and substantial influence of financial factors on carbon emissions across all quantiles. Specifically, domestic financing to the private sector indicates a negative and statistically significant link with carbon emissions across all quantile levels. This conclusion shows that an increase in domestic lending to the private sector has the ability to ameliorate environmental challenges by lowering carbon emissions. It stresses the significance of financial resources in supporting technological innovation, boosting energy efficiency, and enabling the shift toward sustainable economic activity. Conversely, the ratio of wide money supply to narrow money demonstrates a positive and statistically significant influence on carbon emissions, constant across all quantiles. This study shows that the extension of the money supply may encourage economic activity and energy consumption, hence leading to increasing carbon emissions. Such results underscore the need for a better study of the environmental repercussions of monetary policy. Furthermore, the financial development index is shown to have a positive and considerable influence on carbon emissions, underlining the possible harmful environmental implications connected with financial development. This shows that although financial development might drive economic expansion, it may also hasten environmental damage. Therefore, linking financial growth plans with environmental sustainability objectives is crucial to offset these negative consequences.

The findings of this study provide empirical evidence supporting the existence of an N-shaped EKC across all quantiles, indicating a nonlinear, cubic relationship between economic development and environmental degradation in the European Union nations and Türkiye. This discovery challenges the traditional inverted U-shaped EKC hypothesis, which posits that environmental degradation initially intensifies with economic growth, subsequently declines as economies shift toward cleaner technologies and more stringent environmental regulations, and ultimately stabilises. Instead, the observed N-shaped pattern suggests a more complex and dynamic relationship, wherein environmental deterioration initially escalates alongside economic expansion, subsequently declines due to technological advancements and institutional improvements, only to re-emerge at higher levels of economic prosperity as production and consumption activities intensify.

Table 7: Results from quantile regression

Variable	10th	25th	50th	75th	90th
DCP	-0.211*** (0.070)	-0.028* (0.009)	-0.059*** (0.027)	-0.094* (0.053)	-0.116*** (0.031)
M3/M1	0.459** (0.214)	0.358** (0.146)	0.252** (0.115)	0.128 (0.162)	0.352* (0.166)
FDI	0.530*** (0.164)	0.447*** (0.112)	0.360*** (0.088)	0.258** (0.124)	0.296** (0.106)
GDP	39.451*** (9.904)	39.900** (20.285)	40.371** (15.843)	40.922* (22.630)	41.261** (10.199)
GDP ²	-3.799* (1.353)	-3.860* (2.002)	-3.924** (1.564)	-3.999* (2.235)	-4.046* (1.982)
GDP ³	0.121 (0.097)	0.124** (0.065)	0.126** (0.051)	0.129** (0.073)	0.131*** (0.038)
Intercept	9.859** (2.857)	5.672*** (1.922)	19.757*** (2.189)	-24.047*** (1.417)	25.177*** (2.854)

Source: Research findings; Note: ***, **, and * indicate significant p values at the 1, 5, and 10% level, respectively.

This nuanced relationship underscores the limitations of conventional EKC analyses, which predominantly employ quadratic functional forms to model the link between economic growth and environmental quality. By overlooking the possibility of a cubic specification, much of the prior literature may have oversimplified the trajectory of carbon emissions, erroneously endorsing the inverted U-shaped framework while disregarding the resurgence of environmental degradation at advanced stages of economic development. This methodological oversight carries significant implications for environmental policy formulation, as policies informed by the traditional EKC perspective may inadequately address the long-term sustainability challenges posed by economic expansion.

The unequal effect of financial development across quintiles indicates that a single policy strategy is not sufficient. Countries in the upper quintiles (e.g., Poland, Germany, Turkey) may require exact green banking regulations and promotions for financing decarbonization, while countries in the lower quintiles (e.g., Estonia, Malta) could profit more from basic institutional strengthening and access to clean technology finance. This underlines the necessity for progressive climate financing policies.

The reappearance of environmental deterioration at later stages of economic growth suggests that beyond a certain income threshold, factors such as increased industrial output, higher energy demand, and resource-intensive consumption patterns offset the environmental gains achieved through earlier regulatory and technological improvements. This phenomenon highlights the necessity of dynamic and adaptive environmental policies that extend beyond early-stage interventions and incorporate strategies for mitigating the resurgence of carbon emissions at higher income levels.

Furthermore, the N-shaped EKC pattern emphasises the importance of integrating environmental concerns into long-term economic planning to ensure that sustainability gains are not reversed as economies advance. Policymakers must therefore adopt a more holistic approach, incorporating regulatory frameworks, technological innovation, and economic incentives to break the cyclical trend of environmental degradation associated with economic progress. By acknowledging and addressing the complexities inherent in the economic-environmental nexus, this study contributes to a more comprehensive understanding of sustainable development pathways for the European Union and Türkiye.

The results of this study correspond with and confirm the conclusions of past research that has revealed an N-shaped EKC, such as Allard et al. (2018), Shehzad et al. (2022), and Fakher et al. (2023). These studies similarly stress the need to account for higher-order linkages when examining the interplay between economic expansion and environmental effects. By including a cubic specification, this work adds to a more nuanced understanding of the EKC, giving compelling evidence for the need to establish policies that address the complete trajectory of economic growth and its environmental effects. This involves implementing forward-looking initiatives to limit the re-emergence of carbon emissions in the latter phases of economic development via sustainable resource management, technological innovation, and targeted regulation of the environment.

To examine the robustness of the primary findings, this work conducts an extra estimation using Driscoll-Kraay standard errors, which are resilient to heteroskedasticity, autocorrelation, and cross-sectional dependency, which are typically encountered in macro panel datasets. The results of this robustness assessment, reported in Table 8, broadly accord with the primary findings of the quantile regression analysis, indicating the dependability and consistency of the study's conclusions.

Table 8: Robustness results using Driscoll-Kraay Standard Errors

Variable	Driscoll-Kraay Standard Errors
DCP	-0.054 (0.036)
M3/M1	0.255* (0.134)
FDI	0.382** (0.153)
GDP	38.211*** (6.022)
GDP ²	-3.707*** (0.593)
GDP ³	0.119** (0.019)
Intercept	-126.535*** (20.673)
R ²	0.401
Observations	378

Source: Research findings; Note: ***, **, and * indicate significant p values at the 1, 5, and 10% level, respectively.

The coefficient on domestic credit to the private sector is still negative, although it is not statistically significant at normal levels. This finding backs up the hypothesis that domestic credit could be linked to fewer carbon emissions, albeit other ways of estimating it may not be as accurate. The M3/M1 ratio has a positive and statistically significant association with carbon emissions, which is in accordance with the baseline model. This suggests that increasing the money supply may harm the environment by promoting activities that produce a lot of carbon.

More crucially, the coefficient for financial development stays positive and statistically significant at the 5% level. This backs up the first conclusion that financial development may help the economy thrive, but it can also lead to more carbon emissions if there is no green financial compliance.

The GDP factors also back up the N-shaped EKC theory. The linear term for GDP is positive and very significant, the squared term is negative and significant, and the cubic term is positive and statistically significant. This constant cubic pattern in both the main model and the robustness

models shows that there is a nonlinear and changing link between economic development and environmental damage in EU members and Turkey.

Taken together, robustness checks employing Driscoll-Kraay estimators strengthen the empirical dependability of the findings and indicate that the study's major outcomes are not susceptible to estimation methodologies. The constant direction and significance of the important variables emphasise the validity of the theoretical findings, notably regarding the role of financial development in defining the trajectory of carbon emissions and the value of the N-shaped EKC framework.

5. Conclusions and Policy Implications

This study delves into the intricate relationship between financial development and carbon emissions, revealing a multifaceted and dynamic interaction. Financial development, while recognised as a catalyst for economic growth, exhibits both positive and negative environmental implications. The analysis underscores the existence of an N-shaped EKC, which deviates from the traditional inverted U-shaped EKC hypothesis. This nuanced trajectory indicates that carbon emissions initially rise with economic growth, decline as economies adopt cleaner technologies and environmental regulations, and subsequently increase again at advanced stages of development due to intensified production and consumption. This finding highlights the necessity of a comprehensive understanding of how financial and economic dynamics shape environmental outcomes across different developmental phases.

This research dives into the deep link between financial development and carbon emissions, demonstrating a nuanced and dynamic interplay. Financial development, although regarded as a fuel for economic progress, has both good and negative environmental repercussions. The investigation emphasises the presence of an N-shaped EKC, which deviates from the classic inverted U-shaped EKC concept. This complex trajectory demonstrates that carbon emissions first rise with economic expansion, fall as countries embrace cleaner technology and environmental restrictions, and then increase again at advanced levels of development owing to increased production and consumption. This study underlines the requirement of complete knowledge of how financial and economic factors impact environmental outcomes throughout various developmental periods.

Empirical data derived from the panel quantile regression analysis reveal the diversity of financial development's effect on carbon emissions across different degrees of emission intensity. Specifically, domestic lending to the private sector demonstrates a persistent negative correlation with carbon emissions, underlining the role of financial resources in enhancing energy efficiency, encouraging technological innovation, and fostering low-carbon economic activity. Conversely, the ratio of broad money supply to narrow money demonstrates a positive influence on carbon emissions across all quantiles, suggesting that monetary expansion could mistakenly favour energy-intensive enterprises and enhance carbon footprints. Furthermore, the Financial Growth Index is positively connected with carbon emissions, suggesting that while financial growth may boost economic success, it also has the potential to worsen environmental degradation when not aligned with sustainability objectives.

The observed N-shaped EKC underlines the intricacy of the economic-environmental link and the limits of standard models that generally depend on quadratic assumptions. The cubic link revealed in this research illustrates that environmental deterioration is not a one-dimensional process but progresses through multiple stages as economies grow. In the early phases of economic expansion, industrialisation and growing energy consumption drive up carbon emissions. As economies grow and embrace cleaner technology and tighter environmental rules, emissions fall. However, at greater levels of economic growth, growing consumption, production, and lifestyle changes may spark a comeback in carbon emissions. This conclusion calls for a review of existing policy frameworks and a move toward adaptive, forward-looking solutions that handle these complex processes.

The findings of this study hold significant implications for policymakers striving to reconcile economic growth with environmental sustainability. In light of the demonstrated N-shaped EKC, it is imperative to design and implement multidimensional policy frameworks that not only foster economic expansion but also ensure long-term ecological balance. A crucial aspect of this approach involves the establishment and institutionalisation of green financial mechanisms that integrate financial development with sustainability objectives.

To this end, policymakers should actively promote investments in renewable energy sources, energy efficiency initiatives, and low-carbon technologies, as these measures contribute to both economic development and environmental preservation. Targeted financial instruments, such as

green bonds, carbon pricing mechanisms, and sustainability-linked loans, can play a pivotal role in directing financial resources toward environmentally sustainable activities. Green bonds, for instance, offer a structured means of financing projects with positive environmental impacts, while carbon pricing through mechanisms like carbon taxes or cap-and-trade systems creates economic incentives for reducing greenhouse gas emissions. Sustainability-linked loans, on the other hand, encourage businesses to adopt environmentally responsible practices by linking favourable financing terms to measurable sustainability performance indicators.

Moreover, the role of financial institutions in fostering sustainability cannot be overstated. Banks, investment funds, and other financial intermediaries should be incentivised to incorporate environmental, social, and governance (ESG) criteria into their lending and investment decisions. By embedding ESG considerations into financial risk assessments and capital allocation strategies, financial institutions can mitigate climate-related financial risks while simultaneously promoting responsible corporate behaviour. Regulatory bodies should facilitate this transition by developing comprehensive ESG reporting standards and ensuring that financial institutions disclose their environmental impact transparently.

Furthermore, governments must adopt a proactive approach to strengthening public-private partnerships in the field of green finance. Collaborative efforts between the public and private sectors can accelerate the transition toward a low-carbon economy by mobilising capital for sustainable infrastructure projects, fostering innovation in clean technologies, and expanding access to climate finance for small and medium-sized enterprises (SMEs). In addition, the integration of sustainability principles into national financial policies and macroeconomic planning is essential to ensuring that economic growth trajectories do not contribute to renewed environmental degradation at advanced stages of development.

In conclusion, aligning financial development with environmental sustainability requires a comprehensive and forward-looking policy approach that encompasses regulatory incentives, market-based instruments, and institutional reforms. By leveraging green finance as a strategic tool, governments can create a resilient economic model that prioritises both economic progress and environmental stewardship, thereby mitigating the risks associated with the re-emergence of environmental degradation at higher levels of economic prosperity.

Second, regulatory frameworks must be developed to offset the detrimental environmental implications of financial development. Financial systems should integrate mandated sustainability reporting, higher environmental compliance requirements, and carbon emission restrictions for sectors benefitting from financial growth. Such approaches will guarantee that the environmental consequences of financial growth are appropriately handled and reduced.

Third, the N-shaped EKC underlines the necessity for various policy measures depending on the stage of economic growth. In emerging economies, efforts should concentrate on early adoption of clean technology, capacity-building for sustainable behaviours, and investments in green infrastructure. In contrast, industrialised economies must emphasise innovation in sustainable manufacturing processes, circular economy models, and energy transition plans to address the return of emissions in the latter phases of growth.

Financial institutions and central banks also have a vital role to play in aligning monetary policy with environmental goals. The positive link between the money supply and carbon emissions shown in this research implies that expansionary monetary policy might unwittingly worsen environmental concerns. Policymakers must explore incorporating environmental impact evaluations into monetary policy frameworks to guarantee that economic development is divorced from carbon emissions.

Finally, international coordination is required to address the transboundary character of climate change and the globalisation of financial systems. Initiatives such as the New Common Quantified Goal of Climate Finance (NCQG) should be broadened to encourage fair financial flows from industrialised to poor nations. This includes supporting renewable energy projects, adaptation measures, and loss and damage activities. Additionally, standardising green finance rules and increasing knowledge-sharing across states will be crucial in solving global environmental concerns.

This study's contribution to the field of carbon emissions lies not only in its nonlinear presentation of the relationship between financial development and environmental degradation, but also in its provision of an empirical framework that takes into account the quantile heterogeneity of this relationship. In particular, the study's proposed N-shaped EKC demonstrates that policymakers should not focus solely on environmental improvements at intermediate stages of development but should also consider carbon

emissions, which may rise again during periods of advanced economic growth.

In this context, the results of the study have obvious policy implications for European Union institutions, environmental regulators and public budget authorities. For example, Germany attempts to integrate economic growth with environmental goals through the use of green finance instruments (e.g. green bonds and sustainable financing programs). Similarly, in France, the required ESG reporting by financial institutions permits systematic monitoring of environmental repercussions. Such techniques are consistent with the purpose of “financial development compatible with sustainable development” established in our study.

International civil society groups also play an important role in this system. For example, the UNEP Finance Initiative and the World Resources Institute (WRI) are developing capacity-building initiatives that bridge the gap between the financial sector and climate policy. Such international initiatives can overcome institutional capacity shortages in poor countries and assist in executing the “quantile-based differentiated policy approach” indicated by the study. This work makes substantial theoretical and empirical additions to the field by modelling the multi-layered link between carbon emissions and financial institutions, not merely at the macroeconomic level. It also has practical benefits by delivering empirically grounded, disaggregated, and time-sensitive suggestions for policymakers.

In conclusion, this analysis underscores the imperative need for integrated and flexible policy frameworks that effectively balance economic growth with environmental sustainability. The intricate and multidimensional interactions among economic development, financial mechanisms, and environmental outcomes highlight the necessity of adopting a comprehensive approach to sustainable policymaking. In this regard, policymakers in European Union countries and Türkiye can leverage the insights derived from this study to develop long-term strategies that harmonise economic and environmental objectives. This study makes a significant contribution to the existing literature on the Environmental Kuznets Curve by offering a more nuanced perspective on the relationship between economic progress and ecological preservation. Moving beyond traditional approaches, it provides critical policy recommendations on how financial mechanisms can be structured to support the transition toward sustainable growth and a low-carbon economy.

Future research should explore sectoral and regional variations in this relationship to facilitate the development of more targeted and effective policy instruments. In this context, achieving a balance between financial sustainability and environmental protection is not only essential for the continuity of economic growth but also a crucial prerequisite for addressing global environmental challenges.

CRedit authorship contribution statement

Turan Karimli: Conceptualisation, Data curation, Formal analysis, Methodology. **Özlem Durgun:** Conceptualisation, Resources, Visualisation, and Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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