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Can Green Technological Innovation Offset the Environmental Costs of Finance? Insights from OECD Countries

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Abstract

Advancing ecological sustainability while limiting the harm caused by ecological degradation has emerged as a shared international priority. Moreover, the degree to which specific OECD countries can curb ongoing ecological decline is still not well understood. The present study investigates the interplay among economic growth, Green Technological Innovation (GTI), Financial Development (FD), and Ecological Policy Stringency (EPS), with particular attention to the moderating role of GTI in shaping ecological outcomes. The paper evaluated these dynamic links using panel data from 1990 to 2022 within the frameworks of Environmental Kuznets Curve (EKC) and Load Capacity Curve (LCC) hypotheses. To address this inquiry, the analysis applied the novel Method of Moments Quantile Regression (MMQR). The research outcome disclosed that FD consistently contributes to ecological deterioration across the distribution of environmental outcomes. GTI and EPS exert a uniformly beneficial effect on ecological quality, with stronger improvements observed in higher-degradation regimes. Additionally, the results provide strong evidence for the EKC and LCC hypotheses. More importantly, the interaction term between GTI and FD indicates green innovation mitigates the environmental pressures induced by FD and enhances the capacity of financial systems to support environmental quality. The findings offer actionable insights for policymakers in OECD economies, highlighting that fostering green innovation within financial systems can effectively curb ecological degradation.

Keywords: Ecological sustainability, Green technological innovation, Financial development, Economic growth.

1 | Introduction

In recent decades, scholars and international institutions have paid growing attention to the accelerating pace of environmental decline and the intensifying risks associated with climate change [1], with developed countries often highlighted due to their substantial ecological footprint [2]. Much of this deterioration arises

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from extensive resource use and the greenhouse gases released through such demand [3], [4]. Given that the OECD nations are responsible for almost 36% of the world's CO2 emissions, they must prioritize environmental sustainability [5]. These emissions stemmed from a broad set of economic and financial activities, including energy-intensive production systems and the heavy reliance on fossil fuel consumption [6]. In pursuing the commitments set out in the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), countries continue to seek pathways that align economic progress with environmental stewardship. This global effort has elevated interest in how technological advancement can reinforce ecological priorities [7]. Within this broad agenda, green technology innovation has become a central strategy for shaping development trajectories that reduce long-term ecological pressures. Green technology innovation encompasses the creation and adoption of technologies that limit environmental damage, improve the efficiency of energy use, and facilitate low-carbon transitions [8]. It is increasingly viewed as a critical catalyst for sustainable development, particularly in advanced economies navigating intense industrial activity and rising growth expectations [9].

Environmental challenges have moved to the forefront of international discourse as their impacts grow more visible [10]. A frequently cited framework for interpreting how rising income levels interact with ecological conditions is the Environmental Kuznets Curve (EKC) (hereafter, EKC). It proposes that environmental performance tends to deteriorate during the early stages of economic expansion because production and consumption intensify [11]. As development advances further, conditions are expected to shift. Higher income levels can raise public expectations for cleaner environments and support technologies that strengthen environmental stewardship [12]. The Load Capacity Curve (LCC) (hereafter, LCC) hypothesis offers an additional framework for understanding how economic expansion interacts with environmental conditions. It proposes that rising income levels can support ecological stability up to a threshold. After that threshold is crossed, continued economic growth leads to deteriorating environmental performance [13].
Fig. 1 visualizes these connections by comparing the LCC with the standard EKC framework. While the EKC suggests that environmental quality declines and then improves with rising income, the LCC proposes a U-shaped evolution in which economic progress first weakens ecological capacity and subsequently reinforces it once appropriate structural and institutional arrangements emerge.

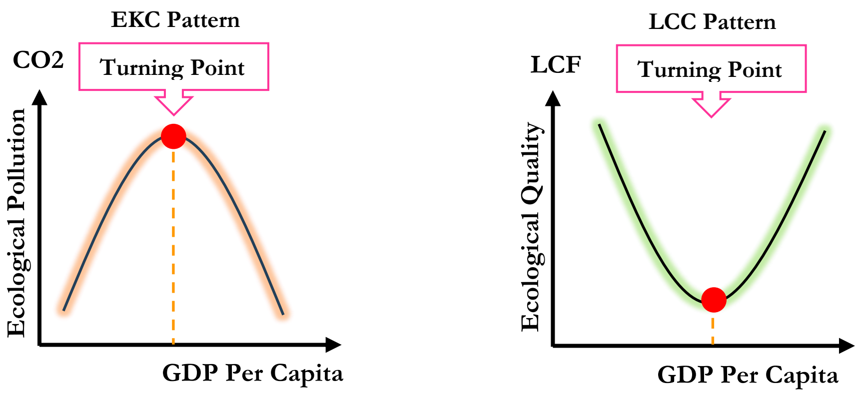

Fig. 1. LCC and EKC hypothesis [14].

These countries are selected because they consistently rank among the global leaders in Green Technological Innovation (GTI) and environmental R&D, making them ideal cases for examining the role of GTI [15]. Moreover, they possess highly developed and structurally diverse financial systems, providing a robust context for evaluating the finance-environment relationship [16]. In addition, their environmental policy frameworks, ranging from stringent regulatory regimes in Nordic countries to more flexible approaches in the UK and the USA, offer valuable institutional variation for assessing the effectiveness of environmental policy stringency [17].

This study contributes to the existing literature in four key ways. First, to the best of our knowledge, it is the first to examine the effect of GTI on ecological sustainability through the lens of the Load Capacity Factor (LCF) and CO2 emissions in the context of selected OECD economies, particularly as nations pursue economic growth while implementing Paris Agreement commitments. Second, we scrutinize the nexus between economic growth and ecological sustainability within the framework of LCC hypothesis. Third, we advance previous research by investigating the moderating role of GTI in the relationship between Financial Development (FD) and ecological sustainability. In other words, we assess whether GTI amplifies or mitigates the influence of FD on ecological outcomes. Finally, unlike the previous studies that have ignored the endogeneity issue widely, we have addressed this issue by deploying the novel Method of Moments Quantile Regression (MMQR) followed by Machado and Silva [18]. This study employs this estimator, which effectively addresses Cross-sectional Dependence (CD) and endogeneity, two persistent challenges in panel data analysis. The main advantage of this approach is its ability to efficiently address CD, which is a major challenge in panel data analysis, as well as issues related to endogeneity.

Several studies have explored the key determinants that contribute to achieving ecological sustainability goals. However, none has examined the role of GTI in reshaping the relationship between FD and ecological sustainability within the framework of the EKC and LCC hypotheses for selected OECD economies. The primary objective of this study is to fill this gap by examining the moderating role of GTI in promoting ecological sustainability across a group of OECD countries, including Denmark, the Netherlands, Sweden, Switzerland, the UK, and the USA, using the MMQR approach. This study provides new insights that can strengthen GTI initiatives aimed at enhancing FD and lowering environmental pollution, particularly within OECD economies. Based on the above discussions, the following Core Questions (CQs) are formulated for the selected OECD countries: CQ1: Do the EKC and LCC hypotheses hold between economic growth and ecological sustainability?; CQ2: Does FD reduce ecological sustainability?; CQ3: Does Ecological Policy Stringency (EPS) improve ecological condition?; CQ4: Does GTI enhance ecological sustainability? ; and CQ5: Does GTI play a moderating role in the relationship between FD and ecological sustainability?

The remainder of the paper is structured as follows. Section 2 presents the empirical literature review, while Section 3 describes the data and methodological framework. Section 4 reports and discusses the empirical findings, and Section 5 concludes the study with key insights and policy recommendations.

2 | Literature Review and Research Hypothesis

This section reviews the principal strands of scholarship relevant to the present inquiry and identifies the conceptual and empirical gaps that motivate further investigation. The set of variables employed in this study provides a distinct analytical advantage, allowing us to probe dimensions and hypotheses that have received limited attention yet are grounded in established theoretical and empirical work. The literature review is organized around the following thematic domains: 1) the relationship between ecological sustainability and FD, 2) the relationship between ecological sustainability and green technology; and 3) the connection between ecological sustainability and EPS. For each thematic relationship, the corresponding Research Hypotheses (RH) are subsequently articulated.

2.1 | Ecological Sustainability and Financial Development

FD plays a vital role in shaping ecological conditions, and by promoting investment in carbon-intensive activities, it further contributes to the deterioration of environmental quality [19], [20]. For instance, to support the positive aspect, the recent study by Elatroush [21] has suggested that FD in emerging and developing countries reduces environmental degradation and stimulates environmental sustainability. Likewise, the previous study by Adebayo et al. [22] in the USA investigates the impact of FD on LCF from

1980 to 2021. Their outcomes confirm FD's positive effects on environmental sustainability. Similarly, Nuta et al. [23] also endorse FD's positive role in achieving environmental sustainability in European countries. On the other hand, the existing studies also highlight the negative influence of FD on environmental sustainability. For example, Fan et al. [24] documented the consequences of ecological outcomes, drawing evidence from BRICS-T region from 1990 to 2020. According to their study, FD significantly increases the level of ecological footprint. In another studies, Ahmad et al. [25] and Horky and Fidrmuc [26] investigated the role of FD. They highlighted its negative impact on the environment in 32 European Union (EU) and ASEAN countries. Accordingly, we formulate the following hypothesis:

RH1. FD has a positive ecological impact on the environment.

2.2 | Ecological Sustainability and Green Technology

Green technology has been added to the empirical model by academics to more accurately analyze the factors that boost CO2 emissions. Drawing on this evidence, advances in environmentally oriented innovation, including both green technologies and eco-innovative practices, emerge as crucial mechanisms for strengthening the foundations of a sustainable economic system while curbing resource losses and ecological degradation [27]. Empirical work further indicates that such innovation plays a decisive role in shaping corporate sustainability outcomes, a pattern especially evident within sectors characterized by high energy consumption [28]. Using data for China covering the period from 1990 to 2020, He et al. [29] examine the influence of green innovation on ecological sustainability. Their findings indicate that green innovation plays a significant role in reducing CO2 emissions. Radulescu et al. [30], drawing from panel quantile autoregressive distributed lag in the 26 EU members for data during 2011–2021, revealed that green innovation appears to be a powerful tool for achieving rapid environmental advantages, leading to a considerable reduction in environmental footprint across various levels. Besides, in their study, Sethi et al. [31] scrutinize how GTI affects ecological sustainability in 25 select developing countries. Deploying the Driscoll-Kraay and two-step System Generalized Method of Moments estimators, the authors unveiled that green innovation is critical in elevating ecological sustainability. However, Bai et al. [32] argue that when income inequality is high, innovation in both renewable and fossil-fuel energy can still lead to higher CO2 emissions. Considering the previous discussions, we propose the following hypothesis:

RH2. GTI enhances ecological sustainability.

2.3 | Ecological Sustainability and Ecological Policy Stringency

In the past decade, research on EPS and its role in ecological quality has expanded markedly. Degirmenci et al. [33] conduct an empirical analysis of G-7 economies over the period 1990-2020. Their results show that stricter environmental policy enhances the LCF, indicating a positive contribution to ecological sustainability. In another study conducted by Cohen and Tubb [34], they reported that environmental rules and regulations lead to novelty in clean technologies and depress the enlargement of "dirty" technologies thus minimizing degradation of the environment. In line with these research, Yirong [35] examined the case of high-polluted economies from 1990 to 2019 and discovered that an increase in EPS improves the ecological sustainability by reducing CO2 emissions in the long run. Similarly, according to Wang et al. [36], the favorable impact of EPS on ecological sustainability is confirmed. Considering the preceding discussions, we propose the following hypothesis:

RH3. EPS increases ecological sustainability.

2.4 | Gap in the Literature

Although the existing empirical literature explores the relationships among GTI, FD, economic growth, and ecological sustainability, it does not account for the moderating role of GTI in reshaping the connection between FD and ecological sustainability, particularly within the context of the LCF and EKC frameworks simultaneously for selected OECD economies. To address the limitations of prior studies, the present research employs the MMQR estimator to identify and evaluate this moderating effect. The main advantage of this approach is its ability to efficiently address CD, which is a major challenge in panel data analysis, as well as issues related to endogeneity.

3 | Data, Model, and Empirical Strategy

3.1 | Data Description

This study employs panel data for the selected OECD countries covering the period from 1990 to 2022. The variables used include GTI, FD, and economic activity GDP. The selected timeframe is determined solely by the availability of data for all variables. Detailed definitions and descriptions of the variables are provided in *Table 1*.

Table 1. Summary of study variables.

Variables	Acronyms	Definition and Measures	Source
Load capacity factor	LCF	Biocapacity/Ecological Footprint	[37]
CO2 emission	CO2	Metric Tons Per Capita	[38]
Economic growth	GDP	Per capita USD Constant	[39]
Green technology innovation	GTI	Patents on environmental technologies	[40]
Financial development	FD	Domestic credit to privately (percentage of GDP)	[41]
Ecological policy stringency	EPS	The index measures the stringency of 13 environmental policy tools, primarily related to climate change and air pollution	[42]

Note: GFN: global footprint network, WDI: world development indicators. OECD: organization for economic cooperation and development.

Additionally, *Fig. 2* illustrates the geographical distribution of the selected countries, classifying them into two groups based on their LCF values: economies with an LCF greater than 1 and those with an LCF below 1. Among these countries, Sweden exhibits the highest LCF (1.49), whereas Switzerland shows the lowest value (0.25).

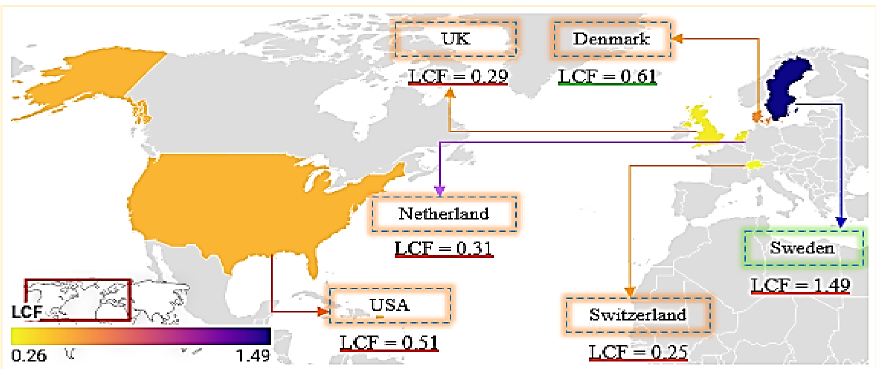

Fig. 2. Geographical coverage of selected economies.

3.2 | Model Construction

The study has adopted the following empirical model of Fakher [43] to investigate the ecological impact of economic growth, GTI, FD, and EPS in selected OECD economies. The functional form of the relationship between explanatory and dependent variables is defined in *Eq. (1)*.

$$\mathrm{EO} = \mathrm{f(GDP, GTI, FD, EPS)}. \tag{1}$$

In this model, EO represents ecological outcomes. The dependent variables (ecological outcomes) consist of the LCF, which serves as an indicator of environmental sustainability, and CO2 emissions, which represent ecological degradation. In contrast, GDP, GTI, FD, and EPS capture economic growth, green technology innovation, FD, and EPS, respectively. The econometric specification of *Eq. (1)* is presented as follows.

$$\mathrm{lnEO_{it}} = \alpha_0 + \beta_1\mathrm{lnGDP_{it}} + \beta_2\mathrm{lnGDP_{it}^2} + \beta_3\mathrm{lnFD_{it}} + \beta_4\mathrm{lnGTI_{it}} + \beta_5(\mathrm{lnGTI_{it}} \times \mathrm{lnFD_{it}}) + \beta_6\mathrm{lnEPS_{it}} + \varepsilon_{it}. \tag{2}$$

From *Eq. (2)*, the coefficient β_5 offers two econometric insights: 1) the effect of FD on EO depends on the coefficients β_3 and β_5, and 2) differentiating EO with respect to FD allows us to determine the marginal impact of FD on EO conditioned by GTI. This marginal effect is derived as follows.

$$\frac{\partial \mathrm{EO}}{\partial \mathrm{FD}} = \beta_3 + \beta_5\mathrm{GTI}. \tag{3}$$

Based on previous studies and our empirical analysis, we expect the coefficient β_5 to be positive (β_5>0). In other words, favorable GTI development is expected to mitigate the negative effects of FD on EO (when $\beta_3 < 0$) or to strengthen the positive contribution of FD to EO (when $\beta_3 > 0$).

3.3 | Estimation Strategy

Given that, in global issues such as ecological sustainability, countries tend to be exposed to common influences including worldwide shocks, the presence of CD is highly plausible [2]. To obtain reliable parameter estimates, we therefore applied a CD test. In addition, this study employed a Slope Heterogeneity (SH) test to determine whether the slope coefficients are uniform across countries or differ from one country to another. For this purpose, the Delta test proposed by Pesaran and Yamagata [44] was implemented. To reduce the likelihood of misleading statistical inferences and to verify whether the variables share a long-term equilibrium, this study applied the Westerlund [45] cointegration procedure. This approach is well suited to panel settings that exhibit CD and allow for heterogeneous structural features. Concerns associated with Ordinary Least Squares motivated the use of quantile regression, a technique that characterizes responses at various points of the conditional distribution rather than restricting attention to the mean [46]. The analysis employed the MMQR developed by Machado and Silva [18]. This estimator adapts quantile regression to panel frameworks by integrating moment conditions, which enables a joint assessment of how covariates influence both the central tendency and dispersion of outcomes across quantiles. Formally, the conditional quantile function for the τ-th quantile is expressed as:

$$\mathrm{Q_\tau(Y_{it}|X_{it})} = \mathrm{X'_{it}}\beta_\tau, \tag{4}$$

where $\mathrm{Q_\tau(Y_{it}|X_{it})}$ is the τ-th conditional quantile of the dependent variable Y (LCF and CO2 emissions). $\mathrm{X_{it}}$ is a vector of independent variables (GDP, GTI, FD, EPS) while β_τ represents the quantile-specific coefficients. Accordingly, the methodological steps of this study are depicted in *Fig. 3*.

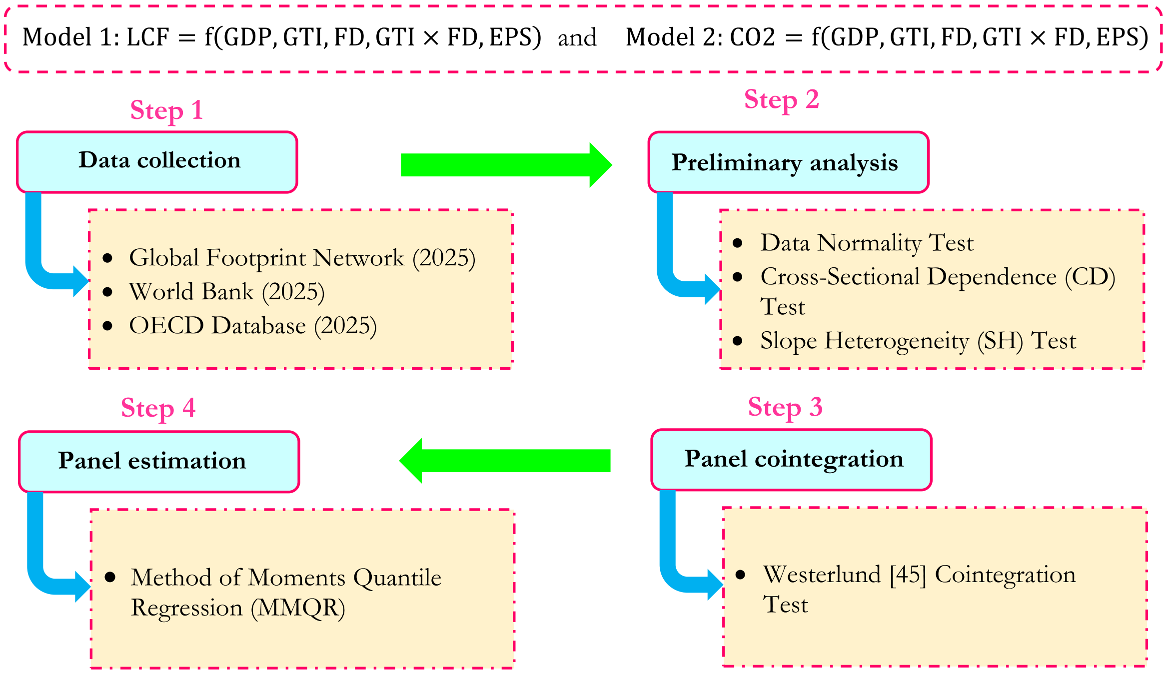

Fig. 3. Methodological steps of current study.

4 | Empirical Results and Discussions

We began by examining the descriptive properties of the dataset presented in *Table 2* The transformation of the variables helps moderate variance, which can be seen in the lower standard deviations for indicators such as GDP and GTI. This adjustment also promotes steadier patterns across the sample. Despite this improvement, GDP shows pronounced kurtosis, suggesting a sharp distribution or the influence of extreme values within the growth series. Such features may complicate subsequent regressions because they create risks of heteroskedastic errors and possible non-linear relationships. To evaluate the distributional shape of the data, the Jarque-Bera (JB) test was applied. The results indicate that every variable other than FD departs from normality at the 1% threshold, while FD is significant at the 10% level.

Table 2. Descriptive statistics after transformation to logarithm.

Variables	Mean	Maximum	Minimum	Skewness	Kurtosis	JB Stats
LCF	0.322	1.408	- 0.714	0.510	1.618	10.2***
CO2	0.481	2.012	- 1.721	- 0.198	1.622	11.14***
GDP	1.869	3.317	- 2.341	- 2.314	8.117	358.4***
FD	-1.027	- 0.216	- 1.896	0.186	2.199	5.126*
GTI	2.088	3.418	0.128	1.189	3.378	10.12***
EPS	-3.712	- 1.701	- 5.348	0.238	1.361	18.28***

Note: *** and * show 1 % and 10% significance level, respectively.

To identify suitable econometric specifications for estimating the coefficients and to manage recurring issues in panel datasets, we applied the CD and SH diagnostics. The results in *Table 3* report the Pesaran [47] CD-test, which indicates strong CD across all variables at the 1% level. This outcome signals substantial interlinkages among ecological outcomes, financial structures, technological progress, EPS, and economic activities within OECD countries.

Table 3. CD test.

Variable	CD-Test	p-Value
lnLCF	9.980***	0.000
lnCO2	8.250***	0.000
lnGDP	5.770***	0.000
lnFD	4.840***	0.000
lnGTI	4.980***	0.000
lnEPS	4.690***	0.000

Note: *** shows 1 % significance level.

Table 4 reports the outcomes of the SH assessment, and both the Delta tilde and its adjusted form show clear evidence of heterogeneous coefficient structures across the OECD sample. These findings imply that the effects of economic activity, green technological progress, financial conditions, and EPS on environmental indicators differ markedly from one country to another.

Table 4. Testing for SH.

	Statistics	p-Value
Delta tilde	3.234***	0.000
Delta tilde adjusted	4.388 ***	0.000

Note: *** shows 1 % significance level.

Table 5 presents the outcomes of the panel stationarity analysis and reveals that the variables do not share a uniform order of integration. Based on the CIPS approach (2nd generation unit root test), many variables fail to demonstrate stationarity in their level form yet become stationary after first differencing at the 1% threshold. EPS and GTI are exceptions since they remain stationary in levels. In contrast, variables such as CO2 and GDP attain stationarity only once differenced. To reduce the likelihood of misleading regression results and to verify whether the variables move together over the long term, the Westerlund [45] cointegration procedure was applied. This method is well suited for panels characterized by CD and variation in slope parameters.

Table 5. Panel stationarity test.

Variable	CIPS	
	At Level	At 1st Diff.
lnLCF	- 1.821	- 2.308**
lnCO2	- 2.135	- 3.608***
lnGDP	- 1.598	- 3.311***
lnFD	- 1.418	- 4.097 ***
lnGTI	- 3.629***	- 5.309***
lnEPS	- 2.667 ***	- 4.417 ***

Note: ***, ** and * show 1 %, 5% and 10% significance level, respectively.

Table 6 reveals that the Westerlund [45] cointegration assessment provides clear evidence of a stable long-run association within the panel. The variance ratio statistics reach significance at the 1% threshold, which leads to a rejection of the null hypothesis of no cointegration and affirms the alternative view that the panels exhibit a sustained equilibrium relationship among the variables.

Table 6. Westerlund [45] cointegration test.

Models	Model 1: LCF		Model 2: CO2	
Variance ratio	Statistics	P-Value	Statistics	P-Value
	4.389***	0.000	3.411***	0.000

Note: *** shows 1 % significance level.

Once the study established a stable long-run linkage among the variables, the authors evaluated the strength of this relationship using a recently applied methodological innovation, the MMQR. The resulting estimates are reported for two dependent variables. *Table 7* presents the findings in which CO2 serves as a proxy for ecological degradation, and *Table 8* displays the outcomes where LCF reflects ecological sustainability.

Table 7. MMQR results.

Dependent Variable: lnCO2			Quantiles				
Regressors	**Location**	**Scale**	**Q10**	**Q25**	**Q50**	**Q75**	**Q90**
lnGDP	0.298***	- 0.048	0.249***	0.238***	0.225***	0.201***	0.108*
lnGDP2	- 0.097***	- 0.028	- 0.058*	- 0.066**	- 0.079***	- 0.118***	- 0.203***
lnFD	0.469***	- 0.138	0.708***	0.559***	0.487***	0.330**	0.228
lnGTI	- 0.029**	- 0.018**	- 0.021**	- 0.034***	- 0.042***	- 0.058**	- 0.069***
lnEPS	- 0.480***	0.029*	- 0.528***	- 0.501***	- 0.498***	- 0.452***	- 0.426***
lnGTI×lnFD	- 0.388**	- 0.087	- 0.363*	- 0.394**	- 0.418**	- 0.453**	- 0.531**
Constant	- 0.578	0.654*	- 1.608**	- 1.089*	- 0.534*	- 0.127*	- 0.208**

Note: ***, **, and * show 1 %, 5% and 10% significance level, respectively.

Table 7 demonstrates how the selected drivers shape ecological degradation, proxied by CO2 emissions, across different points of the conditional distribution. According to the MMQR results, GDP exhibits a positive and significant effect on CO2 emissions in almost all quantiles, with the magnitude gradually declining from lower quantiles (Q10) to the highest quantile (Q90). Conversely, GDP2 is negative and highly significant throughout, with a sharper negative effect at higher emission levels (Q90). Together, these results strongly confirm the EKC for CO2 emissions, indicating that emissions rise at early development stages but fall after a turning point. In OECD economies, this EKC pattern emerges because these economies rely heavily on renewable energy deployment, energy efficiency programs, and green innovation ecosystems, all of which allow income to eventually reduce emissions.

This finding is fully consistent with the studies of Şerifoğlu et al. [48] and Akar et al. [49], who report a similar shift from environmental deterioration to relative improvement in developed economies. Moreover, FD is a strong driver of higher CO2 emissions, particularly in low-to-median quantiles (Q10-Q50). This suggests that in economies with lower levels of emissions, financial deepening still channels investment towards carbon-intensive activities, contrary to the findings by Adebayo et al. [22] and Nuta et al. [23].

Additionally, GTI exerts a negative and significant influence on CO2 emissions across all quantiles, with the magnitude intensifying at higher quantiles (from -0.021 at Q10 to -0.069 at Q90), indicating that such innovation delivers its strongest environmental benefits in high-emission regimes. This aligns with earlier work by Sethi et al. [31] and Radulescu et al. [30], who highlight the disproportionate importance of innovation in curbing emissions where pollution levels are most acute. EPS also maintains a strong negative association with CO2 emissions at every quantile, though the effect becomes slightly less pronounced as emissions rise.

This result underscores the regulatory effectiveness of stringent environmental policies, echoing evidence from Degirmenci et al. [33], Yirong [35], and Wang et al. [36] who note that rigorous policy frameworks reduce carbon intensity. More importantly, the interaction term (GTI×FD) is consistently negative and significant, indicating that GTI fundamentally reshapes the environmental consequences of FD. GTI dampens, and at higher quantiles even reverses, the emission-escalating effects of FD. This illustrates a transition from "brown finance" to "green finance," aligning with contemporary evidence that innovation-aligned finance can be an environmental game-changer. Related empirical work supports this synergy; for example, Yu and Xiao [50] illustrate how innovation-oriented financial systems mitigate the ecological burden of capital expansion.

Table 7. MMQR results.

Dependent Variable: lnLCF			Quantiles				
Regressors	**Location**	**Scale**	**Q10**	**Q25**	**Q50**	**Q75**	**Q90**
lnGDP	0.169***	- 0.032	- 0.209**	- 0.198***	- 0.161***	- 0.142**	- 0.128*
lnGDP2	- 0.041**	- 0.009	0.022*	0.025*	0.027**	0.028*	0.029*
lnFD	0.488***	- 0.002	- 0.387***	- 0.386***	- 0.385***	- 0.383***	- 0.381***
lnGTI	- 0.032***	- 0.008	0.018***	0.021***	0.027***	0.028***	0.029***
lnEPS	- 0.342***	0.005	0.368***	0.365***	0.362***	0.360***	0.358***
lnGTI×lnFD	0.281**	0.018	0.258**	0.269**	0.275**	0.289**	0.296**
Constant	- 0.856**	0.289*	1.341***	1.118***	0.856**	0.547	0.389
Observations	264	264	264	264	264	264	264

Note: ***, **, and * show 1 %, 5% and 10% significance level, respectively.

Table 8 extends the analysis by examining ecological sustainability, proxied by the LCF. Based on the MMQR estimates, GDP exhibits a negative and statistically significant effect on the LCF across all quantiles, while GDP2 displays a positive and significant effect consistently throughout the distribution. This nonlinear pattern suggests a U-shaped relationship between economic growth and ecological sustainability within OECD countries. This stands in contrast to the CO2 model in *Table 7* (which supported an inverted-U EKC), indicating the presence of a U-shaped LCC pattern for LCF.

These results are in line with those of Almulhim et al. [5]. Furthermore, FD exhibits a negative and significant effect on LCF across all quantiles (approximately - 0.38 consistently). This indicates that FD tends to erode ecological sustainability, mirroring the "financial-ecological degradation" viewpoint observed by Fan et al. [24]. GTI demonstrates a positive, statistically significant, and stable effect on the LCF across all quantiles. This implies that green innovation systematically enhances ecological sustainability in OECD countries, and its influence remains consistently beneficial regardless of a country's initial LCF level. OECD countries lead globally in energy-efficient technologies, circular economy innovation, and eco-efficient industrial processes. These innovations reduce per-capita ecological footprint, thereby improving the LCF. This finding is supported by the empirical results of Khan et al. [27] and Lou et al. [28].

Additionally, EPS exhibits a positive and statistically significant coefficient across all quantiles of the LCF distribution. This means that stricter environmental policies improve ecological sustainability in OECD countries. The coefficients remain relatively stable, ranging from approximately 0.368 at Q10 to 0.358 at Q90, demonstrating both the consistency and robustness of this relationship.

This result coincides with those of Degirmenci et al. [33] and Yirong [35], who confirmed positive effects of EPS on ecological sustainability. More specifically, the interaction term (GTI×FD) exerts a consistently positive effect on LCF across the entire distribution, indicating that innovation enhances the capacity of financial systems to support ecological sustainability. This dynamic contrasts with the negative interaction found for CO2 emissions in *Table 7*, reinforcing that sustainability-oriented outcomes respond differently to financial-technological synergies. Following the above interpretations, the graphical summary of the results is depicted in *Fig. 4*.

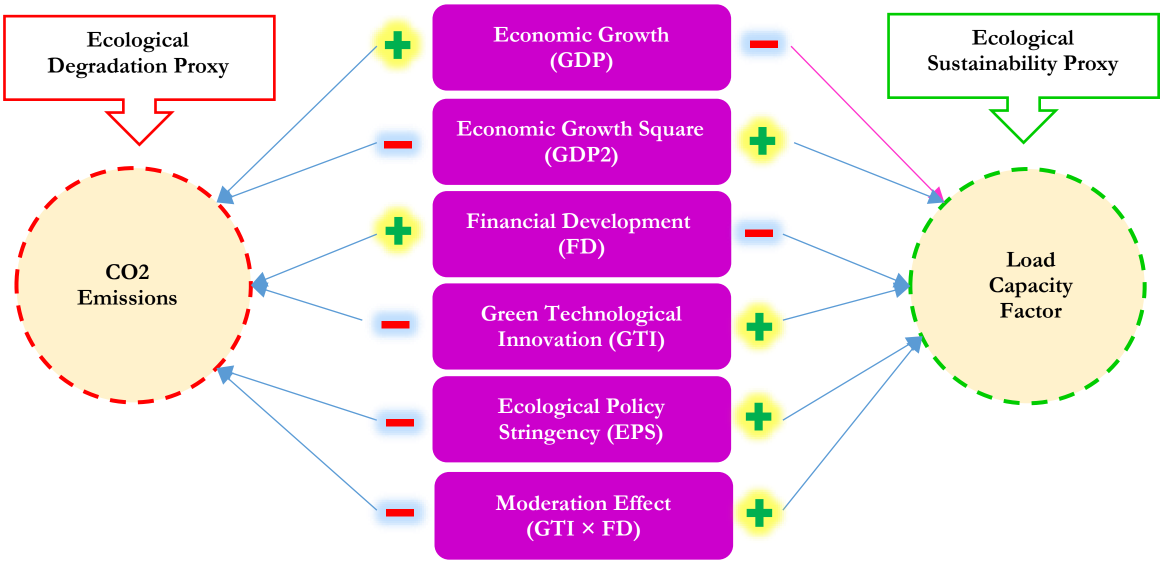

Fig. 4. Graphical summary of results.

5 | Conclusion

Although there have been many discussions on the role of GTI and FD in ecological sustainability, none has examined the role of GTI in reshaping the relationship between FD and ecological sustainability within the framework of the LCC for selected OECD economies. More specifically, this study uses balanced panel data containing countries from 1990 to 2022, and adopts MMQR approach to overcome possible CD, endogeneity, etc. The main conclusions of this study are as follows. First of all, the MMQR estimates reveal a nonlinear relationship between economic growth and ecological condition, confirming the EKC and LCC hypotheses in OECD economies. Second, FD consistently contributes to ecological deterioration across the distribution of ecological outcomes. Third, GTI exerts a uniformly beneficial effect on ecological sustainability, with stronger improvements observed in higher-degradation regimes. Fourth, EPS shows a stable and positive impact on environmental quality across all quantiles. More importantly, the favorable moderating effect of GTI on the FD-ecological sustainability nexus is identified, that is, the adverse impact of FD on ecological sustainability can be mitigated by GTI development, and the better the GTI development, the lesser the adverse impact.

5.1 | Policy Recommendations

Based on the empirical evidence derived from the OECD sample, several policy implications emerge. First, given the nonlinear relationship between economic growth and ecological conditions, policymakers should adopt growth strategies that accelerate the transition from environmentally harmful to environmentally enhancing stages, particularly by expanding clean technologies, efficiency-improving investments, and low-carbon industrial upgrading. Second, as FD consistently contributes to ecological deterioration, OECD economies should redesign financial frameworks to limit capital flows toward environmentally harmful activities and strengthen regulations that internalize environmental risks within financial markets. Third, the uniformly positive role of GTI underscores the need for sustained public and private investment in research and development, innovation incentives, and technology diffusion mechanisms, especially in high-degradation sectors where the environmental gains from GTI are largest. Fourth, the stable and positive contribution of environmental policy stringency suggests that maintaining and continuously upgrading regulatory standards, such as carbon pricing, emissions caps, and environmental compliance requirements, is essential for long-term ecological sustainability. Finally, the moderating effect of GTI on the adverse environmental impacts of FD highlights the importance of integrating innovation-oriented criteria into financial decision-making. Strengthening green finance taxonomies, expanding green credit lines, and aligning FD with innovation-driven sustainability objectives can ensure that the expansion of financial systems supports, rather than undermines, ecological quality.

5.2 | Limitations and Directions for Future Research

This study, despite its comprehensive empirical design, is subject to several limitations that open avenues for future research. First, the analysis focuses exclusively on OECD economies, which limits the generalizability of the findings to developing or non-OECD countries with different institutional, financial, and technological structures. Future studies may extend the sample to a broader set of economies. Second, the study relies on two aggregate indicators of ecological quality. Although widely used, these indicators may not fully capture multidimensional ecological pressures such as water pollution, or land-use degradation. Incorporating additional or more granular ecological indicators could yield a more nuanced understanding of ecological dynamics. Third, this research applies the MMQR approach, which effectively captures distributional heterogeneity but does not explicitly model potential endogeneity among key variables such as FD, GTI, and environmental outcomes. Future work may apply causal identification techniques, such as dynamic panel methods, instrumental variables, or structural modeling, to strengthen the robustness of the inferred relationships. Fourth, green innovation and FD are treated as aggregate measures, potentially masking sector-level or technology-specific heterogeneity. Future research could explore sectoral green innovation, the composition of financial portfolios, and the distinction between green and brown financial instruments to provide more targeted policy insights. Finally, the moderating role of GTI on the finance–environment nexus is examined in a static framework. Investigating how this moderating effect evolves over time, interacts with policy reforms, or responds to external shocks (e.g., energy crises or technological breakthroughs) represents a promising direction for further inquiry.

Authors' Contributions

R. M.: software, writing-original draft, methodology, conceptualization, data curation, and formal analysis. B. S.: methodology, investigation, writing-review and editing, and validation. M. P.: Conceptualization, and formal analysis, writing-review and editing, and validation. C. M.: writing-review and editing, research design, formal analysis, and validation. The authors have read and agreed to the published version of the manuscript.

Data Availability

Data will be made available from the corresponding author upon reasonable request.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this research.

Consent for Publication

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Ethics Approval and Consent to Participate

This study does not involve any research conducted on human participants or animals.

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