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Synthesizing eco-efficiency within EU's inclusive finance: Do environmental policy stringency and renewable energy make a difference?

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ABSTRACT

The European Union (EU) is at the forefront of policy initiatives to address worsening environmental challenges of the 21st century. Although the EU is a financially developed zone, it is still unclear if inclusive finance enhances better eco-efficiency given the economic growth drive of the continent that has triggered high eco-intensity with the resultant historical anthropogenic emissions. Hence, the incessant calls for environmental policy initiatives to tackle climate challenges. Hence, we scrutinize whether environmental policy stringency (ENI) makes difference in attaining climate goals while examining the connectedness of inclusive finance and eco-efficiency among 14 EU countries. Deploying method of Moments Quantile Regression in data analysis facilitated the incorporation of renewable energy, reliance on natural resources, and demographic factor. We observed that inclusive finance does not necessarily curtail worsening eco-intensity if ENI is absent. Essentially, while renewable energy boosts eco-efficiency, natural resources depletion and demographic factor abate EU's eco-efficiency. However, environmental policy stringency positively moderates the undesirable ecological impacts of inclusive finance in the EU. Hence, while it's recommended to keep the momentum on renewable energy investments, the EU needs to continue to leverage environmental policy stringency to curtail the impacts of financial inclusivity on the bloc's eco-intensity.

1. Introduction

Ecological degradation has become a major challenge to achieving not just environmental quality goals but also portends potential impediments to sustainable economic development targets. As aggressive natural resource exploitation persists, resource depletion and attendant environmental degradation often characterize most resource-endowed economies around the world [1]. Over time, a gradual decline in nations' total eco-efficiency tends to rise as noticeable in terms of the country's economic size to the ratio of its total ecological footprint [2]. This decline in environmental quality levels will also be reflected via the declining carbon eco-efficiency levels as more carbon tends to be emitted per unit of economic progress recorded in the country. The persistent aggressive resource exploitation can invariably diminish the stock as well as the quality of available overall economic resources, thus, translating to a decline in economic production capacity over the long run. Consequently, with lower production, the country's economic growth gradually contracts over time connoting a significant threat to sustainable economic growth objectives for countries as enunciated in the United Nations (UN)' SDG-8. Furthermore, the historical growth of pollution does not only harm individual countries, but it can also be contagious through climate change risks at a global scale. The World Bank estimates that carbon emissions on a global scale have been increasing in the last decade from 30.2 million kt in 2010 to 35.4 million kt in 2020 [3]. Thus, ensuring that economic units in countries implement eco-efficiency in their production line is crucial to minimize environmental risks in the future.

Eco-efficiency is defined as economic profit per unit of environmental impact [4]. This is one of the metrics to measure environmental quality in a country where higher eco-efficiency should correspond to higher environmental quality. Production based on eco-efficiency works by the principle of environmentally friendly techniques to use fewer natural resources and thus produce less waste or pollution. Basically, it is a concept that critically juxtaposes economic progress with environmental quality. This concept was initially introduced in the early 1990s by the World Business Council for Sustainable Development. This

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concept operates with key principles of the necessities for the reduction in waste, emissions, and resource utilization footprints while progressively maintaining the growth of an economy at the same time in a sustainable manner. By implementing this concept, a production unit is expected to gain a competitive advantage by utilizing lower resources to attain the same desired productivity level. However, although the concept of eco-efficiency is getting more popular today, its implementation and attainments are quite challenging because it requires a high cost of initial investments. Besides, implementing eco-efficiency strategies can also complicate the supply chain and business process, which is usually avoided by companies due to higher adjustment costs. Finally, customers' willingness to opt for an eco-efficient product is not always certain and this further complicates the inherent challenges of attaining eco-efficiency despite being an effective business model to ensure that a production unit's practices are environmentally sustainable. Given the importance of eco-efficiency implementation, understanding the determinants of eco-efficiency is considered crucial.

The bulk of the global footprint is traceable to the pressure of meeting up with energy demand to sustain the global economic system which has been argued to be overly dependent on fossil energy resources [5,6]. Hence, the targets of clean energy and climate actions have been highlighted amongst the sets of objectives in the famous UN's Sustainable Development Goals (SDG) 7 and 13. In this vein, many European Union (EU) countries are at the forefront of policy initiatives to address worsening environmental challenges confronting humanity in the 21st century. Although the EU is a financially developed area, it is still unclear if inclusive finance enhances better eco-efficiency given the economic growth drive of the continent that has triggered high eco-intensity with the resultant historical anthropogenic emissions [7]. Therefore, the calls for environmental policy initiatives to tackle climate challenges are growing.

We argued in this study that the desire to abate pollution levels should not be equated to the actual actions taken to reach such desired goals. Hence, considering environmental policy stringency (ENI) levels as one of the potential determinants of eco-efficiency, we scrutinize whether this factor makes any difference in attaining climate goals while examining the connectedness of inclusive finance and eco-efficiency among 14 EU countries where this indicator has been steadily rising as seen in Fig. 1. We utilized the policy stringency index provided by the OECD as it affords us the benefits of assessing the extent to which price penalties are specifically outlined for pollution as enshrined in various environmental policies [8].

Furthermore, available studies investigating the determinants of eco-efficiency within the framework of inclusive finance have not been conducted intensively. The bulk of attention seems to be solely on how eco-efficiency influences the quality of the environment rather than understanding the far more important question of how and what determines the attainments of this efficiency level. Some studies have demonstrated a positive association between eco-efficiency and environmental quality, such as demonstrated by Anu et al. (2023) [9], Hou et al. [10], Zhang et al. [11], and Saber et al. [4], among others. Zhang et al. [11] for instance, demonstrated that higher eco-efficiency is found in advanced economies compared to low-income economies. This happens most likely because developed countries have more access to the latest technology compared to the less developed ones. Hence, it is expected that there is a strong association between eco-efficiency and technological innovation. Most studies investigating eco-innovation demonstrate its positive impact on countries' environmental quality. Take for example, studies from Zhong and Kan [12], Musah et al. [13], Valero-Gil et al. [14], Zhe et al. [15], Ding et al. (2021), Jiang et al. [16], Ahmad and Wu [17] and Costantini et al. [18], among others. They agree with the result that a positive association exists between eco-innovation and environmental quality, both in the short and long run. On the aspect of financial inclusion, its environmental impacts have hitherto been only explored in some studies. For example, Zhe et al. [15], Ansari et al. [19], Zhang et al. [20], Li et al. [21], and Chen et al.

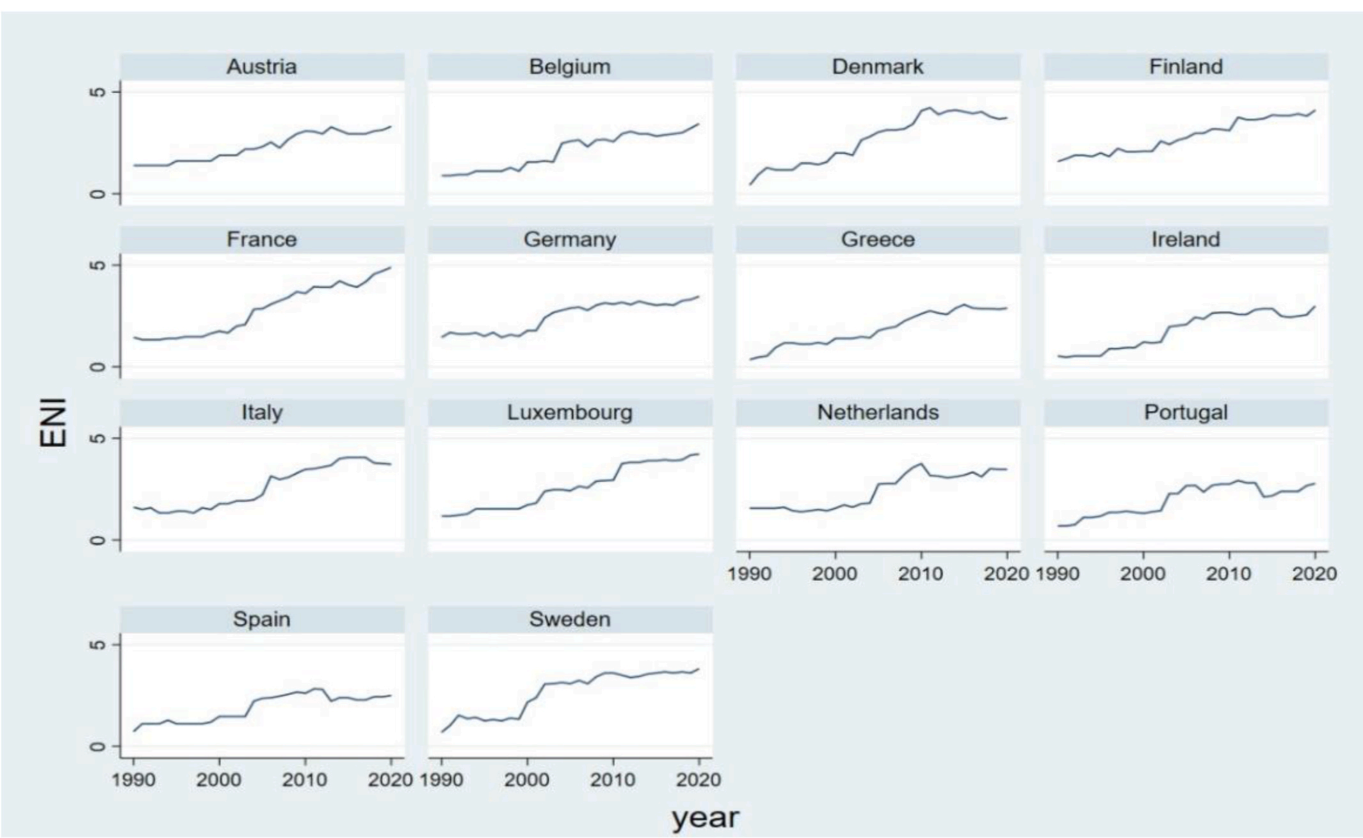


Fig. 1. Trends in environmental policy stringency levels.

[22], among others.

This study reconciles the existing gaps in the approaches taken by extant studies by specifically focusing on the grey area of the determinants of eco-efficiency. In this regard, this study focuses on examining the connectedness of inclusive finance and eco-efficiency while scrutinizing whether environmental policy stringency (ENI) level makes any difference within this connection in attaining climate goals among 14 EU countries including Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, and Sweden. Although the sample country and time-span selection were primarily based on the data availability to ensure a balanced panel set, it is good to note that these EU countries have reported a considerable relative decrease in ecological footprint in the sampled period [2]. Additionally, these countries have also extended endeavors to increase the stringency of their environmental policies in reaction to rising ecological challenges. The 14 EU members have observed a notable increase in environmental policy stringency index i.e. Austria from 1.39 to 3.31; Belgium from 0.89 to 3.44; Denmark from 0.42 to 3.72; Finland from 1.58 to 4.11; France from 1.44 to 4.89; Germany from 1.44 to 3.47; Greece from 0.36 to 2.89; Ireland from 0.53 to 3; Italy from 1.61 to 3.72; Luxembourg from 1.17 to 4.22; Netherlands from 1.56 to 3.47; Portugal from 0.69 to 2.78; Spain from 0.72 to 2.5; and Sweden from 0.69 to 3.83 in the period from 1990 to 2020 [8].

Other additional merits of the study lie in the robust approaches followed within the analytical context of the model which incorporates multiple proxies of financial inclusion and a broader measure of eco-efficiency. The latter approach justifies a better validation of results vis-à-vis a comparative analysis of the outcomes with extant studies. Lastly, the findings from this study provide useful inputs for policy-makers' consideration while formulating environmental policies on the grounds of the need to boost eco-efficiency. This study is structured as follows. The first section is an introduction. The second section literature review and detailed examination of past literature. The third section includes the empirical approaches, and the last section concludes the research.

2. Literature review

Synoptic Review of Eco-efficiency and Policy Stringency in Environmental Quality Context.

Eco-efficiency is defined as the economic profit per unit of environmental impact [4]. The goals of any environmentally-conscious production unit are to attain a maximum efficiency level by ensuring a minimum ecological footprint for every economic profit recorded. Hence, it is expected that a higher efficiency level would translate to better environmental quality performance. As such, researchers in extant studies have sort to assess how this efficiency level impacts common indicators of environmental quality. Ahmad and Wu [17] investigated this relationship in the case of 20 OECD countries. The result shows that eco-efficiency is strongly associated with higher environmental protection. Saber et al. [4] investigate the role of eco-efficiency on environmental impact in the context of farming in Iran. The study compares the differences in eco-efficiency among 200 farms. The study demonstrates that eco-efficiency is significantly associated with lower environmental impact and higher production per unit.

Given the importance of eco-efficiency on environmental quality, accommodative environmental policy and financial inclusion must be prepared to support eco-efficiency. However, this may not often be the case. For instance, Czyżewski, Smędzik-Ambroży, and Mrówczyńska-Kamińska (2020) demonstrated that local environmental policy has no significant impact in boosting eco-efficiency in the country sample. Their assertion was based on the investigation of the relationship between environmental policy and eco-efficiency in the case of Poland. A different study by Rodriguez-Garcia et al. [23] also investigated the association between eco-efficiency and environmental quality in some north and south American nations. The result shows that eco-efficiency is significantly associated with higher financial performance. Thus, with higher financial performance, a firm is expected to invest more in combating environmental degradation especially when there are adequate environmental policies and implementations. Filiou, Kesidou, and Wu [24] show that the production of green patents increases, which means higher eco-innovation when digital policies are implemented in cities that have adopted strict environmental policies. Shuliang, Linjiao, Arkoful, and Hui (2023) also demonstrate that informal environmental regulation can even be significant in improving eco-innovation.

In the context of potential investments to boost eco-efficiency, energy innovations have always dominated the discussion in the literature. This is mainly because, at the moment, most industrial production activities and the global economic system are mainly driven by conventional energy [25,26]. Therefore, to attain the needed eco-efficiency level, energy innovations must be encouraged. Anu, Singh, Raza, Nakonieczny, and Shahzad (2023) following their investigation noted that efficiency in energy utilization aids the quality of the environment. Hou et al. [10] also back this claim noting that the significant relationship is exclusively relevant in the long run and not short run. This implies that energy efficiency may require ample time to realize. On a greater scale, Zhang, Mao, Jiao, Shuai, and Zhang [11] incorporate 102 sample countries and demonstrate that higher eco-efficiency is found in higher economic developing countries than the lower. This finding is understood since developed countries have more access to the latest technology compared to the less developed ones.

Eco-innovation is a popular term in environmental studies today given the expected strong association between eco-efficiency and technological innovation [10,11]. Kemp and Pearson (2007) define eco-innovation as the modification of a production process that is novel to the organization and is environmentally risk-reducing (pollution or other negative impacts). Theoretically, Barney [27] and Hart [28] in Valero-Gil, Surroca, Tribo, Gutierrez, and Montiel [14] refer eco-innovation to a theory of natural resource-based view that associates eco-innovation and environmental quality. Horbach, Rammer, and Rennings [29] show that different types of eco-innovation are driven by different determinants. Using Germany as the sample country, the study demonstrates that firm-specific, demand factors, regulation, cost savings, and customer requirements are significant determinants of eco-innovation.

Eco-innovation has a strong correlation with environmental quality. Many studies have investigated the relationship between eco-innovation and environmental quality in various settings. Most of the studies demonstrate a positive association between eco-innovation and environmental quality. For example, Zhong and Kan [12] demonstrate that eco-innovation significantly affects environmental quality both in the short and long run in China. In both time horizons, eco-innovation is significant and negative in affecting carbon emissions. They also demonstrated that eco-innovation reflects the Environment Kuznet Hypothesis (EKC) in China. This implies that eco-innovation gradually increases environmental quality after a particular pollution threshold is reached. Chen, Rehman, Luo and Ali [22] have also provided some complementary evidence supporting the Chinese EKC on the premise of eco-innovation.

Most studies in the area of eco-innovation and environmental quality converge to the result of a positive relationship between the two. For example, Valero-Gil, Surroca, Tribo, Gutierrez, and Montiel [14] demonstrate that eco-innovation affects environmental performance positively. Specifically, more green patent production significantly increases the environmental quality. Eco-innovation in the study is proxied using two variables. The first variable is the number of green patents registered and granted by the patent office, while the second variable is the number of citations. The study is conducted at firm level, covering 266 corporations over 13 industries in the period of 2014–2016. Similarly, Anu, Singh, Raza, Nakonieczny, and Shahzad (2023) demonstrate that eco-innovation plays a key role in reducing carbon emissions and improving environmental quality. Developed countries have a better opportunity to do this than developing countries. Furthermore, in the case of G7 and G11 economies, Zhe, Su, Zhu, Mahmoud, and Akhtar [15] demonstrate that, based on a non-linear relationship, eco-innovation imposes a positive impact on environmental quality and reduces carbon emissions. This finding is also confirmed by Ding, Khattak, and Ahmad (2021) and Jiang et al. [16], both in the case of G7 countries. Furthermore, in the case of OECD countries, Ahmad and Wu [17] demonstrate that eco-innovation promotes ecological protection of the environment across all quantiles. Specifically, the significance of protection is higher in countries with higher ecological footprints compared to the lower ones. A similar finding is also found in European industries through the study from Costantini, Crespi, Marin, and Paglialunga [18] demonstrating that eco-innovation promotes clean technologies and thus reduces environmental stress. A positive and significant association between eco-innovation and environmental quality is also found in the case of the United States [30], Malaysia [31], and China [21].

2.1. Financial inclusion and environmental quality

Financial inclusion is generally defined as any effort to provide wider society with wider and more affordable financial products and services. Anu, Singh, Raza, Nakonieczny, and Shahzad (2023) demonstrate that financial inclusion positively affects ecological footprint, but it only happens in higher quantile countries where the level of ecological footprint has been high. This finding implies that financial inclusion contributes to environmental degradation. This study is investigated for developed and developing countries over 2000–2018. Financial inclusion in the study is proxied using the IMF financial inclusion index. Similarly, Liu, Chau, Duong, and Hoang (2024) [32] investigated the impact of financial inclusion on environmental quality in Vietnam over the period of 2013–2023 and demonstrated that financial inclusion deteriorates environmental quality in the country. Similarly, Saqib, Ozturk, and Usman (2023) [33] investigate the impact of financial inclusion on ecological footprints in emerging economies over 1990–2019. Holding technological innovation and renewable energy unchanged, the study also shows that financial inclusion reduces environmental degradation in emerging countries. Thus, financial inclusion must be integrated with technological innovation and renewable energy to generate a favorable impact on environmental quality. This finding signals that the development level of a country may have a significant impact on the direction of financial inclusion on environmental quality.

On the contrary, in the case of G7 and G11 economies, Zhe, Su, Zhu, Mahmoud, and Akhtar [15] demonstrate that, based on a non-linear relationship, financial inclusion promotes financial technology and then reduces carbon emissions. Ansari, Sajid, Khan, Antohi, Fortea, and Zlati [19] support this finding by demonstrating that financial inclusion helps a country like Pakistan to achieve stronger environmental quality, but it happens when financial inclusion interacts with digital finance. Likewise, Zhang, Bakhsh, Ali, and Anas (2024) demonstrate that financial inclusion significantly improves environmental sustainability in China. The study is focused on the digital financial inclusion index, which is proxied using multiple measures such as broad money growth and domestic credit to GDP ratio. Similarly, Li, Zhao, Hei, Li, and Zhang (2024) also investigate the role of financial inclusion in China and demonstrate that financial inclusion increases access to financial services and thus improves environmental quality in the country. The study uses a wide span of data samples. Chen, Rehman, Luo and Ali [22] also investigate the impact of financial inclusion on ecological footprint in the context of (EKC) hypothesis. The study was conducted for China over the period of 1980–2020 and demonstrates that financial inclusion tends to increase ecological footprint, which means reducing environmental quality, in the country. In conclusion, the relationship between financial inclusion and environmental quality does not fully converge to a consensus. Some studies demonstrate that financial inclusion is negatively correlated with environmental quality, which means reducing environmental quality. On the other hand, other studies demonstrate that financial inclusion can improve environmental quality through the provision of higher financial access.

2.2. Literature gap, merits and contributions

The current literature exploration underscores some of the major merits and contributions of this study vis-à-vis the existing gaps. Firstly, the disproportionate attention of researchers has always been concentrated on linking eco-efficiency to environmental quality but neglecting the bigger picture of investigating the potential determinant factors that influence the environment and eco-efficiency nexus. In this regard, this study focuses on environmental policy stringency as one of the grey areas of these determinants. Secondly, the study leverages advanced approaches to examine the connectedness of inclusive finance and eco-efficiency while further scrutinizing whether environmental policy stringency (ENI) level makes any difference within this connection in attaining climate goals among 14 EU countries.

3. Empirical model, data, and methodology

3.1. Data summary

This study delves into the direct influence of environmental policy stringency in an exploration of how inclusive finance and other factors like renewable energy, real GDP per capita, reliance on natural resources, and population impact eco-efficiency performance. In addition to direct impacts, this study assesses whether environmental policy stringency curtails or boosts the ecological impact of inclusive finance for 14 European Union countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, and Sweden) from 1990 to 2020. The selected time period was based on certain considerations. Firstly, the availability of environmental policy stringency data as these were available only from 1990 to 2020. The data for environmental policy stringency index were not available before 1990 and beyond 2020 thus, limiting the data span to 31 years. Due to the unavailability of environmental policy stringency index data in balanced form for Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, Romania, and Slovenia, these countries were not considered in the present study. Moreover, the Czech Republic, Estonia, Hungary, Poland, and Slovakia were eliminated as the data on ecological footprint, reliance on natural resources, and population were not available in a balanced form for the sample period.

Secondly, the focus on the selected EU members is further justified by the fact that all selected countries have reported a considerable decrease in ecological footprint in the sampled period [2]. Meanwhile, these countries have extended endeavors to increase the stringency of their environmental policies in reaction to rising ecological challenges. In addition, as of 2020, the selected EU members have a more inclusive financial system than the nations excluded from the analysis. Specifically, the 14 EU members showcased an average financial development index of 0.686, whereas the excluded members altogether have an average of 0.365 in 2020 [34]. Lastly, it is also worth noting that the understudied EU members manifested a relatively higher level of electricity generation from renewable sources. In particular, the average value of renewable electricity, as a % of the total for the 14 EU members stands at (50.357) which substantially outpaced the average reported for the excluded EU members (32.438), as well as the average for the entire EU (38.380), and the OECD (30.030) as of 2020 [35].

The response variable, total eco-efficiency, measured in constant 2015 US$/global hectare per capita, was calculated by authors by retrieving the data on ecological footprint from the Global Footprint Network database [2] and the data on real GDP per capita from the World Bank [3]. To inspect the robustness of our empirical analysis, this study employs an alternative proxy for eco-efficiency calculated by authors by dividing real GDP per capita and carbon footprint (collected from the Global Footprint Network database - [2]). Table 1 portrays the

Table 1
Essential information on variables.

Explanation and unit of measurement	Symbol	Reference
Population – Total labor force participation rate, (% of population older than 15 years)	PR	WB [3]
Income – gross domestic product - GDP per capita (constant 2015 US$)	IN	WB [3]
Reliance on natural resources (total natural resources rents/GDP)	RN	WB [3]
Environmental policy stringency index	ENI	OECD [8]
Renewable energy (renewable electricity, % total electricity generation)	RW	OECD [35]
Inclusive finance 1 (financial development index)	IFFD	IMF [34]
Inclusive finance 2 (financial institutions efficiency index)	IFFI	IMF [34]
Total eco-efficiency (IN/total ecological footprint, constant 2015 US$/global hectare per capita)	EE	GFN [2]
Carbon eco-efficiency (IN/carbon footprint, constant 2015 US$/global hectare per capita)	CE	GFN [2]

explanation of variables, units, sources, and symbols.

The explanatory variables encompass renewable energy measured by renewable electricity, % total electricity generation obtained from the Organisation for Economic Co-operation and Development (OECD) Green Growth database [35]. This study also employs two broad indicators of inclusive finance namely the financial development index (IFFD) and the financial institutions efficiency index (IFFI) derived from the International Monetary Fund (IMF, 2022). As for the environmental policy stringency, this variable was sourced from the Organisation for Economic Co-operation and Development [8]. Reliance on natural resources is measured by total natural resources rents/GDP, whereas the total labor force participation rate (% of population older than 15 years) is used as a proxy for population. The data on both variables are sourced form the World Bank [3].

The justification behind selecting eco-efficiency as a dependent variable is that it sets out the proportion of economic output to ecological deterioration, acknowledging both economic and ecological facets of sustainability [36–39]. Although eco-efficiency is a comprehensive facet of ecological sustainability, the exploration of its drivers is generally omitted. To fill the void, this study delves into the interplay between the selected independent variables and the twin features of eco-efficiency. On account of the aforesaid theoretical association between the chosen variables, this study predicts that inclusive finance may amplify or impair the eco-efficiency of EU [40–43] such that (i.e. $\frac{\partial ECE_{it}}{\partial IF_{it}} > 0 \; or \; \frac{\partial ECE_{it}}{\partial IF_{it}} < 0$). Environmental policy stringency may either ameliorate or aggravate eco-efficiency (i.e. $\frac{\partial ECE_{it}}{\partial ENI_{it}} > 0 \; or \; \frac{\partial ECE_{it}}{\partial ENI_{it}} < 0$) [44–47]. Similarly, the logical connection between the variables anticipates rather beneficial or adverse environmental impact of the reliance on natural resources (i.e. $\frac{\partial ECE_{it}}{\partial RN_{it}} > 0 \; or \; \frac{\partial ECE_{it}}{\partial RN_{it}} < 0$) [48–50]. Next, renewable energy consumption is presumed an ultimate facet to ameliorate the eco-efficiency of selected EU countries such that (i.e. $\frac{\partial ECE_{it}}{\partial RW_{it}} > 0$) [44,49,51]. We also elucidated the interplay between income and environment leaning on a discourse of EKC approach which holds if $\frac{\partial ECE_{it}}{\partial IN_{it}} > 0$ and $\frac{\partial ECE_{it}}{\partial IN2_{it}} < 0$ [13,52]. We also inspect the nexus between population and eco-efficiency while expecting the harmful environmental impact (i.e. $\frac{\partial ECE_{it}}{\partial PR_{it}} < 0$) [51–53]. ENI is predicted to moderate the interplay between inclusive finance and eco-efficiency [54–56]. The information on the descriptive statistics is detailed in Table 2.

In Table 2, the average value of real GDP per capita equals 39532.98 constant 2015 US$) and is the highest followed by carbon eco-efficiency (10287.91 constant 2015 US$/global hectare per capita) and total eco-efficiency (6142.82 constant 2015 US$/global hectare per capita). The maximum standard deviation is gauged for real GDP per capita, and the minimum is for financial institutions' efficiency index. Given the skewness values, only the population and financial development index are negatively skewed whereas all other variables are positively skewed. The kurtosis measures highlight that most of the variables are leptokurtic (value > 3) with the exemption of ENI, PR, RW, and IFFD which are platykurtic (value < 3). The essential information on correlation coefficients is tabulated in Table 3.

Given the outcomes displayed in Table 3, there is a positive correlation between total eco-efficiency and environmental policy stringency, real GDP per capita, population, renewable energy, reliance on natural resources, and financial development index whereas, total eco-efficiency is negatively correlated with financial institutions' efficiency index. Figs. 2 and 3 provide a clearer summarized depiction of how both carbon eco-efficiency and total eco-efficiency relate with the other indicators. Similarly, Table 3 highlights the positive correlation between CE and IN, ENI, PR, RW, RN, and IFFD. The negative correlation coefficient is displayed between CE and IFFI but is not statistically significant.

3.2. Theoretical underpinning and empirical model

This section elucidates the logic behind the inclusion of the explanatory variables, namely: inclusive finance, environmental policy stringency (ENI), reliance on natural resources, renewable energy, population, and real GDP per capita to explore the drivers of eco-efficiency. The present study establishes on [13,38,41,46,55,57–59] to dive into the ecological impact of the independent variables listed in Table 1. The theoretical underpinning unfolds the two opposing viewpoints on the interplay between inclusive finance and the environment [40–43,60,61]. First, by empowering people and businesses to take advantage of reasonably priced financial services, inclusive finance is not only a core determinant of economic growth but is also distinguished as one of the vital predictors of the environment. Inclusive finance drives economic growth as it generates savings, creates more employment, and encourages manufacturing. In this fashion, inclusive finance ensures that the income is distributed more harmoniously among a population and weakens the information-sharing issues that cause distrust between parties. Relating to the interplay between inclusive finance and the environment, an inclusive financial system helps in taking more reasonable financial decisions by encouraging people and businesses to exploit financial resources in a productive manner. Comfortable financial solutions and cheaper credits might attract business investments and lead to vertical or horizontal industrialization. By virtue of horizontal industrialization, business investors would enhance the manufacturing capacity that intensifies the use of natural resources and fosters ecological intensity towards ecological degradation. Individuals might also spur ecological degradation by using inexpensive credits to purchase energy-unfriendly items that cause energy waste and discourage the betterment of ecological performance. However, vertical

Table 2
Synopsis of summary statistics.

Statistics	EE	IN	ENI	PR	RW	RN	IFFD	IFFI	CE
Mean	6142.82	39532.98	2.35	57.86	26.64	0.24	0.65	0.59	10287.91
Stand. dev.	1770.38	19090.82	0.98	5.05	21.00	0.32	0.13	0.08	3627.43
Max	18346.75	112418.00	4.89	68.12	81.62	2.11	0.90	0.84	35144.22
Min	2911.35	14572.30	0.36	47.27	0.72	0.01	0.33	0.39	5157.20
Skewness	1.631	1.881	0.132	−0.286	0.862	2.741	−0.586	0.837	2.301
Kurtosis	10.338	7.206	2.029	2.116	2.775	11.601	2.660	4.254	12.051

Table 3
Synopsis of correlation outcomes.

	EE	IN	ENI	PR	RW	RN	IFFD	IFFI	CE
EE	1								
IN	0.556a	1							
p-value	*0.000*								
ENI	0.608a	0.372a	1						
p-value	*0.000*	*0.000*							
PR	0.396a	0.236a	0.226a	1					
p-value	*0.000*	*0.000*	*0.000*						
RW	0.348a	0.120b	0.384a	0.276a	1				
p-value	*0.000*	*0.012*	*0.000*	*0.000*					
RN	0.117b	0.095b	0.244	0.539a	0.155a	1			
p-value	*0.015*	*0.048*	*0.000*	*0.000*	*0.001*				
IFFD	0.419a	0.302a	0.528a	0.221a	0.002	0.074	1		
p-value	*0.000*	*0.000*	*0.000*	*0.000*	*0.972*	*0.123*			
IFFI	−0.015	0.117b	−0.041	0.314a	−0.129a	0.262a	0.227a	1	
p-value	*0.754*	*0.015*	*0.399*	*0.000*	*0.007*	*0.000*	*0.000*		
CE	0.903a	0.349a	0.563a	0.391a	0.398a	0.204a	0.330a	−0.036	1
p-value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.449*	

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance.

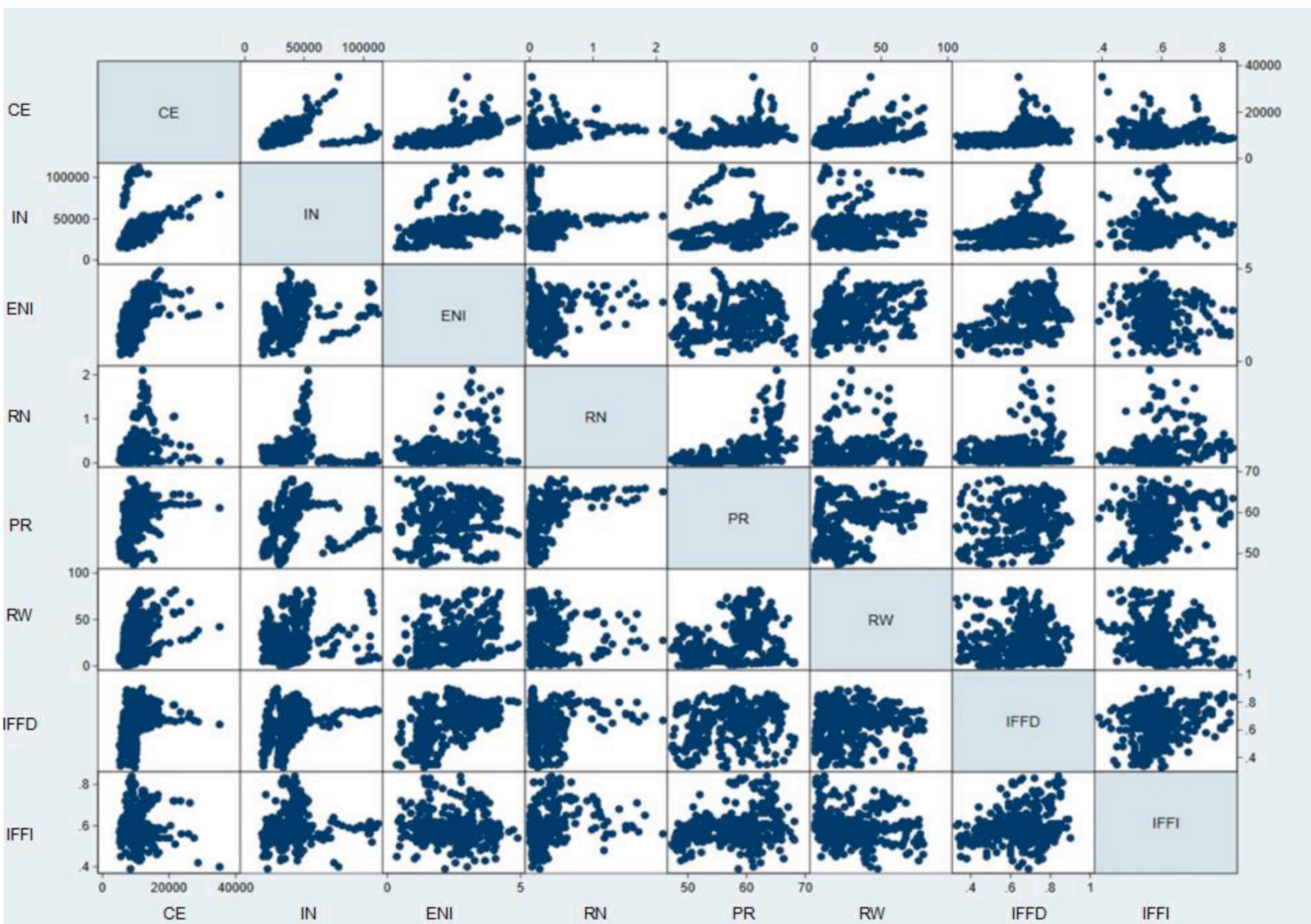


Fig. 2. Scatter plot of carbon eco-efficiency's interaction with other indicators.

industrialization may encourage ecological sustainability by introducing new technologies that could adopt industrial plants to become more efficient and alleviate anthropogenic emissions from industrial processes. Easy-to-use credit services need to be used in a more sustainable manner in households that will purchase energy-saving products, implicitly supporting the advancement of ecological performance. Through the lens of these channels, the interplay between inclusive finance and the environment is still undecided. Doing this is quite imperative for this study considering that the levels of IFFD has relatively grown among all the EU countries, while IFFI has remained largely dynamic as its performance varies across the countries as seen in Figs. 4 and 5 respectively.

Environmental policy stringency (ENI) allows the exploration of the interplay between the stringency of policies and ecological performance

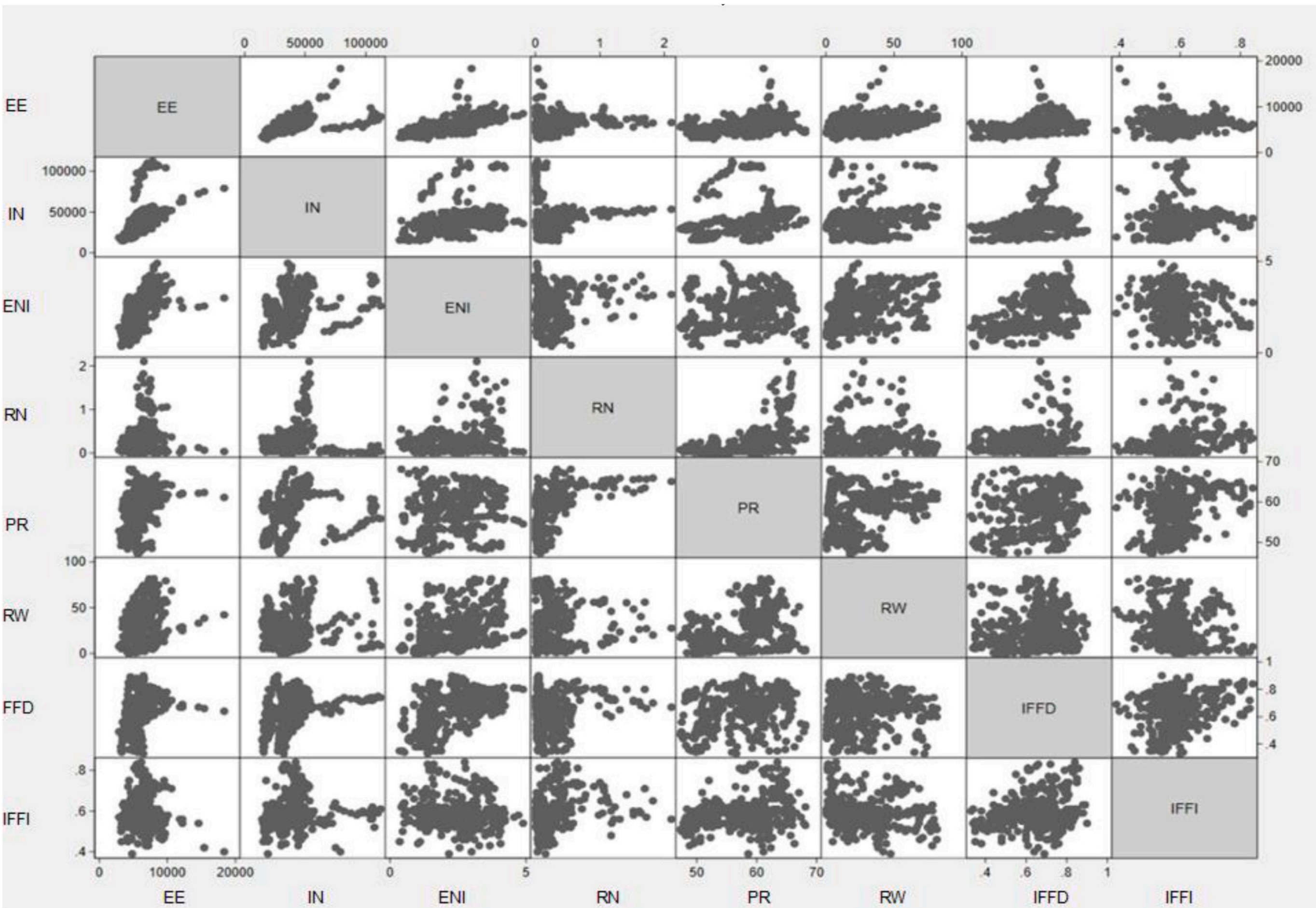


Fig. 3. Scatter plot of total eco-efficiency's interaction with other indicators.

to prevent regressive policy effects. Two distinct strands of argument evidence indecisive conclusion on the nexus between ENI and the environment [44–47,58]. First, ENI may boost the ecological performance by putting higher price on eco-unfriendly behavior. More stringent environmental policies aim to uphold the cost of polluting activities, ultimately inspiring households, and businesses to move in the direction of more environmentally unhazardous production and consumption. Subsequently, it could turn out to be necessary to restrain unhealthy components, which might drive up the cost of contaminating activities and encourage businesses to reduce or eliminate these activities. By imposing more stringent environmental policies, larger energy consumers might be replaced with energy-efficient gadgets, being the motivation to switch to renewable energy for ecological sustainability. The second argument claims that costs associated with more stringent environmental policies circumvent businesses to opt for green technologies and impede them from considering industrial upgrading for green growth. Moreover, rising costs restrict businesses from pursing the transition towards renewable energy that prioritizes eco-efficiency. A more feasible argument supporting the adverse environmental impact of ENI is the weak organization of environmental legislation that does not encourage the business sector to lean toward low-carbon technologies that can alleviate the harmful impact of anthropogenic emissions. Consequently, developed countries are exporting their eco-unfriendly operations to countries with poor enforcement of environmental legislation to circumvent the increasing cost due to compliance with environmental legislation.

Renewable energy (RW) is an additional core element that is acknowledged to have an impact on the eco-efficiency of the European Union [62]. Given the rising environmental issues, transitioning to renewable energy has been scrutinized yardstick to help the betterment of the environmental quality. Any attempts to elucidate these issues directly related to energy use and generation, request for alternatives to fossil fuels. Being derived from nature, renewable energy is a viable alternative to fossil fuels in powering a safer energy future [44,49,51,59,63]. Also, RW emits little or zero pollutants and is mostly less expensive in comparison with fossil fuels guiding countries to shift towards energy generated from water, wind, or sun. Renewable energy adds to economic output while shrinking the consumption of dirty energy that deters the environmental quality. Given that renewable sources can generate energy accompanied by the environmental betterment impact, RW is recognized as a vital element to ease the environmental pressure attributable to fossil fuels. Herein, clean energy sources pave the way to eco-efficiency for ecological sustainability. In view of this, the utmost targets of Sustainable Development Goals (SDGs) can be reached via the means of clean energy transition.

It is of vital importance to explore the interplay between reliance on natural resources and eco-efficiency as overutilization of natural resources might be destructive for the environment [48–50,57]. However, there are two conflicting standpoints on the environmental impact of RN. First, the exploitation of natural resources is among the top energy gluttons and as such drives up pollutant emissions. Herein, the unstainable consumption of natural resources does not only reduces the quality and quantity of the available resources but also escalates the environmental pressure. Second, reliance on natural resources might alleviate environmental deterioration by using natural resource funds to support renewable energy projects and technological innovation to make extraction activities more sustainable [64]. Among the other independent variables, our study adopts the premise of the environmental

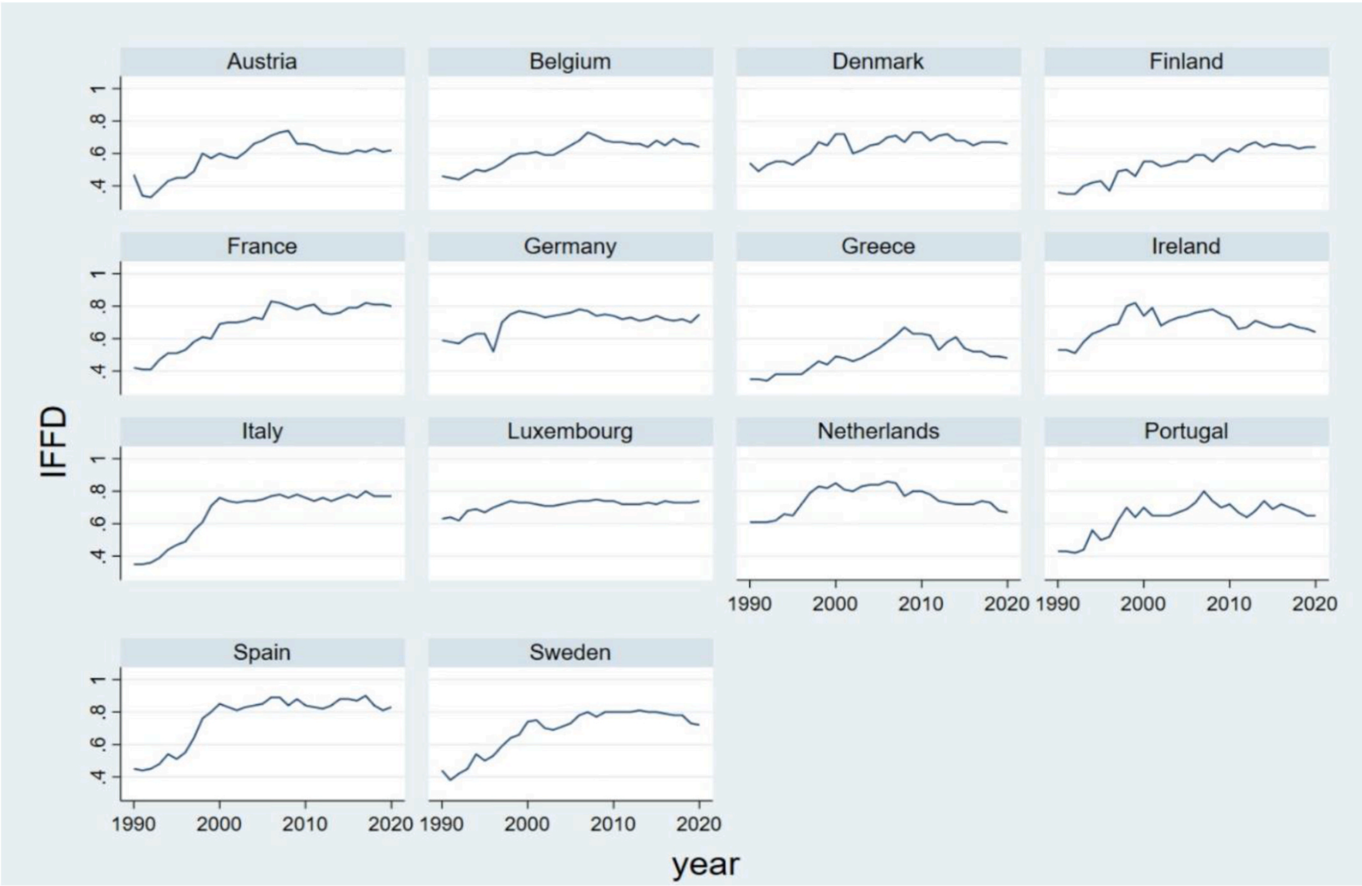


Fig. 4. Trends in financial development index (yearly).

Kuznets curve (EKC) hypothesis assuming that the advanced income (IN) deters the environmental quality in the developmental stages but elucidates the beneficial environmental impact at the higher stages of growth positing and inverted U-type interplay between IN and the environment [13,52,65,66]. An increasing population consumes more resources being the cause of environmental pollution (ENP). Population also increases energy consumption ultimately aggravating the energy-related anthropogenic emissions [51–53,57]. Lastly, this study unveils the role of environmental policy stringency in moderating the effect of financial inclusion on eco-efficiency [54–56,67,68]. By implementing increasing stringency levels, financially inclusive systems might direct affordable loans to speed up the development of low-carbon technologies. Furthermore, utilizing accessible financial services, more stringent environmental legislation might reinforce research and development expenditure to develop green technologies by curtailing the cost of their development.

Bearing in mind the previously described theoretical underpinnings, this study leans on a prominent discourse of the EKC hypothesis whereby income is the pivotal determinant of the environment. Additionally, the on-hand study incorporates inclusive finance, environmental policy stringency, renewable energy, reliance on natural resources, and population to adopt the model, as portrayed below (Eq. (1)):

$$ECE_{it} = f(IN_{it}, IN2_{it}, PR_{it}, RW_{it}, ENI_{it}, RN_{it}, IF_{it}) \quad (1)$$

To cope with potential heteroskedasticity and serial correlation impediment, all the accommodated variables were converted to the natural logarithm. We can modify Equation (1) in the log-linear pattern as (Eq. (2)):

$$LECE_{it} = \omega_0 + \omega_1 LIN_{it} + \omega_2 LIN2_{it} + \omega_3 L\,PR_{it} + \omega_4 LRW_{it} + \omega_5 LENI_{it} + \omega_6 LRN_{it} + \omega_7 LIF_{it} + \varepsilon_{it} \quad (2)$$

In Equation (2), $\omega_1 - \omega_7$ signal the parameters of income (IN), income squared (IN2), population (PR), renewable energy (RW), environmental policy stringency (ENI), reliance on natural resources (RN), the twin aspects of inclusive finance (IF) namely (financial development index – IFFD, and financial institutions efficiency index – IFFI). Also, ECE delineates the twin features of eco-efficiency (IN/total ecological footprint – EE, and IN/carbon footprint – CE) which is an advanced framework relative to ecological sustainability. *L* is the portrayal of natural logarithm, *i* stands for the selected EU countries, *t* is the chosen time-span, ω_0 is the intercept while ε_{it} indicates error terms. Accordingly, the econometrics specification in Equation (2) is modified to accommodate for interaction term between ENI and IF as in Equation (3):

$$LECE_{it} = \omega_0 + \omega_1 LIN_{it} + \omega_2 LIN2_{it} + \omega_3 L\,PR_{it} + \omega_4 LRW_{it} + \omega_5 L\,Mod_{it} + \omega_6 LRN_{it} + \omega_7 LIF_{it} + \varepsilon_{it} \quad (3)$$

Such that Mod = ENI*IF. We predict that inclusive finance eases the ecological pressure through the channel of environmental policy stringency (i.e. $\frac{\partial ECE_{it}}{\partial ENI_{it} * IF_{it}} > 0$) gauging that the joint impact of ENI and IF would be of the pivotal drivers of ecological sustainability.

3.3. Estimation procedures

The estimation procedure of the current study is based on six steps (see Fig. 6). A comprehensive elaboration of each step is given below. To avoid biased empirical results, it is essential to assess the existence of the cross-sectional dependence (DEP) and slope heterogeneity (SHR) issues in panel data.

To begin with the assessment of DEP, this study leans on the test developed by Pesaran [69]. It also safeguards the application of the

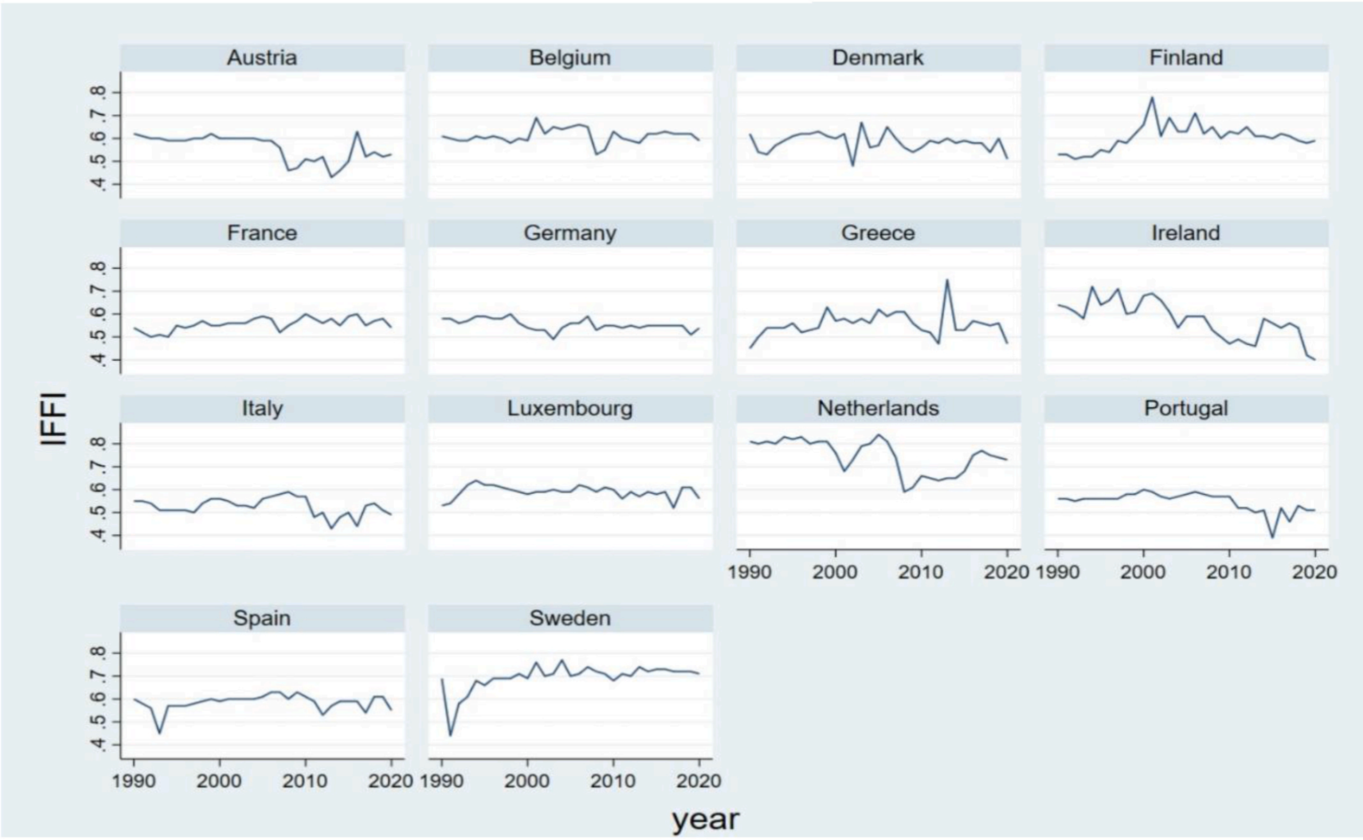


Fig. 5. Trends in financial institutions' efficiency index (yearly).

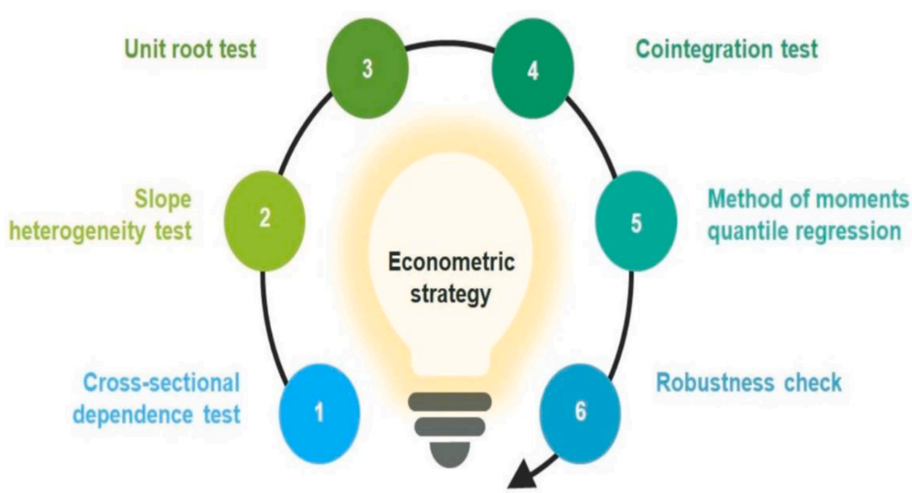


Fig. 6. The estimation procedures.

econometrics methods that cope with the DEP issue. The mathematical expression of the Pesaran [69] DEP test is provided as:

$$CD=\sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}\right) \tag{4}$$

In Eq. (4), T depicts the time, N cross-sections and $\widehat{\rho}_{ij}$ correlation. In particular,

$$\widehat{\rho}_{ij}=\widehat{\rho}_{ji}=\frac{\sum_{t=1}^{T}\varepsilon_{it}\varepsilon_{jt}}{\left(\sum_{t=1}^{T}\varepsilon_{it}^2\right)^{\frac{1}{2}}\left(\sum_{t=1}^{T}\varepsilon_{jt}^2\right)^{\frac{1}{2}}} \tag{5}$$

The test statistics displayed in Eq. (4) hypothesize H_0 of "no DEP" whereas alternative hypothesis assumes the presence of cross-sectional dependence. Our preliminary analysis further integrates the assessment of slope heterogeneity to secure the consistent and unbiased findings. In this vein, this study makes use of Pesaran and Yamagata [70] SHR test described as (Eqs. (6) and (7)):

$$\widehat{\Delta}_{SHR} = \sqrt{N}\cdot\sqrt{2k}\cdot\left(N^{-1}\cdot\widehat{S}-k\right) \tag{6}$$

$$\widehat{\widehat{\Delta}}_{ASHR} = \sqrt{N}\cdot\left(\frac{2k\cdot(T-k-1)}{T+1}\right)^{-1/2}\cdot\left(N^{-1}\cdot\widehat{S}-2k\right) \tag{7}$$

Such that, $\widehat{\Delta}_{SHR}$ signals the SHR and ASHR adjusted SHR statistics. Under the null hypothesis, slopes are homogenous, while the alternative hypothesis presumes the viability of SHR issue. Differing from the first-generation unit root tests (URTs), the second-generation URTs allow accommodating the DEP and SHR issues. Perceived upon it, this study uses the augmented cross-sectional Im, Pesaran and Shin test (CIPS) by Pesaran [71], to check for the UR facets of the study variables. The test statisics is reported as (Eq. (8)):

$$CIPS = N^{-1}\sum_{i=1}^{n} CADF \tag{8}$$

With the mathematical expression of Cross-sectional Augmented Dickey-Fuller (CADF) as following (Eq. (9)):

$$\Delta Y_{it} = \rho_i + \rho_i Y_{it-1} + \rho_i X_{t-1} + \rho_i T + \sum_{j=1}^{n}\rho_{ij}\Delta Y_{it-j} + \theta_{it} \tag{9}$$

In Eq. (9), Y_{it} are the study variables, Δ is the sign for the first difference and θ_{it} depicts the error term. To check the existence of the long-run interplay between IN, IN2, PR, RW, ENI, RN, IF, and eco-efficiency, this study makes use of the cointegration test by Westerlund [72]. The null hypothesis highlights no cointegration (CGR), and its non-validation will thereby highlight the presence of CGR.

For the principal empirical assessment, this study exploits the Method of Moments Quantile Regression (QLR) by Machado and Silva [73]. Unlike traditional panel data estimators that only report the mean effects and overlook the discrepancy across EU nations with different levels of eco-efficiency, QRL details the findings across heterogeneous quantiles of EE and CE [74]. Moreover, mean effects estimators yield estimates for the entire sample, neglecting the distributional features of the investigative laboratory of countries. To resolve this matter, QRL produces estimates at heterogeneous quantiles of EE and CE [75]. This further enhances the robustness of QLR as it permits the variability of eco-efficiency to change across its subsequent predictors [76]. The selection of this sophisticated method is motivated by the fact that it yields efficient results in the case of outliers [74]. In addition, there is no requirement to meet distributional assumptions and QLR accommodates the DEP and SHR issues in panel data of the selected European Union countries. As such, QRL endorses a more nuanced understanding of how financial inclusion and environmental policy stringency impact EE and CE at the diverse positions in the distribution. Additional motivation for selecting this econometric strategy is justified on the ground that it allows the control of individual effects and provides efficient outcomes in the case of endogeneity issues [75]. Moreover, QRL matches the research objective of incorporating the non-linear relationship between income and ecological efficiency [77]. This is because it does not rigorously rely on the normal distribution and can work well in the case of small T. Due to its capacity to set up the non-linear nexus between eco-efficiency and its subsequent determinants, QLR is chosen to mean effects models. With the utilization of QRL, the current research designs policy implications that keen to dive into the specific ecological prospects of the selected EU members as the effects of factors such financial inclusion, environmental policy stringency, reliance on natural resources, renewable energy, income and population may differ significantly across countries with low, middle, and high levels of eco-efficiency [76]. For instance, the implication of renewable energy on eco-efficiency may be more substantial in countries where eco-efficiency is higher than at lower quantiles of EE. The QRL model applied in this study is reported as (Eq. (10)):

$$Q_{Y_{it}}(\tau|X_{it}) = \alpha(\tau)' X_{it} + \beta_i, i = 1, \dots, N, t = 1, \dots, T \tag{10}$$

Here Y_{it} displays the LEE, X_{it} is the representation of LIN, LIN2, LPR, LRW, LENI, LRN and LFI, $\alpha(\tau)$ signals the unknown coefficients, β_i is the individual effect. Especially, our baseline and augmented models are given as (Model 1 – Eq. (11); Model 2 – Eq. (12); Model 3 – Eq. (13); Models 4 – Eq. (14)):

$$Q_{LEE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LENI_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFD_{it} + \beta_i \tag{11}$$

$$Q_{LEE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LENI_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFI_{it} + \beta_i \tag{12}$$

$$Q_{LEE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LMod1_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFD_{it} + \beta_i \tag{13}$$

$$Q_{LEE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LMod2_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFI_{it} + \beta_i \tag{14}$$

Such that, Mod1 = ENI*IFFD and Mod2 = ENI*IFFI.

To judge the soundness of our baseline model, we are scrutinizing the robustness of baseline results. In this respect, we employ the ordinary least square with Driscoll-Kraay standard errors (OLS-DK) to re-estimate the models 1–4. To validate our baseline findings, this study also accommodates the alternative indicator of eco-efficiency (IN/carbon footprint) providing the following model specifications (Eq. (15)–(18)):

$$Model5: Q_{LCE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LENI_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFD_{it} + \beta_i \tag{15}$$

$$Model6: Q_{LCE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LENI_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFI_{it} + \beta_i \tag{16}$$

$$Model7: Q_{LCE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LMod1_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFD_{it} + \beta_i \tag{17}$$

$$Model8: Q_{LCE}(\tau|X_{it}) = a_{1\tau}LIN_{it} + a_{2\tau}LIN2_{it} + a_{3\tau}LPR_{it} + a_{4\tau}LRW_{it} + a_{5\tau}LMod2_{it} + a_{6\tau}LRN_{it} + a_{7\tau}LIFFI_{it} + \beta_i \tag{18}$$

Here, CE stands for the carbon eco-efficiency.

4. Results and discussion

In view of the DEP and SHR concerns of longitudinal data, the current study uses the test by Pesaran [69] and Pesaran and Yamagata [70] prior to the assessment of regression coefficients. The results of DEP tests for inspected models are placed in Table 4. The statistically significant values of DEP tests establish the cross-sectionally dependent pattern of our models.

In particular, the outcomes detailed in Table 4 exposed that the null hypothesis of no DEP is denied at a 1 % significance level manifesting that regional integration in EU provokes interconnectedness bringing out the DEP concern. Herein, shocks of environmental policy stringency, inclusive finance, renewable energy, population, reliance on natural resources, income, or eco-efficiency in one the EU members will be influencing the other countries in EU. The findings of Pesaran and Yamagata [70] SHR tests are demonstrated in Table 5.

Results in Table 5 prompt us to decline the null hypothesis and to figure out the absence of homogeneous slopes. The values of delta and delta adjusted substantiated that specified models have a heterogeneous

Table 4
Synopsis of cross-sectional dependence outcomes.

Test/ Model	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LEE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LEE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LCE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LCE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)
Pesaran CD	9.88a	9.30a	9.88a	9.30a	18.34a	18.42a	18.34a	18.42a
p value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance.

slope. Given that our findings offer strong evidence on the presence of DEP and SHR concerns, it is necessary to employ the second-generation URT to check the stationary level of studied variables, as documented in Table 6.

The outcomes of CIPS test (Table 6) signify that income, income squared, population, and reliance on natural resources constitute the URT concern at the level. Nevertheless, first differencing of panel data affirms the stationary properties of our variables. Hence, all of the chosen variables validate the absence of URT. Table 7 establishes the outcomes of Westerlund's [72] technique.

Results in Table 7 manifest the rejection of H_0 on no long-run association at a 5 % significance level. It can be noticed from the Westerlund's [72] scores that the components responsible for eco-efficiency, namely environmental policy stringency, inclusive finance, renewable energy, population, reliance on natural resources, and income are cointegrated and advance together in the long-run. Table 8 details the empirical outcomes of the formal analysis by summarizing the elasticity coefficients.

Subsequent to certifying the long-run association between eco-efficiency and its predictors, the current study applies QLR econometric technique to estimate the respective elasticity coefficients. Table 8 showcases the elasticity estimates at the odd quantiles whereas Fig. 7 (panel A to D) displays the impact of independent variables on eco-efficiency at even quantiles. The first finding of QLR is that environmental policy stringency positively influences EE across EU members with low, middle, and high levels of eco-efficiency. The effect of ENI is statistically significant across all quantiles and weakens from the 10th to 90th quantiles, suggesting that more stringent environmental legislation may harm eco-intensity thus boosting ecological sustainability of EU members. Thus, environmental policy stringency manifests an EE advancement effect, subsequently decreasing for middle and upper quantiles of eco-efficiency. Models 1 and 2 depict only the direct influence, whereas models 3 and 4 assess the interaction term between ENI and the twin indicators of financial inclusion. The favorable ecological impact of ENI can be justified in that more stringent environmental legislation punishes polluting behavior by escalating the costs associated with eco-unfriendly activities. Along these lines, stricter environmental policies imposed by governments may incentivize the business sector to make necessary steps towards eco-friendly production. Considering the households, environmental policy action might motivate individuals to substitute energy-draining items with high-efficiency appliances for an eco-efficient future. Another viable reasoning of the eco-efficiency improvement impact of ENI is that it concentrates on mitigating climate change by forfeiting the advancement of new technologies that adopt low carbon energy and optimize energy utilization. This result endorses the earlier findings of Li et al. [45] manifesting that environmental policy stringency advances the environmental performance of emerging countries. Herein, environmental sustainability is indispensably linked with stricter environmental policies. The favorable environmental impact of ENI has also been adopted in recent research by Liu et al. [46] delineating that ENI scales down the anthropogenic emissions of BRICS countries insinuating that environmental policy actions play a substantial role in ecological sustainability. Similarly, Ahmad and Satrovic [43] performed the analysis on the sample of OECD countries and showed that environmental legislation eases the environmental pressure of developed economies. To further enhance the robustness of the eco-efficiency advancement impact of ENI, our study opts for the more recent empirical evidence by Ref. [58]. They unveiled that stringent implementation of environmental standards alleviates carbon

Table 6
Synopsis of unit root outcomes.

Variables	Level	First diff.	Variables	Level	First diff.
	C&T	C&T		C&T	C&T
LEE	3.710a	−6.019a	LRN	−2.455	−5.610a
LIN	−2.202	−3.305a	LIFFD	−3.687a	−6.148a
LIN2	−2.179	−3.302a	LIFFI	−4.079a	−6.204a
LENI	−4.056a	−5.812a	LCE	−2.927b	−5.811a
LPR	−2.016	−5.070a	LMod1	−4.082a	−5.847a
LRW	−3.539a	−5.917a	LMod2	−3.852a	−6.142a

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance, C - constant and T - trend.

Table 7
Synopsis of cointegration outcomes.

Test/ Model	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)
Variance ration	−2.189b	−2.008b	1.879b	2.198b
p value	*0.014*	*0.022*	*0.031*	*0.014*

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance.

Table 5
Synopsis of slope heterogeneity outcomes.

Test/ Model	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LEE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LEE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LCE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LCE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)
Delta	12.30a	11.82a	12.30a	11.82a	14.10a	13.47a	14.10a	13.47a
p value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*
Delta adj.	14.60a	14.03a	14.60a	14.03a	16.73a	15.99a	16.73a	15.99a
p value	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance.

Table 8
Synopsis of OLS-DK and QLR (LEE – dependent variable).

Model	Var./QR	OLS-DK		10		30		50		70		90	
		Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.
LEE = f(LIN, LIN2, LPR, LRW,	LIN	−2.023b	0.023	−2.191	0.105	−2.105b	0.024	−2.026b	0.010	−1.958b	0.036	−1.838	0.235
LENI, LRN, LIFFD)	LIN2	0.129a	0.002	0.136b	0.032	0.133a	0.002	0.129a	0.000	0.126a	0.004	0.121c	0.095
	LPR	−0.286b	0.033	−0.386	0.135	−0.335c	0.060	−0.288c	0.054	−0.248	0.164	−0.177	0.549
	LRW	0.064a	0.000	0.064a	0.000	0.064a	0.000	0.064a	0.000	0.065a	0.000	0.065a	0.000
	LENI	0.129a	0.000	0.132a	0.000	0.130a	0.000	0.129a	0.000	0.128a	0.000	0.125a	0.000
	LRN	−0.027a	0.003	−0.023c	0.056	−0.025a	0.003	−0.027a	0.000	−0.028a	0.001	−0.030b	0.032
	LIFFD	−0.084a	0.008	−0.075	0.214	−0.080c	0.057	−0.084b	0.017	−0.087b	0.037	−0.093	0.177
LEE = f(LIN, LIN2, LPR, LRW,	LIN	−2.432a	0.001	−2.460b	0.045	−2.447a	0.005	−2.432a	0.001	−2.420a	0.005	−2.399c	0.087
LENI, LRN, LIFFI)	LIN2	0.147a	0.000	0.148b	0.010	0.148a	0.000	0.147a	0.000	0.147a	0.000	0.146b	0.027
	LPR	−0.309b	0.024	−0.351	0.167	−0.331c	0.070	−0.309b	0.038	−0.291	0.100	−0.260	0.371
	LRW	0.061a	0.000	0.061a	0.000	0.061a	0.000	0.061a	0.000	0.062a	0.000	0.062a	0.000
	LENI	0.111a	0.000	0.111a	0.000	0.111a	0.000	0.111a	0.000	0.110a	0.000	0.110a	0.000
	LRN	−0.029a	0.001	−0.027b	0.023	−0.028a	0.001	−0.029a	0.000	−0.030a	0.000	−0.032b	0.017
	LIFFI	−0.218a	0.001	−0.200b	0.013	−0.209a	0.000	−0.218a	0.000	−0.226a	0.000	−0.239b	0.010
LEE = f(LIN, LIN2, LPR, LRW,	LIN	−2.023b	0.023	−2.191	0.105	−2.105b	0.024	−2.026b	0.010	−1.958b	0.036	−1.838	0.235
LMod1, LRN, LIFFD)	LIN2	0.129a	0.002	0.136b	0.032	0.133a	0.002	0.129a	0.000	0.126a	0.004	0.121c	0.095
	LPR	−0.286b	0.033	−0.386	0.135	−0.335c	0.060	−0.288c	0.054	−0.248	0.164	−0.177	0.549
	LRW	0.064a	0.000	0.064a	0.000	0.064a	0.000	0.064a	0.000	0.065a	0.000	0.065a	0.000
	LMod1	0.129a	0.000	0.132a	0.000	0.130a	0.000	0.129a	0.000	0.128a	0.000	0.125a	0.000
	LRN	−0.027a	0.003	−0.023c	0.056	−0.025a	0.003	−0.027a	0.000	−0.028a	0.001	−0.030b	0.032
	LIFFD	−0.213a	0.000	−0.207a	0.009	−0.210a	0.000	−0.213a	0.000	−0.215a	0.000	−0.219b	0.016
LEE = f(LIN, LIN2, LPR, LRW,	LIN	−2.432a	0.001	−2.460b	0.045	−2.447a	0.005	−2.432a	0.001	−2.420a	0.005	−2.399c	0.087
LMod2, LRN, LIFFI)	LIN2	0.147a	0.000	0.148b	0.010	0.148a	0.000	0.147a	0.000	0.147a	0.000	0.146b	0.027
	LPR	−0.309b	0.024	−0.351	0.167	−0.331c	0.070	−0.309b	0.038	−0.291	0.100	−0.260	0.371
	LRW	0.061a	0.000	0.061a	0.000	0.061a	0.000	0.061a	0.000	0.062a	0.000	0.062a	0.000
	LMod2	0.111a	0.000	0.111a	0.000	0.111a	0.000	0.111a	0.000	0.110a	0.000	0.110a	0.000
	LRN	−0.029a	0.001	−0.027b	0.023	−0.028a	0.001	−0.029a	0.000	−0.030a	0.000	−0.032b	0.017
	LIFFI	−0.329a	0.000	−0.311a	0.000	−0.319a	0.000	−0.329a	0.000	−0.336a	0.000	−0.349a	0.000

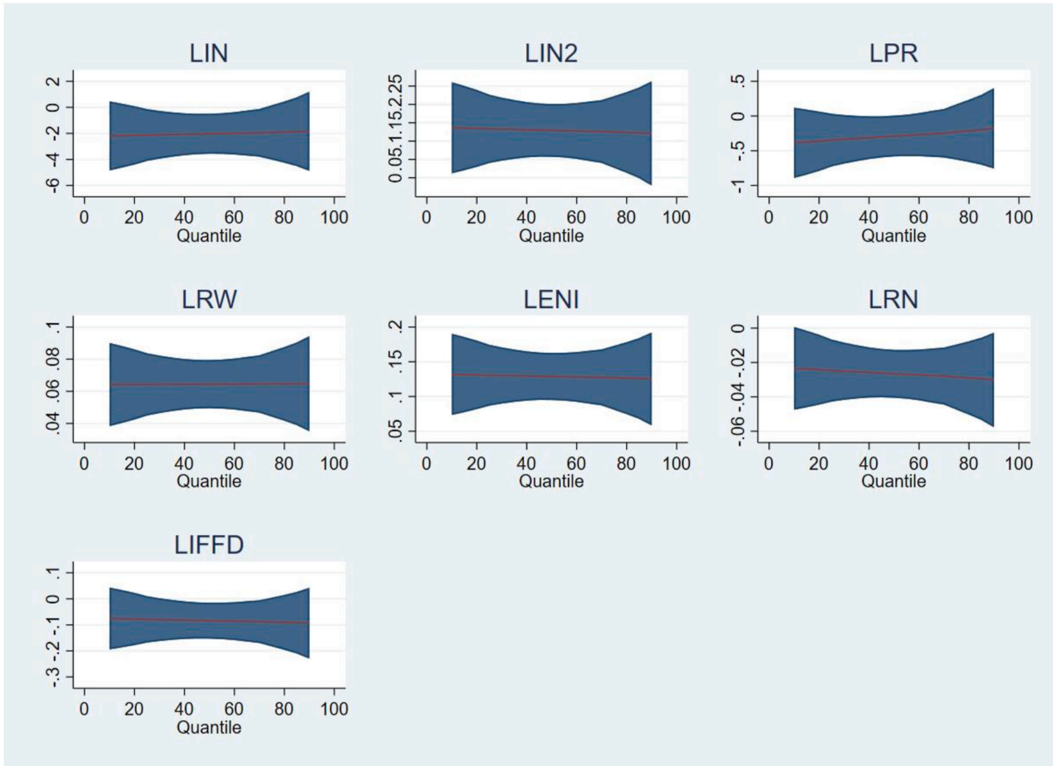
Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance, QR – quantile regression.

emissions. As such ENI is acknowledged a critical tool in controlling pollutant emissions for more sustainable future.

The second finding of QLR is that financial inclusion instigates the ecological deterioration of the selected EU member states. Notably, the negative coefficient values of inclusive finance elucidate the decrease in eco-efficiency due to a rise of financial development index (Model 1), and financial institutions efficiency index (Model 2). These findings assert a harmful ecological impact of inclusive finance. In addition, the findings manifest the declining effect from 10th quantile to 90th quantile, statistically significant from 30th quantile to 80th quantile (Model 1) and across all quantiles (Model 2). It underscores that more inclusive financial system would be harmful for eco-efficiency especially across the inspected countries with lower levels of EE. According to the outcome presented in Tables 8 and in Fig. 7 (Panel A to D), more inclusive financial systems aid into ecological pressure of EU members. The harmful damaging ecological impact of inclusive finance can be clarified in that affordable loans might assist business sector to pursue for horizontal industrialization that will increase manufacturing. Intensified manufacturing will demand more resources from nature, and their extraction is likely to enlarge energy consumption and accordingly produce more pollutant emissions. Pertaining to households, inclusive financial systems might drive towards ecological sustainability by enabling individuals to buy households items that use the most energy. Another justification is that more inclusive financial systems enable business to access cheap loans necessary to establish a business or to broad their ongoing business. If not accompanied by technological advancement, this scenario is likely to yield harmful ecological impacts. Herein, this increase in output attributable to financial inclusion is likely to instigate energy utilization and subsequently boosts the emissions of pollutants. Previous studies lend credence to this outcome as they communicated the ecological harmful impact of financial inclusion. For instance, Ullah et al. [41] came to analogous conclusion gauging that IF amplifies the emission of pollutants in developed countries. Likewise, inclusive financial systems are degrading the ecological sustainability in Africa underscoring the positive link of IF on carbon emissions [40]. In the same fashion, Habiba et al. [42] performed the assessment of the interplay between IF and environment outlining that financial inclusion might help in worsening the environmental quality of low-carbon economies. Another study in the context of European countries portrayed the adverse ecological impact of financial development uncovering its positive link with carbon dioxide emission [61]. Similarly [60], configured that financial inclusion may jeopardize the utilization of low carbon energy and intensify carbon intensity of energy generation in the sample of EU members.

Continuing with the third finding of QLR, it can be exhibited that renewable energy is a significant driver of eco-efficiency. The empirical outcomes affirm that renewable energy positively impacts eco-efficiency for ecological sustainability of EU members. In other words, by utilizing more low carbon energy, the selected countries affirm their ecological purity. It has been portrayed in Table 8 that all coefficients of RW are statistically significant and positive with an increasing trend. Consequently, as EU members use more renewable energy, their environmental performance is upgraded, with a stronger endowment in the EU members with relatively high eco-intensity. The eco-efficiency betterment effect of renewable energy is less substantial for lower quantiles and grows strongly for middle and upper quantiles of EE. Thus, renewable energy more profoundly fortifies the ecological purity of EU members with higher levels of eco-efficiency. According to the empirical outcomes outlined in Table 8 and Fig. 7, the EU members may reach the conclusion that it is critical to substantiate growth in the long-run by guaranteeing the energy transition that will ensure the responsible utilization of material capital. The justification for the affirming environmental impact of renewable energy is that the generation of RW produces minor or no contamination and is generally cheaper than non-renewable sources. As such, RW has a potential to further boost manufacturing while keeping the pollution at the same level or even boosting the reduction of emissions. Herein, renewable energy is approved as a source of energy that generates more energy with favorable environmental impact. Another plausible reasoning of the positive ecological impact of RW is that it opens the window of opportunities to

Panel A



Panel B

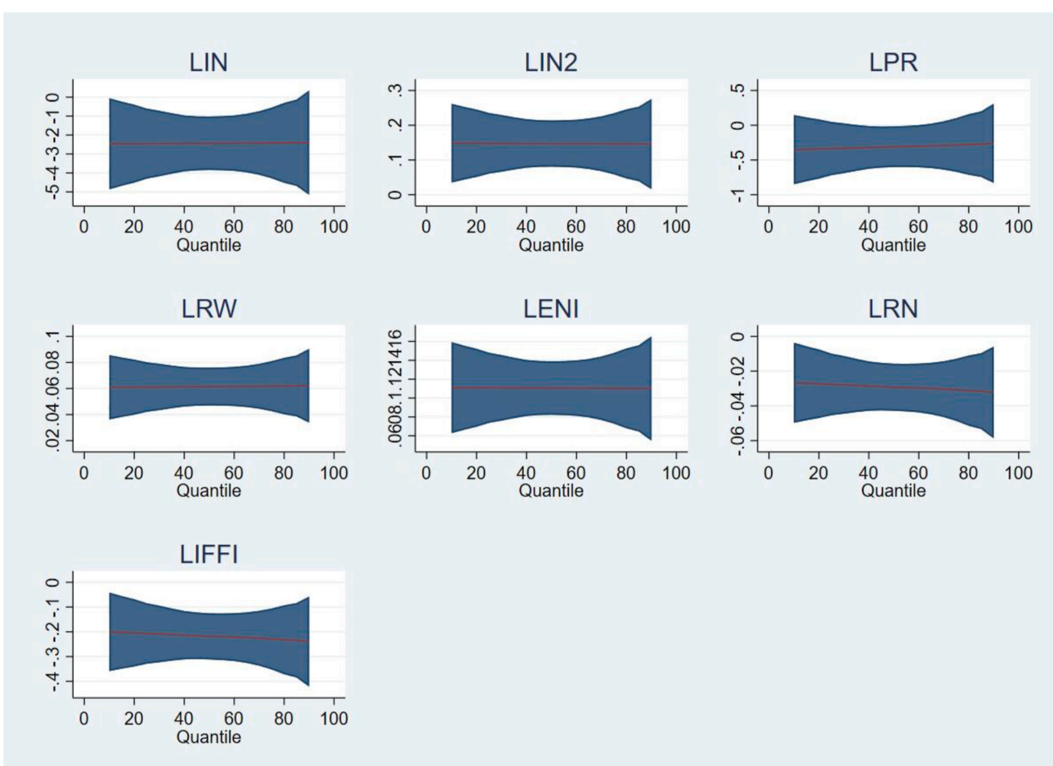
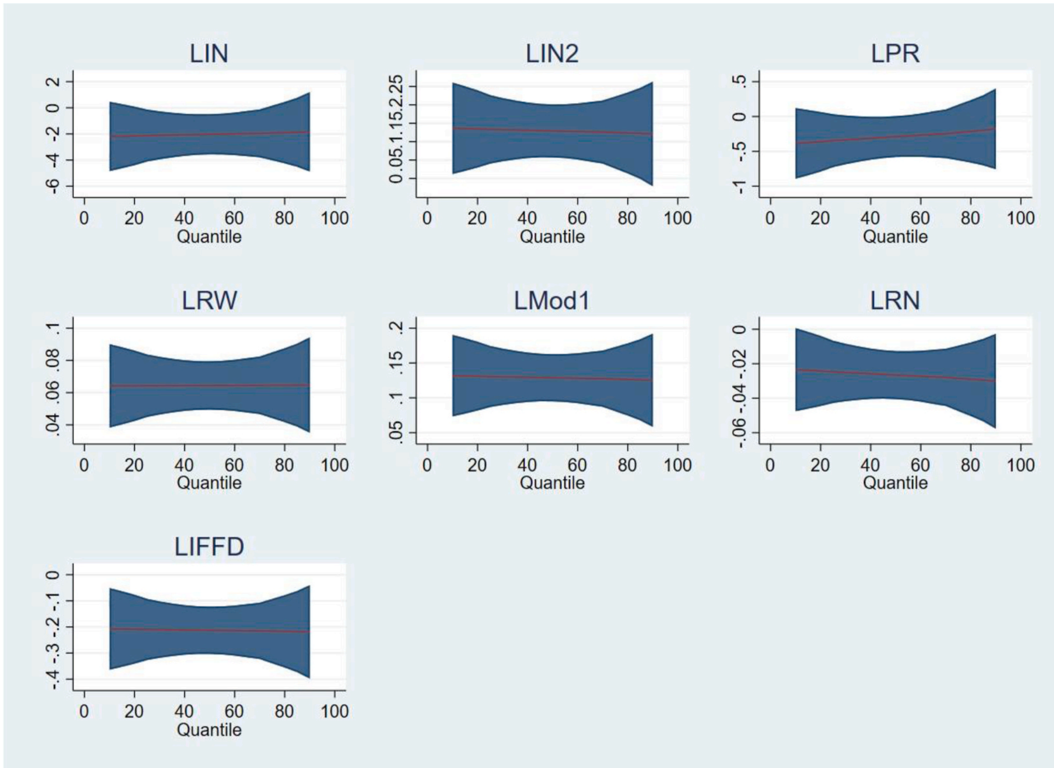


Fig. 7. QLR plots for models with LEE – as the explained variable (panel A to D)

Panel C



Panel D

Fig. 7. (*continued*).

reduce the reliance on fossil fuels and thus alleviate anthropogenic gasses associated with energy production. To further heathen the robustness of the eco-efficiency improvement effect of RW, Wang et al. [44] claimed the inverse nexus between renewable energy and carbon emissions. Executing the data for BRICS economies, Wang et al. [44] delineated the ultimate role of renewable energy in tackling environmental challenges. Likewise, Li et al. (2022) stated that environmental unsustainability can be neutralized through the channel of renewable energy. Reporting the negative association between RW and ENP acknowledges the paramount role of green energy sources to realize the SDGs. Sun et al. [51] also showed the substantial reduction of environmental pollution provoked by RW. Another study considering European Union posited that renewable energy plays a vital role in tackling carbon emissions [63]. Likewise [59] deciphered that the transition to low carbon energy sets the scene for curtailing the reliance of EU members on fossil fuels and consequently reduces pollutants.

Afterward, the fourth finding of QLR is that income demonstrates the U-type linkage with EE. Specifically, the coefficient of income is negative while the coefficient with income squared is positive. Herein, our study fails to authenticate the validity of EKC phenomenon forming the U-type nexus among the studied variables. This finding affirms that eco-efficiency decreases in the early stages of development process, but surges in the later stages. Thus, an increase in economic output may hamper the ecological purity of EU members initially. However, the subsequent increase in economic output may raise the ecological awareness requesting intensified commitment towards eco-efficiency improvement. Thus, at the higher levels of IN, economic output keeps on rising but brings about less harmful ecological consequences by tackling pollutant emissions. The initial intensification of ecological challenges in EU is attributable to the scale effect. However, the subsequent relaxation of these challenges is due to the composition and technique effects that insinuate the transition from labor- and capital-intensive towards knowledge intensive sectors and technological advancement that jointly enable intensification of production with minimal ecological effects. In line with our outcomes, Ochoa-Moreno et al. [78] affirmed the non-existence of EKC phenomenon in Latin America and Kilinc-Ata and Likhachev [79] in the case of Russia. According to the empirical outcomes of [65], the assessment of the non-linear association between income and ecological footprint uncovers that ecological challenges are magnified by the increase in output in the early stages of growth. However, European Union members experience the relaxation of ecological challenges at the later growth stages attributable to growing environmental awareness.

Considering the fifth finding of QLR, it can be revealed that natural resources deter the eco-efficiency of EU members. The coefficient of reliance on natural resources, Table 8 and Fig. 7 (from Panel A to D) display the negative coefficient of reliance on natural resources affirming that overdependence on natural resources curtails the environmental performance of EU members, an outcome consistent with [48, 49]. This impact is statistically significant across all quantiles of EE. A possible explanation is that overconsumption of natural resources may intensify the extraction process that is acknowledged as a substantial generator of water and air pollution. Moreover, the extraction process is harmful for biodiversity and may bring about water stress. Economic growth accelerates the utilization of natural resources generating substantial amount of waste. To justify these outcomes in the context of EU members [57], acknowledged that the rising utilization of biological materials increases global temperature producing irreversible damages for ecosystem and accelerating greenhouse gasses. After, the sixth finding of QLR is that population is negatively associated with eco-efficiency. Herein, our findings detailed the hazardous environmental impact of population statistically significant across middle quantiles adhering with [51–53]. This is since growing population increases energy utilization and as such magnifies toxic gas emission associated with energy production. Moreover, to feed increasing population, forest areas are converted to agricultural fields that bring about the deforestation issues. Herein, the rising population accelerates manufacturing and energy utilization contributing to the toxic emission from the use of coal, oil, and natural gas. Moreover, the disadvantageous impact of population can be justified through the land-use adjustments, influencing the exchange of toxic gasses between the Earth and atmosphere. In addition, the use of chemicals in agricultural production causes soil and water pollution and instigates methane emission. Our findings are also in line with [57] who identified that increased population of EU members accelerated the demand for biological capital and accelerated natural resources extraction related ecological challenges.

Most importantly, the last finding is that environmental policy stringency positively moderates the impact of financial inclusion on eco-efficiency. Models 3 and 4 embrace the interaction of ENI with inclusive finance. The coefficients of Mod1 and Mod2 are positive curtailing that inclusive finance might upgrade the eco-efficiency of EU members via the means of environmental policy stringency. Our findings show that the effect of interactive term is positive and statistically significant across all quantiles but dwindles from lower to higher quantiles. Herein, stricter environmental legislation might drive inclusive financial systems towards achieving the targets of SDGs. The direction of the elasticity of the moderator is opposite from the main effect of inclusive finance. Thus, by plugging in the interaction term, the ecological effect of inclusive finance is conditional on environmental policy stringency. In other words, more stringent environmental policy may shift the harmful ecological impact of inclusive finance into the beneficial one. The positive coefficients of Mod1 and Mod2 can be justified in that more stringent environmental legislation may prompt the inclusive financial systems to undertake the projects of green technology innovations. In addition, inclusive financial systems are encouraged to fund research and development projects to pave EU's way towards decarbonization in securing net zero emissions in the future. Identical outcomes are elucidated by Balsalobre-Lorente et al. [56] positing that ENI negatively moderates the link between IF and ecological footprint. Performing the data on Asia-Pacific Economic Cooperation members, the authors portrayed that a rise in interaction term of ENI with IF is anticipated to deteriorate the ecological footprint bringing an improvement in environmental quality. In the similar fashion, Batóg and Pluskota [67] pointed out the vitality of financial instruments in the energy sector transformation acknowledging the conducts towards low carbon energy as vital policy targets. Likewise, Wang et al. [68] unearthed that stringent environmental policies may incentivize the implementation of green financing and thus transform the adverse ecological impact of financial inclusion into the advantageous one. Specifically, by fostering the investment in advanced machinery and production techniques, green finance is likely to ameliorate the efficiency of energy consumption and alleviate emissions of toxic gasses.

4.1. Robustness checks

To probe the outcomes of our baseline models (Models 1–4), this study assesses alternative model approaches by utilizing the CE (IN/carbon footprint) to capture the ecological impacts as a response variable in Models 5–8. The empirical outcomes exhibited in Table 9 and in Fig. 8 (Panel A to D), depicts the negative impact of reliance on natural resources, population, and inclusive finance on eco-efficiency, whereas renewable energy and environmental policy stringency support the eco-efficiency of EU members. Confidence intervals are outlined in Table A1 and Table A2 (Appendix). Parallel to baseline findings, the alternative specifications (Models 5–8) opted for the negative coefficient of income and positive coefficient of its squared term insinuating the U-type interplay between income and eco-efficiency and disproving the EKC phenomenon. The outcomes detailed in Table 9 and Fig. 8 (from 8a to 8d) generate consistent findings with those of Models 1–4 as the magnitude of regression coefficients yields minor deviations from our baseline models. An alternative estimator, namely OLS-DK is also applied in this study to authenticate the robustness of baseline model

Table 9
Synopsis of OLS-DK and QLR (LCE – dependent variable) robustness check.

Model	Var./QR	OLS-DK		10		30		50		70		90	
		Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.	Coef.	p val.
LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LIN	−5.808a	0.000	−6.563a	0.003	−6.233a	0.000	−5.876a	0.000	−5.523a	0.000	−4.956b	0.039
	LIN2	0.311a	0.000	0.343a	0.001	0.329a	0.000	0.314a	0.000	0.299a	0.000	0.275b	0.014
	LPR	−0.867a	0.000	−0.804b	0.048	−0.831a	0.005	−0.861a	0.000	−0.891a	0.001	−0.938b	0.034
	LRW	0.103a	0.000	0.107a	0.000	0.105a	0.000	0.103a	0.000	0.101a	0.000	0.098a	0.000
	LENI	0.153a	0.000	0.138a	0.002	0.144a	0.000	0.152a	0.000	0.159a	0.000	0.170a	0.001
	LRN	−0.039b	0.026	−0.027	0.157	−0.032b	0.023	−0.038a	0.001	−0.043a	0.001	−0.051b	0.015
	LIFFD	−0.187a	0.000	−0.184b	0.041	−0.186a	0.005	−0.187a	0.000	−0.189a	0.001	−0.191c	0.052
LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LIN	−7.110a	0.000	−7.795a	0.000	−7.475a	0.000	−7.147a	0.000	−6.852a	0.000	−6.291a	0.007
	LIN2	0.370a	0.000	0.399a	0.000	0.386a	0.000	0.372a	0.000	0.359a	0.000	0.335a	0.002
	LPR	−0.879a	0.000	−0.744b	0.033	−0.807a	0.001	−0.872a	0.000	−0.930a	0.000	−1.041b	0.022
	LRW	0.102a	0.000	0.108a	0.000	0.105a	0.000	0.103a	0.000	0.100a	0.000	0.096a	0.000
	LENI	0.112a	0.001	0.090a	0.006	0.101a	0.000	0.111a	0.000	0.120a	0.000	0.138a	0.001
	LRN	−0.044b	0.010	−0.033b	0.048	−0.038a	0.001	−0.043a	0.000	−0.048a	0.000	−0.057a	0.008
	LIFFI	−0.317a	0.000	−0.307a	0.006	−0.312a	0.000	−0.317a	0.000	−0.321a	0.000	−0.330b	0.022
LCE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LIN	−5.808a	0.000	−6.563a	0.003	−6.233a	0.000	−5.876a	0.000	−5.523a	0.000	−4.956b	0.039
	LIN2	0.311a	0.000	0.343a	0.001	0.329a	0.000	0.314a	0.000	0.299a	0.000	0.275b	0.014
	LPR	−0.867a	0.000	−0.804b	0.048	−0.831a	0.005	−0.861a	0.000	−0.891a	0.001	−0.938b	0.034
	LRW	0.103a	0.000	0.107a	0.000	0.105a	0.000	0.103a	0.000	0.101a	0.000	0.098a	0.000
	LMod1	0.153a	0.000	0.138a	0.002	0.144a	0.000	0.152a	0.000	0.159a	0.000	0.170a	0.001
	LRN	−0.039b	0.026	−0.027	0.157	−0.032b	0.023	−0.038a	0.001	−0.043a	0.001	−0.051b	0.015
	LIFFD	−0.340	0.000	−0.322a	0.007	−0.330a	0.000	−0.339a	0.000	−0.347a	0.000	−0.361a	0.006
LCE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)	LIN	−7.110a	0.000	−7.795a	0.000	−7.475a	0.000	−7.147a	0.000	−6.852a	0.000	−6.291a	0.007
	LIN2	0.370a	0.000	0.399a	0.000	0.386a	0.000	0.372a	0.000	0.359a	0.000	0.335a	0.002
	LPR	−0.879a	0.000	−0.744b	0.033	−0.807a	0.001	−0.872a	0.000	−0.930a	0.000	−1.041b	0.022
	LRW	0.102a	0.000	0.108a	0.000	0.105a	0.000	0.103a	0.000	0.100a	0.000	0.096a	0.000
	LMod2	0.112a	0.001	0.090a	0.006	0.101a	0.000	0.111a	0.000	0.120a	0.000	0.138a	0.001
	LRN	−0.044b	0.010	−0.033b	0.048	−0.038a	0.001	−0.043a	0.000	−0.048a	0.000	−0.057a	0.008
	LIFFI	−0.430a	0.000	−0.397a	0.001	−0.412a	0.000	−0.428a	0.000	−0.442a	0.000	−0.468a	0.002

Note: a - 1 % level of significance; b - 5 % level of significance, c- 10 % level of significance, QR – quantile regression.

approaches and is portrayed in Tables 8 and 9. The outcomes of the model specifications that assess only direct impact (Models 1–2, 5–6) depict that ENI exhibits positive and statistically significant interplay with the indicators of eco-efficiency proving that a 1 % increment in environmental policy stringency is likely to increase EE and CE by 0.129 % (Model1), 0.111 (Model 2), 0.153 % (Model 5) and 0.112 % (Model 6), respectively. The elasticities of renewable energy unveil that a 1 % upsurge in RW induces eco-efficiency by 0.064 % (Model 1 and 3), 0.061 % (Model 2 and 4), 0.103 % (Model 5 and 7), and 0.102 % (Model 6 and 8), respectively. Moreover, the impact of RN is negative insinuating that the reliance on natural resources supports the eco-intensity of EU members such that a 1 % rise in RN causes a drop in eco-efficiency by 0.027 % (Model 1 and 3), 0.029 % (Model 2 and 4), 0.039 % (Model 5 and 7), and 0.044 % (Model 6 and 8), respectively.

Our outcomes further unfold the unfavorable eco-efficiency impact of population highlighting that a 1 % increase in population tends to deteriorate the eco-efficiency by 0.286 % (Model 1 and 3), 0.309 % (Model 2 and 4), 0.867 % (Model 5 and 7), and 0.879 % (Model 6 and 8), respectively. The results depict the negative coefficient of IN and positive coefficient of income squared lending credence to the U-type pattern between income and eco-efficiency contradicting the underpinnings of the EKC phenomenon. Inclusive finance exerts a negative statistically significant influence on eco-efficiency in the models that assess only direct impact insinuating that IF supports the impairment of eco-efficiency in EU members. The coefficient of environmental policy stringency interaction with inclusive finance proves to be positive and statistically significant unveiling that ENI positively moderates the impact of inclusive finance on EE and CE. Herein, alternative model specifications and alternative estimators in the present study yield findings that are robust to baseline outcomes with respect to the sign and significance.

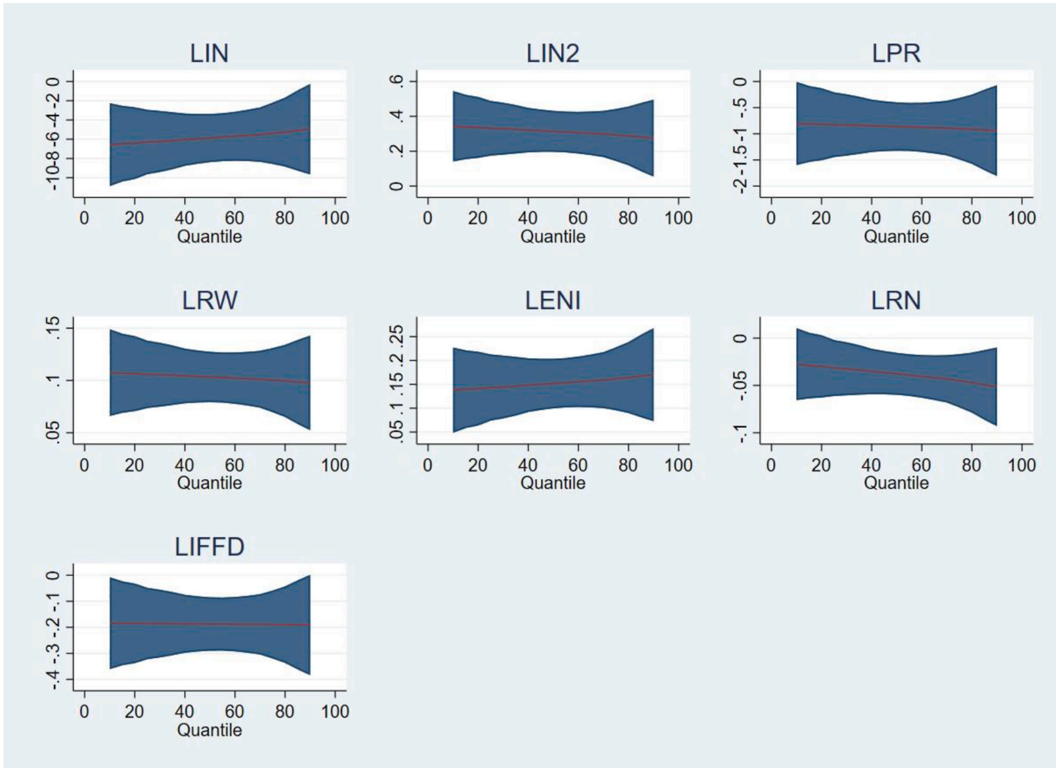
5. Conclusion and policy framework

Inclusive assess to finance drives the economic activity causing an upswing in energy consumption and energy-related anthropogenic emissions. European Union (EU) countries are aiming for higher economic growth; however, economic expansion has triggered their eco-intensity causing a drop in eco-efficiency. Herein, the European Union is maintaining more stringent environmental policies to help reduce eco-intensity and alleviate ecological pressure. Within this framework, this study sought to unriddle the interplay between environmental policy stringency (ENI), renewable energy, inclusive finance, reliance on natural resources, population, and eco-efficiency in chosen 14 EU countries. Deploying the Method of Moments Quantile Regression, empirical findings disclosed that ENI and renewable energy boost eco-efficiency and unfolded a U-type relationship between real GDP per capita and eco-efficiency. On the contrary, reliance on natural resources, population, and financial inclusivity tends to curtail eco-efficiency in the model without an ENI moderator. Subsequent to the favorable direct environmental impact of ENI, our empirical findings further show that environmental policy stringency positively moderates the effect of inclusive finance on eco-efficiency. Our baseline findings are found robust to the alternative estimator (the ordinary least square with Driscoll-Kraay standard errors - OLS-DK) and an additional proxy for eco-efficiency.

From these findings, inclusive finance is a new avenue wherein stricter environmental policy can strengthen eco-efficiency and pave way in accommodating the requirements of Sustainable Development Goals (SDGs) in particular Goals 7 and 13. Herein, this study recommends the consolidation of financial inclusion strategies with more stringent environmental policies to facilitate eco-efficiency. By supporting more stringent environmental policies, inclusive finance might improve the efficiency of resource allocation to pursue ecological sustainability.

Furthermore, given the outcomes, stringent environmental policies are seen as a panacea to negative externalities in the environment among the EU countries. Therefore, increasing pollution costs via stringent environmental policy is found effective in making pollution-inducing economic activities and other related environmentally

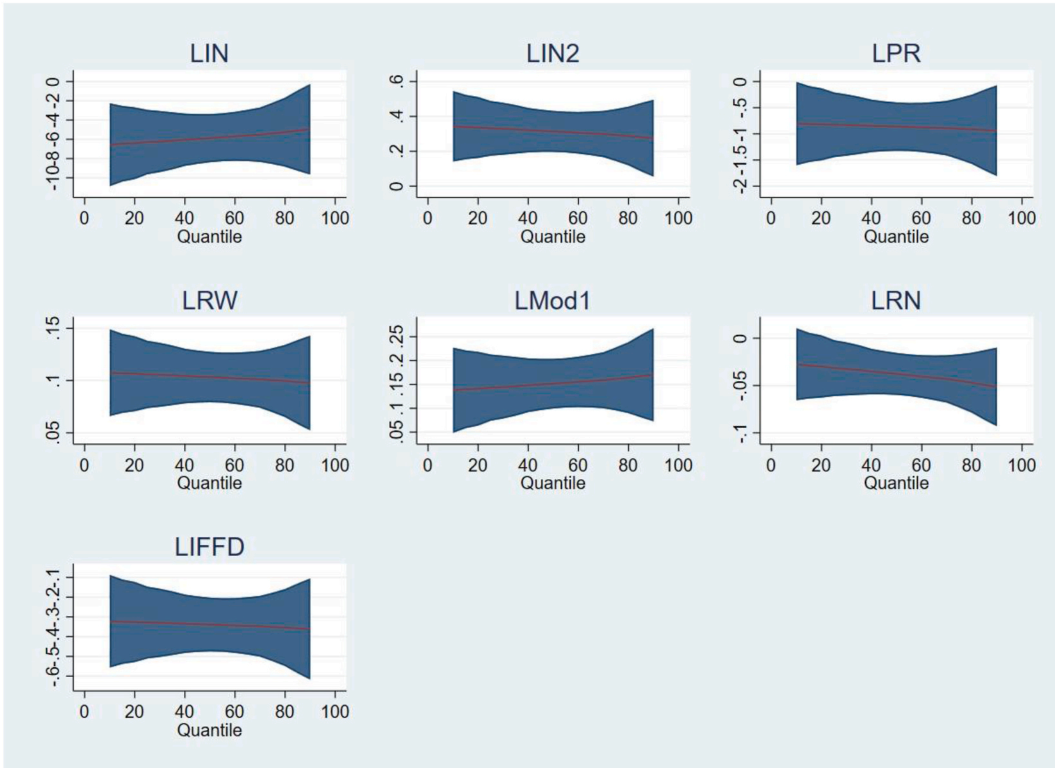
Panel A



Panel B

Fig. 8. QLR plots for models with LCE – as the explained variable (panel A to D)

Panel C



Panel D

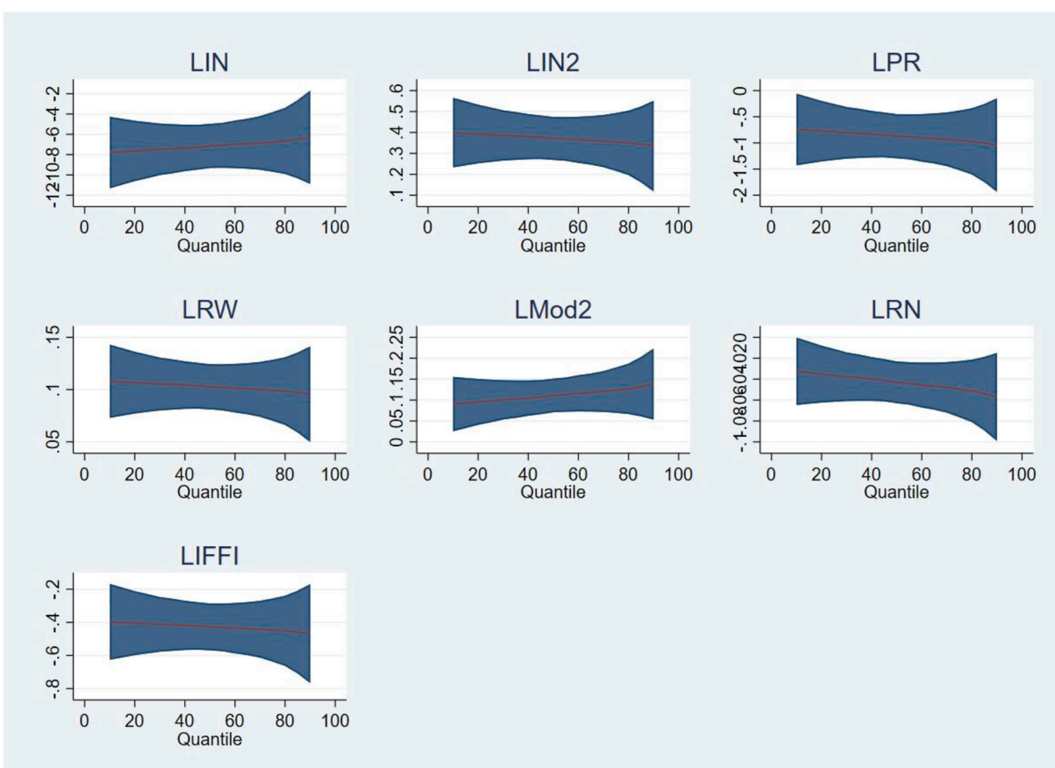


Fig. 8. (*continued*).

unsustainable practices less attractive. We further recommend that such regulations should be carefully designed to inculcate other economic incentives for production units that are adopting emissions-reducing innovative technologies. Ensuring the latter action is quite imperative to dissuade a potential pollution haven scenario. In essence, the environmental protection policies should be designed to encourage the EU production units to stay and operate responsibly within the EU zone rather than shifting out pollution to other parts of the world where there is less stringent environmental protection. In this regard, a strategically designed policy that accommodates commensurate incentives for compliance would not only produce environmental gains via abatement of ecological degradation but also facilitate retention of employment opportunities within the zone as factories and manufacturing units are encouraged to operate within the EU zone. In essence, it is recommended that environmental stringency costs should be strategically designed such that they do not exceed the potential costs of adopting alternative innovative technologies or sustainable production practices.

Additionally, we recommend that the EU countries should continue to leverage their developed financial sector to provide more incentives for renewable energy technologies research and project developments. In this vein, financial regulatory authorities should promote policy initiatives that are designed to encourage financial institutions' capabilities and willingness to support R&D in renewable energy technologies. By doing this, the eco-footprint of the understudied EU countries' production units can be lessened, thereby facilitating the realization of the EU's broad vision 2030 goals.

Lastly, given the economic relevance of inclusive finance, it is, important that policy makers design the most suitable stringency costs in each of the understudied EU countries, bearing in mind the possibilities of individual country-specific characteristics. Although the current findings underscore the significance of stringency in environmental policy implementation for eco-efficiency gains, however, in practice, stringency measures should be executed with caution. An overly stringent policy may limit financial institutions' ability to maximize their profits and this also cast limits to the desires of the eco-efficiency concepts that encompasses optimal environmental gains without necessarily jeopardizing economic goals. For instance, some bankable customers may not be able to operate entirely in an environmentally friendly manner. If the percentage of such customers is substantial, losing them could decrease banking profitability, jeopardize banking capital, and increase economic woes like unemployment. Consequently, intensive supervisions and monitoring by authorities and stakeholders are essential to ensure that well desired stringency policy measures adapt to actual realities that financial institutions are facing to minimize risks from both financial and environmental perspectives. Hence, more cooperation across various institutions is encouraged, for instance, between the ministry of environment and the financial services authority in implementing well designed policy measures to facilitate the attainment of eco-efficiency goals and objectives.

5.1. *Limitations and directions for future studies*

The current study has provided a broad synthesis of eco-efficiency within the trends of inclusive finance in the EU. The study also takes initiatives to see if environmental policy stringency and renewable energy make any difference in the EU eco-efficiency quest. Although the even spread of the analyzed countries across all regions in the present study helped to reduce potential region-specific bias, there are certain limitations in terms of the generalizability of the findings considering that not all the 27 EU member countries are covered in the analysis. Hence, aside from expanding the scope of analysis, future study can also explore country level analysis for each EU member country within the developed framework of the current study. This disaggregated approach would be helpful in examining whether stringency levels significantly moderate environmental degradation rates in each country separately thereby catering for country-specific differences that may influence the general outcomes. Overall, this can enhance further country-level policy directives to enhance eco-efficiency level across the EU.

CRediT authorship contribution statement

Elma Satrovic: Visualization, Formal analysis, Data curation, Conceptualization. **Stephen Taiwo Onifade:** Writing – review & editing, Writing – original draft, Conceptualization. **Ilham Haouas:** Writing – original draft.

Availability of data and materials

The data for this present study are sourced from the Global Footprint Network- GFN, (http://www.footprintnetwork.org/), the Organization for Economic Co-operation and Development – OECD, (https://www.oecd.org/), the International Monetary Fund (https://www.imf.org/en/Data), and the database of the World Development Indicators (https://data.worldbank.org).

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Declaration of competing interest

The authors wish to disclose here that there are no potential conflicts of interest at any level of this study.

APPENDIX

Table A1
Confidence intervals (OLS-DK and QLR; LEE – dependent variable)

Model	Var./QR	OLS-DK		10		30		50		70		90	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LIN	−3.740	−0.305	−4.843	0.461	−3.936	−0.274	−3.561	−0.491	−3.786	−0.129	−4.871	1.195
	LIN2	0.050	0.208	0.012	0.260	0.047	0.218	0.057	0.201	0.040	0.212	−0.021	0.263
	LPR	−0.547	−0.026	−0.891	0.120	−0.684	0.014	−0.581	0.005	−0.597	0.101	−0.755	0.402
	LRW	0.046	0.083	0.038	0.090	0.046	0.082	0.049	0.079	0.047	0.082	0.035	0.094
	LENI	0.078	0.179	0.073	0.190	0.090	0.171	0.095	0.163	0.087	0.168	0.058	0.192
	LRN	−0.043	−0.010	−0.047	0.001	−0.042	−0.008	−0.041	−0.013	−0.044	−0.011	−0.058	−0.003
	LIFFD	−0.144	−0.024	−0.194	0.043	−0.162	0.002	−0.153	−0.015	−0.169	−0.005	−0.229	0.042

(*continued on next page*)

Table A1 (*continued*)

Model	Var./QR	OLS-DK		10		30		50		70		90	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
LEE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LIN	−3.848	−1.015	−4.862	−0.059	−4.174	−0.720	−3.841	−1.023	−4.092	−0.748	−5.151	0.352
	LIN2	0.083	0.211	0.035	0.262	0.066	0.229	0.081	0.214	0.068	0.226	0.016	0.276
	LPR	−0.575	−0.043	−0.848	0.146	−0.689	0.027	−0.600	−0.017	−0.637	0.056	−0.830	0.310
	LRW	0.044	0.079	0.036	0.086	0.043	0.079	0.047	0.076	0.045	0.079	0.034	0.090
	LENI	0.071	0.151	0.063	0.159	0.076	0.146	0.082	0.139	0.077	0.144	0.055	0.165
	LRN	−0.045	−0.013	−0.050	−0.004	−0.044	−0.011	−0.043	−0.016	−0.046	−0.014	−0.059	−0.006
	LIFFI	−0.344	−0.093	−0.359	−0.042	−0.323	−0.095	−0.311	−0.125	−0.336	−0.116	−0.421	−0.058
LEE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LIN	−3.740	−0.305	−4.843	0.461	−3.936	−0.274	−3.561	−0.491	−3.786	−0.129	−4.871	1.195
	LIN2	0.050	0.208	0.012	0.260	0.047	0.218	0.057	0.201	0.040	0.212	−0.021	0.263
	LPR	−0.547	−0.026	−0.891	0.120	−0.684	0.014	−0.581	0.005	−0.597	0.101	−0.755	0.402
	LRW	0.046	0.083	0.038	0.090	0.046	0.082	0.049	0.079	0.047	0.082	0.035	0.094
	LMod1	0.078	0.179	0.073	0.190	0.090	0.171	0.095	0.163	0.087	0.168	0.058	0.192
	LRN	−0.043	−0.010	−0.047	0.001	−0.042	−0.008	−0.041	−0.013	−0.044	−0.011	−0.058	−0.003
	LIFFD	−0.309	−0.116	−0.363	−0.051	−0.318	−0.102	−0.303	−0.122	−0.323	−0.107	−0.397	−0.040
LEE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)	LIN	−3.848	−1.015	−4.862	−0.059	−4.174	−0.720	−3.841	−1.023	−4.092	−0.748	−5.151	0.352
	LIN2	0.083	0.211	0.035	0.262	0.066	0.229	0.081	0.214	0.068	0.226	0.016	0.276
	LPR	−0.575	−0.043	−0.848	0.146	−0.689	0.027	−0.600	−0.017	−0.637	0.056	−0.830	0.310
	LRW	0.044	0.079	0.036	0.086	0.043	0.079	0.047	0.076	0.045	0.079	0.034	0.090
	LMod2	0.071	0.151	0.063	0.159	0.076	0.146	0.082	0.139	0.077	0.144	0.055	0.165
	LRN	−0.045	−0.013	−0.050	−0.004	−0.044	−0.011	−0.043	−0.016	−0.046	−0.014	−0.059	−0.006
	LIFFI	−0.453	−0.205	−0.477	−0.145	−0.439	−0.200	−0.426	−0.231	−0.452	−0.221	−0.540	−0.159

Table A2
Confidence intervals (OLS-DK and QLR; LCE – dependent variable)

Model	Var./QR	OLS-DK		10		30		50		70		90	
		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]		[95 % conf. interval]	
LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFD)	LIN	−7.947	−3.669	−10.867	−2.259	−9.405	−3.061	−8.380	−3.373	−8.346	−2.699	−9.656	−0.255
	LIN2	0.215	0.408	0.141	0.545	0.180	0.478	0.197	0.432	0.167	0.432	0.055	0.496
	LPR	−1.297	−0.437	−1.599	−0.008	−1.417	−0.245	−1.324	−0.399	−1.412	−0.369	−1.807	−0.070
	LRW	0.076	0.130	0.066	0.149	0.075	0.136	0.079	0.127	0.074	0.128	0.052	0.143
	LENI	0.077	0.229	0.048	0.227	0.079	0.210	0.100	0.204	0.100	0.217	0.073	0.268
	LRN	−0.072	−0.005	−0.066	0.011	−0.060	−0.004	−0.060	−0.016	−0.068	−0.018	−0.093	−0.010
	LIFFD	−0.275	−0.100	−0.361	−0.008	−0.316	−0.056	−0.290	−0.085	−0.304	−0.073	−0.384	0.002
LCE = f(LIN, LIN2, LPR, LRW, LENI, LRN, LIFFI)	LIN	−8.971	−5.249	−11.314	−4.275	−10.012	−4.938	−9.319	−4.974	−9.489	−4.214	−10.886	−1.696
	LIN2	0.287	0.454	0.233	0.566	0.266	0.505	0.269	0.474	0.234	0.483	0.118	0.552
	LPR	−1.300	−0.458	−1.428	−0.060	−1.300	−0.314	−1.294	−0.449	−1.442	−0.417	−1.934	−0.148
	LRW	0.080	0.125	0.073	0.143	0.080	0.131	0.081	0.124	0.074	0.126	0.050	0.141
	LENI	0.050	0.174	0.025	0.155	0.054	0.147	0.071	0.151	0.072	0.169	0.053	0.223
	LRN	−0.076	−0.011	−0.065	0.000	−0.061	−0.015	−0.063	−0.023	−0.072	−0.024	−0.099	−0.015
	LIFFI	−0.482	−0.153	−0.523	−0.090	−0.468	−0.156	−0.450	−0.183	−0.484	−0.159	−0.613	−0.047
LCE = f(LIN, LIN2, LPR, LRW, LMod1, LRN, LIFFD)	LIN	−7.947	−3.669	−10.867	−2.259	−9.405	−3.061	−8.380	−3.373	−8.346	−2.699	−9.656	−0.255
	LIN2	0.215	0.408	0.141	0.545	0.180	0.478	0.197	0.432	0.167	0.432	0.055	0.496
	LPR	−1.297	−0.437	−1.599	−0.008	−1.417	−0.245	−1.324	−0.399	−1.412	−0.369	−1.807	−0.070
	LRW	0.076	0.130	0.066	0.149	0.075	0.136	0.079	0.127	0.074	0.128	0.052	0.143
	LMod1	0.077	0.229	0.048	0.227	0.079	0.210	0.100	0.204	0.100	0.217	0.073	0.268
	LRN	−0.072	−0.005	−0.066	0.011	−0.060	−0.004	−0.060	−0.016	−0.068	−0.018	−0.093	−0.010
	LIFFD	−0.481	−0.200	−0.556	−0.088	−0.503	−0.157	−0.475	−0.202	−0.501	−0.194	−0.617	−0.105
LCE = f(LIN, LIN2, LPR, LRW, LMod2, LRN, LIFFI)	LIN	−8.971	−5.249	−11.314	−4.275	−10.012	−4.938	−9.319	−4.974	−9.489	−4.214	−10.886	−1.696
	LIN2	0.287	0.454	0.233	0.566	0.266	0.505	0.269	0.474	0.234	0.483	0.118	0.552
	LPR	−1.300	−0.458	−1.428	−0.060	−1.300	−0.314	−1.294	−0.449	−1.442	−0.417	−1.934	−0.148
	LRW	0.080	0.125	0.073	0.143	0.080	0.131	0.081	0.124	0.074	0.126	0.050	0.141
	LMod2	0.050	0.174	0.025	0.155	0.054	0.147	0.071	0.151	0.072	0.169	0.053	0.223
	LRN	−0.076	−0.011	−0.065	0.000	−0.061	−0.015	−0.063	−0.023	−0.072	−0.024	−0.099	−0.015
	LIFFI	−0.615	−0.244	−0.626	−0.169	−0.577	−0.248	−0.569	−0.287	−0.613	−0.270	−0.767	−0.170

Data availability

Data will be made available on request.

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