Exploring the Environmental Phillips Curve: How Do Globalization, Economic Growth, and Institutional Quality Shape Load Capacity Factors in Highly Globalized European Countries?

Mohammad Mafizur RAHMAN[*] Seyit Ali MİÇOOĞULLARI[†] Süleyman DEĞİRMEN[‡] Erdal ALANCIOĞLU[§]*and Maya MOALLA[**]

Abstract

This study examines the Environmental Phillips Curve (EPC) hypothesis by analyzing the relationship between the unemployment rate (UR) and Load Capacity Factor (LCF) in the 10 most globalized European countries from 1996 to 2022. Using modern econometric methods, including the STIRPAT model and CS-ARDL, the study assesses the effects of economic growth (GDP), energy consumption (PEC), institutional quality (INQ), and globalization (KOF) on environmental sustainability. The findings robustly support the EPC hypothesis, showing that higher unemployment rates positively impact LCF, enhancing environmental quality. This effect is most evident in highly globalized nations like Germany, Sweden, and Switzerland, where decreased economic activity lowers environmental pressures. The results also reveal that economic growth negatively impacts LCF in the long run, emphasizing sustainable development needs. While energy consumption degrades the environment, institutional quality and globalization contribute positively to sustainability. A unique aspect of this study is the interaction term UR*INQ, demonstrating that institutional quality moderates the UR-LCF relationship, further validating the EPC hypothesis. These insights underscore the importance of integrated strategies for economic and environmental goals in globalized European countries.

[*] Prof., University of Southern Queensland, School of Business, Toowoomba, Australia. Orcid: 0000-0002-7950-1961, Email: mafiz.rahman@unisq.edu.au
[†] Assoc. Prof., Kilis 7 Aralık University, Department of Foreign Trade, Kilis, Turkiye. Orcid: 0000-0001-9266-1559, Email: s.alimicoogullari@kilis.edu.tr
[‡] Prof., Mersin University, Department of Economic Policy, Mersin, Turkiye. Orcid: 0000-0001-8750-652X, Email: sdegirmen@mersin.edu.tr
[§] Assoc. Prof., Harran University, Department of Accounting and Tax Applications, Şanlıurfa, Turkiye. Orcid: 0000-0002-5008-4957, Email: ealancioglu@harran.edu.tr
[**] Dr., Mersin University , Department of Economics, Mersin Turkiye. Orcid: 0000-0003-4076-2790, Email: mayamoalla@hotmail.com

- Corresponding author

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1. Introduction

Among the most significant and intricate challenges humanity faces currently are the environmental concerns on a global scale; possessing not only profound environmental miens but also economic and social dimensions (UNEP, 2023). These environmental concerns pose worrying threats to agriculture and food security (FAO, 2024), economic stability, public health (Azam, 2016; Warner et al., 2010; WHO, 2024), and sustainable development (Diamond and Wang, 2024; WB, 2024). Furthermore, factors highlighted as serious, such as the process of industrialization and that of energy production and consumption, are severely threatening the sustainability of the environment, emphasizing the urgent need for action (Alshehry and Belloumi, 2015; IPCC, 2023; Shahbaz et al., 2017; Guliyev, 2024; Rao et al., 2024). In the fight against global environmental crises, carbon dioxide (CO2) releases' control holds critical weight (Olivier et al., 2017), as CO2 is recognized as the most significant trigger of climate change, accounting for approximately 80% of total greenhouse gas releases (IPCC, 2023). With this respect, international initiatives, encompassing agreements such as the Kyoto Protocol and the Paris Agreement, are vital for environmental sustainability and stand out as significant steps towards reducing greenhouse gas releases and limiting global warming (UNFCCC, 2015); however, it has been observed that CO2 releases continue to rise globally, indicating that these initiatives have proven inadequate (Peters et al., 2013). Highly globalized countries such as Switzerland, Belgium, the Netherlands, Sweden, Germany, Austria, the United Kingdom, Denmark, Finland, and France are endeavoring to align their goals of economic growth with environmental sustainability, with Europe leads the charge of tackling global environmental concerns. These countries are facing challenges from rising CO2 releases and environmental deterioration despite being at the helm of environmental sustainability policies (EEA, 2023). The emerging imbalances between Europe's biocapacity and its ecological footprint further validate this situation.

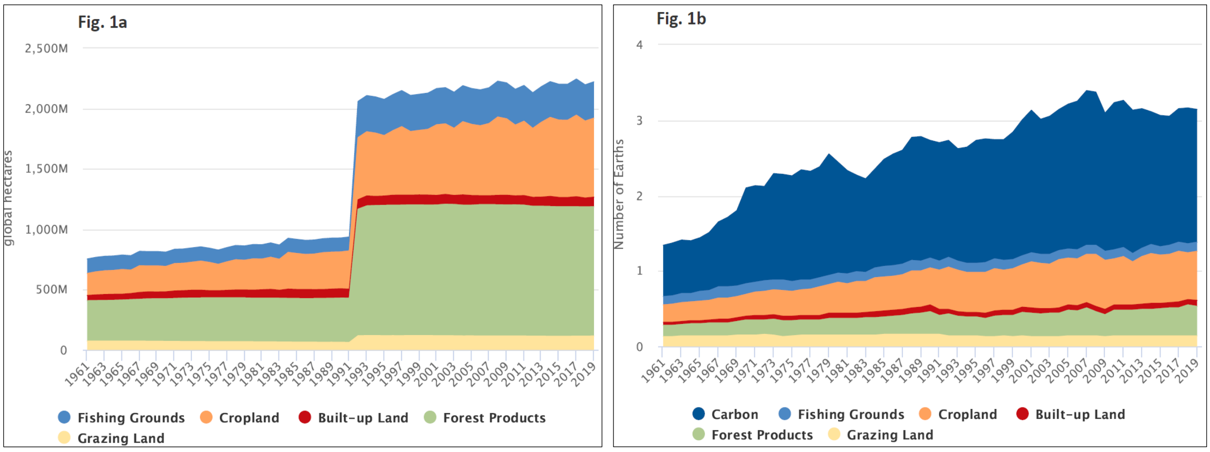

Figure 1: Biocapacity and Ecological Footprint in Europe
Source: GFN (2025)

Fig. 1a reveals that during the period spanning from 1960 to 2019, Europe's biocapacity has stayed relatively consistent, though there have been increases, particularly in agricultural land and forest products. In comparison, Fig. 1b demonstrates a considerable upsurge in Europe's ecological footprint during the same period, accompanied by a notable rise in carbon releases. Such figures distinctly point out the challenges Europe faces regarding environmental sustainability. Measures targeting to tackle these challenges have been implemented in some European countries such as Germany's initiatives to shift from fossil fuels to renewable energy through its energy transformation process (Energiewende) despite its insufficiency in reducing CO2 releases to a desirable level (German Federal Ministry, 2021), and the French dependency on nuclear energy despite the difficulties in reducing CO2 releases from the industrial and transportation sectors (French Ministry of Ecological Transition, 2020). Along with these environmental challenges, unemployment has arisen as a crucial macroeconomic concern for many European countries. Figure 2 depicts the nexus between the unemployment rate (UR) and Load Capacity Factor (LCF) changes among the ten most globalized European countries during the period spanning from 1996 to 2022.

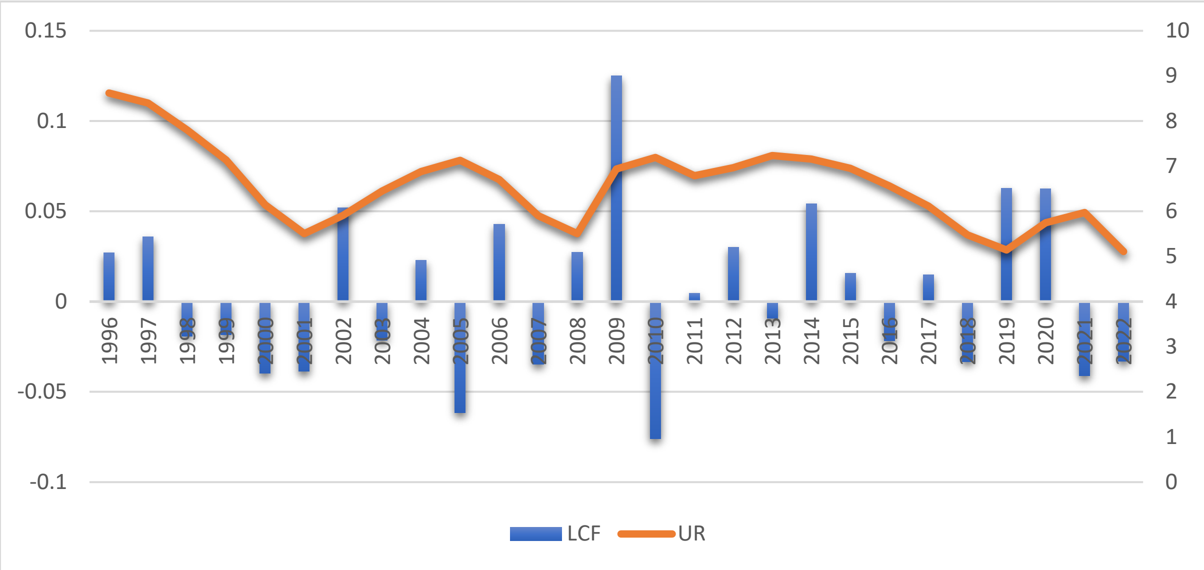

Figure 2: LCF change and UR in 10 Country (%).
Source: GFN (2025), WB (2025)

This Figure shows a distinct nexus between unemployment rates and LCF over the years, predominantly emphasizing the close relationship that exists between environmental sustainability and unemployment rates during economic recessions. Meanwhile, there has been a marked increase in unemployment rates following the COVID-19 pandemic, specifically among the youth population. Across Europe, the labor markets have experienced a major shrinkage due to the pandemic, especially impacting service sector employees and temporary workers (OECD, 2021). Moreover, the COVID-19 pandemic-induced economic downturn has caused unemployment rates to increase rapidly in many European countries. In the Eurozone, the unemployment rate rose 8.3% by the end of 2020, remaining high in 2021(Eurostat, 2021). In some countries, more than 30% of young people are unemployed, worsening the obstacles they face in securing employment (Eurostat, 2021). ILO cautions that this wave of unemployment could have lasting miens on the young workforce, adversely impacting long-term economic evolution (ILO, 2021). Unemployment goes beyond an economic concern, because of its indirect miens on the sustainability of the environment; thus the stringency of the environmental policies may decrease due to the high unemployment rates, resulting in hastening environmental deterioration. Moreover, governments tend to loosen environmental standards during periods of economic stagnation, posing a risk to environmental sustainability (Bae, 2017; Kenny, 2019; Koyuncu et al., 2023), and sparking critical concerns regarding the future of environmental policies when unemployment rates are high. Furthermore, high unemployment may lead to a reduction in environmental investments due to its adverse miens on economic evolution. Kydland and Prescott (1977) argue that unemployment and low economic growth may decrease funding for public and private sector environmental improvement projects; accordingly, this could hinder progress toward achieving sustainable development intentions and hasten environmental deterioration. Moreover, the unemployment challenge in Europe could further complicate the attainment of essential environmental objectives like enhancing energy efficiency and adopting renewable energy solutions; thus, this scenario goes beyond social and economic aspects, it also poses critical challenges influencing environmental sustainability. Subsequently, policies combating unemployment should prioritize supporting environmental sustainability. Considering this amplifying extent, tackling the nexus between unemployment and environmental deterioration is essential, and Kashem and Rahman (2020) conducted a pioneering investigation proposing the Environmental Phillips Curve (EPC) hypothesis to address this affiliation. The EPC hypothesis demonstrates that a boost in economic evolution and employment (which in turn lowers unemployment rates) might also increase environmental deterioration; which is further validated by a multitude of studies that identify a strong association between unemployment and environmental deterioration. The economic literature on EPC hypothesis incorporates empirical investigations that utilized different indicators such as CO2 releases (Bhowmik et al., 2022; Kashem and Rahman, 2020; Shang and Xu, 2022; Durani et al., 2023; Djedaiet, 2023; Azimi & Rahman, 2024) and Ecological Footprint (EF) (Anser et al., 2021; Daştan & Eygü, 2023; Ng et al., 2022; Haciimamoğlu, 2023). The unique contribution of this paper to the existing literature can be demonstrated by employing the Load Capacity Factor (LCF) as an environmental proxy, following the works of Yavuz et al. (2023) and Ayad and Djedaiet (2024); which offers a more comprehensive indicator of the environmental sustainability and gauges the effectiveness of energy production capacity. Moreover, it may facilitate the optimization of energy production capacity considering both economic perspectives and environmental sustainability; thus, playing a critical role in understanding the long-term environmental miens of energy policies and achieving sustainable development objectives. As per the KOF index, the EPC hypothesis has not been tested in European countries with the highest levels of globalization, and this study aims to fill this gap, examining the miens of globalization, economic growth, unemployment, and institutional quality on the Load Capacity Factor (LCF) and testing the EPC hypothesis in European countries with the highest levels of globalization using data from the period 1996-2022. To investigate the long-term nexus among the variables, the STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology) and CS-ARDL (Cross-Sectional Autoregressive Distributed Lag) are employed. At the inception, cross-sectional dependence and slope homogeneity tests followed by second-generation unit root tests will be conducted, to subsequently, undertake the Westerlund (2008) cointegration test to gauge the long-term nexus between the variables. Ultimately, the CS-ARDL methodology will be employed to determine the long-term elasticity estimates and develop policy recommendations, making contributions of this study to the literature highly significant by offering valuable conclusions both in theoretical and practical terms through testing the EPC hypothesis in highly globalized European countries, scrutinizing the miens of institutional quality and globalization on environmental outcomes, and utilizing modern econometric approaches. Moreover, by providing weighty intuitions into the design and implementation of environmental policies and offering new perspectives on the environmental impacts of globalization, the consequences will provide convenient insights for both academic circles and policymakers alike. The remaining segments of the article are organized as follows: In the second segment, the literature tackling the validity of the EPC hypothesis is scrutinized comprehensively. In the third segment, the data sources, model specifications, and econometric approaches utilized in the research are detailed. In the fourth segment, the findings and their alignment or differences with the existing literature are discussed. In the last segment, the findings' potential miens on environmental and economic policies and policy recommendations are presented.

2. Literature on the EPC

In this section, the focus will be on theoretical and empirical studies that investigate the nexus between the Load Capacity Factor (LCF) as a proxy of environmental sustainability and variables such as unemployment rate (UR), economic growth (GDP), energy consumption (PEC), globalization (KOF), and institutional quality (WGI). There are investigations in the existing literature that draw on various econometric approaches across distinct geographical territories to consider the miens of these variables on LCF.

2.1. LCF and Unemployment Rate (UR)

The Load Capacity Factor (LCF) is an indispensable indicator for measuring the environmental outcomes of economic activities, evaluating the effects of energy production capacity on environmental sustainability. Beyond being a measure of economic health, the unemployment rate is considered an important factor that has a bearing on environmental deterioration; however, studies questioning the miens of unemployment rates on the sustainability of the environment in the existing literature are typically bordered within the scope of the EPC hypothesis. As one of the first studies proposing the EPC hypothesis, Kashem and Rahman (2020) indicated that there be a reverse affiliation between unemployment rates and environmental deterioration, and their study serves as a critical touchstone for elucidating the potential miens of unemployment rates on environmental sustainability, suggesting that high unemployment rates could pave the way for a downturn in economic activities, thereby lowering CO2 releases and possibly enhancing environmental sustainability. Another pioneering study conducted by Pata and Isik (2021) revealed a significant bearing of unemployment rates on LCF, by investigating the miens of unemployment rates on environmental sustainability being indicated by utilizing the Load Capacity Factor (LCF) and considering the miens of economic evolution, energy intensity, and resource rents in China. The increase in LCF is ascribed to the expansion of the unemployment rates, the diminishment in economic activities, and accordingly the curtailment of environmental deterioration. The limiting bearings of unemployment rates on environmental deterioration are subsequently confirmed by Anser et al. (2021) for BRICST countries; Ng et al. (2022) for OECD countries; and Djedaiet (2023) for African OPEC countries. These studies indicate the validity of the EPC hypothesis, particularly in industrialized countries; demonstarting that while economic evolution and the use of energy tend to increase environmental deterioration, rising unemployment rates could mitigate this bearing. Recent inquiries led by Ayad and Djedaiet (2024) and Azimi and Rahman (2024) on G7 countries demonstrate the validity of the EPC hypothesis considering the nexus between LCF and UR. Ayad and Djedaiet (2024) support the accuracy of both the EPC and the Load Capacity Curve (LCC) hypotheses, demonstarting a negative correspondence between unemployment and ecological degradation.

2.2. LCF and Economic Growth (GDP)

The environmental economics literature comprehensively addresses the affiliation between economic evolution and environmental sustainability. The Environmental Kuznets Curve (EKC) hypothesis supplies an essential theoretical structure, suggesting a U-shaped liaison between economic evolution and environmental deterioration (Grossman & Krueger, 1991). In accordance with EKC, environmental deterioration intensifies during the onset of economic evolution; however, once a particular income threshold is accomplished, augmentations in environmental indicators are observed. This framework has been substantiated through studies demonstate the positive nexus between economic evolution, the use of energy, and CO2 releases such as those conducted by Shahbaz et al. (2013), Balsalobre-Lorente et al. (2018), Mardani et al. (2019), Salari et al. (2021), and Madaleno & Nogueira (2023). LCF, as a proxy for environmental sustainability, is being more prevalent in exploring its liaison with economic evolution. Pata and Isik (2021) and Dogan and Pata (2022) substantiated the EKC hypothesis, respectively unveiling a U-shaped nexus between economic evolution and LCF in China and G7 countries. Azimi and Rahman (2024) and Ayad and Djedaiet (2024) confirmed these conclusions for G7 countries. Caglar et al. (2024) and Pata and Balsalobre-Lorente (2022) emphasized the bearings of economic evolution on LCF for China and Turkiye respectively.

2.3. LCF and Other Determinative Variables

The economic literature encompasses a variety of investigations that inquire into the liaison between the usage of energy and environmental sustainability revealing similar conclusions. Pata and Isik (2021) demonstrate the undesirable bearings of energy intensity on LCF in China, highlighting the adverse mien of the usage of energy on the environmental sustainability. the scholarly works have also thoroughly covered the renewable energy's facilitative role in indorsing environmental sustainability. This role has been confirmed by Huilan et al. (2022) for Mexico, Khan et al. (2021) for the United States, and Pata et al. (2023) for the Caribbean and Latin America. The environmental bearings of economic evolution and globalization have also been significantly considered. Pata et al. (2023) and Aydin and Degirmenci (2023) reveal that both economic evolution and globalization have adverse mien on LCF, highlighting the economic activities' adverse bearings on environmental sustainability and underscoring imperative for prudent management of such activities; however, some investigations demonstrate that globalization can contribute to environmental sustainability by curtailing carbon releases (He et al., 2021; Aluko et al., 2021; Muoneke et al., 2022; Wang et al., 2023). Institutional quality is indispensable for determining the success of environmental policies and the achievement of sustainability. Moreover, it has a significant bearing on the usage of energy, which reduces environmental degradation as confirmed by Haldar and Sethi (2021). Its supportive mien on environmental sustainability in OECD countries has been identified by Christoforidis and Katrakilidis (2021). Musa et al. (2021) bring to light that institutional quality in EU countries could uplift environmental standards, underscoring their decisive role in promoting environmental sustainability and enhancing the effectiveness of environmental policies. The aforesaid literature stimulates curiosity about the relevance of LCF as a core proxy in gauging environmental sustainability, considering other determinative macroeconomic variables such as unemployment rates, economic evolution, the usage of energy, globalization, and institutional quality. However, the bulk of existing research investigates this liaison focusing on specific geographical regions or economic groups. The current paper seeks to further enrich the current body of literature by reconnoitering the EPC hypothesis for 10 highly globalized European countries making use of LCF as a crux measure, and utilizing modern econometric approaches employed that allowing for a more nuanced exploration of the complex exchanges between the analyzed variables. This paper's uniqueness stems from its dual focus on both questioning the EPC hypothesis in the selected sample and comprehensively analyzing the bearings of institutional quality and globalization on LCF. Drawing from this literature, the existing gaps in the literature will be addresed by testing the formulated hypotheses.

3. Model, Data, and Methodology

3.1. Model Specification

This study takes cues from the STIRPAT model, which is a contemporary adaptation of the IPAT model originally put forth by Ehrlich and Holdren (1971) and broadly utilized in environmental impact investigations. The STIRPAT model can be harnessed to detailedly appraise various socioeconomic and technological variables' bearings on environmental sustainability (Lohwasser et al. 2020; Ayad et al. 2023); introducing a versatile and resilient analytical framework to scrutinize how environmental miens (I) are molded by factors such as population (P), welfare (A), and technology (T). . Equation (1) symbolizes the model:

$$I_{it} = \alpha_{it} P_{it}^{\beta 1} A_{it}^{\beta 2} T_{it}^{\beta 3} \varepsilon_{it} \tag{1}$$

In this investigation, to facilitate a deeper examination of the miens of economic policies and institutional structures on ecological sustainability, variables like globalization and institutional quality have been consolidated into the STIRPAT model, treating the LCF as the dependent variable. The modified version of the STIRPAT model is harnessed to scrutinize the consequences of GDP, UR, PEC, INQ, and KOF on LCF; encompassing the interaction between the unemployment rate and institutional quality (UR * INQ) to gauge its repercussions on LCF. In this concern, the subsequent model specification has been drawn in alignment with the works of Ahmad and Satrovic (2023) and Yavuz et al. (2023):

$$ln\mathrm{LCF}_{it} = \alpha_O + \beta_1 ln\mathrm{GDP}_{it} + \beta_2 ln\mathrm{UR}_{it} + \beta_3 ln\mathrm{PEC}_{it} + \beta_4 ln\mathrm{KOF}_{it} + \beta_5 ln\mathrm{INQ}_{it} + \beta_6 ln(\mathrm{UR} * \mathrm{INQ}) + \varepsilon_{it} \quad (2)$$

Where, α_O denotes the constant term, ε_{it} denotes the error term. While *t* symbolizes the time dimension, β_1, β_2, β_3, β_4, $\beta_5$and β_6 represent the regression coefficients. Table (1) depicts the Coefficients' Anticipated Signs and see Table 2 for the description of variables.

Table 1: Coefficients' Anticipated Signs

Coefficient	Symbol	Anticipated Signs	Explanation
β_1	GDP	Negative (-)	Derived from the EKC hypothesis, worsening of environmental deterioration is anticipated during the early stages of economic evolution; however, once a certain income level is attained, an improvement in environmental quality might manifest, although a generally adverse nexus is expected.
β_2	UR	Positive (+)	The literature generally signals that an upturn in unemployment rates customarily promotes the quality of the environment; however, this investigation posits that low unemployment rates have an adverse mien on the environment.
β_3	PEC	Negative (-)	A negative nexus is anticipated as the surge in energy usage generally has an adverse mien on the quality of the environment.
β_4	KOF	Uncertain (+/-)	The mien of globalization on the environment can be multifaceted, manifesting both positive and adverse bearings.
β_5	INQ	Positive (+)	A positive nexus is anticipated since high institutional quality typically heightens the aptitude for environmental protection.
β_6	UR*INQ	Positive (+)	The engagement between the quality of institutions and unemployment rates is predicted to have a positive mien on the environment, considering that resilient institutions can counteract environmental deterioration while addressing unemployment

This research introduces an innovative involvement through its modeling framework that clearly separates the institutional quality's direct bearings on economic structures and its indirect bearings on environmental outcomes. While direct miens demonstrate how variables such as economic evolution, unemployment rates, the usage of energy, globalization, and institutional quality influence environmental performance indicators, the indirect ones highlight the bearing of institutional quality on environmental sustainability, outstandingly through its interactions with unemployment rates and globalization. With this regard, the coefficient β_2 denotes the unemployment rate's direct mien on the environmental performance indicator; however, the coefficient β_6 demonstrates the indirect bearing of institutional quality interacting with the unemployment rate on environmental sustainability. The existing literature shows that variables such as economic evolution and the usage of energy have often been examined for their miens on environmental sustainability; however, as far as we know, research specifically addressing the interaction between institutional quality and unemployment rate and its bearings on the Load Capacity Factor (LCF) is absent. To tackle this gap, this study identifies the indirect miens of institutional quality on unemployment, and accordingly its bearing on environmental outcomes. Moreover, the incorporation of the KOF globalization index within the modeling framework represents another innovative aspect of this study. Globalization's mien on the environment is generally evaluated via the lens of scale, composition, and technique repercussions (Grossman and Krueger, 1991; Dreher, 2006; Le and Ozturk, 2020). Assimilating the KOF index into the model enables a deeper exploration of globalization's bearings on economic and environmental dynamics. Incorporating globalization into the modeling framework is imperative to ascertain its overall ramifications on environmental sustainability, as it drives economic evolution and poses threats to environmental sustainability.

3.2. Data

The modelling framework in this paper was applied to annual data spanning from 1996 to 2022 owning to ten high globalized European countries as per the KOF index; namely, Austria, Belgium, Denmark, Finland, France, Germany, Netherlands, Sweden, Switzerland, and the United Kingdom. These countries are clear demonstrations of globalization's bearings on economic and environmental dynamics. Globalization boosts their economic evolution; however, it instantaneously enlarges their Ecological Footprint and raises their environmental pressure (Figge et al., 2017). Globalization may lead to both negative (Yang et al., 2021) and positive (Christoforidis and Katrakilidis, 2021; Haldar and Sethi, 2021; Musa et al., 2021; Azam et al., 2021; Jianguo et al., 2022) miens on the usage of energy and the sustainability of environment, drawing attention to the importance of investigating these countries to understand the environmental bearings of globalization and developing sustainability policies (Wiedmann & Lenzen, 2018; Leal & Marques, 2019). Despite the fact that globalization's bearings on economic evolution and sustainability of environment have been previously scrutinized (Pata et al., 2023; Aydin and Degirmenci, 2023; He et al., 2021; Aluko et al., 2021; Muoneke et al., 2022; Wang et al., 2023); this paper contributes a new perspective to the existing literature by questioning these bearings in the context of LFC for highly globalized European countries. Below, Table 2 shows the descriptions of the utilized variables and their data sources

Table 2. Variable description and data sources

Variable	Symbol	Unit	Source
Load capacity factor	LCF	Biocapacity/Ecological ffootprint per person	GFN (2025)
Unemployment rate	UR	Unemployment (% of total labor force)	WDI (2025)
Institutions Quality	INQ	The International Country Risk Guide (ICRG) Indicator of Quality of Government (index)	World Bank-Prosperity Data360 (2025)
Economic growth	GDP	GDP per capita (constant 2015 US$)	WDI (2025)
Primary energy consumption	PEC	kWh/person	OWID (2025)
Globalization	KOF	Index (from 0 to 100)	KOF Swiss Economic Institute (2025)

Utilizing these facilitates the analysis of critical economic and social aspects concerning environmental sustainability. The proxy of environmental sustainability, LCF, is calculated by taking the biocapacity per capita and dividing it by the ecological footprint. The rest variables of unemployment rate, economic evolution, the usage of primary energy, the quality of institution, and globalization, have been incorporated into the model to evaluate their bearings on environmental sustainability.

3.3. Econometric Methodology

To begin with, the dataset was scrutinized utilizing slope homogeneity and cross-sectional dependence tests, to subsequently be assessed by applying second-generation unit root tests to test the series' stationarity, followed by employing the Durbin-Hausman Cointegration Test proposed by Westerlund (2008) to identify the variables' long-term nexus. Then the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) approach was taken to scrutinize the long- and short-term dynamics of the selected panel during the period spanning from 1996 to 2022. What sets this methodology apart is its capability to adeptly handle short-term shifts as well as long-term liaisons. Moreover, it allows the results to be analyzed independently, considering country-specific differences. Furthermore, this approach enables more reliable approximations as it minimizes potential causality issues and contributes through including lagged variables; providing a comprehensive and robust framework for examining the bearings of economic evolution, unemployment rates, energy usage, and institutional quality on environmental sustainability. Ultimately, benefiting from the outcomes, policy strategies, and their implications will be deliberated thoroughly. Figure 3 represents the empirical analysis steps.

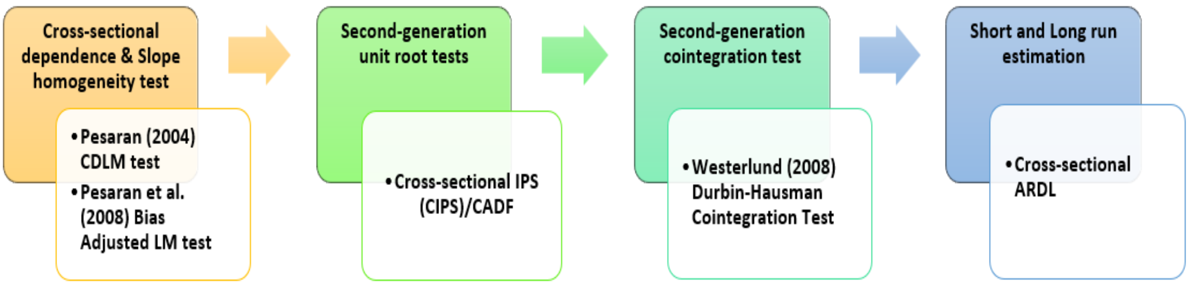

Figure 3: Methodology

3.3.1. Cross-sectional dependence - Slope homogeneity test

Assessing cross-sectional dependence is essential in panel data studies, particularly for representative nations like developing, emerging, and transitioning economies with comparable economic traits. The susceptibility of an economy to other countries' external shocks increases owning to globalization, financial integration, and international trade. Hence, analyzing cross-sectional dependence is vital in empirical studies involving panel data. Conventional panel data approaches assume that cross-sectional units are independent and that regard slope coefficients are homogeneous; however, estimators that ignore cross-sectional dependence might yield erroneous inferences (Chudik and Pesaran, 2013). Furthermore, the estimated coefficients might fluctuate across cross-sectional units; thus, checking for the presence of cross-sectional dependence and slope homogeneity holds priority in empirical analyses.

To attain this outcome, the Cross-Sectional Dependence LM (CD_{LM}) test put forward by Pesaran (2004) and the Bias-Adjusted LM tests introduced by Pesaran et al. (2008) are engaged; as these approaches are applicable in cases when N>T ve T>N. Thus, the relevant CD_{LM} and Bias-Adjusted LM (LM_{adj}) test statistics are ascertained as follows:

$$\text{CD}_{LM} = \sqrt{N/(N(N-1))} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(T\hat{\rho}_{ij}^2 - 1\right) \tag{3}$$

$$\text{LM}_{\text{adj}} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left((T-k)\hat{\rho}_{ij}^2 - \mu_{Tij}\right)/\left(V_{Tij}\right) \tag{4}$$

Where, $\hat{\rho}_{ij}$ denotes the correlation between cross-sectional units, μ_{Tij} denotes the cross-sectional means and V_{Tij} expresses variance. The null and alternative hypotheses for these evaluations are presented as follows:

$\boldsymbol{H_0}$: No dependence exists between cross-sections.

$\boldsymbol{H_1}$: Cross-sectional dependence exists.

The homogeneity test weighs whether a change unfolding in one nation considered in the panel data analysis comparably influences the other countries, indicating the significance of the countries' economic conditions. Moreover, the type of unit root tests to be applied to the dataset is influenced by the variables' homogeneity or heterogeneity estimated in this paper utilizing the Delta test developed by Pesaran and Yamagata (2008). The hypothesis is laid out as follows

$\boldsymbol{H_0: \beta_i = \beta}$

$\boldsymbol{H_1: \beta_i \neq \beta}$

The null hypothesis's rejection demonstrates the attendance of slope coefficients' heterogeneity in the panel data models. Subsequent to these initial evaluations, the Cross-Sectionally Augmented Dickey-Fuller (CADF) test will be enacted to appraise the variables' stationarity levels.

3.3.2. Panel unit root test

The stationarity examination and the unit root presence detection are decisive for forestalling erroneous regression consequences. Numerous panel unit root tests, comprising a range of pros and cons, are involved in the existing literature. The selection of these tests is influenced by ingredients such as sample size and test power (Narayan and Narayan, 2010). The existence of cross-sectional dependence determines the choice of a specific unit root test to be applied to the dataset. As the cross-sectional dependence is evident in the selected panel, second-generation unit root tests that account for such dependencies have been applied, namely, the Cross-Sectionally Augmented Dickey-Fuller (CADF) test developed by Pesaran (2007) being calculated as follows:

$$\boldsymbol{\Delta y_i = a_i + b_i y_{i,t-1} + c_i \bar{y}_{t-1} + \sum_{j=0}^{p} d_{ij}\, \Delta \bar{y}_{t-j} + \sum_{j=1}^{p} \delta_{ij} \Delta\, y_{i,t-j} + e_{i,t}} \tag{5}$$

Where $\bar{y}_t$ denotes the average of all N cross-sections at time T. It is pertinent to note that the CADF test's results are harnessed to investigate each cross-sectional series' stationarity rather than the entire panel data set. The mean of the CADF *t*-statistics estimated for each cross-section is used to evaluate the entire panel's stationarity, and is referred to as the Cross-Sectionally Augmented IPS (CIPS) statistic calculated as follows

$$\boldsymbol{CIPS = N^{-1}\sum_{i=1}^{N} CADF} \quad (6)$$

The CADF and CIPS test statistics are estimated utilizing Equations 5 and 6, then compared to the critical values provided by Pesaran (2007) to determine whether to accept or reject the null hypothesis indicating the presence of a unit root in the series. The null hypothesis is rejected if the estimated test statistic exceeds the corresponding critical table value, showing that the series does not contain a unit root and is therefore stationary.

3.3.3. Panel cointegration test

The Durbin-Hausman (DH) cointegration test, developed by Westerlund (2008), yields numerous advantages. Initially, it can undertake analyses detached from variables' stationary phases and allows for the examination of multiple independent variables, as the standard normal distribution of this test is a significant advantage. Moreover, it considers ingredients like cross-sectional dependence and heterogeneity. It is worth noting that the dependent variable must be I(1) for the DH cointegration test to be applicable:

$$DH_{panel} = \hat{s}_n(\varphi_1 - \varphi_2)^2 \sum_{i=1}^{N}\sum_{t=2}^{T} \hat{e}_{i(t-1)}^2 \; ; \; DH_{group} = \sum_{i=1}^{N} \hat{s}_n(\varphi_1 - \varphi_2)^2 \sum_{t=2}^{T} \hat{e}_{i(t-1)}^2 \quad (7)$$

Whereas DH_{group} test assumes that the parameters are heterogeneous, DH_{panel} assumes that the autoregressive parameter is consistent across the panel, with null hypothesis indicates the nonattendance of cointegration for both test statistics.

3.3.4. Heterogeneous parameter estimates

In this study, to appraise both long- and short-term coefficients, the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model developed by Chudik et al. (2016) and Chudik and Pesaran (2015) is harnessed. The CS-ARDL estimator's principal advantage is its ability to provide consistent consequences irrespective of the series' cointegration or stationarity levels. Moreover, as an extension of ARDL, the dynamic common correlated effects (CCE) approach adeptly deals with cross-sectional dependencies by incorporating lagged dependent variables along with lagged means from across sections (Chudik and Pesaran, 2015). Furthermore, it considers the slope coefficients' heterogeneity through mean group estimates. The CS-ARDL model's mean group variation serves as an indicator for latent common factors and their corresponding lags; complementing the ARDL estimates for each cross-section by utilizing cross-sectional means (Chudik et al., 2016). This approach is exceptionally efficient in tackling complexities and potential biases associated with weak exogeneity arising from lagged dependent variables' inclusion in the model. The basic regression model of the CS-ARDL estimation process is as follows:

$$\boldsymbol{y_{i,t} = \alpha_i + \sum\nolimits_{l=1}^{p_y} \lambda_{l,i}\, y_{i,t-1} + \sum\nolimits_{l=0}^{p_x} \beta_{l,i}\, x_{i,t-1} \sum\nolimits_{l=0}^{p_\varphi} \varphi'_{i,l}\, \bar{z}_{i,t-1} + \varepsilon_{i,t}} \quad (8)$$

Where $\boldsymbol{y_{i,t}}$ denotes the dependent variable (LCF), $\boldsymbol{x_{i,t}}$ symbolizes a function that incorporate the independent variables (UR, INQ, GDP, PEC, KOF, UR*INQ). $\boldsymbol{\bar{z}_{i,t-1}}$ denotes the lagged cross-sectional means. The following equation is used to determine the mean group estimates' long-term coefficients:

$$\hat{\theta}_{\text{CS-ARDL},i} = \sum_{l=0}^{p_x} \hat{\beta}_{l,i} / \left(1 - \sum_{l=1}^{p_y} \hat{\lambda}_{l,i}\right), \hat{\theta}_{\text{MG}} = 1/N \sum_{i=1}^{N} \hat{\theta}_i \quad (9)$$

Where $\widehat{\boldsymbol{\theta}}_{\boldsymbol{i}}$ symbolizes each cross-section's estimate. Chudik and Pesaran (2013) perceived that the lagged augmented CCE mean group estimator offers consistent functionality corresponding to bias, size, and power; however, in cases where T is less than 50, they identified a negative bias. To alleviate this small sample time series bias, Chudik and Pesaran (2015) endorse adopting the panel Jackknife approach developed by Dhaene and Jochmans (2015) or the Recursive Average Adjustment (REC) approach proposed by So and Shin (1999). The REC method has been selected in this investigation as it yields more consistent consequences. The basic equations of the REC method are as follows:

$$\hat{y}_{i,t} = y_{i,t} - (1/(t-1)) \sum_{s=1}^{t-1} y_{i,s} \quad (10)$$

$$\widetilde{\omega}_{i,t} = \omega_{i,t} - (1/(t-1)) \sum_{s=1}^{t-1} \omega_{i,s} \quad (11)$$

The CS-ARDL estimates' bias-correction consequences applied utilizing the REC method will also be demonstrated as the time span of this research is 26 years (T<50).

4. Evidence-Based Outcomes

As an initial phase and to obtain consistent measures, both cross-sectional dependence and homogeneity tests were scrutinized. Table (3) demonstrates the fallouts of the Pesaran (2004) CD_{LM} investigation and the Bias-Adjusted LM inquiries developed by Pesaran et al. (2008) employed to evaluate cross-sectional dependence, coupled with the fallouts of the Delta inquiry developed by Pesaran and Yamagata (2008) employed to reconnoiter variables' homogeneity. These inquiries' fallouts hold an essential function in appraising the assumptions of cross-sectional dependence and homogeneity for the correct specification of the model.

Table 3. CSD and heterogeneity check

Panel (a) CSD Tests		
Variable	$\mathbf{CD_{LM}}$	$\mathbf{LM_{adj}}$
*ln*LCF	134.471***	114.981***
*ln*GDP	210.982**	201.609***
*ln*UR	32.160***	12.091***
*ln*PEC	34.581***	13.453***
*ln*KOF	25.331**	8.332**
*ln*INQ	128.901***	119.112***
ln(UR*INQ)	32.077***	7.383**

Panel (b) homogeneity test for $lnLCF_t = (lnGDP_t, lnUR_t, lnPEC_t, lnKOF_t, lnWGI_t, ln(\text{UR} * \text{INQ}))$			
$\hat{\Delta}$ test	p-value	$\hat{\Delta}_{adj}$ test	p-value
21.743	0.000	17.278	0.001

Note: *** and ** symbolize the rejection of the null hypothesis at the 1%, and %5 levels correspondingly.

Table (3) demonstrates different significance levels' rejection of the null hypothesis declining the supposition of cross-sectional independence in both the CD_{LM} and LM_{adj} investigations, signifying the presence of CSD in the chosen model. These fallouts highlight the substantial economic and environmental interfaces among the European nations, as shocks occurring in one country also spread to other ones with high levels of globalization. Moreover, Delta investigations' null hypothesis was rejected at the significance level of 1%, indicating the slope coefficients' heterogeneity in the selected model. In the subsequent phase, the CIPS unit root investigation was accomplished to appraise the variables' stationarity properties. Table 4 demonstrates the fallouts incorporating those from both level and first difference.

Table 4. CIPS Panel unit root investigation fallouts

Variable	I(0)	I(1)	Implications
*ln*LCF	-1.110	-3.590***	I_1
*ln*GDP	-1.981	-6.987***	I_1
*ln*UR	-1.732	-4.009***	I_1
*ln*PEC	-1.655	-7.323***	I_1
*ln*KOF	-2.208***	-	I_0
*ln*INQ	-0.940	-3.909s***	I_1
ln(UR*INQ)	-3.012***	-	I_0

Note: *** symbolizes the rejection of the null hypothesis at the significance level of 1%

Table 4 indicates that whereas the variables LCF, GDP, UR, PEC, and INQ are grouped as I(1), meaning they have a unit root and are non-stationary, those of lnKOF and ln(UR*INQ) are grouped as I(0), indicating that these variables do not have a unit root and are stationary. The variables' different stationarity levels do not pose a concern for the analysis's subsequent phase, as the CS-ARDL approach can be applied to variables of different stationarity levels. Thus, to scrutinize the long-term nexus, the Durbin-Hausman (DH) cointegration test was carried out in the analysis's third phase. Table 5 presents the fallouts, confirming the null hypothesis's rejection at the significance level of 1%.

Table 5. DH cointegration investigation fallouts

Model	Constant		Constant and trend	
Tests	Statistic	*p*-value	Statistic	*p*-value
DH_{panel}	123.801***	0.000	163.370***	0.000
DH_{group}	18.199***	0.000	21.098***	0.000

Note: *** stands for that the null hypothesis being rejected at the significance level of 1%.

Reflecting the quantitative consequences vis-à-vis CSD, heterogeneity, unit root, and DH cointegration investigations, the use of the CS-ARDL estimator has been preferred for the analysis as the fourth step to thoroughly question both short- and long-term affiliations. Under conditions of CSD and different stationarity levels, the CS-ARDL method provides consistent upshots. The mean group CS-ARDL model has been estimated to derive coefficients tailored to cross-sectional units, with the optimal lag structure being determined using an F-test moving from general to specific. As well, the REC technique proposed by So and Shin (1999) has been applied to reduce small sample time series bias. Table 6 demonstrates the obtained fallouts.

Table 6. CS-ARDL approximation

$lnLCF_t = (lnGDP_t, lnUR_t,\ lnPEC_t, lnKOF_t, lnWGI_t, ln(\text{UR} * \text{INQ})$		
	CS-ARDL	CS-ARDL_{REC}

Short run	Coefficient	Std. error	*p*-value	Coefficient	Std. error	*p*-value
ΔLCF_{t-1}	0.503***	0.124	0.001	0.487***	0.119	0.000
ΔGDP	-0.148*	0.079	0.059	-0.138*	0.072	0.065
ΔUR	0.104	0.073	0.189	0.114	0.067	0.272
ΔPEC	-0.284***	0.094	0.004	-0.272***	0.091	0.005
ΔKOF	0.096*	0.057	0.064	0.091*	0.055	0.067
ΔINQ	0.178	0.267	0.019	0.171	0.065	0.189
Δ (UR*INQ)	0.153**	0.062	0.037	0.146**	0.059	0.041
Long run	Coefficient	Std. error	*p*-value	Coefficient	Std. error	*p*-value
GDP	-0.243**	0.102	0.019	-0.227**	0.098	0.023
UR	0.186**	0.091	0.042	0.204**	0.086	0.037
PEC	-0.401***	0.115	0.001	-0.389***	0.109	0.002
KOF	0.124***	0.064	0.048	0.109*	0.061	0.052
INQ	0.309***	0.084	0.003	0.297***	0.079	0.004
UR*INQ	0.219***	0.076	0.005	0.211***	0.071	0.004
ECT_{t-1}	-0.552***	0.104	0.000	-0.537***	0.102	0.000
Adjusted R^2	0.62			0.71		

Table 6 demonstrates the miens of GDP, UR, PEC, INQ, and KOF on LCF from both short- and long-term perspectives utilizing the CS-ARDL and $CS\text{-}ARDL_{REC}$ and mirroring the validity of the Environmental Phillips Curve (EPC). Considering the variables' log-transformed values, the coefficients symbolize the elasticities of LCF concerning the independent variables. The upshots revealed that a 1% appreciation in GDP corresponds to a 0.148% decrease in LCF in the short term and 0.243% in the long term. Comparable outcomes were confirmed by the $CS\text{-}ARDL_{REC}$ model, with shrinkage of 0.138% in the short term and 0.227% in the long term, reflecting the alignment with the literature backing the adverse miens of economic evolution on environmental sustainability (Pata and Balsalobre-Lorente, 2022; Yavuz et al., 2023; Caglar et al., 2024), and suggesting that long-term growth policies may overlook environmental sustainability. Whereas the CS-ARDL model directs a positive LCF increase of 0.104% in the short term and 0.186% in the long term stemming from UR, the $CS\text{-}ARDL_{REC}$ model identified positive miens of 0.114% in the short term and 0.204% in the long term; with statistically insignificant short-term miens confirmed by both models. Moreover, as per the EPC hypothesis, an adverse affiliation is expected between the rates of unemployment and the quality of the environment; however, the exposed positive one observed in the long term is attributed to the consideration of LCF, the proxy of the environmental quality.

If a variable condenses environmental pollution, it likewise boosts environmental quality (Yavuz et al., 2023); thus, when inspecting the validity of the EPC with LCF as an environmental quality proxy, the coefficient of the unemployment variable is expected to be positive. The attained fallouts designate that increases in the unemployment rate have positive miens on LCF in the long term, reflecting important insights concerning the validity of the EPC and aligning with the studies conducted by Kashem and Rahman (2020), Anser et al. (2021), Bhowmik et al. (2022), Shang and Xu (2022), Ng et al. (2022), Djedaiet (2023), Daştan and Eygü (2023), Haciimamoğlu (2023), Durani et al. (2023), Yavuz et al. (2023), Ayad and Djedaiet (2024), and Azimi and Rahman (2024). Furthermore, the CS-ARDL model indicates a LCF reduction of 0.284% in the short term and 0.401% in the long term stemming from PEC, aligning with the CS-ARDL$_{REC}$ model revealed a similar declining trend, identifying reductions of 0.272% in the short term and 0.389% in the long term. These outcomes highlight the environmental harms associated with energy consumption, aligning with the studies conducted by Pata and Isik (2021), Huilan et al. (2022), Khan et al. (2021), and Pata et al. (2023). Moreover, while the CS-ARDL model shows a positive and significant KOF mien of 0.096% in the short term on LCF, the CS-ARDL$_{REC}$ model indicates an effect of 0.091%, with significant effects detected at 0.124% and 0.109%, respectively in the long term. This evidence demonstrates that globalization can boost environmental sustainability, facilitating the transfer of technology and environmentally friendly practices (He et al., 2021; Aluko et al., 2021; Muoneke et al., 2022; Wang et al., 2023). In addition, both the CS-ARDL and CS-ARDL$_{REC}$ models revealed no statistically significant INQ impact on LCF in the short term; however, positive and significant miens of 0.309% and 0.297% are noted in the long term respectively; suggesting that enhancing long-term environmental protection and supporting environmental sustainability require resilient institutional structures and good governance (Christoforidis and Katrakilidis, 2021; Haldar and Sethi, 2021; Musa et al., 2021; Azam et al., 2021; Jianguo et al., 2022). Ultimately, a positive mien on LCF was recorded for the UR*INQ variable, which depicts the indirect bearing of institutional quality interacting with the unemployment rate on environmental sustainability. Both the CS-ARDL and the the CS-ARDL$_{REC}$ model revealed significant positive bearings of 0.153% in the short term and 0.219% in the long term; and 0.146% in the short term and 0.211% in the long term, respectively. These results validate the EPC hypothesis, indicating that resilient institutions enable enhancing environmental sustainability while combating unemployment, and highlighting the critical weight of deliberating the interaction between unemployment and institutional quality when formulating environmental sustainability policies**.**

5. Conclusions

5.1. Concluding remarks

This study validates the Environmental Kuznets Curve (EPC) hypothesis in the ten most globalized European countries during the time period spanning from 1996 to 2022 using modern econometric methods such as the STIRPAT model and CS-ARDL and considering the bearings of GDP, PEC, INQ, and KOF on LCF. Cross-sectional dependence and slope homogeneity investigations were applied, revealing meaningful correlations across all variables with weighty interactions among countries. Second-generation unit root investigations indicated different stationarity levels of the variables at I(0) and I(1). Moreover, the Westerlund (2008) cointegration investigation confirmed the presence of long-term nexus among the variables. Furthermore, the CS-ARDL approach was utilized to measure the long-term elasticities and ensure the results' consistency in the presence of different stationarity levels. This study's essential fallouts can be summarized as follows: First, the EPC hypothesis holds true, indicating that reductions in economic activities in highly globalized countries like Germany, Sweden, and Switzerland alleviate environmental pressures. Second, there exists a negative long-term mien on LCF stemming from GDP, underscoring the magnitude of sustainable development strategies to alleviate the harmful miens of economic evolution on environmental sustainability. Third, as PEC reduces LCF in both the short and long, it contributes to environmental degradation. Fourth, there exist positive bearings of INQ and KOF on LCF in the long term that accordingly increase the sustainability of the environment, suggesting that countries with high institutional quality require deepening their environmental management capacities. Ultimately, one of the study's original involvements is the inclusion of the UR*INQ variable, which recorded a positive mien on LCF, indicating that resilient institutions enable enhancing environmental sustainability while combating unemployment, and validating the EPC hypothesis.

5.2. Policy implications

This study provides policy implications concerning the nexus between economic evolution and environmental sustainability in the most globally integrated European countries. First, policymakers ought to construct integrated strategies that reduce unemployment while enhancing environmental sustainability, considering the positive affiliation between unemployment rates and environmental quality. Creating green jobs, especially in industrial-centric economies such as Germany and the Netherlands, will both reduce unemployment and contribute to environmental objectives. Moreover, investing in eco-friendly sectors like sustainable agriculture, renewable energy, and waste management offers a solution that is compatible with the employment structures of these countries. Secondly, there exists a negative mien of economic evolution on the environmental quality. This consequence holds particular relevance for nations with significant industrialization like France and the United Kingdom, where improving energy efficiency, adopting more eco-friendly production techniques, and promoting the use of renewable energy sources are indispensable for curbing the negative environmental miens of economic evolution. Denmark's experience with the broad utilization of renewable energy can serve as a blueprint for other countries to follow. Third, it is imperative to solidify environmentally friendly policies and international cooperation in these countries, considering the positive miens of globalization and resilient institutional structures on Sustainable environmental practices. The resilient institutional structures in countries like Sweden and Switzerland with high globalization levels optimize the efficacy of environmental strategies, facilitating the achievement of sustainability objectives, and helping manage global environmental challenges more effectively.

5.3. Limitations

This research has distinct challenges and new avenues for further investigation. First, the study evaluated the EPC hypothesis exclusively in the context of the 10 leading globalized European nations. Further research could broaden the applicability of outcomes by investigating the EPC's relevance across nations with alternative economic and institutional environments. The EPC hypothesis could, for instance, be assessed in nations with less globalization or those with distinct institutional structures. As a second point, the model utilized LCF as an environmental metric; however, future studies could investigate the EPC with alternative indicators, such as CO_2 releases or ecological footprint. Notably, the mien of CO_2 releases on the EPC may be investigated extensively in high-carbon-emission nations, such as France and Germany. Ultimately, this research applied the CS-ARDL approach; however, subsequent investigations could consider other econometric methods (for instance, quantile panel regression) to conduct more detailed analyses, contingent on the data structure and research inquiries. This could facilitate a deeper comprehension of the EPC dynamics, particularly throughout different economic cycles.

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