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Environmental pollution and economic growth in the European Union countries: A systematic literature review

Błażej Supron[1]

Abstract

This study presents a comprehensive analysis of the relationship between economic growth and CO_2 emissions in the European Union, with a particular focus on the Environmental Kuznets Curve (EKC) hypothesis. Through a systematic review of approximately 1,250 scientific publications, machine learning techniques, and multivariate statistical analysis, significant yet complex relationships between these variables have been identified. While the EKC hypothesis often posits a U-shaped or N-shaped relationship, the findings of this research indicate that the actual relationship can vary depending on factors such as foreign trade, energy consumption, and econometric methodologies. Numerous studies emphasise the importance of integrating renewable energy into these models. Overall, the results suggest that the EKC may be insufficient to fully comprehend the intricacies of sector-specific environmental-economic dynamics within the EU.

Keywords

- environment
- Kuznets curve
- economic growth
- European Union
- CO_2
- energy
- systematic review

JEL codes: C1, C55, O44, Q56

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Introduction

Environmental pollution resulting from human economic activity gained significant international attention at the 1979 World Climate Conference in Geneva, which underscored the rising levels of greenhouse gases and their climatic impacts (Newell & Paterson, 1996). This concern prompted major global initiatives, including the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the Kyoto Protocol in 1997, aimed at reducing emissions and enhancing environmental protection (Böhringer, 2003). While the 2015 Paris Agreement set ambitious targets to limit temperature increases at below 2°C, some researchers argue that these efforts remain inadequate (Schleussner et al., 2016; Spreng & Spreng, 2019).

The European Union plays a leading role in climate action through the Green Deal, which sets stricter targets: climate neutrality by 2050 and a 55% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels), alongside increasing renewable energy to at least 40% by 2030 (Szpilko & Ejdys, 2022). Beyond climate policy, the Green Deal drives transformations in energy, industry, and finance, reshaping economic and social landscapes (Samper et al., 2021; Vela Almeida et al., 2023). Understanding these dynamics is crucial for evidence-based policymaking that balances economic growth with climate goals.

Given the central role of economic activity in greenhouse gas emissions, understanding its relationship with environmental degradation is crucial, particularly considering the EU's climate targets. Despite over 6,000 related articles having been published between 2014 and 2024 (BASE database), gaps remain in integrating economic theory, systematic reviews, and advanced analytics. Bridging these gaps is essential for aligning economic and environmental goals. Additionally, advanced technologies like text mining and machine learning are increasingly vital for extracting insights from this extensive literature.

This study synthesises research from 2014 to 2024, integrating theoretical and empirical insights to examine the relationship between economic growth and CO_2 emissions in the EU. It has four key objectives. Firstly, it identifies primary research areas on economic growth and environmental factors, with a focus on the Environmental Kuznets Curve (EKC) hypothesis. Secondly, it applies advanced statistical tools to uncover interrelationships among key topics. Thirdly, it evaluates how theoretical frameworks shape approaches to global warming, particularly through EKC insights. Lastly, it critically assesses the economic impact of CO_2 emissions in the EU, highlighting research gaps and future directions.

The present study makes several key contributions to the existing body of knowledge. Firstly, it examines the European Union, a region with uniquely ambitious climate targets, thus offering a valuable case study on economic-environmental dynamics. Secondly, it applies advanced methodologies, including the machine learning-based LitsearchR, for systematic review automation and multivariate techniques such as log-linear analysis and Multiple Correspondence Analysis, enhancing analytical depth. Thirdly, by leveraging data from major global databases, it overcomes the limitations of earlier reviews reliant on narrower sources. Lastly, integrating systematic and synthetic reviews with naïve search models reduces bias, providing a more balanced research perspective.

The article is structured as follows: Section 1 explores the theoretical foundations of the environmental-economic relationship; Section 2 details the methodology, including data collection and analysis; Section 3 presents the results, followed by a comparison with existing studies in Section 4; last Section concludes with key implications and future research directions.

1. Literature review

The relationship between economic growth and environmental pollution has been a subject of intense academic scrutiny. The concept of the Environmental Kuznets Curve originates from Kuznets' (1955) hypothesis on income inequality, which was later adapted to environmental economics by Grossman and Krueger (1991). The EKC suggests that in the early stages of economic development, environmental degradation intensifies with increasing GDP per capita. However, after reaching a certain income threshold, further economic growth leads to improvements in environmental quality due to technological advancements, regulatory policies, and shifts toward service-based economies (Panayotou, 1993).

Several modifications to the original EKC framework have emerged. Some studies indicate a U-shaped or N-shaped relationship between GDP and CO_2 emissions (Brock & Taylor, 2010; Fakher et al., 2023; Kaika & Zervas, 2013; Leal & Marques, 2022), while others question the universality of the EKC, arguing that factors such as energy consumption, regional differences, trade openness, and institutional quality significantly shape the emissions trajectory (Mardani et al., 2019; Shahbaz & Sinha, 2019; Tchapchet Tchouto, 2023).

Given the emphasis in research on the impact of regional conditions on the shape and trajectory of the EKC curve, it is imperative that studies focusing on specific regions consider the heterogeneity of these conditions (Bibi & Jamil, 2021; Kaika & Zervas, 2013). Empirical research on the EKC in the EU presents mixed findings. Early studies such as Bengochea-Morancho et al. (2001) examined panel data from 1981–1995 and found that a 1% increase in GDP raised emissions by 0.18% in middle-income EU countries and 0.97% in low-income ones.

Later studies expanded on these findings; Martínez-Zarzoso et al. (2007) demonstrated that population growth disproportionately affects emissions in newer EU members, whereas older members exhibited elasticity below one; Kasman and Duman (2015) confirmed an inverted U-shaped EKC for 27 EU countries, emphasising the role of trade openness and energy consumption; Pejović et al. (2021) used a VAR model to show that GDP growth led to short-term emission reductions in some EU countries; Onofrei et al. (2022) analysed fixed-effects panel data from 2000–2017, indicating that GDP increases marginally slow emissions growth but does not eliminate it. These discrepancies highlight the role of methodological choices and country-specific factors in shaping EKC outcomes (Leal & Marques, 2022). Given the EU's ambitious climate targets, the generalizability of EKC findings remains uncertain.

Beyond economic growth, several exogenous factors influence CO_2 emissions. A growing body of literature emphasises the importance of energy consumption patterns in EKC dynamics. Dogan and Seker (2016) found that renewable energy contributes to emission reductions, whereas non-renewable sources exacerbate environmental degradation. Al-Mulali et al. (2015) confirmed that financial development and urbanisation increase CO_2 emissions, but trade openness and renewable energy mitigate this effect.

Technological innovation is another critical factor. Stern (2017) suggested that advances in energy efficiency can decouple GDP growth from emissions, while Voumik et al. (2022) demonstrated that EU countries with higher R&D investments in green technologies show stronger evidence of EKC trends. However, other studies argue that technological progress alone is insufficient without strong regulatory frameworks (Albulescu et al., 2020; Husnain et al., 2021).

Empirical investigations of the EKC employ a variety of econometric methods, each with unique strengths and limitations, while influencing the results obtained. Methods based on regression and panel data regression are commonly used (ARDL, FMOLS, DOLS, VAR). The widespread use of these methodologies is a consequence of their capacity to address the heterogeneity that is evident at the cross-country level (Acaravci & Ozturk, 2010; Gardiner & Hajek, 2020).

Recent years have seen a shift in the focus of EU-level research, with a growing emphasis on the utilisation of new methodologies. The employment of quantile regressions and non-linear models has emerged as a pivotal approach, facilitating a more nuanced and adaptable evaluation of EKC configurations (Bilgili et al., 2016; Hasanov et al., 2021; Wang et al., 2023). The development of AI and machine learning methods has also enriched research with new methods based on neural networks (Arévalo & Antonio, 2024). Due to the intricacy of research on the relationship between economy and environmental contamination, a comprehensive comparative analysis of EKC studies and methods is presented in Appendix A in the Supplementary materials.

To sum up the literature review and the systematic analysis presented in Appendix A, despite extensive research on the EKC, key gaps remain. Most studies focus on aggregate GDP-CO_2 relationships, overlooking sector-specific trends, while the impact of EU climate policies on EKC trends remains underexplored. Additionally, research largely neglects non-CO_2 pollutants, and the use of advanced econometric methods, such as AI-based forecasting and Bayesian inference, could improve EKC estimates. Addressing these gaps with targeted, policy-relevant research will enhance the robustness of EKC findings in the EU context.

2. Research methodology and data

Systematic reviews differ from traditional literature reviews by aiming to identify all relevant studies on a research objective while minimising selection, publication, and data extraction biases (Nightingale, 2009). They offer a transparent, replicable approach to synthesising scientific evidence, evaluating all published findings and their quality (Lame, 2019). As the digital knowledge base expands, traditional analysis of individual publications becomes increasingly complex and time-consuming (Xiao & Watson, 2019). Advances in computational algorithms and machine learning significantly enhance knowledge synthesis (Grames et al., 2019).

The synthetic literature review highlights the diverse methods and topics in studies on economic growth and CO_2 emissions. Given the vast research landscape, analysing all relevant publications required a multi-method approach integrating machine learning and multivariate statistics. Our study followed a multi-stage process, combining statistical analysis, text mining, and log-linear modelling. The research was conducted in five main stages. The entire research process is illustrated in Figure 1.

The first stage of article selection applied a set of keywords based on a comprehensive literature review. These keywords covered topics related to carbon dioxide emissions, ecological footprint, environmental degradation, and environmental quality and sustainability. They were combined with terms referring to economic growth, financial development, foreign direct investment, natural resources, trade openness, energy consumption, and technological innovation. Additionally, articles were required to address the European Union, which was ensured by the inclusion of relevant keywords. Further terms included references to the Kuznets curve, regression techniques, and panel data analysis. These criteria, grounded in the literature review, resulted in

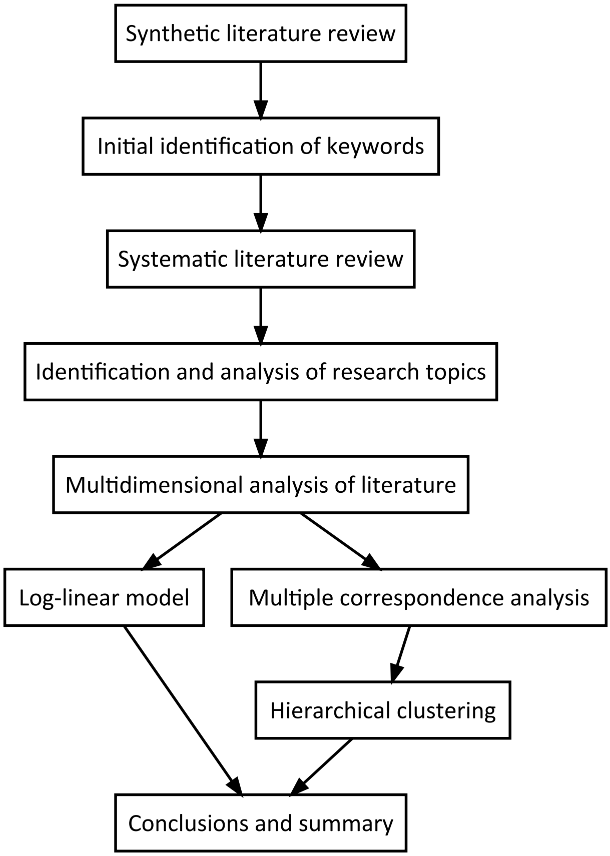

Figure 1. Review of the research process

Source: own elaboration.

the selection of 1548 unique articles that met the search requirements from 2014 to 2024, sourced from Google Scholar, Web of Science (WoS), and BASE.

The verification process was conducted based on several criteria, including authors' personal data, article title, journal title, and DOI number. In the library used, duplicates were removed at the bibliographic data import stage, ensuring that they were not included in the final dataset. In the second stage, the LitsearchR library (2019) was used for a naive keyword search. This library was chosen for its ability to automate and enhance the systematic review process, particularly in identifying relevant keywords with minimal bias. LitsearchR supports the automatic generation of Boolean search strings in up to 53 languages and offers stemming capabilities for English, making it highly versatile for multilingual datasets. It also facilitates bibliographic data extraction from sources like Google Scholar, which do not support native API access. The tool can cross-check search results against a set of known relevant articles, providing performance metrics to ensure precision and recall in the retrieval process.

To extract research themes, text mining was conducted using the Rapid Automatic Keyword Extraction (RAKE) algorithm (Rose et al., 2010). RAKE was selected for its efficiency in identifying highly relevant keywords through co-occurrence analysis within the text. This algorithm requires minimal computational resources and complements other NLP models, leveraging open-source implementations.

With the assistance of LitsearchR, the retrieved articles were analysed, and the initial keywords were narrowed down to those with the highest relevance. A Document-Feature Matrix (DFM) was then constructed to create a co-occurrence map, which highlights how frequently and closely terms are linked, revealing underlying research themes and relationships. Node strengths within the map were optimised using change-point methods (2019), allowing for the identification of the most significant terms, while filtering out redundancies or less relevant data. To ensure precision, the "only shortest unique substrings" criterion was applied to further refine the keywords.

These keywords were thematically grouped and used to create a new query for further searches of bibliographic databases. The articles retrieved in the subsequent search were then compared with the previously selected articles, leading to the exclusion of 181 articles from the original dataset. Additional validation using fuzzy matching resulted in the removal of further 44 articles. This method, which measures textual similarity, helps identify duplicate entries or different versions of the same work, thereby enabling the detection of working papers later published in journals. Finally, a DFM matrix was constructed for further multidimensional analysis, and another matrix was created for additional analysis. The process of literature refinement and selection is summarized in the PRISMA flowchart (Figure 2), which provides a step-by-step visual representation of the screening and reduction stages.

In the third stage, key terms were extracted from the analysed publications using the LitsearchR package, based on co-occurrence networks and node strength, and then reduced accordingly. These terms and keywords were grouped thematically, creating a binary co-occurrence matrix for further analysis. The research methodology proposed by Bąk and Cheba (2023) was applied for the statistical examination of literature, with a focus on interactions between binary variables (Wiedermann & von Eye, 2020).

To determine relationships between research topics, a bootstrap χ^2 test was conducted to identify which topics co-occur in models examining the relationship between economic growth and CO_2 emissions in EU countries. Unlike the classical χ^2 test, which relies on a theoretical distribution of the test statistic, the bootstrap χ^2 test uses multiple re-samplings (bootstrapping) from the original data to empirically determine the distribution of χ^2 values. Both

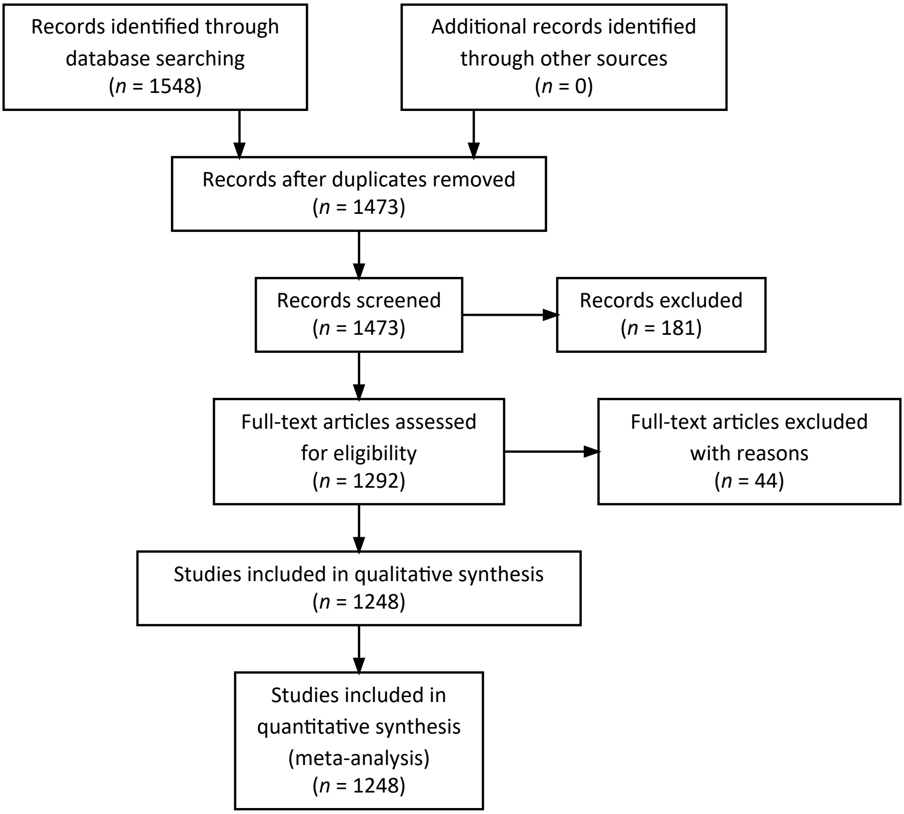

Figure 2. PRISMA flow diagram for the literature studied

Source: own elaboration.

approaches test the same null hypothesis (H_0)—that there is no dependence among the categorical variables—but the bootstrap method is especially advantageous for smaller datasets (Azen & Walker, 2021).

The literature discusses various methods for analysing interactions among categorical variables, including log-linear models, logistic regression, and generalised additive models (Agresti & Liu, 1999). The choice of model depends on the specific research context and data characteristics. Considering the objectives and the structure of the data, a log-linear model was employed to investigate interactions between topics, allowing for the modelling of categorical variables based on the Poisson distribution. The appropriate model was selected iteratively by reducing interaction levels and comparing the significance of modifications, using the gllm library. The general form of the log-linear model is as follows (Goodman, 1979):

$$\ln(Y) \sim XB + \epsilon \tag{1}$$

The detailed form of the log-linear model used in the study was defined as follows:

$$\ln\left(\hat{n}_{(ijkl\ldots)}\right)=\lambda_i^Y+\sum_{s=1}^{p}\lambda_j^{X_s}+\sum_{t=1}^{p}\lambda_{it}^{YX_t}+\sum_{u<v}\lambda_{uv}^{X_uX_v}+\ldots+\lambda_{i,j,k,\ldots}^{Y,X_1,X_2,\ldots,X_p} \tag{2}$$

where λ represents the model parameters in the following rows of interactions, and p is the number of independent variables.

In the next stage, key topics were grouped into main categories. Due to the numerous variables, dimensionality reduction was necessary. Multiple Correspondence Analysis (MCA) was applied to analyse relationships between categorical data (Hjellbrekke, 2018). MCA, which generalises Principal Component Analysis (PCA) for qualitative variables (Abdi & Williams, 2010), was performed using the FactoMineR package (Husson et al., 2017). The optimal MCA results were then subjected to hierarchical cluster analysis, enabling the identification of co-occurring research topics and the formation of distinct clusters. Clustering and visualisation were conducted using the FactorExtra library.

3. Systematic literature review

3.1. Keyword, thematic analysis and classification

In the first stage, a database of 1,548 publications indexed in the leading global databases was compiled. Based on titles, keywords, and abstracts, the key terms describing the relationships between CO_2 emissions and economic growth in European Union countries were identified. At this stage, the Litsearchr package was used twice. Initially, a naive search method was employed, allowing for the identification of the most significant keywords related to the links between CO_2 emissions and economic growth in the EU. The list of keywords used is presented in Table B1 in the Supplementary materials.

These keywords were then used to formulate a query aimed at narrowing down the search results, ultimately yielding a final set of 1,248 publications. Based on the keywords identified by the Litsearchr algorithm, a reduction was performed using the compute node strength method. As a result, only those keywords corresponding to nodes with high strength were retained. The term strength shift method was applied to pinpoint the jump points in the strength of individual terms. In this analysis, a midpoint was used to balance precision and brevity (presented in Figure B1 in the Supplementary materials).

In the second stage, based on the results from the naive search, selected keywords were further refined. The literature was then retrieved again using the narrowed keywords. After searching the literature and the selected keywords, a co-occurrence network of the chosen terms was visualised. Additionally, a document-feature matrix in binary form was created, which was used in subsequent stages of the study (Figure 3).

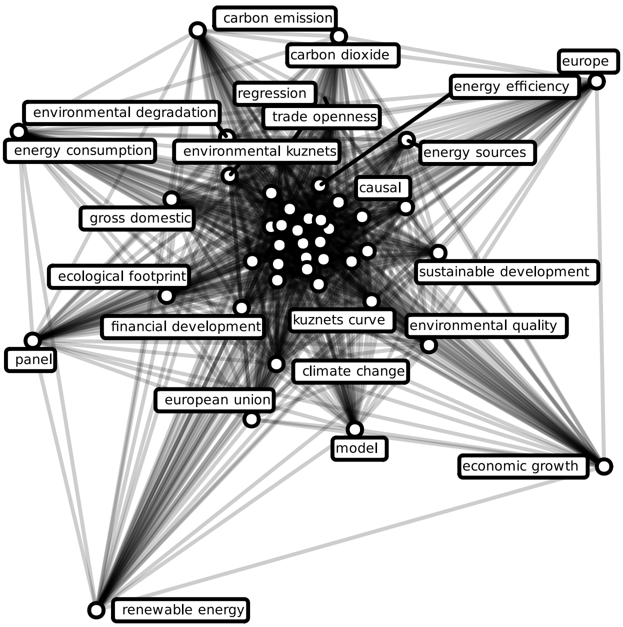

Figure 3. Nodal graph of main research terms

Source: own elaboration.

The analysis of the co-occurrence network and the document-feature matrix indicates that research on CO_2 emissions and economic growth in the European Union encompasses not only the direct relationship between these variables but also broader contexts, such as energy policy, technological development, and environmental progress. Based on the analysis of the co-occurrence network, the studied topics were grouped, as presented in Table B2 in the Supplementary materials. Furthermore, the analysis led to the formulation of the following conclusions:

1. **Central Concepts:** The highest concentration of connections is found around terms such as economic growth, carbon emission, environmental pollution, renewable energy, and sustainable development. This suggests that these topics are most frequently analysed together.
2. **Co-occurrences:** Topics such as panel causality, technological innovation, renewable energy, economic development, and energy consumption are

often linked to studies on CO_2 emissions and GDP. This suggests that the analysed research also considers the impact of technology, energy consumption, and sustainable development policies.

3. **Research Directions:** The connections between topics like carbon emissions, energy sources, non-renewable energy, and fossil fuels indicate numerous studies examining the relationships between CO_2 emissions and different types of energy, particularly renewable energy. The themes related to renewable and non-renewable energy dominated a significant number of studies.
4. **Topic Dispersion:** In addition to the main themes, the analysed studies also focused on less central concepts such as urbanization, climate change, ecological footprint, and environmental quality, indicating a broad range of factors considered in the research.

In the third stage, based on the data collected, a Boolean dependent variable *Y* was constructed. This variable indicates whether a scientific publication addresses issues related to models defining the relationship between eco-

Table 1. Characteristics of study variables

Variable	Name	Description
*X*1	Environmental Impact Factors	factors related to environmental degradation, pollution, environmental quality, climate change, ecological footprint
*X*2	Energy and Efficiency	variables related to energy, energy consumption, energy efficiency and energy transition
*X*3	Economic and Urban Development	factors related to economic development, urbanisation and financial development supporting economic growth
*X*4	Institutional and Sustainable Development	quality of institutions and sustainability
*X*5	Trade and Investment Openness	variables related to trade openness and foreign direct investment
*X*6	Natural Resources	fossil fuels, energy sources and resources
*X*7	Technological Innovation and Human Capital	technological innovation and human resources that support economic development and efficiency
*X*8	Econometric Methods and Models	variables related to statistical methods, regression analyses and causal models
*X*9	Renewable and Non-Renewable Energy	renewable and non-renewable energy and their impact on the economy and environment
Y	Dependent Variable	indicates whether a scientific publication addresses models of the relationship between economic growth and co_2 emissions in the european union (studies using a model or empirical evidence for the Kuznets curve)

Source: own elaboration.

nomic growth and CO_2 emissions in the European Union, particularly in the context of using a model or empirical evidence confirming the Kuznets curve. The construction of *Y* was based on content analysis (titles and abstracts) for the presence of specific keywords such as "nexus", "model", "regression", and "empirical evidence". If at least one of these keywords was identified, the publication was classified as meeting the criteria for variable *Y*.

Additionally, based on the analysis of the terms studied, independent binary variables were constructed, indicating whether a particular topic is addressed in the publication. These variables are presented in Table 1. All variables included in the analysis were selected based on their theoretical relevance and frequent occurrence in the scientific literature addressing this relationship. These variables reflect key research areas such as environmental impact, energy efficiency, economic development, trade openness, natural resources, technological innovation, and econometric methods. Each category was included to represent different dimensions of this multifaceted issue.

3.2. Relationship and log-linear analysis

To assess the significance of the relationships between the variables studied and the dependent variable *Y*, a χ^2 test was conducted, the results of which are presented in Table 2. Initially, variables such as *X*2, *X*4, *X*5, and *X*7 were included due to their theoretical relevance in studies on CO_2 emissions and economic growth. These variables represent key aspects often discussed in the literature, such as energy transition, institutional quality, trade liberalisation, and technological progress. However, the results of the χ^2 test indicated that these variables are not significantly associated with the dependent variable *Y* (p-value > 0.1).

The analysis suggests that only the main factors and, at most, second-order interactions effects should be included in the model, as these effects achieved statistical significance in both the χ^2 test of significance ($df = 15$, $\chi^2 = 95.18$, $p < 0.05$) and the Pearson test ($df = 15$, $\chi^2 = 81.24$, $p < 0.05$). Higher-order effects (third-order and above) were not significant, indicating that their inclusion would not provide additional benefits for the model.

Table 3 presents the results of marginal and partial association tests, showing how the variables (*X*1, *X*3, *X*6, *X*8, *X*9) relate to the dependent variable *Y* and how they interact with one another. In less technical terms, the log-linear model under consideration clarifies the impact of each variable on *Y*, while simultaneously accounting for their mutual interdependencies. The analysis indicates the significance of all interactions between *Y* and the *X* variables and suggested that the model should include the interactions: *X*1**X*3, *X*1**X*6, *X*1**X*8, *X*3**X*8, *X*3**X*9 and *X*8**X*9.

Table 2. Preliminary χ^2 test of the relationships between the variables *X* and *Y*

Variable	χ^2	*p*-value
*X*1	31.331	0.001
*X*2	2.666	0.121
*X*3	3.478	0.064
*X*4	1.536	0.233
*X*5	0.024	0.877
*X*6	3.523	0.071
*X*7	0.030	0.890
*X*8	8.666	0.003
*X*9	3.959	0.047

Source: own elaboration.

The full log-linear model is shown in Table B3 in the Supplementary materials, and detailed diagnostics of the model's fit to the data are presented in Figure B2 in the Supplementary materials. The points aligning along the straight line indicate that the model's predicted frequencies closely match the observed values, and the lack of marked deviations suggests that the residuals do not substantially violate the model's assumptions. The goodness-of-fit statistics—a likelihood ratio of 10.550 ($p = 0.159$) and Pearson's χ^2 of 11.430 ($p = 0.131$)—indicate that there is no basis for rejecting the hypothesis of

Table 3. Boundary and partial relationships tests

Interaction	Df	Partial relationships		Boundary relationships	
		χ^2	*p*-value	χ^2	*p*-value
*Y***X*1	1	30.799	0.000	30.048	0.000
*Y***X*3	1	3.546	0.060	2.981	0.082
*Y***X*6	1	4.875	0.027	6.277	0.012
*Y***X*8	1	9.457	0.002	6.731	0.009
*Y***X*9	1	4.410	0.036	3.615	0.057
*X*1**X*3	1	3.037	0.081	2.044	0.153
*X*1**X*6	1	2.744	0.098	4.019	0.045
*X*1**X*8	1	3.682	0.055	1.966	0.161
*X*1**X*9	1	0.000	0.993	0.122	0.727
*X*3**X*6	1	0.501	0.479	0.556	0.456
*X*3**X*8	1	2.879	0.090	3.203	0.073
*X*3**X*9	1	5.551	0.018	7.016	0.008
*X*6**X*8	1	0.776	0.378	1.149	0.284
*X*6**X*9	1	0.192	0.661	0.203	0.653
*X*8**X*9	1	16.276	0.000	16.141	0.000

Source: own elaboration.

a good fit (the model adequately explains the relationships among the analysed variables). Furthermore, the findings suggest that research focusing on the relationships among factors (*X*1, *X*3, *X*6, *X*8, *X*9) may yield more accurate conclusions and guide better decisions, particularly when multiple overlapping phenomena are examined simultaneously.

During the analysis, we also assessed whether higher-order interactions (third-order and beyond) provided significant contributions to the model. They proved insignificant, hence, only the key interactions were retained to keep the model as simple and transparent as possible, without compromising the accuracy of the relationships under investigation.

3.3. Multiple correspondence analysis

Finally, based on the model obtained, the analysis suggests that models explaining the relationships between CO_2 emissions and economic growth in the European Union are shaped by the following factors:

– Environmental Impact Factors,
– Economic and Urban Development,
– Natural Resources,
– Econometric Methods and Models,
– Renewable and Non-Renewable Energy.

Additionally, the following interactions were indicated by the analysis:

– Environmental Impact Factors and Economic and Urban Development,
– Environmental Impact Factors and Natural Resources,
– Environmental Impact Factors and Econometric Methods and Models,
– Economic and Urban Development and Econometric Methods and Models,
– Economic and Urban Development and Renewable and Non-Renewable Energy,
– Renewable and Non-Renewable Energy and Econometric Methods and Models.

The results of the cluster analysis confirm the association between the following research areas in the analysed literature:

– Environmental Impact Factors, Economic and Urban Development, Econometric Methods and Models, and Renewable and Non-Renewable Energy,
– Environmental Impact Factors, Econometric Methods and Models, and Renewable and Non-Renewable Energy,
– Economic and Urban Development and Renewable and Non-Renewable Energy,

– Environmental Impact Factors, Economic and Urban Development, and Renewable and Non-Renewable Energy.

To summarise this stage of the study, it can be stated that the main research axis of CO_2 emissions and economic growth in the European Union focuses on issues related to the use of renewable and non-renewable energy. These studies appear both independently and with regard to other factors, such as natural resources and economic development. Research on the relationship between economic growth and CO_2 emissions in EU countries is also linked to advanced econometric methods, including panel studies, quantile regressions, and ARDL models.

To further investigate the leading research areas in the analysed literature, a correspondence analysis was conducted. The data were divided into five categories, each assigned corresponding values. All categories with codes are included in Table 4.

Table 4. Categories used in multiple correspondence analysis

Category	Code	Description
Energy Sources (ES)	ES:1	no reference
	ES:2	non-renewable energy
	ES:3	renewable and non-renewable energy
State Quality and Sustainable Development (IQ)	IQ:1	no reference
	IQ:2	sustainable development
	IQ:3	institutional quality and sustainable development
Economic and Financial Development (EG)	EG:1	no reference
	EG:2	financial development
	EG:3	economic growth and financial development
Investments and Trade (IT)	IT:1	no reference
	IT:2	trade openness
	IT:3	foreign direct investment and trade openness
Environmental Pollution and Climate Change (PC)	PC:1	no reference
	PC:2	climate change
	PC:3	environmental pollution and climate change

Source: own elaboration.

The classification of articles based on these categories enabled the use of Multiple Correspondence Analysis (MCA) to explore the relationships between different thematic groups. Given the extensive size and dimensionality of the dataset (1248 × 14), the Burt matrix method was selected for its ability to manage large, high-dimensional categorical data. This approach is particularly well suited to situations where complex interrelationships between multiple categorical variables need to be examined. The Burt matrix allows for the efficient construction of contingency tables that facilitate the assessment of associations between categories, capturing intricate patterns and dependencies without oversimplifying the data.

To analyse the relationships between the categories, eigenvalues were derived from the MCA, and the optimal number of dimensions was determined using the elbow criterion. Based on the screen plot, three dimensions were identified as explaining 50.84% of the variance in the dataset (Table 5). While this value represents a substantial proportion of the variance, it is important to note that an explanation of 50% variance is often considered a reasonable threshold in social science research. In the context of large, multidimensional datasets, this level of explained variance provides sufficient explanatory power to uncover meaningful patterns and relationships, while at the same time allowing for the complexities inherent in the data (Hair et al., 2013). This balance ensures that the results remain robust, while avoiding overfitting or oversimplification of the model. Finally, a two-dimensional plot (Figure 4) of the coordinates for dimensions 2 and 3 was created to visualise the relationships and interdependencies among the thematic categories, offering a clear representation of the research themes derived from the MCA.

Table 5. Eigenvalues and variance explained by dimensions in multiple correspondence analysis

Dim	Eigenvalue	Percentage of variance	Cumulative percentage of variance
1	0.23	12.53	27.82
2	0.21	11.75	39.57
3	0.20	11.26	50.84
4	0.20	10.88	61.72
5	0.18	10.14	71.86
6	0.18	9.83	81.69
7	0.17	9.43	91.11
8	0.16	8.89	100.00

Notes: Dim: refers to the dimension identified by the MCA, Eigenvalue: measures the importance of each dimension in explaining the variance in the dataset.

Source: own elaboration.

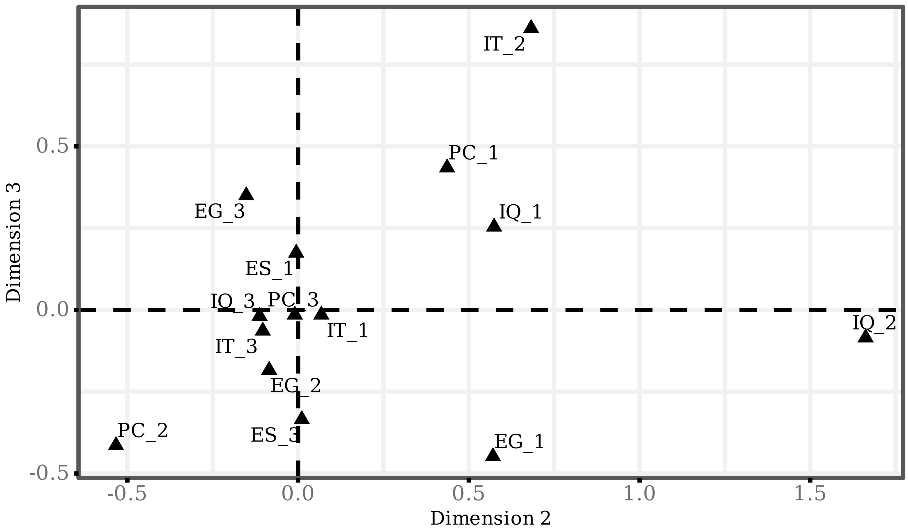

Figure 4. Distribution of variable categories in factor space (Dim 2 and Dim 3)

Notes: The figure covers five categories: ES (Energy Sources), IQ (State Quality and Sustainable Development), EG (Economic and Financial Development), IT (Investments and Trade), and PC (Environmental Pollution and Climate Change). The numeric indices (1, 2, 3) represent subcategories.

Source: own elaboration.

The resulting plot indicates that topics related to EG : 2 (financial development) and ES : 3 (non-renewable and renewable energy) are often considered together. Research in these areas is frequently combined with topics such as IT : 3 (foreign direct investment and trade openness) and PC : 3 (environmental pollution and climate change). The influence of renewable energy, specifically PC : 2 (climate change), is often considered separately. Topics such as IQ : 2 (sustainable development) and IT : 2 (trade openness) are typically considered independently, as their points are furthest from the centre of the plot. The distance of ES : 1 (energy sources) from the other items suggests limited overlap with the other topics. This indicates that research in this area focuses on the general impact of energy consumption on economic growth and CO_2 emissions, without a detailed distinction between renewable and non-renewable energy sources.

To summarise the relationships in the topics analysed here, a dendrogram was created. Based on the results obtained from the MCA, clustering was performed using three dimensions, with Euclidean distance and a modified Ward method. The results of the analysis are presented in Figure 5. Analysis of the dendrogram reveals three main clusters within the research themes. Group I includes studies (ES : 3) related to renewable and non-renewable energy, which co-occur with topics related to sustainable development (IQ : 2).

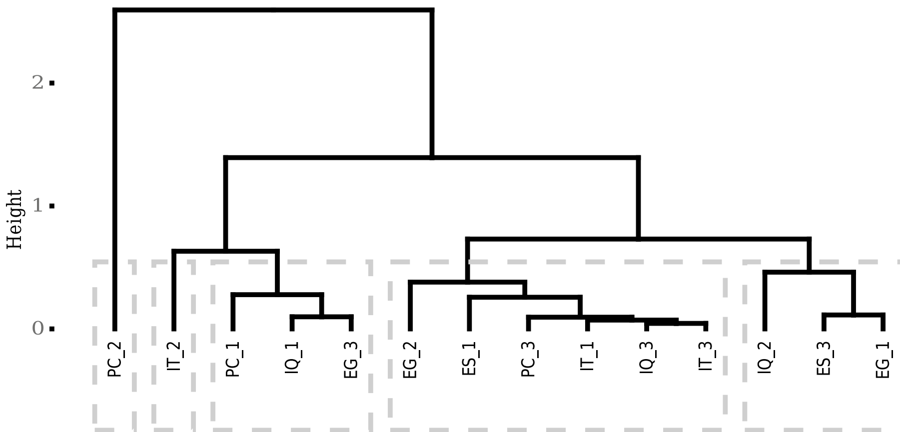

Figure 5. Classification based on clusters for the thematic categorisations studied

Source: own elaboration.

Group II consists of research linking financial development (EG : 2) with environmental pollution and climate change (PC : 3), as well as factors such as international trade and foreign direct investment (IT : 3), and institutional quality and sustainable development (IQ : 3). Some of these studies do not distinguish between renewable and non-renewable energy. Group III comprises studies focusing on economic growth and financial development (EG : 3) but not addressing climate change and environmental pollution (PC : 1) alongside sustainable development (IQ : 1). These studies are thematically connected to issues of trade openness (IT : 2). Nonetheless, all the studies are related to the broader theme of climate change (PC : 3).

4. Discussion

A systematic and synthetic analysis of the literature, as well as a log-linear model, shows that economic development factors and the use of renewable and non-renewable energy sources are particularly important in the study of the EKC in EU countries. The co-occurrence of these factors indicates that they are key in modelling the relationship between GDP and CO_2 emissions (Lau et al., 2023; Shahbaz & Sinha, 2019). In turn, the MCA study identified several clear research directions, focusing on assessing energy use (renewable and non-renewable) in combination with sustainable development, financial development and commercial openness to reduce CO_2 emissions in EU countries (Barros & Martínez-Zarzoso, 2022; Lau et al., 2023).

The cluster classification further distinguished groups combining diverse thematic areas (e.g., financial development and trade with climate issues, and climate change and economic development with specific environmental aspects), confirming earlier observations about the cross-fertilisation of different scientific fields in EKC research (Hasanov et al., 2021; Leal & Marques, 2022). Considering these findings, it is apparent that the key area for research into the relationship between CO_2 emissions and economic growth in the EU remains the topic of energy (RES vs. fossil fuels), which coincides with many studies highlighting the impact of energy consumption patterns on emissions intensity and climate policy orientations (Anwar et al., 2022; Sarkodie & Strezov, 2019).

The quality of institutions, international trade and financial development are secondary themes; however, their role is sometimes classified differently by different authors or only hinted at (Bąk & Cheba, 2023; Barros & Martínez-Zarzoso, 2022). The results of empirical studies lend credence to the thesis that these variables interact with each other, which, given the different methodologies, explains the multiplicity and sometimes contradictory conclusions about the properties of the EKC (Kaika & Zervas, 2013; Leal & Marques, 2022; Sovacool et al., 2021). The results obtained indicate that EKC analysis requires not only looking at the relationship between GDP growth and emissions, but also considering a combination of energy, socio-economic and methodological factors (Bąk & Cheba, 2023; Mardani et al., 2019; Shahbaz & Sinha, 2019).

Conclusions

This study aimed to identify key research areas concerning the link between GDP and CO_2 emissions in research on EU countries with a particular focus on the EKC hypothesis. A review of theoretical concepts and empirical studies indicates that the relationship between the economy and the environment occupies an important place in the field of economic science. However, this study shows that there are still many issues that have not been sufficiently clarified, some concepts are controversial, and others are in constant evolution.

Empirical and theoretical concepts are evolving with new variables and methodologies; despite a significant number of studies, new articles are still emerging that introduce additional factors to better understand the relationship between GDP and CO_2 emissions. The analysis conducted reveals that studies in the area of EKC take into account numerous additional factors such as innovation, legislation, geography, production structure and urbanisation. The individual studies also apply geographical differentiation, taking account of different regions and countries according to data availability. However, there is less research in the area of environment-economy relations focusing specifically on EU countries than there is on developing countries from the African and Asian region (Anwar et al., 2022; Lau et al., 2023).

The results of the log-linear and MCA analyses indicate that EKC research on the EU concentrates on the relationship between GDP and CO_2, primarily focusing on factors such as energy, financial development, foreign investment, and natural resources, all of which are closely tied to institutional quality, sustainability, and climate change. Among the analysed topics, the most attention is given to the impact of renewable energy on CO_2 emissions, which largely reflects the EU's climate and energy objectives.

The study also indicates that many research topics are closely linked to specific econometric methods and models, which are essential tools for studying CO_2-GDP relationships. These methods are used in particular for analysing how renewable and non-renewable energy use, and environmental factors affect CO_2 emissions in the EU. Common approaches include the autoregressive distributed lag (ARDL) regression model (OLS), quantile regression (QR) and various causality tests (Granger and Toda-Yamamoto).

The study identifies research gaps in the existing literature on the GDP--CO_2 relationship. Firstly, individual country analyses should be prioritized over large aggregates, considering country-specific factors in panel studies for consistency. Secondly, more research is needed on the impact of various pollutants on economic growth, as most studies focus solely on CO_2. Thirdly, sectoral studies on the EKC for the EU remain limited, particularly regarding transport and agriculture, despite some focus on energy and industry. Such research is crucial for effective emission reduction strategies. Lastly, there is a significant gap in examining technological progress and trade openness, especially concerning pollution exports.

The study highlights that the link between economic growth and emissions in the EU remains insufficiently explored. Therefore, increased funding is needed for research on climate policy's economic impact, along with in-depth sectoral analyses, particularly in transport and agriculture. Collecting long-term, detailed data at national and EU levels is also crucial to support new research and theories for informed economic and climate policy decisions.

This study has several limitations. First, the analysis relied on articles from major databases (2014–2024) using specific keywords, which may have led to omissions. The reviewed literature employs diverse methods and control variables, leading to discrepancies and limiting universal conclusions. While focused on the EU, most studies use panel data with common assumptions, potentially overlooking country-specific factors like economic development or energy structure.

Future research on the GDP-CO_2 relationship in EU countries should address research gaps by applying modern econometric techniques, including convergence and longitudinal effects, and using longer time series for deeper insight into pollution reduction. It should also consider shocks like the war in Ukraine and new US policies. Additionally, studies on the EKC and systematic reviews should explore non-traditional methodologies, such as Bayesian inference, deep learning, and AI experiments.

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