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The role of agricultural production, economic growth, renewable and fossil energy consumption on load capacity factor in the EU countries: Evidents from MMQR methodology

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Abstract

Purpose: This study aims to analyze the effects of economic growth, agricultural production, and renewable and fossil energy consumption on environmental quality, measured by the load capacity factor, in 24 European Union (EU) countries over the period 2000–2023. By focusing on the load capacity factor and employing the augmented mean group (AMG), common correlated effects (CCE), and method of moments quantile regression (MMQR) estimators, the study contributes to the literature by examining the agriculture–environment nexus and testing the Load Capacity Curve (LCC) hypothesis within the EU context.

Design/Methodology/Approach: Following the confirmation of unit root, cointegration, and cross-sectional dependence, the study employs AMG and CCE estimators for the initial long-run analysis. To account for potential distributional asymmetries and non-normality, MMQR is applied. Furthermore, a Wald test for coefficient equality is conducted to statistically assess whether the estimated effects vary across the 10th to 90th quantiles or remain structurally stable.

Findings: The empirical results indicate that the LCC hypothesis does not hold for EU countries. Agricultural production is found to improve environmental quality, likely reflecting the adoption of sustainable and resource-efficient farming practices in the region. Renewable energy consumption enhances environmental resilience, highlighting its role in reducing ecological pressures, whereas fossil energy consumption consistently deteriorates environmental quality due to its carbon-intensive nature. Crucially, the Wald test results indicate that the estimated coefficients are statistically homogeneous across all quantiles, suggesting that the impacts of economic growth, energy transition, and agricultural productivity are structurally stable and consistent across countries with varying levels of environmental performance.

Originality/Value: This study contributes to the literature by extending the analysis of agriculture–environment interactions beyond conventional environmental pressure indicators and by adopting the load capacity factor as a more comprehensive measure of environmental resilience. Unlike previous studies that focus on average effects, this research applies the MMQR method and tests for coefficient equality, suggesting that the drivers of environmental quality in the EU are structurally stable across countries.

Keywords: Agricultural production, economic growth, energy consumption, load capacity factor, quantile regression

AB ülkelerinde tarımsal üretim, ekonomik büyüme, yenilenebilir ve fosil enerji tüketiminin yük kapasite faktörü üzerindeki etkisi: MMQR metodolojisinden kanıtlar

Özet

Amaç: Bu çalışma, 2000–2023 döneminde 24 Avrupa Birliği (AB) ülkesinde ekonomik büyüme, tarımsal üretim ve yenilenebilir ile fosil enerji tüketiminin yük kapasitesi faktörü üzerindeki etkilerini analiz etmeyi amaçlamaktadır. AMG (Genişletilmiş Ortalama Grup), CCE (Ortak Korelasyon Etkileri) ve Momentler Yöntemi ile Kantil Regresyon (MMQR) tahmin yöntemlerini kullanarak, çalışma tarım–çevre ilişkisini incelemekte ve AB bağlamında Yük Kapasite Eğrisi (LCC) hipotezini test ederek literatüre katkı sağlamaktadır.

Tasarım/Metodoloji/Yaklaşım: Birim kök, eşbütünleşme ve yatay kesit bağımlılığı testlerinin ardından, çalışmada uzun dönem analiz için AMG ve CCE tahmin yöntemleri kullanılmıştır. Tahminlerde olası dağılım asimetrilerini ve normal dağılım varsayımına aykırılıkları dikkate almak amacıyla MMQR yöntemi uygulanmıştır. Ayrıca, tahmin edilen katsayıların 10. ve 90. kantiller arasında homojen olup olmadığını istatistiksel olarak değerlendirmek için Wald testi gerçekleştirilmiştir.

Bulgular: Ampirik bulgular, AB ülkelerinde LCC hipotezinin geçerli olmadığını göstermektedir. Tarımsal üretim çevresel kaliteyi artırmakta olup, bu durum sürdürülebilir ve kaynak verimli tarım uygulamalarının çevre üzerindeki olumlu etkisini yansıtmaktadır. Yenilenebilir enerji tüketimi çevre dostu niteliği nedeniyle çevresel kaliteyi artırırken, fosil enerji tüketimi karbon yoğun yapısı nedeniyle çevresel kaliteyi sürekli olumsuz etkilemektedir. Wald testi sonuçları, tahmin edilen katsayıların tüm kantillerde homojen olduğunu göstermektedir. Bu sonuç, ekonomik büyüme, enerji geçişi ve tarımsal üretimin çevresel kalite üzerindeki etkilerinin, farklı çevresel performans seviyelerine sahip ülkelerde yapısal olarak istikrarlı ve tutarlı olduğunu ortaya koymaktadır.

Özgünlük/Değer: Bu çalışma, tarım–çevresel kalite ilişkisini geleneksel çevresel bozulma göstergelerinin ötesine taşıyarak ve yük kapasitesi faktörünü çevresel kaliteyi daha kapsamlı ölçen bir gösterge olarak kullanarak literatüre katkıda bulunmaktadır. Önceki çalışmalar ortalama etkiler üzerine odaklanırken bu çalışmada MMQR yöntemi uygulanmış ve katsayı eşitliği testi gerçekleştirilerek AB ülkelerinde çevresel kaliteyi belirleyen etkenlerin yapısal olarak istikrarlı olduğu gösterilmiştir.

Anahtar kelimeler: Tarımsal üretim, ekonomik büyüme, enerji tüketimi, yük kapasite faktörü, kantil regresyon

INTRODUCTION

Climate change and environmental degradation pose significant challenges to all living organisms by disrupting ecological systems and undermining natural balance. These interrelated phenomena contribute directly to growing food, water, and energy insecurity, thereby threatening both human well-being and ecosystem resilience. Climate change and environmental degradation evolve in parallel and reinforce one another through a vicious cycle. Climate change accelerates environmental degradation and biodiversity loss, which in turn intensify climate change processes (UNDP, 2023). Given the severity and global scale of these impacts, a substantial body of research has sought to identify the key drivers of environmental degradation. Among these drivers, agricultural production has emerged as a critical determinant influencing environmental quality owing to its extensive reliance on land, other natural resources and water. Despite its significance, the environmental impacts of agricultural production remain ambiguous, particularly within the European Union context. Limited research has explored how agricultural activities affect the load capacity factor (LCF). Within this framework, the Load Capacity Curve (LCC) hypothesis offers a perspective for assessing whether economic activities initially degrade environmental quality but may ultimately improve it after a certain threshold is reached (Pata and Kartal, 2023). Analyzing agriculture in relation to the LCF helps evaluate how such activities affect the balance between environmental demand and ecological biocapacity. Addressing this gap is essential for determining whether agricultural production supports or undermines ecological sustainability and for guiding effective policies that balance food production with environmental protection.

Agricultural production may play a dual role in the context of environmental quality. On the one hand, it is vital for ensuring food security and achieving Sustainable Development Goal (SDG)-2, which aims to combat hunger and ensure access to nutritious food (UN, 2025a). On the other hand, the intensification of agricultural practices may place significant pressure on natural ecosystems (Demirkol, 2022). Intensive farming practices often involve extensive land conversion, intensive use of chemical fertilizers and pesticides, increased water withdrawals, and elevated energy consumption, each of which contributes to the degradation of soil quality, water pollution, biodiversity loss, and greenhouse gas emissions (Apoorva and Kundlas, 2024). As agricultural systems increasingly exceed ecological limits, they may reduce biocapacity and weaken environmental resilience, thereby exacerbating environmental degradation. Conversely, the adoption of sustainable agricultural practices may mitigate environmental pressures and promote ecological stability (European Commission, 2025a). The relationship between agricultural production and the LCC hypothesis may operate through several channels. For example, agricultural activities can increase the ecological footprint and reduce the load capacity factor through energy-related emissions, high water consumption, and fertilizer-induced greenhouse gas releases. Moreover, agriculture influences the Earth's biocapacity through land use decisions, soil management practices, and their long-term effects on ecosystem productivity, particularly as economic growth rises (Shahbaz et al., 2025). Conversely, sustainable agricultural practices that enhance soil organic matter may positively influence biocapacity (Cozim-Melges et al., 2024), especially after a specific economic threshold has been attained. From the perspective of the LCC framework, agricultural production may influence environmental sustainability through its dual role in shaping both ecological footprint and biocapacity. Therefore, understanding the environmental implications of agricultural production within the LCC framework requires examining both its pressures on ecological systems and its contributions to the Earth's regenerative capacity.

Beyond agricultural activities, the type of energy consumed plays a vital role in shaping environmental outcomes and environmental degradation. In this context, SDG-7 emphasizes the importance of achieving universal access to affordable, reliable, and clean energy services (UN, 2025b). The composition of the energy mix has direct implications for environmental quality. While renewable energy sources contribute to mitigating environmental degradation by curbing greenhouse gas emissions and reliance on finite resources, fossil energy sources remain a major source of air pollution and carbon emissions. Continued reliance on fossil energy intensifies climate change and environmental degradation, whereas a transition toward renewable energy can support ecological sustainability and environmental resilience (UNDP, 2025). Therefore, examining energy structure alongside agricultural production is essential for understanding the broader drivers of environmental degradation. Within the LCC framework, the turning point at which economic growth begins to enhance environmental quality depends on the energy structure (Bucak and Çatık, 2025). When economic growth is accompanied by a transition toward renewable energy, the ecological footprint may decline more rapidly, allowing the load capacity factor to increase (Shang et al., 2022). Conversely, if growth continues to rely on fossil fuels, the ecological footprint may keep expanding, preventing the environmental improvements predicted by the LCC hypothesis (Raihan et al., 2023). Therefore, analyzing the energy mix within the LCC framework is essential for understanding how economic growth interacts with environmental outcomes.

Economic growth also plays a critical role in assessing the underlying dynamics of environmental degradation. In this regard, SDG-8 emphasizes the promotion of sustainable economic growth by decoupling economic progress from environmental harm (UN, 2025c). A key issue in the growth–environment nexus is whether the relationship follows a linear or nonlinear trajectory and whether, beyond a certain threshold, economic growth intensifies or mitigates environmental impacts. Within this framework, the LCC hypothesis has gained prominence as an alternative approach to examining the relationship between growth and environmental well-being. The load capacity factor serves as a comprehensive proxy for environmental quality, as it captures both the demand placed on the environment and the Earth's capacity to meet this demand through its natural regenerative processes. A U-shaped link between growth and the load capacity factor indicates the validity of the LCC hypothesis. The economic mechanisms underlying the LCC hypothesis suggest that, in the early stages of development, economic expansion typically involves increased production, fossil fuel consumption, and natural resource extraction. These activities collectively expand the ecological footprint, thereby reducing the load capacity factor. As economies progress, industrialization and urbanization often intensify land use, increase reliance on fossil fuels, and raise emissions, further contributing to environmental degradation. However, once a certain income threshold is reached, wealth accumulation, technological innovation, and institutional advancements enable cleaner production processes, more efficient resource use, and greater investment in environmental protection. This structural transformation allows economic growth to coincide with improvements in the load capacity factor, producing the characteristic U-shaped pattern of the LCC hypothesis (Pata and Kartal, 2023). Recent studies have examined this hypothesis, including Doğan and Pata (2021) and Bucak and Çatık (2025); however, the existing literature has yet to reach a consensus. Therefore, further empirical research remains essential to clarify the validity of this relationship across different contexts and time periods.

By considering these factors, this study aims to analyze the validity of the LCC hypothesis and to analyze the effects of agricultural production, renewable energy consumption, and fossil energy consumption on the load capacity factor for European Union (EU) countries. The EU constitutes a particularly relevant sample for this analysis, given its strong institutional commitment to sustainability and environmental protection. Through the Common Agricultural Policy (CAP), the EU actively manages the transition toward a more sustainable food system while strengthening farmers' contributions to climate objectives and environmental preservation (European Commission, 2025a). Moreover, the EU has assumed a global leadership role in combating climate change by promoting renewable energy adoption and implementing ambitious environmental regulations (European Commission, 2025b). To achieve the objectives of the study, the common correlated effects (CCE), augmented mean group (AMG) estimators, and the method of moments quantile regression (MMQR) are employed. Unlike prior research, which often analyzes the LCC hypothesis separately from the roles of energy and agriculture, this study adopts an integrated approach within the EU framework, contributing additional empirical evidence on the dynamics of sustainable development and ecological quality. The remainder of the paper is organized into sections covering the literature review, methodology, data, results and discussion, and policy implications.

LITERATURE REVIEW

Agricultural production constitutes one of the most significant human activities shaping environmental outcomes and ecological sustainability. While agriculture is indispensable for ensuring food security and achieving SDG-2 (Zero Hunger), its expansion and intensification have profound implications for the environment. Agricultural practices may rely heavily on land, chemical inputs, water extraction, and energy consumption, all of which place substantial pressure on natural ecosystems. From a sustainability perspective, the environmental impacts of agriculture are closely aligned with SDG-12 (Responsible Consumption and Production) and SDG-15 (Life on Land), which emphasize the need to promote resource-efficient production systems, protect terrestrial ecosystems, and halt land degradation and biodiversity loss (UNEP, 2025). Agricultural activities that exceed ecological limits may reduce biocapacity and weaken environmental resilience, thereby intensifying the imbalance between human demand and the planet's regenerative capacity. Conversely, environmentally sustainable agricultural practices may mitigate environmental pressures and contribute to ecological stability. In this context, examining the environmental consequences of agricultural production provides valuable insights into whether agricultural development supports or undermines environmental sustainability. This approach provides a more holistic assessment of agriculture's role in shaping environmental quality within the broader framework of sustainable development.

A substantial body of literature reports that agricultural production increases ecological degradation, particularly in developing and resource-intensive economies. Using time-series approaches such as ARDL, studies on Nigeria, India, Türkiye, and Somalia (Udemba, 2020a, 2020b; Boluk & Karaman, 2024; Warsame et al., 2023) generally find that agricultural expansion intensifies ecological pressure through land use, energy consumption, and

carbon-intensive production processes. Similarly, panel-based studies employing FMOLS, CS-ARDL, and PMG estimators across African countries, a sample of 77 countries, and G20 economies (Olanipekun et al., 2019; Alvarado et al., 2021; Li et al., 2025) confirm that agricultural activity or value added contributes positively to the ecological footprint. However, the literature also reveals heterogeneous findings depending on methodology, regional structure, and agricultural composition. For example, Pata (2021), using the Fourier-ADL approach for BRIC countries, reports no significant relationship. Warsame et al. (2023) show that the environmental impact varies according to crop composition in Somalia, while Salari et al. (2021) demonstrate that agriculture's effects differ across ecological footprint quantiles in 21 emerging countries. These differences indicate that the environmental consequences of agricultural production are sensitive to econometric specification, country characteristics, and the level of ecological pressure. This motivates further investigation within the EU context, where agricultural policies may shape the relationship differently.

In contrast to the extensive ecological footprint-based literature, research focusing on the relationship between agriculture and the load capacity factor remains relatively scarce. Existing studies offer mixed evidence. Jiaduo et al. (2023) find that agricultural employment significantly enhances LCF in BRICS countries, suggesting a potentially sustainability-improving role of agriculture. Conversely, Ali et al. (2024) report that agricultural expansion adversely affects LCF in Pakistan, while Özbek and Şahin (2025) show that agricultural productivity reduces LCF in Türkiye. Raihan (2025), however, demonstrates that sustainable agricultural practices can strengthen ecological resilience by improving LCF in Thailand. Notably, only one study explicitly examines the validity of the LCC hypothesis while incorporating agricultural factors. Göksu (2025) finds that animal production positively affects environmental quality, whereas crop production has no significant impact on LCF, and concludes that the LCC hypothesis is valid for Türkiye. This mixed and limited evidence underscores the need for further research that jointly examines agricultural activities, load capacity factor dynamics, and the validity of the LCC hypothesis, particularly within a broader cross-country framework. This mixed and limited evidence underscores the need for further research that jointly examines agricultural activities, LCF dynamics, and the LCC hypothesis, particularly within a broader cross-country framework. Addressing this gap is crucial, given that the literature is largely limited to country-specific studies and lacks the comprehensive cross-country analyses necessary for generalizable insights.

Another critical factor influencing environmental resilience is energy consumption, as emphasized under SDG-7. Accelerating the transition to clean and renewable energy while reducing reliance on fossil fuels is essential for improving overall environmental quality. Energy systems play a central role in shaping ecological outcomes, as fossil fuel based energy consumption intensifies environmental pressure by increasing emissions and accelerating the depletion of natural resources (UNEP, 2025). Accordingly, an extensive body of empirical literature has investigated the environmental effects of renewable and fossil energy consumption across different country groups, time periods, and econometric methodologies. This literature consistently underscores the importance of energy consumption as a key determinant of environmental sustainability, making it a crucial control variable in empirical models assessing environmental resilience. In particular, renewable energy consumption is widely identified as an environmentally beneficial factor, as it reduces ecological pressure and enhances environmental carrying capacity. Several studies document a positive association between renewable energy consumption and the load capacity factor (e.g., Shang et al., 2022; Sun et al., 2024; Bucak and Çatık, 2025). In contrast, fossil energy consumption is generally found to exert a detrimental effect on environmental resilience. By increasing environmental degradation, fossil energy use weakens ecological balance and reduces the load capacity factor. Empirical evidence consistently supports this adverse impact, highlighting fossil energy consumption as a significant driver of environmental deterioration (Xu et al., 2022; Raihan et al., 2023). Taken together, these findings justify the inclusion of both renewable and fossil energy consumption as key explanatory variables when analyzing environmental resilience and load capacity dynamics.

Another key determinant of environmental quality is growth. SDG-8 emphasizes that economic expansion should be decoupled from environmental degradation in order to achieve sustainable development (UNEP, 2025). Accordingly, beyond assessing only the impact of growth on ecological quality, understanding the nature and dynamic pattern of this relationship has become a central issue in the economics literature. In particular, scholars have focused on whether the growth–environment nexus follows a nonlinear trajectory rather than a linear pattern. In this context, Pata and Kartal (2023) introduced the LCC hypothesis, which examines whether the link between growth and environmental quality exhibits a U-shaped pattern. The hypothesis suggests that environmental pressure may initially increase with economic growth but eventually decline once a certain threshold is reached. Empirical findings on the validity of the LCC hypothesis, however, remain inconclusive. While some studies provide evidence in support of the hypothesis (e.g., Dogan and Pata, 2022; Feng et al., 2025), others reject it, indicating that economic growth continues

to exert adverse environmental effects even at higher income levels (e.g., Li et al., 2023; Bucak and Çatık, 2025). This mixed evidence highlights the need for further empirical investigation into the growth–environment relationship, particularly using approaches that allow for potential nonlinearities and distributional dynamics.

Despite the growing literature on the environmental effects of economic growth, agriculture, and energy consumption, several important gaps remain. First, most existing studies assess environmental sustainability using the ecological footprint, while relatively few employ the load capacity factor, which captures the balance between biocapacity and environmental pressure. Consequently, the extent to which agricultural activities operate within ecological limits remains underexplored. Second, the limited number of studies focusing on agriculture and LCF provide mixed, country-specific findings, offering no clear consensus on whether agricultural production enhances or undermines environmental resilience. Third, existing research rarely integrates agricultural production with energy consumption and economic growth within a unified empirical framework, despite the strong interlinkages among these factors highlighted by the SDGs. Finally, empirical evidence on the validity of the LCC hypothesis in the presence of agricultural activity remains particularly limited. To address these gaps, this study examines the impact of agricultural production on environmental quality measured by the LCF, while controlling for renewable and fossil energy consumption and economic growth. Using data for EU member states and employing econometric methods that account for cross-sectional dependence and allow for distributional dynamics, the study provides additional evidence on whether agricultural production contributes to or constrains ecological resilience. Moreover, by testing the LCC hypothesis within a quantile-based framework, the study evaluates whether the growth–environment relationship exhibits structural stability across different levels of environmental quality. In doing so, the study complements and extends the existing literature by moving beyond ecological footprint measures and by offering policy-relevant evidence for achieving environmentally sustainable agricultural practices in EU economies.

METHODOLOGY

In this study, tests for cross-sectional dependence and slope homogeneity are conducted to evaluate the key properties of the panel data before implementing the MMQR approach. In this context, LM-based tests are applied to assess the existence of cross-sectional dependence among the sample units. The rationale for using multiple LM-based tests is grounded in the specific characteristics of the sample. The EU member states in this study are highly interconnected in terms of agricultural production and environmental policies (e.g., Common Agricultural Policy, renewable energy targets, Fit for 55 package, Green Deal), which implies a high likelihood of unobserved common shocks and interdependencies. Ignoring cross-sectional dependence when it exists can lead to biased and inconsistent estimates (Pesaran, 2004).

The Breusch–Pagan (1980) LM test for cross-sectional dependence is formulated as follows:

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}^2ij \quad (1)$$

In this expression, $\hat{p}_{ij}$ denotes the sample correlation of the residuals between cross-sectional units i and j. T denotes the time, while N indicates the number of cross-sectional units.

The Pesaran et al. (2008) LM test for cross-sectional dependence is formulated as follows:,

$$LM_{adj} = \sqrt{\frac{2T}{[N(N-1)]}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}^2ij - \sqrt{\frac{2T}{[N(N-1)]}} \quad (2)$$

The Pesaran (2004) LM test for cross-sectional dependence is formulated as follows:

$$CD = \sqrt{\frac{2T}{[N(N-1)]}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{p}ij \quad (3)$$

If the p-value of this test is below 0.05, the series exhibit cross-sectional dependence. The homogeneity of the series is examined using delta tests, where a p-value below 0.05 indicates heterogeneity (Pesaran and Yamagata, 2008). When the results indicate the presence of both cross-sectional dependence and heterogeneity, second-generation panel unit root tests are required to assess stationarity. Unit root tests that ignore cross-sectional dependence may yield misleading inferences regarding the stationarity properties of the series. In such circumstances, the CIPS

unit root test proposed by Pesaran (2007) is the appropriate choice. This test is applied to all variables in the analysis. For illustration, the stationarity of the lnlcf series can be examined using the CIPS test, as shown in Equations (4) and (5).

$$\Delta \text{lnlcf}_{it} = \partial_i + \mu_i \text{lnlcf}_{2it-1} + \vartheta_i \, \overline{lnlcf}_{t-1} + \sum_{l=0}^{k} \tau_{ij} \Delta \overline{lnlcf}_{it-1} + \sum_{l=1}^{k} \omega_{ij} \text{lnlcf}_{it-1} + e_{it} \quad (4)$$

$$CIPS = N^{-1} \sum_{l=1}^{k} t_i(N,T) \quad (5)$$

The CIPS statistic is obtained by taking the mean of the individual t-statistics derived from Equation (5). When the calculated CIPS statistic exceeds the critical values, the null hypothesis of a unit root is rejected, indicating that the series is stationary. In such a case, the stationarity properties of the variables are confirmed. If all variables are identified as integrated of order one, I(1), cointegration analysis can then be performed.

If all series are I(1), it is appropriate to employ the Westerlund cointegration test, which accounts for cross-sectional dependence. Developed by Westerlund and Edgerton (2007), this cointegration test is designed to examine long-run relationships among variables while considering cross-sectional dependence and heterogeneity. To ensure robust inference in the presence of cross-sectional dependence, the test is implemented using bootstrap critical values, as suggested by Persyn and Westerlund (2008). The test equation can be expressed as follows:

$$\Delta lnlcf_{it} = \theta_i d_i + \pi_i (lnlcf_{it-1} - \beta_i' y_{it-1}) + \sum_{j=1}^{m} \pi_{ij} + \Delta lnlcf_{it-j} + \sum_{j=1}^{m} \varphi_{ij} + \Delta y_{it-j} + u_{it} \quad (6)$$

In this equation, d_i represents deterministic components, θ_i denotes the vector of unknown coefficients, and π_i is the error-correction coefficient. To evaluate the existence of a long-run relationship among the variables, the Westerlund cointegration test computes four different test statistics. These statistics and their corresponding expressions are presented in Equations (7), (8), (9), and (10), respectively:

$$G_t = \frac{1}{N} \sum_{i}^{N} \frac{\hat{\alpha}_i}{SE\alpha_i} \quad (7)$$

$$G_a = \frac{1}{N} \sum_{i}^{N} \frac{T\hat{\alpha}_t}{\hat{\alpha}_i(1)} \quad (8)$$

$$P_t = \frac{\hat{a}}{SE(\hat{a})} \quad (9)$$

$$P_a = T\hat{a} \quad (10)$$

The G_t and G_a statistics assess cointegration for the panel as a whole, while the P_t and P_a statistics evaluate the existence of a long-run relationship for individual cross-sectional units. The null hypothesis of the test states that there is no cointegration among the variables. If cointegration is present, point estimators such as CCE and AMG can be utilized. As cointegration is confirmed, the CCE and AMG estimators are applied to obtain the long-run coefficient estimates.

The MMQR approach offers several important methodological benefits compared to conventional panel data estimation techniques. First, unlike traditional point estimators, MMQR allows the effects of explanatory variables to be examined across the conditional distribution of the load capacity factor. Although this framework is often employed to detect distributional heterogeneity, in the present study it serves primarily as a robustness and validation tool to assess whether the estimated relationships remain stable across countries with different levels of environmental performance. Second, the MMQR method is robust to outliers and accommodates potential deviations from classical distributional assumptions. Third, the MMQR framework permits greater flexibility in the distribution of the error term and does not rely on the normality assumption required by many classical estimation methods (Galvão, 2011; Machado and Silva, 2019). Given the structural differences among the 24 EU member states in terms of economic development, agricultural practices, renewable energy adoption, and institutional capacity, employing a distribution-sensitive estimator is methodologically appropriate. While conventional mean-based estimators capture only average

effects, MMQR enables a formal assessment of potential variations across the distribution. This approach is particularly relevant when investigating potential distributional heterogeneity in the relationship between the variables. At the same time, even if the estimated coefficients exhibit limited variation across quantiles, MMQR provides a formal framework to evaluate the stability of relationships across different levels of environmental quality. Therefore, MMQR is employed to assess whether the estimated effects vary across quantiles (τ = 0.10, 0.25, 0.50, 0.75, 0.90). To formally examine whether the estimated coefficients differ across quantiles, a Wald test is conducted within the MMQR framework. If the null hypothesis of coefficient equality across quantiles is not rejected (i.e., homogeneity is found), this does not diminish the relevance of the MMQR approach. On the contrary, the finding of homogeneity itself constitutes a valid empirical result, namely evidence of distributional stability. Conversely, if heterogeneity is detected, this indicates that the effects vary across the conditional distribution of the dependent variable. In either case, the MMQR framework provides a rigorous basis for assessing distributional dynamics. The MMQR model applied in this study is specified as follows:

$$\text{lnlcf}_{it} = \alpha_i + X'_{it}\beta + (\delta_i + Z'_{it}\gamma)U_{it} \quad 11$$

In this specification, X_{it} represents the vector of explanatory variables used in the analysis, including GDPPC, GDPPC^2, agricultural production, fossil energy consumption, and renewable energy consumption. The parameter vector β captures the associated slope coefficients, while α_i denotes individual fixed effects. The term δ_i reflects quantile-specific fixed effects for each cross-sectional unit, and Z_{it} is a vector of differentiable transformations of variables that satisfy the condition $P\{\delta_i + Z'_{it}\gamma > 0\} = 1$. Following the methodological framework of Machado and Silva (2019), the unobserved component U_{it} is assumed to be independent of the regressors. This is a maintained assumption of the MMQR approach and is necessary to ensure that the moment conditions are correctly specified and that the quantile coefficients are consistently estimated. In particular, the consistency of the MMQR estimator relies on standard regularity conditions, including the independence between the unobserved component and the explanatory variables, which guarantees the identifiability of the distributional parameters. If this independence assumption is violated, the moment conditions become misspecified, potentially leading to biased or inconsistent estimates. In EU panel data settings, such violations may arise from unobserved time-varying heterogeneity, cross-sectional dependence, or measurement error correlated with the unobserved component. The parameters $(\alpha, \beta, \delta, \gamma)$ are estimated using moment conditions, following the framework proposed by Machado and Silva (2019).

The expected signs of the coefficients for GDP per capita and its square are theoretically ambiguous. Depending on the context, they may exhibit a non-linear relationship with environmental quality (e.g., an inverted-U or U-shaped pattern), reflecting potential non-linear effects of economic growth on environmental performance. Alternatively, they may show a linear relationship, with either positive or negative signs. This expectation is consistent with the literature, which documents both non-linear linkages (e.g., Dogan and Pata, 2022; Feng et al., 2025) and linear linkages (e.g., Li et al., 2023; Bucak and Çatık, 2025). Agricultural production is also expected to have an ambiguous effect on the load capacity factor. While some studies suggest that agricultural activities, particularly animal production, may enhance environmental quality and thus increase LCF (e.g., Jiaduo et al., 2023), others indicate that agricultural expansion or high productivity can exert pressure on natural resources, reducing LCF (e.g., Ali et al., 2024; Özbek and Şahin, 2025). Additionally, sustainable agricultural practices may strengthen ecological resilience and improve LCF (Raihan, 2025). Therefore, the sign of the coefficient for agricultural production could be positive or negative depending on the context, highlighting the importance of examining this relationship empirically across countries. Fossil energy consumption is expected to have a negative impact on LCF, as it increases emissions, accelerates resource depletion, and weakens ecological balance (Xu et al., 2022; Raihan et al., 2023). In contrast, renewable energy consumption is expected to have a positive effect on LCF, reducing ecological pressure and enhancing environmental carrying capacity (Shang et al., 2022; Sun et al., 2024; Bucak and Çatık, 2025). These expectations are grounded in both theoretical considerations and a broad empirical literature highlighting the role of energy systems in environmental resilience. It should be noted that the MMQR approach estimates the effects of explanatory variables across different quantiles of LCF, meaning that the magnitude and statistical significance of these effects may vary at low, median, or high levels of environmental performance. In this context, MMQR is employed to assess whether such distributional differences exist rather than to assume heterogeneity. While the expected signs indicate the general direction of each effect, MMQR allows for a more nuanced analysis by testing the stability of relationships across the conditional distribution, thereby strengthening the robustness of the empirical findings compared to conventional mean-based models.

DATA

The effects of agricultural production, fossil energy consumption, and renewable energy consumption on the load capacity factor, as well as the validity of the LCC hypothesis, are examined using annual panel data for 24 EU member states (Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden- Cyprus, Hungary, and Malta are excluded from the sample due to incomplete data availability for the variables over the full study period. This restriction is imposed to ensure a balanced panel structure and to maintain comparability of observations across countries and over time. Given that the excluded countries are limited in number and account for a relatively small share of the EU's overall agricultural and energy profile, their exclusion is unlikely to introduce substantial selection bias or to compromise the representativeness of the remaining 24 EU member states.). The selection of countries is based on the EU's institutional commitment to sustainability and environmental protection through key policies such as the Common Agricultural Policy, the Fit for 55 package, and the European Green Deal, which aim to safeguard the environment and ensure food security. Since these countries have committed themselves to taking a leadership role in achieving these goals, it is important to conduct an analysis focusing on them (European Commission, 2025a; 2025b). Data on the load capacity factor are obtained from York University (2025), GDP per capita from the World Bank (2025), agricultural production from FAO (2025), and fossil and renewable energy consumption from Our World in Data (2025). Table 1 demonstrates the variable names, their abbreviations, data sources, and the expected signs of the coefficients.

Table 1. Variable Names, abbreviations, and data sources

Variable	Abbreviation	Unit of Measurement	Database / Source	Expected Sign
Load capacity factor	lcf	Total per capita (biocapacity / ecological footprint)	York University (2025)	
GDP per capita	gdppc	Current US$	World Bank (2025)	+/ -
GDP per capita squared	$gdppc^2$	Current US$	World Bank (2025)	-/+
Agricultural production	agrprod	Gross production value (current thousand US$)	FAO (2025)	+/ -
Fossil energy consumption	fos	Per capita (kWh)	Our World in Data (2025)	-
Renewable energy consumption	ren	Per capita (kWh)	Our World in Data (2025)	+

All variables are transformed into natural logarithms, allowing the estimated coefficients to be interpreted as elasticities. Accordingly, the panel data model is specified as follows:

$$\ln lcf_{it} = \beta_0 + \beta_1 lngdppc_{it} + \beta_2 ln(gdppc)^2{}_{it} + \beta_3 lnagrprod_{it} + \beta_4 lnfos_{it} + \beta_5 lnren_{it} + \varepsilon_{it} \quad (12)$$

ECONOMETRIC RESULTS

Table 2 summarizes the descriptive statistics of the variables included in the analysis. The panel dataset is balanced, covering 24 EU countries over the period 2000–2023, resulting in 576 observations. The analysis ends in 2023 as this is the most recent year for which complete and consistent data are available across all variables. The Jarque–Bera test reveals substantial departures from normality, while the skewness and kurtosis statistics indicate deviations from standard normality assumptions. Although these distributional features may suggest heterogeneous relationships across the conditional distribution of the load capacity factor, non-normality alone does not necessarily imply statistically significant quantile heterogeneity. The MMQR approach is particularly suitable in this context because it allows for the identification of potential conditional heterogeneity in the effects of the explanatory variables across different quantiles of the load capacity factor. Within this framework, the effects of GDP per capita, its squared term, agricultural production, fossil fuel consumption, and renewable energy consumption are allowed to vary across quantiles, thereby enabling a more comprehensive analysis. Following the MMQR estimation, a Wald test is conducted to formally assess whether the estimated coefficients differ significantly across quantiles.

Table 2. Descriptive statistics

	mean	std. dev.	min	max	skewness	kurtosis
lnlcf	-0.71	0.71	-2.39	0.81	-0.12	2.67
lngdppc	10.10	0.79	7.39	11.81	-0.616	3.48
$lngdppc^2$	102.69	15.76	54.62	139.54	-0.367	3.08
lnagrprod	15.58	1.45	12.03	18.27	-0.187	2.4
lnfos	10.29	0.42	9.43	11.62	0.588	3.11
lnren	8.16	1.02	4.16	10.31	-0.666	4.24
# of obs.	576	576	576	576	576	576
JB normality test						
Test result: 25.87	Probability:	0.000				

Note: * p < 0.10, ** p < 0.05, *** p < 0.01.

Table 3 displays the correlation matrix for the variables, highlighting several key patterns. The load capacity factor (lnlcf) shows a negative relationship with GDP per capita (lngdppc, -0.32), agricultural production (lnagrprod, -0.25), and especially fossil fuel use (lnfos, -0.53), indicating that higher levels of fossil energy consumption are associated with lower environmental quality in bivariate terms. In contrast, renewable energy use (lnren) correlates positively with lnlcf (0.26), supporting its role in promoting environmental sustainability. The negative correlation between fossil and renewable energy consumption (-0.22) is modest, suggesting some substitutability between these energy sources without raising serious multicollinearity concerns. These bivariate relationships provide preliminary insights; however, the multivariate analysis presented in the following sections will reveal the conditional effects after controlling for other determinants. Overall, all correlation coefficients remain well below the conventional threshold of 0.80, indicating that severe multicollinearity is unlikely to distort the subsequent econometric estimates (Bryman and Cramer, 2001).

Table 3. Correlation matrix

	lnlcf	lngdppc	lnagrprod	lnfos	lnren
lnlcf	1.00				
lngdppc	-0.32***	1.00			
lnagrprod	-0.25***	0.16***	1.00		
lnfos	-0.53***	0.50***	-0.13***	1.00	
lnren	0.26***	0.50***	0.07**	-0.22***	1.00

Note: * p < 0.10, ** p < 0.05, *** p < 0.01.

Since the analysis focuses on EU member states within a panel data framework, interdependencies across countries are highly probable. Variables may be correlated as a result of unobserved common shocks or tightly linked economic and institutional channels. Such interconnections undermine the core independence assumptions of traditional first-generation panel estimators, and failing to account for them may lead to biased or unreliable estimates. To assess this issue, several cross-sectional dependence tests were applied, and the results are presented in Table 4. The findings consistently indicate strong cross-sectional dependence, while homogeneity tests reveal pronounced differences across countries in the determinants of the load capacity factor. Collectively, these results justify the adoption of second-generation econometric approaches, which explicitly address cross-sectional dependence and allow for heterogeneous slope parameters.

Table 4. Cross-section dependency and homogeneity test outcomes

test	statistic	p-value
LM	496.20***	0.000
LM adj	15.30***	0.000
LM CD*	14.72***	0.000
delta	12.85***	0.000
delta adj	15.27***	0.000

Note: * p < 0.10, ** p < 0.05, *** p < 0.01. Tests include the Breusch–Pagan (1980) LM test, the Pesaran et al. (2008) LM adj test, the Pesaran (2004) CD test, and the delta homogeneity tests by Pesaran and Yamagata (2008).

Once cross-sectional dependence is established, the subsequent step is to examine the stationarity properties of the data using second-generation panel unit root tests that explicitly account for cross-sectional dependence, such as the CIPS test. As reported in Table 5, all variables become stationary after first differencing, implying that each series is integrated of order one. Given that all variables are I(1), the long-run relationship among them is then investigated using the Westerlund cointegration test, which accommodates both cross-sectional dependence and heterogeneity.

Table 5. CIPS panel unit root results

	lnlcf	lngdppc	lngdppc^2	lnagrprod	lnfos	lnren
level	-2.00	-0.90	-0.86	-1.94	-1.35	-2.12
first difference	-3.37***	-3.52***	-3.44***	-3.95***	-3.85***	-3.09***

Note: * p < 0.10, ** p < 0.05, *** p < 0.01. CIPS panel unit root test follows Pesaran (2007).

The Westerlund cointegration test results presented in Table 6 indicate a rejection of the null hypothesis of no cointegration by both group-mean and panel statistics. Using robust p-values, all test statistics are statistically significant, confirming the presence of a long-run association while accounting for cross-sectional dependence and heterogeneity.

Table 6. Westerlund cointegration test results

	value	robust p-value
G_t	-2.89**	0.01
G_a	-7.70*	0.06
P_t	-13.52**	0.01
P_a	-8.05**	0.03

Note: * p < 0.10, ** p < 0.05, *** p < 0.01. Westerlund cointegration test follows Westerlund and Edgerton (2007).

After establishing the presence of cointegration, the long-run coefficients of the model are estimated using AMG and CCE estimators. The results are reported in Table 7. Under the AMG estimator, GDP per capita exhibits a positive (1.46) and statistically significant effect on the load capacity factor, while its squared term is negative (-0.08) and significant, indicating a nonlinear (inverted U-shaped) relationship This finding suggests that the LCC hypothesis does not hold for EU countries. Agricultural production has a positive (0.12) and significant impact on the load capacity factor, whereas fossil fuel consumption exerts a negative (-0.31) and significant effect. Renewable energy consumption, however, does not show a statistically significant influence. The CCE estimates confirm the negative effect of fossil fuel consumption (-0.25) and the positive effect of agricultural production (0.10), although GDP per capita and its squared term have insignificant effects on the load capacity factor. Renewable energy consumption becomes positive and significant (0.03) under the CCE estimator. The relationship between economic growth and the load capacity factor indicates that up to a certain threshold, economic growth supports environmental quality. However, beyond this threshold, further growth increases ecological pressure, failing to improve the load capacity factor. Since EU countries have already reached developed status, economic growth alone may not be sufficient to generate environmental benefits. The positive impact of agricultural production on the load capacity factor may be attributed to several interrelated mechanisms. First, EU countries implement sustainable agricultural practices under the Common Agricultural Policy, which promotes resource efficiency, soil conservation, and biodiversity preservation. Second, the EU's advanced technological infrastructure may facilitate the adoption of low-emission farming techniques. Third, higher levels of domestic agricultural production may reduce dependence on food imports, thereby decreasing transport-related emissions and the environmental externalities associated with global supply chains. Taken together, these channels indicate that agricultural production in the EU context contributes to improvements in biocapacity and strengthens ecosystem resilience. Fossil fuel consumption consistently reduces environmental quality, highlighting the environmental costs of carbon-intensive energy systems. In contrast, renewable energy supports environmental sustainability due to its environmentally friendly nature. These results suggest that economic growth alone is insufficient to achieve environmental improvement, and coordinated agricultural and energy policies are essential to strengthen environmental resilience in EU countries and mitigate the negative impacts of growth beyond a certain point.

However, these mean-based estimators provide limited insight, particularly regarding how these effects vary across countries with different levels of environmental performance. While the AMG results confirm the presence of an inverted U-shaped relationship and the detrimental role of fossil fuels, they only capture the average effect for EU countries. This is substantively important because policy implications may vary depending on a country's current environmental performance. For instance, in countries with already high load capacity factor (e.g., Finland, Sweden), further improvements may depend on different factors than in countries with lower environmental performance (e.g., Belgium, Luxembourg). The nonlinearity suggested by the EKC framework also implies that the economic growth–environment relationship may vary across different stages of development, which mean-based estimators cannot capture. Therefore, this study employs the MMQR approach to formally test whether such distributional differences exist, and conducts Wald tests to assess the statistical significance of any observed variation across quantiles.

Table 7. AMG and CCE results

dependent variable: lnlcf	AMG			CCE		
	coefficient	std. error	p-value	coefficient	std. error	p-value
lngdppc	1.46**	0.72	0.04	-1.33	2.22	0.54
$lngdppc^2$	-0.08**	0.03	0.01	0.04	0.11	0.66
lnagrprod	0.12***	0.03	0.00	0.10*	0.06	0.09
lnfos	-0.31***	0.08	0.00	-0.25**	0.12	0.04
lnren	0.02	0.01	0.18	0.03*	0.01	0.06
constant	-5.89*	3.52	0.09	0.97	7.08	0.89

Note: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. AMG and CCE estimators follows Pesaran (2006) and Bond and Eberhardt (2009).

Following the confirmation of unit root properties, slope heterogeneity, and cross-sectional dependence, the empirical analysis proceeds with the estimation of the MMQR. The results show that GDP per capita exerts a positive and statistically significant effect (0.937), while its squared term remains negative and statistically significant (-0.057), indicating an inverted U-shaped relationship. Agricultural production has a positive and significant impact (0.096), fossil energy consumption is negative and significant (-0.337), and renewable energy consumption remains positive and significant (0.082). To formally test whether the coefficients vary across quantiles, Wald tests for coefficient equality are employed. The null hypothesis is that the estimated coefficients are equal across the 10th to 90th quantiles. Rejection of the null hypothesis would indicate statistically significant heterogeneity in the estimated effects. As shown in Table 8, Wald tests indicate that none of the differences are statistically significant ($p > 0.05$ for all variables). Therefore, while the MMQR estimates visually exhibit minor variations, the effects of GDP per capita, its squared term, agricultural production, fossil energy consumption, and renewable energy consumption are broadly consistent across countries with different levels of environmental quality. The absence of quantile heterogeneity suggests that the relationships between the explanatory variables and environmental quality are stable across EU member states, irrespective of whether a country exhibits low, medium, or high levels of the load capacity factor. This stability may reflect the harmonizing effect of common EU-level environmental policies. In this context, the MMQR framework enables a formal assessment of coefficient homogeneity, which cannot be directly evaluated using conventional mean-based estimators. In addition, even under coefficient homogeneity, MMQR retains several advantages over standard panel estimation techniques. In particular, it is robust to outliers, allows for flexible error distributions, and does not impose the normality assumption commonly required in classical estimators. These properties remain relevant regardless of whether significant heterogeneity is detected across quantiles.

Overall, the quantile estimates suggest minor numerical variations across the 10th to 90th quantiles (GDPPC: 0.931–0.943; $GDPPC^2$: -0.057; agricultural production: 0.092–0.100; fossil energy consumption: -0.320–-0.353; renewable energy consumption: 0.080–0.084), but Wald tests confirm that these differences are not statistically significant. These results indicate that the effects of the explanatory variables on environmental quality are structurally stable across countries with different environmental performance levels, providing a robust basis for designing environmental policies.

Table 8. MMQR results

	location	scale	10th	25th	50th	75th	90th	Wald χ^2 (Q10=Q90)	p-value
lngdppc	0.937***	0.004	0.931***	0.934***	0.937***	0.940***	0.943***	0.00	0.963
	(0.11)	(0.07)	(0.15)	(0.12)	(0.12)	(0.14)	(0.19)		
$lngdppc^2$	-0.057***	-0.000	-0.057***	-0.057***	-0.057***	-0.057***	-0.057***	0.00	0.953
	(0.007)	(0.004)	(0.009)	(0.007)	(0.007)	(0.008)	(0.01)		
lnagrprod	0.096***	0.003	0.092*	0.094**	0.096***	0.098***	0.100***	0.02	0.884
	(0.03)	(0.01)	(0.05)	(0.04)	(0.03)	(0.03)	(0.03)		
lnfos	-0.337***	-0.010	-0.320***	-0.328***	-0.337***	-0.345***	-0.353***	0.31	0.577
	(0.03)	(0.01)	(0.04)	(0.03)	(0.03)	(0.03)	(0.04)		
lnren	0.082***	-0.001	0.084***	0.083***	0.082***	0.081***	0.080***	0.06	0.810
	(0.009)	(0.006)	(0.01)	(0.01)	(0.009)	(0.009)	(0.01)		
constant	-3.02***	0.122	-3.217***	-3.129***	-3.017***	-2.921***	-2.830***		
	(0.70)	(0.44)	(0.89)	(0.73)	(0.70)	(0.85)	(1.08)		

DISCUSSION AND POLICY IMPLICATIONS

Agricultural activity, energy structure, and the growth trajectory are closely intertwined with sustainable development and, consequently, environmental quality. While existing studies have increasingly focused on the environmental effects of agriculture, energy consumption, and economic growth, important gaps in the literature persist. In particular, empirical studies examining the relationship between agricultural production and the load

capacity factor are still limited, and none have employed the MMQR framework for EU countries. Although MMQR allows for examining potential variations across the conditional distribution, Wald test results indicate that these differences are not statistically significant ($p > 0.05$ for all variables). Therefore, the analysis focuses on the consistent effects of agriculture, energy consumption, and economic growth on environmental quality, rather than on quantile-specific outcomes. By doing so, the study provides empirical evidence for analyzing the LCC hypothesis in the EU context and highlights policy-relevant implications for promoting sustainable agricultural and energy strategies across member states.

The empirical findings reveal the existence of a long-run association among the variables. Results obtained from the AMG estimator indicate a nonlinear, inverted U-shaped relationship between economic growth and the load capacity factor. The CCE estimator, however, suggests a U-shaped relationship, but the coefficients for both terms are statistically insignificant. This inverted U-shaped pattern is consistently supported by the MMQR estimates. This outcome is in line with previous studies that also reject the LCC hypothesis, such as Li et al. (2023) and Bucak and Çatık (2025). The rejection of the LCC hypothesis in the EU context may be associated with the region's structural and institutional characteristics. EU member states are predominantly high-income economies with advanced industrial structures, where further economic expansion does not automatically translate into proportional improvements in environmental capacity. As Vogel and Hickel (2023) note, observed decoupling trends in high-income countries remain insufficient to meet the emission reduction targets set under the Paris Agreement. This raises concerns about whether sustained GDP growth alone can generate the net environmental surplus implied by the LCC hypothesis. Despite ambitious policy frameworks, such as carbon pricing mechanisms and the European Green Deal, economic expansion in the EU may still be linked to resource-intensive production patterns and fossil fuel dependence (Arezki et al., 2024). In addition, structural asymmetries across member states lead to variation in policy implementation and effectiveness (Ruiz et al., 2023), limiting the capacity of centralized EU strategies to produce uniform environmental outcomes. Therefore, the empirical rejection of the LCC hypothesis appears consistent with the EU's structural realities, where institutional strength and technological progress may not be sufficient on their own to fully decouple growth from environmental pressures.

With respect to agricultural production, both the AMG and CCE estimators reveal a positive and significant effect on the load capacity factor. The MMQR results further confirm this relationship while Wald test indicates that the effect is broadly consistent across quantiles. This suggests that agricultural production is positively associated with the load capacity factor within the scope of the estimated model. While these findings differ from studies reporting adverse environmental effects of agriculture (e.g., Salari et al., 2021; Warsame et al., 2023; Ali et al., 2024), they are consistent with Raihan (2025), who emphasizes the potential role of sustainable agricultural practices in supporting ecological performance.

Regarding energy consumption, the results show effects depending on the energy type. Renewable energy consumption does not exhibit a statistically significant effect under the AMG estimator; however, the CCE results indicate a positive and significant contribution to the load capacity factor. Both estimators are designed to address cross-sectional dependence and slope heterogeneity in panel time series, but they adopt different approaches to modeling cross-sectional dependence (Pesaran, 2006; Bond and Eberhardt, 2009). These methodological differences may lead to varying estimates of the renewable energy effect. While AMG and CCE estimate average effects across countries, the MMQR framework allows the examination of effects across the conditional distribution of the load capacity factor. Although the point estimates show minor numerical variation across quantiles (0.080 to 0.084), Wald test confirms that these differences are not statistically significant, indicating that the positive impact of renewable energy is statistically homogeneous across the distribution. Overall, the findings suggest that renewable energy consistently contributes to improving environmental quality in EU member states. These results are consistent with Shang et al. (2022) and Sun et al. (2024), who document the environmental benefits of renewable energy use. In contrast, fossil energy consumption is found to exert a consistently negative effect on the load capacity factor across both the AMG and CCE estimators. The MMQR results confirm this adverse relationship, and Wald test indicates that the magnitude of the negative effect does not differ significantly across quantiles. This evidence aligns with prior studies such as Xu et al. (2022) and Raihan et al. (2023), which identify fossil energy consumption as a major driver of environmental degradation.

Overall, the results indicate that the relationships among economic growth, agricultural production, energy consumption, and the load capacity factor are structurally stable across the distribution. Specifically, a 1% increase in GDP per capita is associated with a 0.937% rise in the load capacity factor, while its squared term reduces it by 0.057%, confirming the inverted U-shaped pattern. Agricultural production has a positive association, with a 1%

increase linked to a 0.096% rise in the load capacity factor. In contrast, fossil fuel consumption exerts a negative effect, reducing the load capacity factor by 0.337% for a 1% increase, whereas renewable energy contributes positively, with a 1% increase raising the load capacity factor by 0.082%. These results indicate that policy interventions targeting agricultural production, renewable energy promotion, and fossil fuel reduction can produce measurable effects on environmental performance. By reporting both statistical significance and economic magnitude, the study provides an evaluation of practical importance and underscores the value of using advanced econometric methods in analyzing environmental outcomes.

The findings of this study yield important policy implications for strengthening environmental quality across EU member states. First, the findings provide evidence of an inverted U-shaped link between growth and the load capacity factor. This implies that growth initially enhances environmental quality, but after reaching a threshold, further growth reduces the load capacity factor and intensifies ecological pressure. In other words, while early stages of growth may support environmental improvements through efficiency gains and technological progress, economic growth eventually leads to ecological overshoot, where environmental degradation outweighs the benefits of economic expansion. This inverted U-shaped pattern suggests that, in the EU context, additional economic growth may not necessarily restore environmental balance and may instead be associated with increasing ecological pressure. As a result, the key mechanism predicted by the LCC hypothesis does not hold for these countries. Instead, continued growth amplifies consumption, energy demand, and resource extraction, placing increasing stress on ecological systems and reducing environmental resilience. Hence, economic growth alone does not automatically lead to improvements in environmental quality. This suggests that relying on income-driven environmental improvements may be insufficient. Policymakers may prioritize proactive environmental regulations and sustainability-oriented development strategies rather than assuming that environmental pressures will diminish as economies grow.

Second, agricultural production is positively associated with the load capacity factor. This suggests that agricultural production can be environmentally supportive when accompanied by sustainable and resource-efficient practices that minimize ecological pressure while maintaining productivity. Given their advanced institutional frameworks and access to environmentally friendly technologies, EU countries are well positioned to align agricultural production with environmental sustainability. Moreover, producing agricultural goods within the Union may reduce dependence on imports, thereby lowering pollution associated with transportation and externalized environmental costs. In this context, sustainable agricultural development may simultaneously enhance ecological capacity and strengthen food security, supporting the objectives of SDG-2, SDG-12, and SDG-15.

Third, the results regarding energy consumption emphasize the critical role of the energy transition in improving environmental sustainability. Renewable energy consumption is found to improve the load capacity factor. This suggests that accelerating investments in renewable energy infrastructure may generate substantial sustainability gains. In contrast, the consistently negative impact of fossil energy consumption calls for stricter policies aimed at reducing fossil fuel dependency, such as carbon pricing mechanisms, the removal of fossil fuel subsidies, and incentives for clean energy adoption.

This study is subject to several limitations that may be acknowledged. First, the analysis covers the period 2000–2023; extending the time span as more recent and historical data become available could provide a more comprehensive assessment of long-term dynamics. Second, although the model includes key determinants such as economic growth and energy structure, it does not explicitly incorporate other potentially relevant factors, including economic complexity, institutional quality, governance indicators, and digitalization. Future research that integrates these variables may provide a more comprehensive understanding of the mechanisms linking agricultural production and environmental sustainability. Third, the current framework does not account for potential spatial spillover effects across EU member states. Given the economic and environmental interconnections within the Union, neighboring-country dynamics may influence national load capacity factors. Future studies could extend the analysis by employing spatial econometric approaches to examine cross-country spillovers and regional interdependencies.

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