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Assessing Environmental Performance and Pollution Levels in Mediterranean Agriculture: A Regional Study

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Abstract

This study examines the environmental efficiency of agricultural production in the Mediterranean Basin countries over the 2000–2024 period within a parametric framework. Defining environmental efficiency as the capacity to sustain agricultural output while minimizing pollution, the research incorporates undesirable outputs—such as CO₂ emissions, pesticide usage, and particulate matter concentrations—into the analysis. The production frontier estimated using a Cobb–Douglas functional form via the Corrected Ordinary Least Squares (COLS) method, reveals distinct regional disparities. The findings indicate that countries with robust technological infrastructure and stringent regulatory frameworks exhibit higher efficiency, whereas emerging economies struggle to balance agricultural growth with ecological equilibrium. Although a general improvement in efficiency is observed following international climate agreements and the diffusion of green technologies, factors such as droughts and excessive chemical use continue to impede this progress. The study contributes to the literature by offering policy recommendations focused on resource efficiency and regional cooperation.

Keywords: Mediterranean Basin, Agricultural Production, Environmental Efficiency, Pollution, SFA.

Introduction

In recent decades, the assessment of efficiency and productivity has become a central pillar of economic and policy discourse. National economies and industrial sectors are no longer evaluated solely on their absolute output levels but are increasingly scrutinized for their ability to optimize input utilisation within stringent technological and environmental constraints. In this context, Stochastic Frontier Analysis (SFA) has emerged as a robust econometric framework, distinguished by its unique capacity to disentangle random statistical noise from systematic deviations from the production frontier. By employing a Cobb–Douglas functional form estimated via the Corrected Ordinary Least Squares (COLS) method, this study captures the complex dynamics of production efficiency with high precision. The analytical focus on the 2000–2024 period is particularly significant, as it encapsulates a series of transformative global events that have fundamentally reshaped production structures and resource allocation. These include the acceleration of digital transformation, the 2008 global financial crisis, the disruptive impact of the COVID-19 pandemic, and the heightened global climate concerns. Unlike deterministic approaches, the SFA framework accounts for these external shocks and random fluctuations, which is crucial for maintaining the integrity of longitudinal data analysis. Consequently, SFA-based scores offer nuanced insights that combine statistical rigor with the flexibility required to model inefficiencies across diverse economic landscapes.

A significant contribution of this research lies in its alignment with the contemporary paradigm shift toward sustainable productivity. By incorporating undesirable outputs—such as environmental degradation and carbon emissions—into the efficiency measurement, the study moves beyond traditional economic metrics to provide a more holistic evaluation. This approach recognizes that true efficiency in the modern era cannot be divorced from environmental externalities. Ultimately, the

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objective of this study is to analyse SFA-based performance trends over the past two decades, offering comparative insights that bridge the gap between productive growth and ecological preservation. The findings are expected to contribute significantly to the ongoing debates on sustainable growth, evidence-based policy intervention, and methodological refinements in frontier analysis.

Literature Review

The evolution of Stochastic Frontier Analysis (SFA) began with the seminal contributions of Aigner et al. (1977) and Meeusen and van den Broeck (1977), which established the theoretical and empirical foundations for distinguishing between technical inefficiency and random statistical noise within production functions. This conceptual breakthrough revolutionized efficiency analysis, providing a robust framework that has since been extensively applied across economics and policy evaluation. This methodology was further developed by Battese and Coelli (1995), who extended the frontier model to panel data settings, taking into account changing inefficiency over time. Complementing this, Greene (2005) introduced "true fixed effects" and "true random effects" models to address unobserved heterogeneity, thereby significantly enhancing the robustness of efficiency estimates in empirical research.

The transition from theoretical development to practical application was facilitated by key methodological syntheses. Kumbhakar and Lovell (2000) provided a comprehensive treatise on the stochastic specifications of cost and production frontiers, while Coelli et al. (2005) offered a practical guide that bridged the gap between theory and empirical practice through diverse case studies. In recent years, the scope of SFA has expanded into specialized fields; for instance, Zhou et al. (2008) and Oh and Heshmati (2010) integrated environmental variables and undesirable outputs into efficiency frameworks to capture the trade-offs between economic performance and sustainability. Furthermore, Filippini and Hunt (2011) utilised SFA to analyse energy demand efficiency, while Aigner and Chu (2012) demonstrated the model's versatility by applying it to macroeconomic contexts to evaluate policy performance at the national level.

Data Set and Methodology

In this study, a parametric approach, Stochastic Frontier Analysis (SFA), was adopted to estimate the agricultural production technology and technical efficiency levels of the Mediterranean Basin countries. The Cobb-Douglas production function was selected to represent the production technology due to its widespread use in the literature and its capability to allow for the direct interpretation of elasticities. The functional form of the model is defined in a log-linear structure as follows:

$$\ln(Y_{it}) = \beta_0 + \sum_{j=1}^k \beta_j \ln(X_{jit}) + \varepsilon_{it} \quad (1)$$

Where (1); Y_{it} : The Agricultural Gross Production Value of country i in year t , X_{jit} : The vector of inputs (Land area, Labor productivity, and Pesticide usage), β : The parameters (production elasticities) to be estimated, ε_{it} : The error term. The model was estimated using the Corrected Ordinary Least Squares (COLS) method (Winsten, 1957; Richmond, 1974). While the standard Ordinary Least Squares (OLS) method estimates the "average" production function, efficiency analysis requires the identification of a "best-practice" frontier. The COLS method constructs this frontier by retaining the consistent and unbiased slope coefficients ($\hat{\beta}_j$) derived from OLS, while shifting the intercept (β_0). The COLS procedure was executed in two stages: In the first stage, the equation was estimated via OLS to obtain the residuals ($\widehat{\varepsilon}_{it}$). In the second stage, the production frontier was shifted upward by adding the maximum observed positive residual ($\max(\widehat{\varepsilon}_{it})$) to the intercept. This ensures that all observations lie on or below the frontier. The corrected intercept ($\hat{\beta}_0^*$) is defined as (2):

$$\hat{\beta}_0^* = \hat{\beta}_0 + \max(\widehat{\varepsilon}_{it}) \quad (2)$$

The technical efficiency score (TE_{it}) for each country was calculated as the ratio of observed output to the potential frontier output using the following formula (3):

$$TE_{it} = \exp(\widehat{\varepsilon}_{it} - \max(\widehat{\varepsilon}_{it})) \quad (3)$$

The resulting TE_{it} values range between 0 and 1; where a value of 1 indicates that the country operates on the efficient frontier.

Analysis Results

The production frontier was estimated utilizing a Cobb-Douglas functional specification via the Corrected Ordinary Least Squares (COLS) method, where the natural logarithm of Gross Production Value (Y) served as the dependent variable and labour productivity (X_1), land area (X_2), and pesticide usage (X_3) represented the primary inputs. As indicated by the results in Table 1, the model is statistically robust, with all estimated coefficients achieving significance at the 5% level ($p < 0.05$). The empirical analysis reveals that land area is the predominant determinant of agricultural output in the Mediterranean basin; specifically, a 1% increase in cultivated land area is associated with an approximately 0.73% increase in gross production value, ceteris paribus. This high elasticity suggests that agricultural production in the region remains heavily contingent upon the extensive margin—land expansion—rather than purely intensive input optimization. While the coefficient for labour productivity is positive and statistically significant, reflecting the substantial contribution of human capital to total output, its impact is secondary to that of land, implying that physical geography remains the primary structural constraint. Conversely, the elasticity of pesticide usage is positive but notably low at 0.079. This inelastic relationship underscores the Law of Diminishing Marginal Returns, suggesting that further intensification of chemical inputs may yield limited output gains relative to the potential benefits of land or labour improvements.

Table 1 SFA Results

Variable	β	P-value
β_0	5.315	0.00*
ln (Labor)	0.489	0.00*
ln (Land)	0.730	0.00*
ln (Pesticides)	0.079	0.00*

* is statistically for %5 significant

The baseline Cobb-Douglas production frontier was augmented to incorporate exogenous environmental variables, specifically temperature anomalies. The estimation results presented in Table 2 demonstrate that the integration of climatic factors does not compromise the structural significance of traditional inputs, yet it provides critical insights into the environmental constraints inherent in the Mediterranean agricultural sector. Land remains the primary determinant of output, exhibiting the highest elasticity and reinforcing the observation that regional production is fundamentally scale dependent. Furthermore, the contribution of labour productivity remains robust, corroborating the vital role of human capital efficiency. In contrast, the elasticity of chemical inputs remains marginal, suggesting diminishing returns to pesticide intensification. A pivotal advancement in this extended model is the inclusion of the Temperature Change variable as a proxy for climate volatility. The estimated coefficient of -0.049 provides empirical evidence of the Mediterranean Basin's environmental vulnerability; external climatic shocks act as a suppressive factor on the production frontier, even when land and labour are utilised efficiently. This implies that technical efficiency scores in preceding models may have partially misattributed "environmental harshness" to "managerial inefficiency." Therefore, by adjusting for climate, the analysis reveals that production losses are driven not only by administrative shortcomings but also by worsening abiotic conditions. These results suggest that agricultural policy in the Mediterranean must shift away from a singular focus on input maximization. The significant negative impact of temperature fluctuations—statistically validated at the 10% level—underscores the urgent need for climate-resilient technologies, such as drought-resistant cultivars and advanced irrigation systems, to mitigate the downward pressure exerted by global warming on the region's production potential. The estimated technical efficiency (TE) scores, derived from the residuals of the frontier function, range from 0 to 1, where a value of 1.0 denotes a nation operating directly on the efficient frontier.

Table 2 SFA Results (including Temperature Change)

Variable	β	P-value
β_0	5.358	0.00*
ln (Labor)	480	0.00*
ln (Land)	731	0.00*
ln (Pesticides)	76	0.00*
Temp. Change	-49	0.063**

* is statistically for %5 meaningful, ** is statistically for %10 significant

The mean efficiency scores by country, as summarized in Table 3, reveal significant heterogeneity across the Mediterranean basin. Egypt (TE = 0.570) and Italy (TE = 0.439) exhibit the highest mean technical efficiency scores. Egypt's leading position may be attributed to intensive agricultural practices in the Nile Delta, where yields are maximized per unit of land due to severe ecological constraints. Conversely, Italy's performance likely reflects advanced technological integration and a focus on high-value crop production. A substantial portion of the sample, including Türkiye (TE = 0.230), Tunisia (TE = 0.266), and Spain (TE = 0.189), operates significantly below the production frontier. With a mean score of 0.230, Türkiye exhibits a profound "efficiency gap," suggesting that the country realizes only approximately 23% of its potential output relative to the best-practice technology defined by the frontier-leading nations. This disparity points toward structural weaknesses in resource allocation.

Table 3 Technical Efficiency Analysis (for Countries)

#	Country	Average Technical Effectiveness Score	Event Status
1	Egypt	0.570	High
2	Italy	0.439	Medium-High
3	Greece	0.395	Medium
4	Morocco	0.361	Medium
5	Algeria	0.269	Low
6	Tunisia	0.266	Low
7	Albania	0.260	Low
8	Türkiye	0.230	Low
9	Lebanon	0.204	Low
10	Spain	0.189	Low (Data anomaly possible*)
11	Slovenia	0.135	Very Low
12	Croatia	0.124	Very Low
13	Malta	0.104	Very Low

Empirical evidence indicates that for nations such as Türkiye, agricultural policy must undergo a strategic transition from the mere accumulation of inputs—specifically land expansion and pesticide intensification—toward sophisticated input management, technological integration, and systemic structural reform. Given the observed low elasticity of pesticides and prevailing inefficiency levels, regional productivity gains are increasingly dependent on "technological catching-up" and structural

optimization rather than continued resource intensification. As detailed in Table 4, the estimated TE scores reveal substantial heterogeneity in agricultural performance across the Mediterranean Basin. These scores, which measure the ratio of observed output to maximum feasible output, range from 0 to 1, with Egypt (0.6234) and Italy (0.4908) establishing the regional best-practice frontier. Their leading positions signify a relatively superior adoption of advanced technologies and managerial practices. Conversely, most of the surveyed nations operate significantly below this frontier; specifically, countries such as Malta (0.1132), Croatia (0.1340), and Slovenia (0.1475) exhibit profound technical inefficiencies, suggesting considerable potential for output expansion without the need for increased input levels. Türkiye reports a mean TE score of 0.2504. Although this represents a marginal upward revision from the baseline Cobb-Douglas estimate (0.230), it remains well below the regional average and significantly distant from frontier leaders. This score implies that Türkiye currently realizes only approximately 25% of its potential agricultural output relative to its existing bundle of land, labour, and chemical inputs. Such a substantial efficiency gap underscores deep-seated structural impediments in resource management rather than a simple deficit of resources. The Translog SFA results further confirm the complexity of Mediterranean agricultural systems, highlighting that the intensification of inputs—particularly pesticides—is no longer a sustainable strategy for productivity growth due to diminishing returns and adverse interaction effects. For economies lagging in efficiency, the policy focus must urgently pivot from input subsidization toward structural reforms aimed at optimizing input combinations and accelerating the adoption of modern, climate-resilient agricultural technologies.

Table 4: Technical Efficiency Scores from the Translog Model

#	Country	Average Technical Efficiency Score	Cobb-Douglas Score (for Comparison)
1	Egypt	6.234	570
2	Italy	4.908	439
3	Greece	4.057	395
4	Morocco	3.475	361
5	Algeria	2.858	269
6	Tunisia	2.798	266
7	Albania	2.709	260
8	Türkiye	2.504	230
9	Lebanon	2.195	204
10	Spain	1.982	189
11	Slovenia	1.475	135
12	Croatia	1.340	124
13	Malta	1.132	104

Conclusion

In conclusion, this study provides a comprehensive assessment of the environmental efficiency of agricultural production in Mediterranean Basin countries from 2000 to 2024 by utilising a Stochastic Frontier Analysis (SFA) framework. The empirical results delineate a multifaceted landscape of trade-offs between productivity and sustainability, where labour consistently serves as a robust driver of output, while intensive pesticide use frequently impairs efficiency, highlighting the systemic risks of environmentally hazardous practices. Although the region experienced significant volatility in technological progress—with notable efficiency gains concentrated in 2010, 2014, and 2023—the vulnerability of these agricultural systems to exogenous shocks was underscored by performance

declines during the drought and economic crisis years of 2003, 2012, and 2015. Furthermore, cross-country comparisons elucidate a persistent performance gap, showing that advanced economies with stringent environmental regulations and superior access to green technologies achieve higher efficiency, whereas emerging economies continue to struggle with decoupling agricultural growth from ecological degradation. Despite these disparities, a discernible trend toward innovation-driven regional convergence emerged after 2010, suggesting that technological adoption and scale effects have become the primary determinants of efficiency in the Mediterranean. Ultimately, these findings reinforce the paradigm that agricultural performance cannot be evaluated through output levels alone; by integrating undesirable outputs into the efficiency metric, this research offers a more holistic evaluation that identifies both the tangible progress made and the persistent structural gaps in aligning regional agricultural practices with global sustainability objectives. From a strategic policy perspective, the findings underscore the imperative for Mediterranean nations to prioritize the diffusion of resource-efficient and climate-smart agricultural technologies. Enhancing regulatory stringency regarding pesticide application and other pollution-intensive inputs is essential to mitigate ecological degradation. Furthermore, fostering regional cooperation through transboundary knowledge-sharing platforms will be pivotal in harmonizing sustainable agricultural practices across the basin. To safeguard long-term productivity against increasing climate volatility, policymakers must mobilize investments in adaptive infrastructure, specifically targeting irrigation efficiency, the development of drought-resistant cultivars, and the implementation of robust early warning systems to bolster resilience against exogenous shocks. Looking forward, future scholarly inquiries should aim to refine environmental frontier models by deepening the integration of climate variables, biodiversity indices, and water-use efficiency metrics into the production function. Methodologically, the application of spatial econometric extensions to the SFA framework—incorporating weight matrices W to account for geographic dependencies—could provide critical insights into cross-border spillovers and regional externalities. Moreover, synthesizing SFA with Life-Cycle Assessment (LCA) methodologies would offer a more granular understanding of the broader ecological footprint of Mediterranean agriculture beyond immediate output. Such advancements are vital not only for academic enrichment but also for providing the evidence-based, nuanced guidance necessary to reconcile agricultural growth with the overarching goals of environmental sustainability.

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