Do Sustainability Strategies Affect Technical Efficiency? Evidence from Italian GI Wine Farms

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Abstract

Sustainability has become a central objective of agricultural policies and business strategies as resource constraints and societal expectations increasingly affect production systems. The global wine industry is undergoing a structural transformation in which sustainability is no longer voluntary but increasingly required for market access. In this context, sustainability-oriented strategies adopted by wine farms, such as agri-environmental measures, certification schemes, and labor-related practices, may influence not only environmental and social outcomes but also their productive performance. In Italy, the world's leading wine producer by volume, these dynamics are particularly evident among Geographical Indication (GI) producers, for whom sustainability is a strategic lever to preserve the terroir underpinning product value. This study investigates whether sustainability-oriented strategies are associated with differences in technical efficiency among Italian GI winegrape producers. The analysis adopts a Stochastic Frontier Analysis framework in which technical inefficiency is modelled as a function of farm characteristics and sustainability-related determinants, drawing on a balanced panel of 2,044 observations from the Italian Farm Accountancy Data Network for the period 2021–2023. The results reveal significant heterogeneity in technical efficiency. Our main finding is that organic certification entails a significant short-run efficiency penalty among Italian GI winegrape producers, while participation in agri-environmental schemes under the CAP is associated with improved efficiency, suggesting that public policy instruments can partially, though not fully, compensate for the productive costs of sustainability transitions. Diversification and on-farm processing are also associated with higher inefficiency, reflecting the scope mismatch between the estimated frontier and the full range of activities in which vertically integrated firms deploy their resources. Overall, the findings carry direct implications for management and policymaking in support of the sustainability transition of the Italian GI wine value chain.

Keywords: Stochastic Frontier Analysis; Sustainability; Technical efficiency; Wine economics.

1. Introduction

Over the past decades, sustainability has become a defining challenge for agricultural systems, driven by intensifying climate change impacts, natural resource depletion, and rising regulatory and societal expectations for environmental responsibility [1], [2]. Within the European Union (EU), sustainability has been progressively mainstreamed through major policy frameworks, notably the Common Agricultural Policy (CAP) and the Farm to Fork Strategy. The latter explicitly frames sustainability as a core principle of food systems governance [3], and promotes environmental cross-compliance, agri-environmental payments, and social conditionality mechanisms [4]. These initiatives are embedded within the broader framework of the European Green Deal, which outlines a roadmap toward climate neutrality by 2050 and identifies agriculture as a key sector for reducing greenhouse gas emissions, protecting biodiversity, and enhancing resource efficiency [5].

Among agricultural sectors, the global wine industry is undergoing profound structural transformation [6]. Wine production is characterized by high capital intensity, high sensitivity to climate variability, and exposure to input and market dynamics [1], [7]. Driven by the dual pressures of climate change and shifting consumer preferences for high-quality, ethically produced goods, sustainability has evolved from a voluntary corporate social responsibility goal into a fundamental requirement for market access and competitiveness. According to the International Organisation of Vine and Wine (OIV), sustainability entails a comprehensive approach that integrates economic viability, product quality, environmental protection, and the preservation of cultural and landscape values [8]. Within the wine sector, this concept translates into environmental stewardship, climate change mitigation and adaptation through the conservation of ecosystems, operational efficiency, and social responsibility toward workers, local communities, and cultural identity [1], [9].

The sector is deeply embedded in territorial and cultural contexts, particularly within quality-oriented systems based on Geographical Indications (GI) (i.e., IGT, DOC, and DOCG) wines, where product value is closely tied to terroir-specific attributes, local knowledge, and landscape preservation. In these settings, sustainability becomes a critical driver of quality differentiation, territorial identity, and long-term competitive advantage [10]. In Italy, the world’s leading wine producer by volume, this transformation is particularly visible among producers of GI wines [11], [12]. For these quality-oriented farms, sustainability is not merely an environmental concern but a strategic necessity to preserve the *terroir* that underpins their economic value [13], [14]. Understanding how sustainability-oriented practices are embedded within production and organizational processes is therefore increasingly recognized as crucial for guiding the long-term development and resilience of the wine sector under growing environmental and climatic pressures [15].

However, the integration of sustainability into the wine value chain often creates complex trade-offs. Although the adoption of organic practices or social certifications enhances the "green" value of the final product, it remains unclear how these strategies impact the internal technical efficiency of the production process [16]. Existing research often treats economic efficiency and environmental sustainability as separate performance dimensions [17], [18]. Previous studies have largely focused on structural and territorial determinants of efficiency in viticulture, without explicitly incorporating sustainability-oriented strategies as inefficiency determinants. Fertő and Bojnec (2023) examined the effect of CAP subsidies on technical efficiency in Hungarian wine farms, finding that aggregate subsidy payments are negatively associated with efficiency [19]. However, their analysis does not distinguish between specific policy instruments, notably agro-climatic-environmental (AEC) scheme participation, nor does it account for value-chain transformation strategies such as on-farm processing and diversification. Similarly, Ait Sidhoum et al. (2023) analyzed the effects of AEC schemes on farm-level eco-efficiency across EU member states using the Data Envelopment Analysis (DEA) and focused on dairy and crop production rather than viticulture [20]. No study to date has jointly examined the productive efficiency implications of AEC participation, organic certification, and value-chain transformation strategies among Italian GI winegrape producers using a representative panel dataset.

Against this backdrop, this study investigates whether environmental and social strategies, such as participation in agri-environmental measures, certification schemes, and labor-related practices, are associated with differences in technical efficiency. While organic certification may entail transition and compliance costs that temporarily reduce efficiency, AEC scheme participation could prove compatible with, or even supportive of, productive performance, given the incentive structures embedded in CAP payments [19], [20]. Structural and geographical heterogeneity may mediate the relationship between sustainability strategies and efficiency outcomes, with larger farms and specific AEC contexts potentially moderating both the adoption of green practices and their productive implications [18], [19]. Specifically, the study is guided by two interrelated research questions. RQ1: To what extent do green practices, specifically organic certification and participation in AEC schemes, trade off with productive efficiency among Italian GI winegrape producers? RQ2: Do firm size and territorial location systematically influence the efficiency gap across producers? To this end, we employ a stochastic frontier analysis (SFA) approach, in which we model technical inefficiency as a function of farm characteristics and sustainability-related determinants. The empirical analysis is based on farm-level data from the Farm Accountancy Data Network for Italy (FADN/RICA), focusing on Italian GI producers. This approach enables us to disentangle the efficiency implications of distinct sustainability strategies and to derive policy-relevant insights for the transition of the Italian GI wine value chain. The remainder of the paper is organized as follows. Section 2 reviews the relevant literature on efficiency and sustainability in agricultural and wine systems. Section 3 presents the empirical model and data. Section 4 reports the results of the stochastic frontier estimation. Section 5 discusses the findings along three dimensions: structural and social factors, environmental strategies, and value-chain transformation. Section 6 concludes with policy implications and directions for future research.

2. Literature review on integrating sustainability into firms' efficiency analysis

The concept of efficiency has long been a central reference point within economics, operations research, and policy analysis. Traditionally, it has been defined in narrowly economic or technical terms, emphasizing the relationship between inputs and outputs, cost minimization, productivity maximization, and optimal resource allocation, which have been interpreted as core elements of economic sustainability by enhancing firms' viability, competitiveness, and long-term capacity to operate in the market [21].

However, a growing body of literature has highlighted important limitations of this perspective, particularly regarding the insufficient integration of environmental and social sustainability considerations [22], [23]. Efficiency gains achieved through intensive resource use or through the externalization of environmental costs may therefore prove unsustainable over the long term. Porter and Van der Linde (1995) challenged the notion of an inherent trade-off between environmental protection and economic performance, arguing that innovation-induced environmental improvements can enhance resource productivity and firms' competitiveness [24]. Subsequent contributions have refined this view by emphasizing that complementarities between economic performance and sustainability outcomes are not automatic but context-dependent and contingent on firms' strategic choices and institutional settings, as articulated in the shared value theory [25].

By contrast, the social dimension remains comparatively underexplored. Aspects such as labor conditions, equity, health impacts, and generational renewal are rarely incorporated into efficiency models due to their complexity and the lack of standardized measurement frameworks [26], [27]. As a result, efficiency outcomes may legitimize practices that appear economically optimal but are socially unsustainable in the long run.

Efficiency and sustainability are two fundamental concepts in the management of natural resources, yet significant discrepancies can arise between them. These discrepancies frequently occur in decision-making processes regarding ecosystem management, where trade-offs between efficiency and sustainability must be considered in an integrated manner [28]. Despite their differences (efficiency focuses on avoiding wasteful behavior, while sustainability aims to maintain critical aspiration levels), these two concepts are not necessarily mutually exclusive in the pursuit of optimal long-term solutions in the intertemporal allocation of resources [29].

These conceptual challenges have motivated the development of analytical approaches capable of integrating sustainability dimensions into performance measurement. In particular, environmental considerations have been incorporated into efficiency analysis through methodological extensions of Data Envelopment Analysis (DEA) and SFA that account for undesirable outputs such as emissions and waste [30], [31]. While the comparison between efficiency and sustainability in agricultural production is well documented [32], [33], applications to viticulture and wine production have mainly focused on environmental indicators such as energy and water efficiency [34]. The relationship becomes more complex when considering the social dimension, although Social Life Cycle Assessment can be used in wine research to evaluate the social sustainability of wine production processes [35] or through efficiency frameworks based on farm-level indicators [14].

The urgency to identify strategies capable of generating both efficient and sustainable outcomes has also been emphasized in the agri-food supply chain literature, where integrated performance frameworks are increasingly advocated [36]. Overall, the reviewed literature points to a persistent gap between the methodological advances in integrating sustainability into efficiency analysis and their systematic application to quality-oriented wine systems, particularly with regard to the joint assessment of environmental strategies, CAP instruments, and value-chain transformation. This gap motivates the empirical framework developed in the following sections.

3. Materials and methods

3.1.Model specification

To model the production process of wineries and to investigate how sustainability-related strategies are associated with productive performance, we adopt a SFA approach based on the one-step inefficiency effects model [37]. This framework enables us to modeling technical inefficiency as a function of farm characteristics and environmental and social determinants. Technical efficiency is widely employed as an empirical proxy for the economic dimension of sustainability [38], [39]. Compared to non-parametric alternatives such as DEA, SFA decomposes deviations from the production frontier into a stochastic noise component and a one-sided inefficiency term, allowing formal statistical inference on both technology parameters and inefficiency determinants [40]. The one-step specification is preferable to the two-step approach, in which efficiency scores are estimated first and then regressed on exogenous variables. As Wang and Schmidt (2002) demonstrate, this sequential procedure violates the distributional assumptions maintained in the first stage and yields downward-biased parameter estimates [41]. By simultaneously estimating the production frontier and the inefficiency equation via maximum likelihood, the one-step model avoids this inconsistency, which is particularly relevant in panel settings with exogenous inefficiency determinants. Previous studies have adopted this perspective while treating social, environmental, and structural attributes as determinants of inefficiency rather than as direct measures of sustainability [42]. Accordingly, we employ the inefficiency effects model to assess how these attributes are associated with the efficiency dimension, without equating overall sustainability with technical performance [38], [42].

The analysis is conducted under the assumption of the following production function (Eq. 1):

$$y_{it} = f(x_{it}; \alpha) + v_{it} - u_{it} \tag{1}$$

where y_{it} is the output generated by the firm, x_{it} are the inputs to production, v_{it} indicates stochastic noise and u_{it} represents technical inefficiency. The random errors are assumed to be i.i.d. following a normal distribution $N(0, \sigma_v^2)$, while we model inefficiency as a function of exogenous variables. The inefficiency determinants function follows the form: (Eq. 2)

$$u_{it} = \delta_0 + z_{it}\delta + w_{it} \tag{2}$$

where z_{it} is a vector of technical inefficiency explanatory variables, δ is a vector of parameters, and w_{it} is the i.i.d. error term. Positive coefficients in the inefficiency equation indicate higher inefficiency (i.e., lower technical efficiency), whereas negative coefficients are associated with lower inefficiency (i.e., higher technical efficiency).

We conduct model specification tests to identify the appropriate functional form (i.e., Cobb-Douglas versus Translog), to confirm frontier existence, and to assess the distribution of inefficiency effects. We then apply maximum likelihood to estimate simultaneously the parameters of the SFA and the model for inefficiency effects. We perform all estimations using Stata 18 [43].

3.2. Data

A set of farm-level variables among wine producers under Italy's GI schemes was extracted from the Italian FADN. The dataset provides harmonized structural, economic, social, and environmental information on agricultural holdings through an annual sample survey conducted in all European Union Member States according to a common methodology [44].

The selection of variables is informed by the literature on wine production processes and agricultural sustainability [14], [18]. Specifically, the production frontier includes utilized grape-growing area, labor costs, energy costs, pesticides and fertilizers expenditures. Output is measured as total grape production in kilograms. The inefficiency effects equation includes the core sustainability determinants of interest, organized into three dimensions: (i) social and structural factors, including farmer's age and gender, farm size, altitude, and regional location; (ii) environmental strategies, encompassing organic certification, participation in AEC schemes, and the proportion of expenditures on pesticide classified as toxic relative to total pesticide expenditures (ToxicShare); (iii) value chain transformation, captured by the presence of on-farm processing (transformation of grapes into wine), and diversification into non-agricultural activities (e.g., agritourism). AEC scheme participation involves a multi-year contractual commitment under CAP Rural Development Programmes, agreed prior to the production period, and is therefore not simultaneously determined with annual input allocations. ToxicShare reflects the historical composition of the farm's pesticide portfolio rather than a period-specific optimization choice. Both variables are therefore treated as predetermined determinants of inefficiency.

The inclusion of farmer age and gender as inefficiency determinants follows an established practice in the agricultural efficiency literature and responds to specific features of the Italian wine sector. Younger farmers tend to combine higher propensity toward technological innovation and sustainability adoption with structural disadvantages in access to land and credit, generating theoretically ambiguous effects on short-run efficiency [45], [46]. Female farm holders in Italy face persistent structural inequalities in resource endowments, including access to land, capital, and inputs, documented as primary drivers of performance gaps in the Italian agricultural sector [47]. In the viticulture sector specifically, persistent social norms have historically limited women's access to landownership and decision-making [48]. Moreover, female farmers have been shown to display stronger orientations toward resource efficiency and sustainability practices, including participation in agri-environmental schemes [45]. We base the empirical analysis on a balanced panel dataset of 2,044 observations observed over the 2021–2023 period.

4. Results

4.1. Descriptive statistics

Table 1 presents the descriptive statistics for the variables included in the analysis. Sustainability-related attributes, including organic certification, diversification, farmer demographics, and participation in AEC schemes, display relatively low adoption rates, with mean values ranging from 0.11 to 0.23. Expenditures on toxic pesticides account for approximately 24% of total pesticide spending, suggesting a non-negligible reliance on chemically intensive practices within the sample.

From an economic perspective, the cost structure of production is strongly labor- and input-intensive. Labor represents the largest cost component, averaging €19,346 per farm. Among variable inputs, pesticides account for 37.6% of expenditures, followed by fertilizers (22.6%) and energy (6.8%), highlighting the central role of input management in shaping both productive performance and the resource-use dimension of sustainability.

Average input productivities confirm the structural heterogeneity of the sample. Labor productivity displays particularly strong positive skewness (skewness = 21.70; kurtosis = 545.80), reflecting the coexistence of highly intensive and more extensive producers. A robustness checks excluding observations above the 99th percentile in labor productivity yields efficiency scores with a Pearson correlation of 0.9968 and a Spearman rank correlation of 0.9965 ($p < 0.001$) with the baseline specification, confirming that outliers do not materially affect the frontier estimation. Most farms operate in inland hilly areas (46%), belong to medium–large economic size classes (€100,000–€500,000; 32%), and are located in North-Eastern Italy (35%). The average vineyard area exceeds the national mean (2.8 ha), likely reflecting the exclusion of small farms from the FADN sampling frame. Additionally, 27% of wineries engage in on-farm processing, indicating the presence of vertically integrated production models extending beyond primary grape cultivation.

Table 1. Descriptive statistics

Type	Variable	Description	Unit	Mean	Std. Dev.	Min	Max
Output	Grapes	Grape production	Kg.	851.32	1641.50	9	51160
Inputs	Fertilizer	Fertilizer expenditure	€	2424.67	5408.00	1	83966
	Pesticides	Pesticide expenditure	€	3845.51	6960.88	19	97560
	Land	Agricultural area	Ha.	9.06	13.52	1.36	277.17
	Labor	Labor costs	€	19345.76	33805.46	80	672000
	Energy	Energy costs	€	1114.22	4470.69	1	58072
Inefficiency determinants	Organic	Organic certification	Dummy	0.19	0.39	0	1
	Female	Female farmer	Dummy	0.23	0.42	0	1
	Diversified	Farms undertaking income diversification activities outside primary agricultural production (e.g., agritourism)	Dummy	0.15	0.36	0	1
	Young	Young farmer	Dummy	0.11	0.32	0	1
	AEC	Farms receiving payments under agro-climatic-environmental measures	Dummy	0.21	0.41	0	1
	ToxicShare	Share of expenditure on pesticides classified as toxic relative to total pesticide expenditure	Proportion	0.24	0.39	0	1
	Processing	On-farm processing	Dummy	0.27	0.44	0	1
	Altitude						
	Hills inland	Farms located in inland hilly areas	Dummy	0.46	0.50	0	1
	Hills coastal	Farms located in coastal hilly areas	Dummy	0.12	0.33	0	1
	Mountains	Farms located in mountainous areas	Dummy	0.13	0.34	0	1
	Plains	Farms located in plain areas	Dummy	0.29	0.45	0	1
	Economic size						
	[8k–25k)	Standard Output €8,000–25,000	Dummy	0.14	0.34	0	1
	[25k–50k)	Standard Output €25,000–50,000	Dummy	0.24	0.43	0	1
	[50k–100k)	Standard Output €50,000–100,000	Dummy	0.27	0.45	0	1
	[100k–500k)	Standard Output €100,000–500,000	Dummy	0.32	0.47	0	1

Type	Variable	Description	Unit	Mean	Std. Dev.	Min	Max
	≥ 500k	Standard Output ≥ €500,000					
	Geographic location						
	Centre	Farms located in Central Italy	Dummy	0.15	0.36	0	1
	Islands	Farms located in Italian island regions	Dummy	0.10	0.30	0	1
	South	Farms located in Southern Italy	Dummy	0.20	0.40	0	1
	North-West	Farms located in North-Western Italy	Dummy	0.20	0.40	0	1
	North-East	Farms located in North-Eastern Italy	Dummy	0.35	0.48	0	1

Notes: All dummy variables take value 1 if the condition holds and 0 otherwise.

4.2. Stochastic frontier results

The stochastic frontier estimates reveal considerable heterogeneity in technical efficiency among Italian quality-oriented wineries, confirming that farms in the sample are inefficient (Table 2). Likelihood ratio tests confirm that the Translog form (LR chi2(15) = 130.52) is appropriate and that inefficiency effects are statistically significant (LR chi2(19) = 384.57). Moreover, the lambda parameter is significantly different from zero, indicating that deviations from the frontier are predominantly attributable to inefficiency rather than stochastic noise. The Translog specification uses logarithmic transformations of the continuous production-frontier variables for both econometric and interpretative reasons: it linearizes the multiplicative relationships between inputs and output, stabilizes variance across observations, and reduces the influence of extreme values, while yielding coefficients interpretable as output elasticities.

Geographical conditions, such as regional location and altitude are significantly associated with efficiency differentials, reflecting differences in agro-climatic conditions and territorial contexts [18]. Farm size is also significantly associated with efficiency differentials.

In terms of Utilised Agricultural Area (UAA) classes, average efficiency scores range from 0.67 (<5 ha) to 0.68 (5-15 ha), 0.65 (15-40 ha) and 0.63 (>40 ha), which suggests the importance of also considering the capital value and technological endowment (e.g., technological status) of the farm[1]. Furthermore, operating in the Southern and North Eastern regions of Italy has a positive effect on efficiency, although the use of monetary units for production variables may partly reflect regional differences in input prices.

Table 2. Stochastic Frontier Analysis (SFA) results

Variable	Frontier Coefficient (β)	Std. Err.	p-value	Inefficiency Coefficient (δ)	Std. Err.	p-value
ln(Fertilizers)	-0.013	0.041	0.750	–	–	–
ln(Pesticides)	0.341	0.099	0.001	–	–	–

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[1] Performing an auxiliary regression with UAA classes instead of Economic size does not report statistically significant effects of the former on inefficiency.

Variable	**Frontier Coefficient (β)**	**Std. Err.**	**p-value**	**Inefficiency Coefficient (δ)**	**Std. Err.**	**p-value**
ln(Land)	1.092	0.172	0.000	–	–	–
ln(Labor)	0.004	0.090	0.964	–	–	–
ln(Energy)	0.096	0.030	0.001	–	–	–
ln(Fertilizers) × ln(Pesticides)	0.005	0.008	0.565	–	–	–
ln(Fertilizers) × ln(Land)	-0.014	0.014	0.326	–	–	–
ln(Fertilizers) × ln(Labor)	-0.009	0.010	0.351	–	–	–
ln(Fertilizers) × ln(Energy)	-0.004	0.003	0.109	–	–	–
ln(Pesticides) × ln(Land)	-0.011	0.039	0.771	–	–	–
ln(Pesticides) × ln(Labor)	-0.041	0.020	0.038	–	–	–
ln(Pesticides) × ln(Energy)	-0.021	0.006	0.001	–	–	–
ln(Land) × ln(Labor)	0.066	0.037	0.073	–	–	–
ln(Land) × ln(Energy)	0.048	0.011	0.000	–	–	–
ln(Labor) × ln(Energy)	-0.012	0.006	0.062	–	–	–
ln(Fertilizers²)	0.022	0.004	0.000	–	–	–
ln(Pesticides²)	0.003	0.014	0.835	–	–	–
ln(Land²)	-0.203	0.043	0.000	–	–	–
ln(Labor²)	0.014	0.010	0.179	–	–	–
ln(Energy²)	0.001	0.003	0.682	–	–	–
Organic	–	–	–	0.194	0.076	0.011
Female	–	–	–	0.016	0.066	0.803
Diversified	–	–	–	0.224	0.075	0.003
Young	–	–	–	-0.056	0.085	0.509
AEC	–	–	–	-0.166	0.079	0.036
ToxicShare	–	–	–	0.068	0.071	0.340
Processing	–	–	–	0.717	0.091	0.000
Alt_hills_inland	–	–	–	0.220	0.085	0.010
Alt_hills_coastal	–	–	–	-0.293	0.126	0.020
Alt_mountains	–	–	–	0.070	0.115	0.543
EconSize [25–50k)	–	–	–	-0.271	0.099	0.006
EconSize [50–100k)	–	–	–	-0.372	0.113	0.001
EconSize [100–500k)	–	–	–	-0.465	0.128	0.000
EconSize ≥ 500k	–	–	–	-0.581	0.222	0.009
Reg_Islands	–	–	–	-0.146	0.117	0.211
Reg_South	–	–	–	-0.877	0.148	0.000
Reg_NW	–	–	–	-0.035	0.085	0.683
Reg_NE	–	–	–	-0.724	0.118	0.000
Year	–	–	–	-0.029	0.055	0.597
Constant	2.498	0.537	0.000	0.228	0.173	0.188
Log-likelihood			-923.641			

The Translog production frontier reveals a technology structure in which land is the dominant input (β = 1.092, $p < 0.001$), confirming vineyard area as the primary determinant of grape output among Italian GI producers. The negative and highly significant squared term for land ($\beta = -0.203$, $p < 0.001$) indicates diminishing marginal returns as farm size increases. Pesticide expenditure is the second most influential input ($\beta = 0.341$, $p < 0.001$), while energy contributes modestly but significantly ($\beta = 0.096$, $p < 0.001$). Fertilizer and labor expenditures are not statistically significant at the first-order level. Among the squared terms, only that of fertilizers is significant ($\beta = 0.022$, $p < 0.001$), indicating a non-linear effect. Among interaction terms, pesticides × labor ($\beta = -0.041$, $p = 0.038$) and pesticides × energy ($\beta = -0.021$, $p < 0.001$) are negative and significant, indicating substitutability between chemical inputs and both labor-intensive and energy-efficient practices. Land × energy ($\beta = 0.048$, $p < 0.001$) is positive and significant, reflecting complementarity between farm scale and mechanized operations. Labor × energy ($\beta = -0.012$, $p = 0.062$) is marginally significant and negative. The sum of first-order coefficients implies increasing returns to scale at the sample mean (≈ 1.52), moderated by the concavity of the land response at higher acreage levels. Turning to the inefficiency equation, on-farm processing exhibits the largest positive coefficient ($\delta = 0.717$, $p < 0.001$), followed by diversification ($\delta = 0.224$, $p = 0.003$) and organic certification ($\delta = 0.194$, $p = 0.011$). AEC scheme participation is the only sustainability-related variable associated with reduced inefficiency ($\delta = -0.166$, $p = 0.036$). Economic size displays a monotonic efficiency gradient, from $\delta = -0.271$ for the [25k–50k) class to $\delta = -0.581$ for farms exceeding €500,000 in Standard Output (all significant at $p < 0.01$). Among regional dummies, South ($\delta = -0.877$, $p < 0.001$) and North-East ($\delta = -0.724$, $p < 0.001$) are significantly more efficient than the reference group. Coastal hilly areas are associated with lower inefficiency ($\delta = -0.293$, $p = 0.020$) while inland hills show higher inefficiency ($\delta = 0.220$, $p = 0.010$). Demographic variables (Female, Young), ToxicShare, mountainous altitude, and most regional dummies are not statistically significant.

Evidence from the Mann–Whitney test (Table 3) reveals significant differences between wineries engaged in on-farm processing and those specializing exclusively in grape production. Transforming wineries exhibit lower technical efficiency while simultaneously displaying stronger sustainability profiles, as reflected in higher adoption rates of organic certification and diversification strategies. By contrast, demographic characteristics such as farmer age and gender do not exert a statistically significant influence on efficiency, nor does the share of toxic pesticides in total expenditure. Participation in AEC schemes is associated with improved efficiency, although the effect remains only marginally significant (5% level) and should therefore be interpreted with caution pending further investigation of the specific measures involved.

Table 3. Means, standard deviation and Mann-Whitney statistics for social and environmental sustainability variables.

	Transformation_No (N=1499)		**Transformation_Yes** (N=545)		**Mann—Whitney z**	**P-value**
	Mean	St.Dev.	Mean	St.Dev.		
Organic	0.15	0.36	0.30	0.46	-7.34	0.00
Female	0.22	0.41	0.25	0.44	-1.57	0.12
Diversified	0.09	0.29	0.31	0.46	-11.87	0.00
Young	0.11	0.31	0.13	0.33	-1.20	0.23
AEC	0.20	0.40	0.23	0.42	-1.72	0.09
ToxicShare	0.23	0.39	0.26	0.42	-0.89	0.38
Efficiency	0.72	0.17	0.53	0.20	18.02	0.00

Overall, the results point to systematic differences between specialized and vertically integrated wineries. While grape-focused farms achieve higher efficiency levels, transforming wineries exhibit stronger environmental and organizational orientations, suggesting the presence of short-run trade-offs between technical efficiency and broader sustainability strategies.

5. Discussion

The wine sector represents a particularly relevant context for sustainability analysis, given its strong interdependence between economic performance, environmental stewardship, organizational complexity, and social value creation [2], [49].

This study provides empirical evidence on how economic, environmental, and social dimensions of sustainability coexist and interact within Italian wineries. By adopting an SFA framework, the analysis highlights the role of structural, organizational, and territorial factors in shaping heterogeneous sustainability pathways across firms. Given the static and short-term nature of the empirical setting, the analysis does not capture longer-term dynamics, such as gradual technological change or the evolving impacts of climate change [50]. Interpreting the estimates through the lens of organizational adaptation provides several insights into how sustainability-oriented strategies interact with productive performance in quality-differentiated wine systems.

In what follows, results are discussed according to the three main dimensions included in the inefficiency model: social and structural factors, environmental strategies, and value chain transformation.

5.1.Social and structural factors

From a structural perspective, the prominent role of economic size reinforces the interpretation of efficiency as structurally embedded within firms' organizational capacity [51], [52]. Wineries that invest the most in their growth, anticipate future challenges and interact with interest groups are more likely to be inclined towards adopting sustainability measures [53]. Larger wineries tend to benefit from greater organizational capacity, which supports more efficient resource allocation, investment in innovative technologies, and the integration of sustainability practices into production decisions [1]. These capabilities may facilitate the adoption of sustainability-oriented strategies that require upfront investments and more complex organizational structures.

Territorial conditions further reinforce the interpretation of efficiency as context dependent. Geographical location and altitude capture heterogeneous agro-climatic and institutional conditions that shape production practices and adaptation strategies [54]. In this regard, high-altitude viticulture is often associated with environmental benefits and ecosystem services, while lowland areas tend to be more oriented toward intensive production systems [14], [55]. The strong regional effects, particularly the efficiency advantage of Southern and North-Eastern producers, likely reflect differences in production system specialization, input market organization, and territorial infrastructure [56], [57]. The efficiency advantage of coastal hilly areas over inland zones reflects more favorable microclimatic conditions for viticulture.

The use of monetary input values may partly reflect regional differences in price levels, notably lower costs of goods and services in Southern Italy, which could reduce measured input expenditure and improve apparent efficiency. Furthermore, southern GI wine systems tend to be characterized by higher degrees of production specialization, warmer and more stable climatic conditions that reduce weather-related output variability, and in several appellations, lower yield restrictions compared to Northern GI disciplinaries [57]. Disentangling price effects from genuine technological advantages would require input quantity data, and we acknowledge this as a limitation of the current analysis.

5.2.Environmental strategies

The negative and significant interaction term between pesticides and labor in the estimated frontier provides a technological foundation for interpreting the inefficiency results. Farms adopting labor-intensive vineyard management, as is common among organic producers, face a technology that trades chemical input reductions against higher labor requirements, without a proportional output gain [58]. This pattern is economically coherent and consistent with production theory: the higher inefficiency associated with organic certification reflects the productive cost of operating under binding chemical-input restrictions rather than any intrinsic managerial or technological deficiency. Similarly, the negative interaction between pesticides and energy suggests that farms investing in precision or energy-efficient technologies progressively reduce their reliance on chemical inputs, a pattern consistent with the long-term logic of integrated production systems even if not fully captured by static efficiency scores [59].

Sustainability-oriented strategies are understood as additional constraints imposed on the production problem [40]. Wineries adopting organic certification or participating in AEC schemes operate under binding restrictions on input use, notably chemical inputs, that shift their production possibilities relative to unconstrained producers. Within a static SFA framework, the resulting efficiency gap between organic and non-organic producers is therefore an expected and economically coherent outcome, not necessarily a signal of suboptimal management. The observed inefficiency reflects the cost of the constraint, not the failure of the strategy.

The positive association between AEC participation and efficiency is particularly relevant from a policy perspective. AEC payments function as a compensation mechanism for the efficiency costs associated with greener production practices, contributing to the provision of environmental public goods and reinforcing the social legitimacy of wine producers in responding to societal expectations for environmental responsibility [60]. Investments related to organic certification and diversification do not automatically translate into immediate efficiency gains and often require complementary capabilities to become effective [61]. Overall, the direction of the two coefficients, i.e., positive for organic certification and negative for AEC participation, suggests that current payment levels only partially offset the productive costs of organic conversion. Nonetheless, the positive association between AEC participation and lower inefficiency supports the policy rationale for maintaining and refining agri-environmental payment schemes within the post-2027 CAP framework [62].

5.3. Value chain transformation

Value-chain transformation indicators, specifically on-farm grape processing and diversification into non-agricultural activities such as agritourism are both positively and significantly associated with technical inefficiency. The processing coefficient, the largest in magnitude across all inefficiency determinants, reflects the fundamentally distinct production logic of on-farm winemaking relative to primary viticulture. Vertical integration requires capital endowments, specialized labor, and managerial capacity that are largely unrelated to the input combinations driving grape production efficiency, and whose contribution is not captured by the output variable used in the frontier estimation. This interpretation is further supported by the positive and significant complementarity between land and energy in the estimated frontier, which suggests that scale-intensive farms allocate mechanized operations predominantly toward grape production rather than downstream transformation. The lower efficiency scores of vertically integrated wineries therefore reflect a scope mismatch between the estimated frontier and the full range of activities in which their resources are deployed, rather than suboptimal vineyard management [52], [57].

Sustainability pathways are increasingly shaped by firms' positioning along the value chain [63], [53]. Production-focused wineries tend to rely on specialized and input-intensive structures aimed at maximizing short-term productive performance, whereas those engaged in transformation and diversification adopt more complex, sustainability-oriented strategies along the value chain. Although such strategies may increase organizational complexity and shift managerial attention away from core production activities in the short term, they can be interpreted as adaptive responses that enhance resilience to climatic, market, and regulatory risks. This is particularly relevant in quality wine systems, where differentiation, reputation, and risk management often generate benefits that materialize over longer horizons than those captured by static efficiency frameworks. In this regard, circular business models and sustainability-oriented management systems, including precision viticulture and smart farming, reflect a strategic shift toward data-driven and circular production processes that improve environmental performance through more selective input use, even when these benefits are not fully captured by static efficiency measures [64], [63], [49]. Consistent with existing evidence, value-added and diversification strategies may therefore contribute to more resilient development trajectories despite being associated with lower technical efficiency, reflecting the structural heterogeneity of the Italian wine sector [57], [65].

Growing demand for eco-labels and certification-related signals, together with consumers' willingness to pay price premiums for wines with environmental and social attributes, provides a market-based rationale for sustainability strategies whose benefits may not be immediately reflected in productive efficiency [66], [67]. Diversification strategies may further strengthen the territorial value of quality wine production by reinforcing linkages with tourism and local identity, thereby supporting broader sustainability objectives beyond short-term productive performance [63], [68].

6. Conclusions

This study examined how environmental and social strategies relate to technical efficiency among Italian GI grapevine producers by adopting a SFA approach. The findings reveal substantial heterogeneity in productive performance and indicate that sustainability-oriented choices may entail differentiated short-run efficiency implications depending on the strategy adopted.

First, participation in agri-environmental schemes is associated with lower inefficiency, suggesting that CAP-related measures can support sustainability transitions without compromising productive performance. Second, organic certification is linked to higher short-run inefficiency, a pattern consistent with adjustment and compliance costs rather than with structurally lower productive potential. Third, indicators of value-chain transformation, including on-farm processing and diversification into non-agricultural activities, also correlate with higher inefficiency, likely reflecting increased organizational complexity and the reallocation of resources away from core production activities during phases of strategic adaptation.

The results carry direct policy and managerial implications. Organic certification is associated with an inefficiency increase, while AEC scheme participation is associated with an inefficiency reduction, suggesting that current AEC payments only partially compensate for the productive costs imposed by organic conversion. Farms undertaking organic certification face a net efficiency penalty that existing agri-environmental payment levels may not fully absorb. Designing compensation mechanisms that are explicitly calibrated to the productive costs of organic transition would more effectively support the sustainability transition of GI wine producers while preserving their competitiveness. From a managerial standpoint, the results suggest that producers considering organic certification should anticipate short-run efficiency losses and plan accordingly, particularly in terms of labor organization and input substitution strategies.

Taken together, these findings suggest that observed inefficiencies should not be interpreted solely as indicators of suboptimal performance, but rather as manifestations of ongoing organizational and production restructuring within sustainability-oriented business models.

From a policy and value-chain perspective, the results highlight the importance of designing instruments and private standards capable of reducing transition costs while strengthening firms’ learning processes and managerial capabilities, particularly for smaller wineries and for those undertaking more complex transformation pathways. Enhancing advisory services, facilitating investment mechanisms, and tailoring agri-environmental incentives to quality/GI contexts may help align sustainability objectives with competitiveness and long-term resilience across the Italian wine value chain.

This study has several limitations. Our short-term SFA provides a snapshot of efficiency differentials but does not capture dynamic processes such as technological learning or capital accumulation; future research should adopt dynamic efficiency approaches to assess whether the observed trade-offs evolve as firms accumulate organizational and technological capabilities. The use of grape production in kilograms as output may understate the performance of quality-focused producers who intentionally restrict yields, while the use of monetary input values may introduce price-related components into the efficiency estimates. Finally, the heterogeneity in input productivity distributions suggests the presence of qualitatively distinct production clusters, whose identification represents a promising direction for future research. Notwithstanding these limitations, this study provides novel empirical evidence on the productive efficiency implications of sustainability-oriented strategies among Italian GI winegrape producers, offering actionable insights for the design of agri-environmental instruments and managerial decisions in quality wine systems.

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