Wine productive efficiency and value chain

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Abstract

The global wine industry is shifting from high-volume production to quality-focused "premiumization," creating tension between efficiency (volume per unit of input) and resource-intensive technologies (using inputs to increase quality). This paper provides an evidence-based framework to assess how value chain choices, from viticulture to bottling, influence performance across market segments. Using data from 10 countries, we apply a two-stage approach: first, we measure relative efficiency scores for Value- and Premium-specializing wineries via Data Envelopment Analysis (DEA); second, we use Simar-Wilson regression to assess the impact of several technological factors on these scores. Results show that Value wineries have 41–44% efficiency, while Premium wineries reach 50–53%, indicating more efficient resource use in higher-end firms. For Value wineries, modernization and automation boost efficiency. In Premium wineries, practices such as manual irrigation and stainless-steel aging are key. Manual harvesting decreases efficiency by up to 10.6%, confirming that a focus on quality reduces productive volume. We identified a consistent set of significant variables, with the same signs and similar absolute values, influencing efficiency across both wine types under different hypotheses about returns to scale. This study links detailed technologies to global efficiency, showing that quality investments can be managed for performance.

Keywords: Wine, Value chains, Efficiency frontiers, DEA

1. Introduction

While the global wine industry's transition from high-volume production to quality-driven "premiumization" is well documented, a crucial tension remains unresolved: the inherent trade-off between maximizing technical efficiency and achieving quality. Despite a robust body of literature applying Data Envelopment Analysis (DEA) to the wine sector, existing studies have focused predominantly on organizational forms, regional performance, or firm size, leaving a significant knowledge gap regarding the role of quality as an explicit technological driver of performance. While prior research often treats wine quality as an unobserved background variable, this study identifies a gap in the literature: the lack of evidence-based frameworks to determine how granular technological decisions throughout the value chain—such as specific training systems, maturation controls, or harvesting methods—systematically dictate a winery's distance to the efficiency frontier. We address this gap by moving beyond traditional single-country or regional benchmarks to examine a unique cross-country database of 10 wine-producing nations, explicitly distinguishing between specialized Value and Premium segments. Unlike two-stage DEA studies that often rely on potentially biased Tobit regressions, we use the advanced Simar-Wilson double-bootstrap methodology to provide statistically valid inferences on 40 technological determinants. The value added by this research lies in its ability to empirically provide a decision-support framework that justifies the resource-intensive choices required for quality-driven "premiumization" as strategic adaptations rather than operational failures.

We examine the consequences of specific technological options on efficiency at the vineyard and cellar levels. We aim to assess technical efficiency across wineries in 10 wine-producing countries and evaluate the influence of vineyard and cellar practices on that efficiency. In doing so, we employ a subsample of a comprehensive international dataset, estimate efficiency scores using Data Envelopment Analysis (DEA), and, in stage 2, address the influence of value chain choices on efficiency. We examine how these practices vary with wine quality and how they affect productive efficiency. A central finding is that several practices associated with premium production appear to reduce measured efficiency, showing a tension between quality-enhancing practices and volume-based efficiency.

The DEA method is a mathematical programming approach aimed at estimating the relative efficiency of Decision-Making Units (DMUs), in our case, wineries. It builds a frontier of real-world best practices and compares each DMU of the sample to units on the frontier. Each fully efficient unit receives a score of 1, and each relatively inefficient unit gets a score between 0 and 1. In stage 2, the stage 1 scores are regressed on exogenous explanatory variables (related to value chain choices) to assess their contribution to (in)efficiency [1] [2] [3].

Explicitly, our research questions are: 1) What determines technical efficiency across wineries producing different qualities of wine? 2) How do value chain choices affect efficiency, shifting wineries closer or further to the frontier? Moreover, 3) whether these value chain choices affect efficiency differently between value and premium wine producers?

We identified a consistent set of significant variables, with the same signs and similar absolute values, influencing efficiency across both wine types under different hypotheses about returns to scale. Our models account for approximately 80% of the variation in the efficiency of the evaluated units.

After this Introduction, section 2 analyzes the literature; section 3 presents the materials and methods (data, methodology, and models); section 4 presents the results; section 5 discusses the results; and section 6 concludes.

2. Literature review

The wine industry is currently a globalized sector characterized by increasing competition, evolving consumer preferences, and technological advancements [4]. In a globalized market with low margins and diminishing per capita consumption, identifying the specific value chain drivers of technical efficiency is key to survival. In the late 1960s, traditional European countries, known as the Old World (OW) of wine [5], began to shift their consumption patterns from quantity to quality. In the 1970s–1980s, a wave of market globalization began, quickly transforming the value chain [3]. The share of exports in global production increased from 10% in the 1960s to 15% by 1990 and to 25% by 2000. NW producers gained market share in both export volumes and values and increased quality. Foreign capital was invested in NW wineries, and experts were hired to improve NW industries [4]. The definition of wine quality evolved from terroir to consumer perception and market value [7] [8]. OW countries responded by enhancing the quality and specificity of their regional traditions (terroir) [9].

Major forces of change can be focused on scale concerns [10], climate change adaptation [11], strong branding and adaptation to market tastes, productivity and efficiency [12], quality and premiumization [10], "mega-trends" such as health, convenience, and authenticity, and offering wine as a cultural experience, a tourism destination, and a hospitality service [13].

2.1 Major forces of change

At the vineyard level, wineries evolved to produce higher-quality grapes; old vines were eradicated; vineyards expanded into new, climatically favorable zones; and climate change required adaptation. Changes include precision viticulture, organic and biodynamic farming, and other sustainable practices to reduce chemical inputs, as well as measures to mitigate climate change through variety selection, irrigation techniques, and canopy management [14].

In the winemaking process (vinification), several technological innovations have been introduced, enhancing precision, sustainability, and quality control in production. The use of temperature-controlled fermentation, stainless-steel tanks, and filtration methods; the increased application of enzymes, yeast selection, and other additives to manipulate wine characteristics; and the implementation of quality control measures and sensory evaluation are common throughout the winemaking process [15].

Wine markets have expanded due to increased global trade, online sales platforms, and wine tourism. Demand has decreased in volume but increased across diverse niches, including organic, no- or low-alcohol (NOLO), sulfite-free, and vegan wines. OW continues to dominate the premium market; however, NW producers have increased quality through innovation and gained share [8].

We examine the consequences on the efficiency levels of technological options at the vineyard and cellar levels.

2.2 Value chain options: vineyard level

We considered the following vineyard practices: planting, training systems, Canopy management, weather forecasting, Phytosanitary protection, Maturation control, Irrigation, green harvesting, Harvesting, and Ground and soil maintenance.

Regarding planting methods, manual planting requires skilled human resources. Workers can visually inspect and select the best position for each plant. Instead, the machine follows preset GPS- or laser-guided straight lines. Nevertheless, machinery may damage some root systems during insertion. The choice is essentially a trade-off between the potential for manual precision and quality and mechanical efficiency and cost reduction [16] [17].

The Cordon system trains vines horizontally along a wire and uses winter pruning, making it suitable for mechanized pruning and harvesting. It is ideal in warm, stable climates for robust varieties and high yields. The Guyot system involves yearly cane laying and removal of old wood, requires manual pruning, and is best for low- to moderate-vigor varieties in cool climates. The Gobelet system features spur-pruned, head-trained, bush-like vines that require manual harvesting, are suited to hot, dry conditions, and produce concentrated grapes with low yields. The Smart-Dyson system vertically divides the canopy, with shoots growing up and down, requires manual work, and is ideal for vigorous varieties in fertile soil to manage canopy density for high-volume wines. The Geneva double-curtain (GDC) splits the canopy horizontally with two high wires for high-volume, intermediate-quality wines. Other systems involve complex modifications to natural growth [18] [16] [17] [19]. Canopy Management alternatives include manual and mechanical methods. Manual canopy management requires a skilled labor force; it is slow but allows for precise timing of intervention. It is prioritized for premium wines and delicate varieties. Mechanical canopy management is fast and efficient. It is more appropriate when low cost and volume are prioritized, varieties are more robust and less susceptible to sunburn, and some quality dispersion is acceptable [16] [19] [18] [17].

There are several options for meteorological forecasting. An own weather forecast implies owning and operating facilities that collect hyper-local data. It requires initial investment and demands maintenance costs. It is prioritized for high-value vineyards, precision viticulture, and climates with high variability. Specialized public weather forecast focused on agricultural needs, is affordable by subscription, providing more accuracy, and aimed at mid- to high-quality wine producers who need specific data, or whose microclimate is relatively uniform. Standard Public forecasts provide free, broad regional predictions; however, the information provided may be overly general [16] [14].

Phytosanitary protection defends vineyards against pests and diseases. Conventional methods use chemical fungicides, herbicides, and insecticides, mainly in large vineyards, in humid climates, or where manual labor is unavailable. These methods affect soil biodiversity, can lead to resistance, and are heavily regulated. Sustainable and organic approaches minimize synthetic chemicals by relying on natural controls, but they increase costs. These practices are certified and favored by premium producers [16] [17] [20].

Maturation control methods determine the harvest date, crucial for wine's flavor, balance, and quality. Sugar maturation measures sugar content to predict alcohol and is prioritized across all wine types. Juice pH controls acidity; a high pH increases bacterial risk, so sulfur dioxide is added, whereas a low pH yields a brighter, more stable color, which is important for white, sparkling, and premium reds. Titratable acidity assesses tartaric and malic acids; acidity is too low if it needs to increase and too high if it needs to decrease, particularly for white and sparkling wines in hot climates. Visual and taste checks involve tasting skins, pulp, and seeds to evaluate flavor and color; they are suited to high-quality wines and require skilled labor. Organic control targets phenolic compounds, such as tannins, which are key to premium reds. Laboratory analyses ensure maximum quality, especially for premium wines [16] [15].

Irrigation strategies affect grape quantity, quality, and consistency. Non-irrigation is used for ultra-premium wines in rainy regions to ensure low yields and concentrated grapes. Manual irrigation is labor-intensive, slow, and suitable for small plots or young vines. Surface irrigation uses a lot of water and is well-suited to bulk wine production with low investment. Sprinkler irrigation mimics rainfall. Drip irrigation delivers water to vine bases via hoses, is water-efficient and inexpensive, and induces mild stress to produce consistent, high-quality fruit [16] [17].

Green harvesting involves intentionally removing unripe grape clusters to reduce the final yield after the initial fruit set. It allows the vine to allocate all its resources to the remaining selected clusters. This enhances the concentration of phenolic compounds, color, and flavor of the grapes. It is a practice that sacrifices volume for quality [16] [15].

Manual harvesting increases labor costs and is lengthier than mechanical harvesting; however, it enhances selectivity. It is prioritized for premium wines and for fragile varieties [16].

Conventional ground and soil maintenance uses synthetic herbicides and fertilizers, which ensure high yields but also cause erosion and biodiversity loss. It is prioritized for high-yield vineyards. Sustainable practices minimize chemical use, require machinery and skills, and increase costs. Organic maintenance avoids synthetic inputs, relies on mechanical weed control, cover cropping, and natural fertilizers. It produces lower yields and complex wines, targeting eco-conscious consumers [16] [19] [20] [17].

2.3 Value chain options: cellar level

We considered options for the following processes: Pressing, Malolactic fermentation, Commercial yeast, Fermentation activators, Chaptalization, Stabilization and clarification, Blending, Aging, and Capping.

Pressing separates juice from solids, such as skins, seeds, and stems, after crushing or fermentation. Screw pressing uses a vertical screw and plate to compress solids in a cage, leaving undesirable compounds that cause astringency and oxidation, making it suitable for high-volume, low-cost wines. Pneumatic pressing employs an inflatable membrane in a rotating tank, yielding less but higher-quality juice, ideal for premium wines. Other methods are slow and labor-intensive and are only suitable for small, high-quality batches [16] [15] [21].

Malolactic fermentation converts harsh-tasting malic acid into softer, buttery-tasting lactic acid, making the wine smoother and rounder. It is used in nearly all red wines to soften tannins and ensure stability, and in many premium white wines. It creates a stable, softer, more complex wine, ideal for oak-aged wines [15].

Commercial yeast inoculation of the must aims for clean fermentation results. It is prioritized for most wines. Instead, wild or native fermentation can add complexity and texture but carries a high risk and high variability [16] [15] [22].

Fermentation activators are added to the must to provide nutrients, vitamins, and minerals that support yeast health and growth. It is prioritized in wines made from machine-harvested or high-yield grapes, which can be nitrogen-deficient, and in high-alcohol wines where yeast stress is high [22].

Chaptalization is the addition of sugar to the must before or during fermentation to increase alcohol content. It is used when the wine is otherwise too thin or acidic. It is highly regulated in cool European regions or illegal in many NW regions. It can mask a lack of true phenolic or flavor ripeness [21].

Stabilization and clarification remove suspended particles. They require filters and chillers, ensure a clear appearance, and are prioritized for all commercial wines. For high-quality, age-worthy reds, minimal filtration preserves texture [16] [15].

Blending combines different wine varieties, vineyards, barrels, or vintages to compensate for weaker parcels or vintages. It can correct flaws and add complexity, structure, and balance. It is prioritized for all fine wines, especially those with an origin denomination [16].

Aging affects wine's flavor, texture, stability, and longevity. No aging lowers inventory costs, suitable for inexpensive, high-volume whites and rosé. Steel tanks, costly initially, ensure hygiene, reduce labor, prevent oxidation, and preserve fruit and acidity, making them ideal for crisp whites, aromatic varieties, and rosé. Bottle aging requires space and capital, develops complex aromas, and softens tannins; it is suited to high-quality reds and sparkling wines. Oak aging, which demands high initial costs, favors French oak for premium wines and American oak for bolder ones. Cement tanks are costly but durable, with slow oxygen ingress and natural lees stirring for modern, high-quality wines. Adding oak staves, chips, or powder to tanks imparts flavor for high-volume wines [16], [15].

The choice of closure influences a wine's aging, oxidation, risk of cork taint, and appeal. Natural cork allows oxygen to flow, creating complex aromas, and is considered a quality. Technical cork, made from molded granules, resembles natural cork and reduces the risk of cork taint in mid-range wines. Synthetic corks, plastic-based, look like cork but can cause quick oxidation, suitable for high-volume, short-term wines. Screwcaps and aluminum seals preserve freshness and aroma, making them ideal for aromatic whites, rosé, and early-drinking wines. Vino seals and glass stoppers are ideal for high-quality, fresh wines. Other options include synthetic closures for premium aromatic wines [16].

2.4 Efficiency studies with DEA methodology

We identified 13 DEA-based comparative efficiency studies in the wine industry that use both cross-sectional and panel data to compare characteristics such as scale, region, origin, organizational form, technological choices, innovation systems, and economies of scope. Efficiency studies should compare similar wineries, examining whether efficiency differences stem from input management or from environmental factors such as production scale, soil, climate, or stimuli from different business types. Recent research gaps include the impact of quality on efficiency and cross-country comparisons, which are scarce. Since wine quality varies, efficiency analysis needs to account for differentiation, and our estimates compare wineries that produce wines of similar quality across countries while accounting for each country's unique context.

[23] studied 27 Portuguese wineries (1996-2000), finding cooperatives typically more efficient than private firms. Our sample has about 10% cooperatives and 90% corporations, examining technological choices beyond legal forms. [24] analyzed 87 wineries in Navarra and Rioja (2001), noting that conventional wineries were more efficient than organic ones, which are more common in premium wines. We compare the effects of these technological options on efficiency. [25] studied 300 Macedonian farms (2006–2008), finding that less diversified farms are more efficient; we explore this in another study. [26] examined 34 Spanish DOs (2008–2010), finding that larger DOs are less efficient, but this does not control for our survey. [27] studied 24 Spanish DOs, identifying technical inefficiency as primary. [28] Moreover, [29] assessed efficiency in Ukraine, Bosnia, and internationally, finding that efficiency varies with size and location, with the highest efficiencies in Germany, the US, and New Zealand. Our study models returns to scale and finds that few wineries operate at their optimal scale, yet results show a high correlation. [9] analyzed Portuguese regions (1989–2007), noting stable efficiency. [30] studied 36 German and Ukrainian wineries (2014), identifying optimal size and legal form. [31] (Douro, Portugal, 2016–2017) found that size positively affects efficiency, with technological choices playing a role. [32] looked at Italian farms (2005, 2010), noting that larger firms and those producing wine and grapes are more efficient. Our sample includes vertically integrated wineries, not exclusive grape or wine producers. [33] examined innovation systems across 35 countries (2016–2019), finding positive effects and top performers like New Zealand, Chile, and Italy. [34] evaluated Brazilian grape production efficiency (2017), finding farm size a key factor. Our analysis estimates efficiency scores per winery and regresses them on quality proxies using the Simar-Wilson method.

Summarizing this section, there is a gap on the literature related to efficiency of wineries estimated by DEA addressing quality; cross-country DEA efficiency studies are rare in the literature, where normally they concentrate on specific countries or regions; value chain decisions influencing efficiency are almost inexistent, and when two-stages DEA is used, the method for the second stage (Tobit regression) is not worthwhile in the extant literature. We employ the more advanced Simar-Wilson methodology.

2.5 Summary of the literature review implications

The global wine value chain is shifting from a traditional, producer-driven model to a knowledge-based, market-driven one in which economic, environmental, and cultural factors are increasingly interlinked. The literature suggests that the technological choices made by wineries—ranging from high-precision mechanization to heritage-based winemaking—are not merely operational decisions but strategic responses to an increasingly complex value chain. Wineries do not simply fail to be efficient; they choose to be "inefficient" to create strategic value. We can analytically frame the sacrifice of technical efficiency (volume) as a deliberate and necessary investment in vertical differentiation. This dialogue between economic viability and quality attributes is further enriched by considering the industry's evolution from historically rooted, supplier-driven models to the market-driven frameworks described in [8]. Indeed, [8] see the New World's success as driven by technological modernization and standardization, while critics argue this risks homogenizing taste and eroding cultural heritage. However, these views converge: New World producers adopt territorial valorization through geographical indications, and European producers adopt scientific codification and economies of scale to stay competitive. This economic shift is tied to environmental goals; [24] note that organic and sustainable practices improve efficiency and fetch premiums from eco-conscious consumers. Technologies like precision viticulture and GIS boost environmental resilience by optimizing water use and reducing chemical inputs amid climate change, enabling the preservation of traditional varieties linked to terroir and regional stability. Integrated Territory Management (ITM) turns territories into systems in which cultural and landscape values add intangible value. Finally, consumers now seek experiences blending sensory pleasure with local heritage, turning geographical indications into place-based brands that foster loyalty. These technological descriptive aspects directly affect environmental viability, particularly as firms navigate the short-run efficiency penalties associated with organic and sustainability certifications to secure long-term market access. Furthermore, these practices serve as vital mechanisms for cultural recovery and territorial valorization, where the preservation of the terroir becomes a strategic lever rather than a static inheritance. For Geographical Indication (GI) systems, these integrated elements transform the production chain into a repository of "experiential authority" and local savvy, ensuring that the unique landscape and traditional knowledge add significant value that transcends mere volume-based productivity. Thus, this study addresses a persistent gap by exploring how these diverse drivers collectively dictate a winery's position on the global efficiency frontier while reinforcing its territorial identity.

The positioning of the wine sector within existing Data Envelopment Analysis (DEA) research in agriculture implicitly registers the tension between production efficiency (volume) and product quality (value). While standard agricultural efficiency studies often equate technical success with maximizing physical output, such as tons per hectare, the wine industry challenges this paradigm by treating efficiency and quality not as conflicting goals but as interdependent strategic choices [28]. This shifts away from volume-based DEA toward revenue-oriented models that can account for the "quality-quantity tradeoff" inherent in the sector [27]. For instance, manual harvesting and selective canopy management, while reducing physical volume efficiency, are essential for maintaining the premium status that commands higher price points. Research by [25] highlights that the choice of grape variety (assortment) is a primary determinant of farm efficiency, suggesting that the ability to align local resources with global demand for "value" is the hallmark of an efficient winery. Moreover, while some agricultural sectors prioritize economies of scale to survive on low margins [23], the wine sector shows that scale efficiency is often high across all groups, meaning that future competitiveness stems from internal technological optimization rather than simple extension. The New World's success is theoretically framed as a "scientific approach" to production that codified winemaking practices to ensure consistent quality, allowing latecomers to catch up to traditional leaders who relied on historically protected but often less efficient exploitations [8].

3. Materials and Methods

3.1 Material: Data

Our study uses data from a large-scale international survey of wineries. The database was constructed from a study of nearly 5,300 wineries across 23 countries, conducted between 2019 and 2021, as described in detail in [13].

For the specific purposes of this study on production efficiency, we use a subsample covering ten representative wine-producing countries: five from the Old World (France, Spain, Italy, Germany, and Portugal), and five from the New World (South Africa, Chile, Argentina, Brazil, and Uruguay), each winery (DMU) specializing in one type of wine: value (price under US$ 10) and premium (US$ 10 < Price < US$ 40). Unfortunately, the study omits leading producers such as the United States, which casts doubt on the generalizability of the findings. The reason is the absence of a representative sample in the United States.

The inputs considered are land, grape, labor, and capital (an index obtained from Principal Component Analysis of 18 dummy variables denoting possession of key capital goods). The use of a capital index derived from Principal Component Analysis (PCA) of 18 binary variables is a limitation of the study. Binary variables cannot capture the actual intensity, age, or capacity of capital, potentially biasing the first-stage efficiency scores. However, we do not have access to a more accurate measure of the capital factor. Table 1 defines the variables used in the DEA estimates.

Table 1: Definition of the variables for DEA estimates.

Variable	Definition	Type	Unit
DMU	Winery	Decision-Making Unit	Code to preserve the anonymity of answers
QValue	Value wine production	Output	Liters
QPremium	Premium wine production	Output	Liters
Surface	Vineyard surface	Input	Hectares
Grape	Grape production	Input	Tons
Capital	Capital Index	Input	Index
Employees	Labor force	Input	Persons

In Table 2, we present descriptive statistics for the outputs and inputs of both wine categories. Wineries specialized in premium wines are smaller, using more land and fewer grape kilograms per unit of wine produced, and are relatively more intensive in capital and labor per liter of wine than value wine producers.

Table 2: Descriptive statistics of outputs and inputs.

	Value	N = 540			Premium	N = 709		
Variable	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max
Qvalue	267580	684991	1000	6500000				
Qpremium					62638	79165	1000	507000
Grape	503946	2621410	1050	57000000	111333	138177	2400	1400000
Surface	46	120	0.3	1570	16	20	1	140
Capital	7.7	1.7	0.3	11.4	7.4	1.7	0.3	11.2
Employees	14	22	1	265	15	18	1	237

The mean winery specializing in value wine produces more volume, with more grapes per unit of wine, on larger surfaces, with almost the same capital, and with slightly less personnel than wineries specializing in premium wines.

3.2 The Data Envelopment Analysis Method

Data Envelopment Analysis (DEA) is a non-parametric method for measuring the relative efficiency of Decision-Making Units (DMUs) by using mathematical programming to estimate efficiency frontiers. DEA evaluates each DMU individually by comparing its input-output bundle to an empirical frontier constructed from the best-performing units in the sample. The two primary models are CCR [35], which assumes constant returns to scale (CRS) globally, and BCC [36], which allows for variable returns to scale (VRS).

An alternative to DEA is the parametric Stochastic Frontier Analysis (SFA). Unlike DEA, SFA assumes a functional relationship between variables and can handle multiple inputs and outputs simultaneously without aggregating outputs. DEA finds specific "best-practice" units for each inefficient unit to emulate, while SFA identifies an average trend. In DEA, input weights are determined from the data, letting DMUs choose weights to maximize efficiency. Basic DEA does not account for measurement error; deviations are treated as inefficiencies, and outliers can skew scores. DEA is non-statistical, lacking standard errors or hypothesis testing unless bolstered with techniques such as bootstrapping. Its discrimination ability decreases as inputs and outputs grow relative to the sample size, and, being nonparametric, it does not estimate marginal products or elasticities [1].

This text explains how environmental factors affect efficiency, using a two-stage process: first, via DEA with discretionary inputs and outputs; then, via regression with these scores as dependent variables and suspected influencing factors as independent variables. Since efficiency scores are capped at 1, a Tobit regression is typically used, but standard results may be invalid due to serial correlation in DEA estimates. To address this, a double bootstrap method (Simar-Wilson) is recommended for valid confidence intervals, involving radial efficiency measures, truncated regression, simulation of error correlation, and bootstrap error estimation [2] [3].

3.3 Models

We estimate two efficiency frontiers (CRS and VRS) for each quality level (Value and Premium), with wine production as the output and surface area, grapes, capital, and labor as inputs. Under DEA, models are either output- or input-oriented. In utility sectors, models are typically input-oriented: given an output, how can DMUs reduce inputs to increase efficiency? In wineries, models are output-oriented: given inputs, how can DMUs increase production? All models here are output-oriented. Higher-quality wines often reduce volume, while cheap wines aim for volume at a set quality. In the second stage, we analyze how vineyard and cellar practices affect efficiency.

In BOX 1, we present the variables we test in the second stage. Because efficiency is understood as higher volumes per output unit, practices that trade off quantity for quality (or, equivalently, consume more input units per output unit) are expected to have ≤ 0 signs. Emphasis is expected to differ across wine qualities. We also included country dummies to control for differences attributable to institutional, climatic, historical, and other factors.

BOX 1: Value chain options to test as determinants of efficiency scores

Practices	Variables (hypothesis)	Omitted category
Planting	Manual (≤ 0)	Mechanical

Training system	Cordon (≥ 0)	Guyot (≤ 0)	Gobelet (≤ 0)	Smart-Dyson (≥ 0)	Geneva double curtain (≥ 0)	Other
Canopy management	Manual (≤ 0)					Mechanical
Weather forecast	Own (≤ 0)	Specialized (≥ 0)	General (≥ 0)			No need
Phytosanitary protection	Conventional (≥ 0)	Sustainable (≤ 0)	Organic (≤ 0)			No need
Maturation control	Sugar (≥ 0)	Juice pH (≤ 0)	Titratable acidity (≤ 0)	Visual and taste (≤ 0)		Other
Irrigation	None (≤ 0)	Manual (≤ 0)	Surface (≥ 0)	Sprinkler (≥ 0)	Drip (≤ 0)	Other
Green harvest	Green harvest (≤ 0)					Not applied
Harvesting	Manual (≤ 0)					Mechanical
Ground and soil maintenance	Conventional (≥ 0)					Sustainable or organic
Pressing	Screw (≥ 0)	Pneumatic (≤ 0)				Other
Malolactic fermentation	Malolactic fermentation (≤ 0)					Not applied.
Commercial yeast	Commercial yeast (≥ 0)					Not applied.
Fermentation activators	Fermentation activators (≥ 0)					Not applied.
Chaptalization	Chaptalization (≥ 0)					Not applied
Stabilization and clarification	Stabilization and clarification (≥ 0)					Not applied
Blending	Blending (≤ 0)					Not applied
Aging	No aging (≥ 0)	Stainless steel vats (≥ 0)	French or American oak (≤ 0)	Cement vats (≤ 0)	Bottle (≤ 0)	Other
Capping	Natural cork (≤ 0)	Technical cork (≥ 0)	Synthetic cork (≥ 0)	Screw caps (≥ 0)	Vino seal (≤ 0)	Other

The average efficiency scores for Value wines are 0.41 and 0.44 under CRS and VRS, respectively. In contrast, for Premium wines, the average efficiency is 0.50 under CRS and 0.53 under VRS, respectively, and the dispersion of results is lower under VRS. Both models are highly correlated (91% for value wines and 94% for premium wines).

We also estimate scale efficiency (CRS/VRS), yielding 0.94 for Value wines and 0.96 for Premium wines. Those scores indicate that, on average, units are scale-inefficient by 6% and 4%, respectively; however, it is not clear whether economies or diseconomies of scale predominate.

4. Results

Table 3 presents the results of the four models: Value wines (CRS and VRS) and Premium wines (CRS and VRS).

Table 3: Second Stage Estimates (Simar-Wilson method applied on Value wines under CRS and VRS assumptions, and on Premium wines under CRS and VRS assumptions)

Dependent	Veffcrs5	N = 525	Veffvrs5	N = 520
Efficient DMUs	VALUE (CRS)	15	VALUE (VRS)	31
Bootstraps replic.		1000		1000
Wald chi2(49)		121.9		109.89

Prob > chi2(49)				0					0	
	Coeff.	Bootstrap SE	z	P>0		Coeff.	Bootstrap SE	z	P>0	
Manual planting	-0.002	0.027	-0.07	0.94		0.025	0.029	0.87	0.39	
Cordon	-0.013	0.025	-0.52	0.61		-0.033	0.025	-1.3	0.19	
Guyot	0.014	0.025	0.56	0.58		-0.007	0.027	-0.26	0.79	
Gobelet	0.057	0.031	1.8	0.07	*	0.05	0.032	1.54	0.12	
Smart-Dyson	-0.013	0.05	-0.25	0.8		-0.005	0.052	-0.09	0.93	
Geneva double	-0.062	0.058	-1.07	0.29		-0.045	0.059	-0.76	0.45	
Manual canopy	-0.062	0.031	-1.99	0.05	**	-0.072	0.031	-2.29	0.02	**
Own weather	0.077	0.032	2.38	0.02	**	0.077	0.035	2.22	0.03	**
Specialized weath	0.002	0.025	0.08	0.94		-0.005	0.026	-0.18	0.86	
General weather	0.037	0.023	1.61	0.11		0.044	0.024	1.84	0.07	*
Conv. phyto.	0.032	0.028	1.13	0.26		0.047	0.03	1.57	0.12	
Sugar	-0.01	0.038	-0.25	0.8		0.003	0.04	0.07	0.95	
Juice pH	-0.002	0.024	-0.09	0.93		0	0.025	0.01	0.99	
Titratable acid	0.036	0.024	1.53	0.13		0.035	0.024	1.48	0.14	
Visual and taste	0.012	0.022	0.54	0.59		0.003	0.023	0.12	0.91	
Manual irrigation	0.007	0.063	0.1	0.92		0.008	0.062	0.13	0.9	
Surface irrigation	0.09	0.049	1.82	0.07	*	0.103	0.049	2.09	0.04	**
Sprinkler irrig.	0.01	0.04	0.26	0.79		0.023	0.042	0.53	0.59	
Drip irrigation	0.093	0.023	4	0	***	0.084	0.024	3.45	0	***
Other irrigation	-0.02	0.073	-0.27	0.78		-0.02	0.076	-0.26	0.79	
Manual harvest	-0.082	0.031	-2.68	0.01	***	-0.1	0.032	-3.13	0	***
Conventional soil	-0.035	0.028	-1.24	0.21		-0.035	0.029	-1.21	0.23	
Screw pressing	0.044	0.039	1.13	0.26		0.038	0.039	0.99	0.32	
Pneumatic press.	0.066	0.038	1.73	0.08	*	0.066	0.038	1.73	0.08	*
Malolactic	-0.005	0.026	-0.18	0.85		0.027	0.025	1.07	0.28	
Commercial yeast	0.035	0.029	1.22	0.22		0.026	0.031	0.84	0.4	
Fermentation act.	-0.04	0.025	-1.61	0.11		-0.063	0.027	-2.35	0.02	**
Chaptalization	0.064	0.041	1.58	0.12		0.05	0.044	1.14	0.25	
Stab. and clar.	0.027	0.028	0.97	0.33		0.032	0.029	1.09	0.28	
Blending	0.012	0.023	0.55	0.58		0.004	0.023	0.19	0.85	
Steel aging	0.008	0.023	0.36	0.72		0.004	0.024	0.18	0.86	
Cement aging	0.016	0.027	0.59	0.56		0	0.027	0.01	1	
Bottle aging	-0.02	0.024	-0.83	0.41		-0.022	0.024	-0.93	0.35	
Other aging	-0.088	0.075	-1.18	0.24		-0.048	0.071	-0.67	0.5	
Natural cork	0.014	0.03	0.46	0.64		0.032	0.032	1.02	0.31	
Technical cork	0.012	0.026	0.46	0.65		0.036	0.027	1.36	0.17	
Synthetic cork	0.023	0.03	0.77	0.44		0.036	0.03	1.21	0.23	
Screw caps	0.028	0.031	0.89	0.38		0.037	0.032	1.13	0.26	
Vino seal	0.152	0.072	2.11	0.04	**	0.199	0.073	2.73	0.01	***
French or Am Oak	-0.012	0.023	-0.52	0.6		-0.013	0.023	-0.56	0.57	
Spain	0.071	0.049	1.47	0.14		0.054	0.047	1.15	0.25	
Italy	0.092	0.039	2.38	0.02	**	0.088	0.04	2.2	0.03	**
South Africa	-0.217	0.098	-2.22	0.03	**	-0.252	0.095	-2.64	0.01	***
Chile	0.012	0.074	0.17	0.87		0.009	0.073	0.12	0.91	

Argentina	0.008	0.066	0.12	0.91		0.007	0.068	0.1	0.92	
Brazil	-0.031	0.127	-0.25	0.81		-0.077	0.136	-0.57	0.57	
Uruguay	0.43	0.115	3.73	0	***	0.433	0.122	3.54	0	***
Germany	-0.02	0.059	-0.33	0.74		-0.008	0.063	-0.12	0.9	
Portugal	-0.098	0.06	-1.64	0.1	*	-0.095	0.059	-1.6	0.11	
Constant	0.242	0.076	3.16	0	***	0.257	0.079	3.24	0	***
Sigma	0.196	0.008	25.56	0	***	0.199	0.008	25.47	0	***
Dependent	Peffcrs5	N = 686				Peffvrs5	N = 660			
Efficient DMUs	PREMIUM (CRS)			23		PREMIUM (VRS)			49	
Bootstraps replic.				1000					1000	
Wald chi2(49)				123.1					110.66	
Prob > chi2(49)				0					0.0001	
	Coeff.	Bootstrap SE	z	P>0		Coeff.	Bootstrap SE	z	P>0	
Manual planting	-0.003	0.027	-0.13	0.9		0.011	0.028	0.38	0.71	
Cordon	-0.024	0.021	-1.15	0.25		-0.03	0.022	-1.39	0.17	
Guyot	0.012	0.023	0.52	0.6		0.012	0.023	0.53	0.59	
Gobelet	-0.042	0.025	-1.68	0.09	*	-0.047	0.026	-1.82	0.07	*
Smart-Dyson	0.053	0.136	0.39	0.7		-0.065	0.172	-0.38	0.71	
Geneva double	-0.082	0.145	-0.56	0.57		-0.082	0.145	-0.57	0.57	
Manual canopy	-0.008	0.03	-0.26	0.79		-0.014	0.031	-0.46	0.64	
Own weather	0.013	0.027	0.48	0.63		0.002	0.028	0.08	0.94	
Specialized weath	-0.024	0.022	-1.08	0.28		-0.026	0.023	-1.09	0.27	
General weather	-0.022	0.021	-1.05	0.29		-0.021	0.022	-0.95	0.34	
Conv. phyto.	-0.004	0.029	-0.15	0.88		-0.014	0.031	-0.47	0.64	
Sugar	0.07	0.029	2.39	0.02	**	0.058	0.029	1.96	0.05	**
Juice pH	-0.076	0.023	-3.23	0	***	-0.072	0.024	-2.97	0	***
Titratable acid	0.038	0.021	1.77	0.08	*	0.034	0.022	1.53	0.13	
Visual and taste	0.014	0.023	0.61	0.54		0.013	0.024	0.56	0.58	
Manual irrigation	0.105	0.052	2.02	0.04	**	0.136	0.055	2.49	0.01	***
Surface irrigation	0.015	0.061	0.25	0.8		0.049	0.06	0.82	0.41	
Sprinkler irrig.	-0.084	0.064	-1.32	0.19		-0.028	0.067	-0.42	0.68	
Drip irrigation	0.052	0.025	2.1	0.04	**	0.067	0.026	2.55	0.01	***
Other irrigation	0.068	0.061	1.11	0.27		0.086	0.064	1.35	0.18	
Manual harvest	-0.097	0.033	-2.97	0	***	-0.094	0.034	-2.73	0.01	***
Conventional soil	0.055	0.032	1.71	0.09	*	0.054	0.034	1.59	0.11	
Screw pressing	-0.027	0.03	-0.9	0.37		-0.012	0.032	-0.38	0.71	
Pneumatic press.	-0.01	0.03	-0.34	0.73		-0.008	0.033	-0.25	0.81	
Malolactic	-0.008	0.022	-0.36	0.72		-0.008	0.024	-0.35	0.73	
Commercial yeast	-0.019	0.021	-0.88	0.38		-0.012	0.022	-0.57	0.57	
Fermentation act.	0.015	0.021	0.74	0.46		0.021	0.022	0.96	0.34	
Chaptalization	0.099	0.037	2.68	0.01	***	0.103	0.038	2.74	0.01	***
Stab. and clar.	-0.007	0.02	-0.33	0.74		-0.01	0.02	-0.49	0.62	
Blending	0.04	0.019	2.11	0.04	**	0.036	0.019	1.85	0.07	*
Steel aging	0.045	0.019	2.32	0.02	**	0.042	0.02	2.11	0.04	**
Cement aging	0.026	0.024	1.07	0.29		0.017	0.024	0.7	0.48	
Bottle aging	-0.004	0.018	-0.24	0.81		-0.007	0.019	-0.35	0.73	

Other aging	0.075	0.034	2.21	0.03	**	0.082	0.035	2.32	0.02	**
Natural cork	-0.001	0.025	-0.02	0.98		-0.011	0.027	-0.39	0.69	
Technical cork	0.022	0.024	0.95	0.34		0.02	0.024	0.81	0.42	
Synthetic cork	-0.034	0.037	-0.92	0.36		-0.011	0.039	-0.29	0.77	
Screw caps	0.032	0.041	0.79	0.43		0.029	0.041	0.71	0.48	
Vino seal	-0.086	0.141	-0.61	0.54		-0.086	0.138	-0.62	0.53	
French or Am Oak	0.017	0.019	0.92	0.36		0.016	0.02	0.78	0.44	
Spain	-0.02	0.037	-0.53	0.59		-0.026	0.038	-0.67	0.51	
Italy	0.007	0.027	0.24	0.81		-0.006	0.027	-0.23	0.82	
South Africa	-0.043	0.066	-0.65	0.51		-0.089	0.068	-1.3	0.19	
Chile	-0.227	0.063	-3.58	0	***	-0.23	0.066	-3.51	0	***
Argentina	-0.126	0.056	-2.23	0.03	**	-0.183	0.057	-3.21	0	***
Brazil	-0.476	0.302	-1.57	0.12		-0.5	0.292	-1.71	0.09	*
Uruguay	-0.028	0.118	-0.23	0.82		-0.036	0.123	-0.3	0.77	
Germany	-0.074	0.078	-0.96	0.34		-0.069	0.076	-0.9	0.37	
Portugal	-0.123	0.088	-1.39	0.16		-0.122	0.088	-1.39	0.16	
Constant	0.503	0.066	7.67	0	***	0.53	0.068	7.75	0	***
Sigma	0.201	0.007	29.29	0	***	0.205	0.007	29.51	0	***

Variables show consistent significance across models, with some important for Value and others for Premium wines, mainly due to differences in scale efficiency. Efficiency scores are highly correlated. For Value wines, CRS and VRS models show positive impacts from weather forecast (+7.7%), drip (+9.3%, +8.4%), surface irrigation (+9%, +10.3%), pneumatic pressing (+6.6%), and Vino seal (+15.2%, +19.9%), and negative from manual harvesting (-8.2%, -10%), and negative effects for Manual canopy management (−0.062, −0.072). The Gobelet training system improves CRS efficiency (+5.7%), while the overall weather forecast (+4.4%) raises VRS efficiency, with fermentation activators reducing it (-6.3%). Country effects are positive for Italy (+9.2%, +8.8%) and Uruguay (+4.3%, +4.33%), negative for South Africa (-21%, -25%) and Portugal (-9.8%), relative to France, the omitted country.

Regarding premium wines, 10 key variables influence both CRS and VRS models: 3 negatively and 7 positively. The Gobelet system (-4.2% and -4.7%) and Sugar maturation (+7% and 5.8%) affect performance, as do Juice pH control (-7.6% and -7.2%), Manual irrigation (+10.5% and +13.6%), Drip irrigation (+5.2% and +6.7%), Manual harvest (-9.7% and -9.4%), Chaptalization (+9.9% and +10.3%), Blending (+4% and +3.6%), Steel aging (+4.5% and +4.2%), and Other aging (+7.5% and +8.2%). Negative effects also come from Chile (-22.7% and -23%) and Argentina (-12.6% and -18.3%). A significant negative country effect for Brazil (-50%) appears only in the VRS model. Country effects are relative to France, the omitted country.

The parameter σ represents the unexplained variability in efficiency levels by the environmental variables included in the model. A small σ indicates that environmental variables account for a large portion of the variation in the efficiency of the evaluated units (in our case, $0.196 < \sigma < 0.205$ across the four models). Conversely, a high σ suggests significant "noise" or unobserved factors influencing performance [12]. Thus, our models account for approximately 80% of the variation in the efficiency of the evaluated units.

5. Discussion

Our analysis shows that specific technological choices within the value chain influence technical efficiency in wineries across our ten-country sample. We found that wineries specializing in Premium wines are generally smaller and more capital-intensive per liter than Value wine producers, yet they maintain higher average efficiency.

In the Value wine segment, the positive impact of Own weather forecasts suggests that wineries using internal meteorological data are better equipped to reduce waste and optimize vineyard operations. We also observed that the Gobelet training system significantly improves efficiency under VRS, likely because it is compatible with standardized management practices in Value vineyards.

For Premium wineries, efficiency drivers shift to precision maturation and irrigation. Manual and drip irrigation notably boost efficiency by enabling high-precision water delivery, unlike other systems. In contrast, using Juice pH for maturation consistently reduces efficiency, likely due to labor-intensive adjustments and higher per-liter input requirements. Notably, the Gobelet training system lowers efficiency, suggesting it does not effectively balance canopy management and harvest volume for high-end producers.

We identified Manual harvesting as significantly reducing scores in both Value and Premium wineries. This confirms our central hypothesis: some practices that prioritize quality attributes over volume would reduce technical efficiency. Similarly, we found that Stainless steel aging enhances efficiency in Premium wines, likely because it reduces the long turnover times associated with oak- or cement-vat aging.

Regarding scale, our estimates of scale efficiency suggest that most producers are operating near their optimal size, and that further performance gains must come from technological optimization within the value chain rather than from expansion. For managers, the "takeaway messages" are: in the Value segment, prioritize mechanization and economic closures; in the Premium segment, invest in high-precision training systems and steel-based aging to protect volume while maintaining quality. For policymakers, the significant value of localized weather data suggests that providing public access to specialized meteorological infrastructure could close the efficiency gap for smaller producers who cannot afford "Own weather" systems.

The global wine industry's restructuring can be viewed through the lens of production economics, balancing efficiency (volume) and quality (value). In the "Value" segment, economies of scale lower costs by spreading fixed costs over larger volumes through automation such as mechanical harvesting and cheap sealing. In the "Premium" segment, wineries prioritize quality standards, sacrificing efficiency by employing practices such as manual harvesting, lower yields, or methods that limit productivity to meet Designation of Origin (DO) regulations. Though these practices seem inefficient in terms of volume, they are rational given reputation and price premiums. Practices like using weather forecasts and stainless-steel aging optimize resources, reduce waste, and improve capital productivity, moving wineries toward a technology-driven, knowledge-based approach. The relationship between scale and performance is polarized: large firms dominate by scale, while smaller wineries focus on differentiation and niche products. Future competitiveness depends on aligning technological investments—for instance, mechanization for mass markets versus maturation control for high-end—to market positioning.

Our findings on the technical efficiency of the global wine industry reveal a nuanced strategic landscape that both aligns with and challenges existing literature. We confirm prior DEA evidence of the sector's large-scale efficiency; our results (0.94–0.96) are consistent with the large-scale efficiency reported by [28] and with the prevalence of Constant Returns to Scale identified by [37]. Similarly, our identification of significant country-level effects, notably the strong performance of Italian wineries, corroborates the international benchmarking reported in [33] and the regional leadership noted in [38]. Furthermore, this study extends existing evidence by shifting the analytical focus from structural traits—such as legal form or general size—to specific value chain practices. While previous research has emphasized broad inputs such as capital and land, we provide specific evidence that "precision" tools, such as internal weather forecasts and pneumatic pressing, are critical drivers of efficiency in the "Value" segment. Our finding that stainless steel aging enhances efficiency in "Premium" wineries provides a concrete managerial mechanism for the scientific codification of winemaking. Most significantly, our results diverge from studies that suggest an unambiguous positive correlation between firm size and technical efficiency, such as [32] and [38]. By segmenting by quality, we reveal that smaller "Premium" wineries achieve higher average efficiency scores than their larger "Value" counterparts, suggesting that efficiency is increasingly a product of masterful resource allocation to meet quality standards rather than simple scale. Finally, while [24] found organic systems to be more technically efficient in specific contexts, our findings highlight that labor-intensive practices -such as manual harvesting- systematically reduce technical efficiency scores across all segments, underscoring the enduring "quality-quantity" trade-off in the global value chain.

[39], [40], [41], and [42] offer a cohesive analysis of the wine industry in Italy and across Europe, focusing on premiumization, competitiveness, CAP reforms, and organizational models such as districts and cooperatives. Common themes include sustainability as a central driver, the industry's adaptation to global consumption trends, and the demand for innovative products such as NOLO wines. The need for small, fragmented producers to use alliances and social capital to achieve economies of scale, as EU policies shift from strict production control to support for competitiveness and environmental goals. Our contribution yields some policy-oriented recommendations for large European producers as well as emerging New World competitors.

6. Conclusions

Our study empirically assessed the trade-off between high quality and volume efficiency, since producing premium products entails sacrificing volume. Together, we explored technological choices across the value chain to assess their influence on the distance to the efficiency frontier, yielding interesting managerial and policy guidelines. We examined wineries' productive efficiency for Value and Premium wine producers across 10 countries using a two-stage DEA model. We estimated four efficiency frontiers for both wine qualities under constant- and variable-return-to-scale assumptions. In the second stage, we assessed whether efficiency scores relate to vineyard and cellar choices using Simar-Wilson regressions on DEA scores and variables representing technological options along the value chain. A consistent set of significant variables, with the same signs and similar magnitudes, influenced efficiency across wine types under different returns-to-scale hypotheses.

This study reveals that technological choices across the value chain largely determine productive efficiency, accounting for about 80% of the variability among wineries in 10 countries. Average technical efficiency is higher in the Premium segment than in the Value segment, indicating that high-end wineries allocate resources more efficiently to meet quality standards. For Value producers, efficiency relates to modernization and automation, such as using internal weather forecasts and modern sealing systems like Vino Seal. In contrast, Premium wineries focus on precision practices such as manual or drip irrigation, stainless-steel aging, and specialized training systems. Premium wineries focus on precision practices like stainless-steel aging and drip irrigation, which improve efficiency and berry quality. Manual harvesting highlights the "quality-quantity trade-off,' with wineries sacrificing volume for sensory qualities and reputation. This suggests that while Value producers need mechanization to compete in mass markets, Premium producers should embrace "strategic inefficiency," viewing resource-heavy choices as essential for product differentiation.

A fundamental finding is that practices prioritizing quality attributes over volume, such as manual harvesting or manual canopy management in the production of Value wines, systematically reduce technical efficiency in both segments. Quality is costly in terms of inputs. Furthermore, our results on scale efficiency indicate that most wineries operate near their optimal size, suggesting that future gains in competitiveness must stem from internal technological optimization rather than simple expansion.

From a managerial perspective, this work provides a decision-support framework indicating that wineries should align their investments with their market positioning: mechanization for the mass segment and maturation and freshness-control technologies for the high-end segment. Wineries should align technology investments with their market tiers to support strategic positioning and move beyond 'stuck-in-the-middle' strategies. Value segment producers should adopt cost-leadership strategies, using mechanization and information tools, such as weather forecasting, to optimize vineyard operations and reduce waste, thereby closing efficiency gaps. They should also use high-speed sealing systems to boost efficiency. Premium-segment managers need to focus on value propositions and invest in precision tools such as drip irrigation to command quality and price premiums. Stainless-steel aging enhances capital productivity and reduces maturation times. All wineries must balance the "quality-quantity trade-off': Value producers should avoid labor-intensive practices to compete in mass markets, while Premium producers can use them to enhance reputation. Beyond the cellar, forming alliances with quality marketers or leveraging digital channels helps preserve their brand story amid a fragmented distribution landscape.

Regarding the policy recommendations, this contribution applies to both Old- and New-World realities. For instance, the "New Delivery Model" (NDM) of the CAP (2023–2027) shifts the focus from simple compliance to performance, requiring Member States to define National Strategic Plans tailored to specific territorial needs [39], [40], [41], and [42]. Policy should prioritize the National Support Program (NSP), specifically measures for vineyard restructuring and conversion, which have been shown to directly enhance the technical efficiency and quality of the supply chain. Public mechanisms must support the diffusion of fungus-resistant grape varieties (PIWI) and de-alcoholization technologies. These are seen as "game-changers" for environmental sustainability but require long-term public R&D investment to reduce high production costs and risks for early adopters. For New World producers, less tied to traditions and regulations, flexibility in value chain adjustment offers an opportunity to catch up in quality with Old World producers, while carefully considering the documented consequences for efficiency.

Despite the value of the international database used, the study is limited by its cross-sectional design and the omission of leading producers such as the United States; therefore, future research should shift toward longitudinal analyses that capture the evolution of these practices in response to climate change and market tendencies.

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