# Towards Sustainable Viticulture: Cost Savings and Reduced Chemical Use through Fungus-Resistant Grapevine Varieties

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**Abstract**

Fungus-resistant grapevine varieties represent a promising innovation for reducing the environmental and economic burden of viticulture by decreasing reliance on chemical plant protection products. This study evaluates the economic impact of adopting FRGVs in table grape production in the Apulia region in the Southern of Italy, with a specific focus on plant protection management costs and farm profitability. Using data from 118 commercial vineyards and a simulated counterfactual scenario for conventional cultivars, the analysis compares expenditures on pesticides, water, machinery, and labor for disease control. A partial budgeting approach is applied, and statistical differences are assessed through ANOVA and variance analysis. Results show that FRGV adoption leads to a substantial reduction in plant protection costs (-55%), driven primarily by lower pesticide use (-71%) and fewer treatment applications (-36%). These savings translate into higher Extended Gross Margins, which increase by approximately 7-8% across phenological classes and management systems. In addition, resistant vineyards exhibit significantly lower cost variability, indicating improved economic stability and reduced production risk. Findings confirm that FRGVs enhance both economic efficiency and cost predictability without affecting gross revenues.

**Keywords**: Profitability, Gross Margin Profit, Table grapes, Climate mitigation, Pesticide reduction

## 1. Introduction

Fungus-resistant grapevine varieties (FRGVs) are developed through interspecific hybridization between the Mediterranean grapevine species *Vitis vinifera* and resistant North American and Asian Vitis species, including *V. riparia*, *V. amurensis*, and *V. rupestris* [1]. These hybrids incorporate specific genomic regions (resistance loci) inherited from the wild species that confer resistance to major fungal pathogens, including Powdery mildew (Erysiphe necator) and Downy mildew (Plasmopara viticola) [2]. As emphasized by Gindro and colleagues [3], FRGVs rapidly respond to fungal pathogen infection through the accumulation of high concentrations of stilbene phytoalexins, including viniferins and pterostilbene, at the sites of infection in leaves and berries. Therefore, compared to traditional cultivars, they require significantly fewer fungicide treatments, although they do not completely eliminate the need for them [4, 5]. Studies conducted in Europe have shown that FRGVs can reduce fungicide applications by up to 73-82%, requiring an average of approximately four treatments per growing season in organic vineyards [6, 7] and depending on the different environmental conditions [8]. In addition to the direct impacts, there are indirect benefits related to

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workers' health and safety, reduced soil compaction due to the lower number of spray applications, and positive effects for local communities [9]. However, as Montaigne et al. [10] highlight, the sector is in a transitional phase with many new options still under experimentation. Moreover, FRGVs are still at a relatively early stage of development, and their adoption involves considerable upfront investments with returns expected only over the long term [11]. In the long term, these varieties could become decisive for the market, driven by increasingly environmentally conscious consumers. Therefore, since pesticide use represents one of the main criticalities of environmental impacts across the life cycle of wine production, both in terms of soil and water contamination and atmospheric emissions associated with field operations, the spread of FRGVs is of particular environmental relevance [2, 12]. Viticulture, in fact, is among the most pesticide-intensive cropping systems in Europe, accounting for a substantial share of overall pesticide use, particularly through extensive fungicide applications. Italy reflects this broader trend. According to the latest available data from ISTAT [13], in 2021, 99.34% of the national vineyard area received fungicide treatments, with an average of 17.2 applications per year. This represents a 59.8% increase compared with 2014, while the average amount of fungicide applied reached 24.18 kg per cultivated hectare. In this scenario, the European Commission's Farm-to-Fork Strategy, introduced within the European Green Deal, establishes the first EU-wide targets for pesticide reduction, aiming to cut both the use and risk of chemical pesticides by 50% by 2030, alongside a 50% reduction in the use of more hazardous substances over the same period [14]. In this context, characterized by increasing regulatory pressure and growing consumer awareness of sustainable products, FRGVs emerge as a potential solution to reduce chemical input use and enhance the sustainability of wine production. However, translating the potential of these novel varieties into effective and widespread adoption requires an enabling innovation environment in which knowledge, advice, and technologies can circulate effectively among farmers and other relevant actors. In this context, AKIS plays a crucial role by connecting farmers with researchers, advisors, public institutions, and other stakeholders, facilitating knowledge exchange, co-learning, and the development of solutions tailored to farmers' needs [15, 16]. In this scenario and as stated by Trapp et al. [17], the adoption of FRGVs depends on market acceptance, which is increasing due to the growing awareness of sustainability among winegrowers and consumers. Despite their numerous advantages, the adoption of FRGVs still presents some limitations, particularly due to the potential loss of resistance to downy mildew and powdery mildew over time, as well as the emergence and spread of new grape diseases. Furthermore, under conditions of high disease pressure, phytosanitary treatments may still be necessary, albeit generally less frequently than for conventional varieties [18, 19]. In the case of table grapes, these limitations are compounded by potential additional challenges related to fruit quality, consumer preferences, and

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post-harvest performance. The main question is related to their ability to meet the high aesthetic and quality standards required by the market, particularly in terms of berry size, crispness, and uniformity. Further challenges could be associated with flavour profiles that may not always be appreciated by consumers and with post-harvest shelf life that may not adequately meet the requirements of transport and commercialisation.

Research on FRGVs has largely focused on consumer acceptance, with particular emphasis on how perceptions, preferences, and willingness to pay influence market adoption of wines produced from these novel varieties. The findings highlight a growing acceptance of wines produced from FRGVs, particularly when consumers perceive their environmental benefits and sensory quality. Kiefer and Szolnoki [20] show that consumers with stronger sustainability orientations and wine experts exhibit more favorable attitudes and a higher willingness to pay, whereas traditionalist and more price-sensitive consumers are less interested. Similarly, Nesselhauf et al. [21] report that although price remains the primary purchase criterion, the environmental benefits associated with disease-resistant varieties, particularly the reduction in pesticide use and carbon emissions, offset consumers' limited familiarity with these varieties and increase their willingness to pay. Consistent with these findings, Borrello et al. [22] identify a positive perception of wines produced from FRGVs and consumers' willingness to pay a price premium for sustainable products. However, the authors emphasize that commercial success depends on combining effective communication strategies with high sensory quality. The importance of sensory quality is further confirmed by Kiefer and Szolnoki [23], who find that wines produced from FRGVs are comparable in quality and, in some cases, superior to conventional wines. Consistent with this, Dolet et al. [24] found that sensory analyses revealed no significant differences in liking or sensory profiles of wines, even when participants were informed of the grape type. On the contrary, Espinoza and colleagues [25] found that consumers initially showed a preference for conventional wines based on sensory evaluation, while wines from resistant grape varieties received lower sensory scores. However, providing information on environmental and health benefits, particularly regarding pesticide use and residues, significantly increased consumers' willingness to pay for wines from resistant varieties. Nevertheless, conventional premium wines retained a stable, albeit limited, market share, suggesting that their organoleptic quality continued to play an important role in consumer choices. Therefore, although information about the benefits of FRGVs enhances consumers' perception of product value and promotes acceptance, taste remains the primary determinant of purchase intention. This finding is further supported by Blackford et al. [26], who demonstrate that consumer acceptance of wines produced from FRGVs is primarily influenced by their sensory characteristics, prior knowledge of these varieties, and consumers' membership in specific market segments. The literature consistently indicates that the successful diffusion of these

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wines depends on the combination of product quality, perceived sustainability, and effective communication of their environmental benefits.

Beyond consumer perspectives, the literature has also examined FRGVs adoption from growers' perspectives. The results highlights a growing interest among winegrowers in FRGVs, driven by their potential to reduce plant protection treatments, production costs, chemical inputs, and production risk, while also contributing to greater sustainability [27]. However, their adoption remains constrained by limited agronomic experience, perceived risks associated with the novelty of these varieties, and limited market acceptance. Zachmann et al. [28] confirm the increasing willingness of Swiss winegrowers to adopt FRGVs, showing that adoption intentions are influenced by both farm and individual characteristics, with differences between organic and conventional producers. Therefore, the literature suggests that the diffusion of disease-resistant varieties depends on the interplay between economic incentives, risk perceptions, and structural constraints within the wine sector. In particular, Finger et al. [29] found that the likelihood of adopting FRGVs increases as the distance between producers and final consumers decreases. In detail, winegrowers who primarily sell their wine through direct-to-consumer channels exhibit higher adoption levels, with estimated probabilities ranging from 8% to 38%. The study of Piccoli and Viganò [30] shows that PIWI growers are mainly motivated by environmental concerns, particularly soil health and reduced chemical use, alongside social and cultural factors linked to tradition and community. However, adoption is constrained by high initial costs, delayed returns, regulatory limits, and the need for local adaptability. A recent study [31] compared conventional grape varieties and FRGVs as represented in wine guides to assess whether producers apply price premiums to FRGV wines and whether the value attributes associated with these wines differ from those of conventional wines. The findings indicate that wines produced from resistant varieties can command price premiums, particularly when linked to certifications such as organic production, which appear to be especially valued in this context. Furthermore, producers with lower market reputation may benefit disproportionately from adopting resistant varieties, using them as a strategic tool for differentiation and innovation. This reflects a sector pattern in which firms adopt process and product innovations to increase organizational efficiency and reduce costs, highlighting the importance of innovation and product differentiation [32]. Overall, FRGVs offer promising benefits but their diffusion remains highly context-dependent, requiring further region-specific research.

The economic impact of adopting FRGVs have received relatively limited attention in the literature, although they are crucial for vineyard management decisions. The literature highlights that one of the main economic advantages of FRGVs stems from the substantial reduction in plant protection treatments, resulting in significant savings in production and labor costs. Petucco et al. [2], comparing

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FRGVs and conventional cultivars, show that routine vineyard operations require similar labor inputs, whereas plant protection treatments are reduced from 9.5 to 1.5 hours per hectare. As a result, total vineyard management costs decrease from €1,171 to €487 per hectare, generating savings of approximately €685/ha, mainly due to lower pesticide expenditures (€388/ha) and reduced labor costs. The unit production cost also declines, from €0.18 to €0.06 per kilogram of grapes. Similar findings are reported by Eisenmann et al. [33], who document a reduction in the number of plant protection treatments from 8-11 to 2-5 per season, accompanied by decreases in copper use (62-79%) and sulfur use (60-74%). The resulting reduction in labor requirements (36-76%) translates into cost savings of 46-72%, with vineyard management costs falling from approximately €480-1,000/ha to €230-540/ha. Other studies likewise confirm the economic benefits of disease-resistant varieties, particularly through lower plant protection costs. Sambucci et al. [34] estimate that Powdery mildew control alone costs California approximately US$239 millions annually, of which US$176 millions is attributable to wine production. Similarly, Dressler [35] estimates that the cultivation of disease-resistant varieties in Germany could reduce plant protection management costs by 46-75%, generating savings of up to €1,000/ha. The literature generally agrees that FRGVs enhance the economic sustainability of viticulture by reducing plant protection costs without compromising productivity, while simultaneously contributing to environmental sustainability. However, the vast majority of existing research has primarily focused on consumer-side dynamics, particularly perceptions, acceptance, and willingness to pay for wines produced from these varieties, whereas far less attention has been devoted to farm-level economic analyses aimed at quantifying their actual impact on vineyard profitability and production costs, especially in the table grape sector, which represents a strategic component of the agri-food industry.

In light of the above, the aim of this study is to assess the economic impact of adopting grapevine varieties genetically resistant to the major fungal diseases affecting table grapes, particularly Powdery mildew and Downy mildew, in a representative table grape-growing area of the Apulia region, in the Southern Italy. Specifically, the study compares plant protection management costs in vineyards cultivated with FRGVs and those planted with conventional varieties under comparable pedoclimatic conditions. The analysis focuses on the costs associated with disease control, including expenditures on plant protection products, water consumption, and the operational costs of pesticide applications. The choice of the Apulia region as a case study is linked to the importance of table grape production within the national context (52.9% of Italy's vineyard area and 57.6% of the production harvested in 2025 according to the ISTAT data), as well as to the lack of investment in resistant varieties to date. In Italy, 36 disease-resistant grapevine varieties are currently registered in the National Register of Vine Varieties, all intended for wine production, while no varieties are registered for table grape

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197 production. This situation can be attributed to the relatively recent interest in these varieties within
198 the table grape sector. The area cultivated with FRGVs amounts to 1,289.58 hectares (accounting for
199 only 0.17% of the total national vineyard area, [36]). More specifically, production is predominantly
200 concentrated in the central and northern regions, including Lombardy, Trentino Alto Adige, Friuli-
201 Venezia Giulia, Veneto, Piedmont, Emilia-Romagna, Marche, and Abruzzo. Veneto, in particular,
202 accounts for 657.43 hectares, representing approximately 51% of the total national area planted with
203 FRGVs [37].

204 Theoretically, this study fills a gap in the literature by providing farm-level evidence on the economic
205 implications of FRGVs in the table grape sector. Practically, it quantifies potential cost savings in
206 Apulia, supporting growers' investment decisions and promoting more economically and
207 environmentally sustainable production systems.

208

209 **2. Materials and Methods**

210 The analysis was conducted on a sample of 118 vineyards specializing in table grape production in
211 the Apulia region (Southern Italy), encompassing 34 different cultivars. For each vineyard, data on
212 plant protection treatments were collected from the official farm records (field logs) referring to
213 vineyards cultivated with conventional (non-resistant) cultivars. Based on these data, an alternative
214 scenario was simulated in which the same vineyards were assumed to be planted with cultivars
215 genetically resistant to Powdery mildew and Downy mildew. The dataset covers two growing
216 seasons, 2023/24 and 2024/25. For each vineyard, the values of the two seasons were averaged to
217 obtain a single annual observation. In the simulated resistant-cultivar scenario, the number of plant
218 protection treatments was reduced in line with good agronomic practices to ensure the long-term
219 durability of genetic resistance. In detail, the reduction in the number of treatments was estimated by
220 simulating an alternative crop protection programme for resistant grape varieties and comparing it
221 with the programmes implemented in the vineyards planted with susceptible table grape varieties.
222 The number of treatments was determined based on both experimental evidence [2 ; 33] and
223 observations from commercial vineyards. Treatments targeting pests and diseases other than Powdery
224 mildew and Downy mildew were retained unchanged. Therefore, the simulated value for each
225 vineyard results from these retained treatments plus the simulated anti-mildew programme described
226 below, and the simulated mean is the average across the 118 vineyards.

227 For Powdery mildew, three applications of biological control products were assumed, scheduled at
228 the pre-bloom, bloom, and post-harvest stages. For Downy mildew, although the number of
229 treatments was substantially reduced, targeted applications of copper-based products or resistance

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inducers were retained during periods of high infection risk. To identify these periods, meteorological data from the monthly regional weather bulletins issued by the Civil Protection Department of the Apulia Region were analysed, taking into account the regional scale of the study. Particular attention was paid to precipitation, and daily relative humidity. These data were compared with the timing of crop protection treatments applied in vineyards planted with susceptible varieties, which were also managed according to an integrated pest management strategy, with treatments scheduled in response to disease pressure. This comparison therefore used a reference management strategy that already accounted for phytosanitary risk.

To assess the economic impact of adopting FRGVs, the partial budgeting method was employed, a widely used approach for evaluating the marginal economic effects of specific management changes within agricultural production systems [38]. This method was selected to isolate and quantify changes in costs and revenues directly attributable to the adoption of FRGVs relative to conventional cultivars, while assuming that all other production costs remained unchanged. Accordingly, the analysis focused on the main cost components associated with plant protection practices: (i) expenditures on plant protection products; (ii) water costs for spray applications; and (iii) operational costs related to machinery use and specialized labor required to perform the treatments. Consequently, any observed differences in production costs can be attributed exclusively to the adoption of resistant rather than conventional cultivars.

The monetary values assigned to each cost component were estimated by combining market-based data with information on the actual operations performed at farm level. The costs of phytosanitary products were determined using market information representative of the study area and covering the 2023/24 and 2024/25 production seasons considered in the analysis. Prices for plant protection products were obtained from the official price lists of the main agricultural input suppliers operating in the study area. The plant protection products actually used for the treatments recorded in the vineyard treatment records were matched with their corresponding listed market prices, and these values were used to estimate pesticide expenditures per hectare. Operational costs for pesticide applications were estimated at €132 $ha^{-1}$ per treatment, including VAT, based on the prevailing rates for contracted spraying services in the areas where the farm surveys were conducted. This amount represents a local reference market rate and includes tractor and air-blast sprayer use, fuel consumption, skilled labor, and ancillary operations associated with each application. Thus, the resulting estimates reflect locally observed market quotations and farm-level operational information. Water used for phytosanitary applications was valued at €0.12 $m^{-3}$, corresponding to the estimated average cost of groundwater abstraction from on-farm wells, which are the predominant water source in the study area. Accordingly, the economic valuation combines directly observed market quotations

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for plant protection products with representative local cost estimates for water abstraction and contracted spraying operations. The same valuation criteria were consistently applied to both conventional and simulated FRGV scenarios to ensure comparability and isolate the cost differences attributable to changes in phytosanitary management. In addition, the average annual revenue per hectare was estimated for each vineyard based on table grape sales. Revenue was calculated as the product of the average yield of each cultivar (t $ha^{-1}$), obtained through farm interviews, and the average farm-gate price received by growers for the respective cultivars, derived from local market data.

Consistent with the partial-budgeting approach adopted in this study, the extended gross margin (EGM) was used as the key economic performance indicator. The EGM was calculated as the difference between annual gross revenue from table grape sales and the costs directly attributable to phytosanitary management. The indicator was used to quantify the incremental economic impact associated with changes in plant protection management between conventional and resistant-cultivar scenarios. Therefore, the EGM, in this study, represents a partial economic margin rather than a measure of overall farm profitability, as it does not account for other production and marketing costs, including vineyard establishment, fertilization, general irrigation, pruning, harvesting, packaging, fixed costs, and marketing expenses. Accordingly, the EGM for each vineyard was computed using the following equation:

$$EGM = R - TC \quad \text{(Eq. 1)}$$

where:

EGM = Extended Gross Margin (€ $ha^{-1}$ $year^{-1}$)

R = Annual Revenue per hectare (€ $ha^{-1}$ $year^{-1}$)

TC = Annual Costs per hectare attributed exclusively to phytosanitary management (€ $ha^{-1}$ $years^{-1}$)

Gross revenue was assumed to be identical under the conventional and simulated FRGV scenarios, as the analysis was designed to isolate the economic effects attributable to changes in phytosanitary management. Accordingly, differences in EGM between the two scenarios arise exclusively from differences in phytosanitary management costs.

A descriptive analysis was first performed for the main variables, including the number of plant protection applications, total phytosanitary management costs, expenditures on plant protection products, water costs, contracted spraying costs, and EGM. The analytical dataset comprised 118 matched vineyard pairs. For each vineyard observed under conventional management, a corresponding FRGV scenario was simulated using the same vineyard-specific characteristics, while

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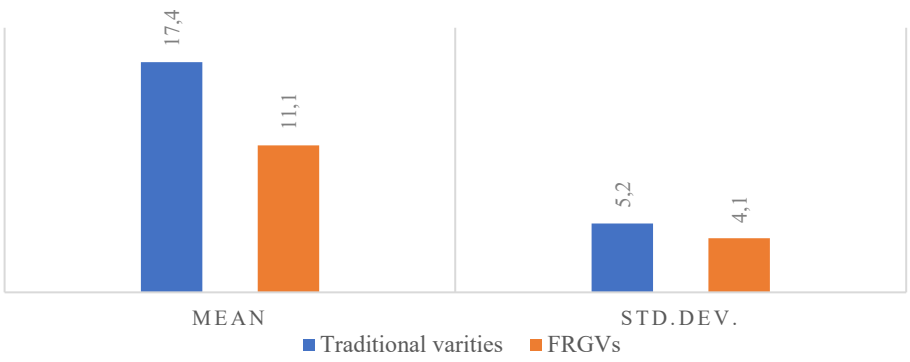
modifying only the phytosanitary management regime according to the assumptions described above. Thus, the conventional and simulated FRGV observations were not considered independent samples, but rather as two paired observations associated with the same underlying vineyard.

To account for this within-vineyard paired structure, differences between conventional and simulated FRGV scenarios were assessed using paired-samples t-tests. For each vineyard pair, within-pair differences were calculated for total phytosanitary management costs, plant protection product expenditures, and EGM, and the null hypothesis that the mean paired difference was equal to zero was tested. This approach controls for time-invariant, vineyard-specific characteristics shared by the two scenarios, thereby allowing the observed differences to be more directly attributed to the change in phytosanitary management associated with the simulated adoption of FRGVs. All statistical analyses were conducted using Stata 17, and statistical significance was assessed at the 5% significance level.

## 3. Results

To assess the extent to which the use of FRGVs is more cost-effective than conventional varieties, an analysis was conducted on 236 observations on 118 vineyards, equally split between FRGVs (n = 118) and conventional cultivars (n = 118). The results show significant economic differences across all cost dimensions related to plant protection management. On average, vineyards planted with non-resistant cultivars incurred total annual plant protection costs of €5,095.4 $ha^{-1}$, compared with €2,270.1 $ha^{-1}$ in FRGVs vineyards, representing a reduction of 55.4%. In particular, the adoption of FRGVs led to a substantial decrease in the average number of annual plant protection applications. Non-resistant vineyards recorded 17.4 treatments $ha^{-1}$ per year, compared with 11.1 treatments $ha^{-1}$ in resistant vineyards (-36.2%).

**Figure 1 - Average number of annual plant protection applications by variety type**




This reduction in the number of applications is reflected in lower expenditures on plant protection products. Indeed, the average cost of plant protection products decreased from €2,802.1 $ha^{-1}$ in non-

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resistant vineyards to €807.2 ha$^{-1}$ in resistant vineyards, corresponding to a 71.2% reduction. These findings highlight the economic benefits associated with the adoption of FRGVs, while also pointing to broader environmental and social advantages. In particular, the reduced use of plant protection products may help mitigate environmental pollution and reduce potential risks to human health for both agricultural workers and local communities. Although these environmental and social benefits were not explicitly quantified in this study, they represent important additional dimensions of the overall sustainability gains associated with resistant varieties. Costs related to water use for spray applications and to machinery rental and skilled labor also decreased. Specifically, the average water cost declined from €1.3 ha$^{-1}$ in non-resistant vineyards to €0.8 ha$^{-1}$ in resistant ones, reflecting lower water demand due to reduced treatment frequency. Similarly, average expenditures for machinery rental and labor decreased from €2,292.1 ha$^{-1}$ to €1,462.1 ha$^{-1}$, driven by fewer applications. The results demonstrate a high level of technical and economic efficiency from the adoption of genetically resistant table grape cultivars, resulting in optimized input use and lower plant protection costs.

**Table 1 – Costs of phytosanitary treatments: traditional varieties vs resistant varieties**

| Variable | Traditional varieties | | Resistant varieties | |
|---|---|---|---|---|
| | Mean €/ha | Std. Dev. €/ha | Mean €/ha | Std. Dev. €/ha |
| Number of treatments | 17.4 | 5.2 | 11.1 | 4.1 |
| Total costs | 5,095.4 | 1,955.8 | 2,270.1 | 1,100.8 |
| *-Pesticides* | 2,802.1 | 1,361.9 | 807.2 | 652.8 |
| *-Water* | 1.3 | 0.4 | 0.8 | 0.3 |
| *-Machinery hire and labor* | 2,292.1 | 682.2 | 1,462.1 | 546.1 |
| Gross revenue | 39,737.3 | 13,627.6 | 39,737.3 | 13,627.6 |
| EGM | 34,641.9 | 12,905.9 | 37,467.2 | 13,209.3 |

*Source: authors' elaboration from survey data*

Table 2 presents the economic impact of adopting resistant table grape cultivars. Specifically, late-ripening cultivars exhibit the largest reduction in average treatment costs, decreasing from €5,897.5 ha$^{-1}$ in non-resistant vineyards to €2,536.2 ha$^{-1}$ in resistant ones, corresponding to a saving of 57.0%. A similar effect is observed for early-ripening cultivars (-56.7%), while for mid-season cultivars the reduction is 48.9%. Therefore, adopting resistant cultivars results in a substantial decrease in plant protection costs across all phenological groups, regardless of ripening time.

**Table 2**. *Average phytosanitary costs and EGM by earliness class and resistance*

| Earliness Class | Resistance | Avg. Cost (€/ha) | Reduction (%) | EGM (€/ha) | Variation (%) |
|---|---|---|---|---|---|

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| | | | | | |
|---|---|---|---|---|---|
| *Late* | No | 5,897.5 | - | 41,406.0 | - |
| | Yes | 2,536.2 | –57.0 | 44,767.4 | +8.1 |
| *Mid-season* | No | 5,779.6 | - | 37,062.5 | - |
| | Yes | 2,952.4 | –48.9 | 39,889.7 | +7.6 |
| *Early* | No | 3,748.5 | - | 24,763.2 | - |
| | Yes | 1,622.0 | –56.7 | 26,889.7 | +8.6 |

*Source: authors' elaboration from survey data*

From a farm profitability perspective, adopting FRGVs increases the Extended Gross Margin (EGM). In particular, late-ripening cultivars show an 8.1% increase in EGM (from €41,406.0 to €44,767.4 $ha^{-1}$), mid-season cultivars an increase of 7.6% (from €37,062.5 to €39,889.7 $ha^{-1}$), and early-ripening cultivars an increase of 8.6% (from €24,763.2 to €26,889.7 $ha^{-1}$). These improvements are primarily driven by reduced variable costs associated with plant protection treatments. However, the EGM should be interpreted as a partial economic indicator rather than a measure of total farm profitability, as it does not account for all production costs. Nevertheless, the consistency of the observed benefits across phenological classes confirms that genetic resistance represents a strategic lever for cost containment and for the optimization of economic margins in table grape production systems.

The study also analyszed average plant protection costs and Extended Gross Margin (EGM) under conditions with and without protective coverage, highlighting an improvement in economic indicators following the adoption of FRGVs, as shown in Table 3. In vineyards without protective covers, average plant protection costs decrease from €5,944.1 $ha^{-1}$ for non-resistant cultivars to €2,505.5 $ha^{-1}$ for resistant cultivars, corresponding to a reduction of 57.9%. This reduction translates into an increase in EGM, which rises from €37,895.9 $ha^{-1}$ to €41,330.5 $ha^{-1}$ (+9.1%). Similar results are observed in vineyards with protective covers. In this case, average costs decline from €4,867.3 $ha^{-1}$ (non-resistant) to €2,209.9 $ha^{-1}$ (resistant), representing a 54.6% reduction. Here as well, the decrease in costs leads to an increase in EGM of 7.9% (€33,767.2 $ha^{-1}$ vs €36,424.6 $ha^{-1}$). The results confirm that the introduction of genetically resistant cultivars generates significant economic benefits, regardless of the presence of protective systems.

**Table 3**. *Average phytosanitary costs and EGM by canopy cover and resistance*

| Plastic Cover | Resistance | Avg. Cost (€/ha) | Reduction (%) | EGM (€/ha) | Variation (%) |
|---|---|---|---|---|---|
| *No* | No | 5,944.1 | – | 37,895.9 | – |
| | Yes | 2,505.5 | –57.9 | 41,330.5 | +9.1 |
| *Yes* | No | 4,867.3 | – | 33,767.2 | – |
| | Yes | 2,209.9 | –54.6 | 36,424.6 | +7.9 |

*Source: authors' elaboration from survey data*

To assess the effect of varietal resistance on phytosanitary management costs while accounting for the paired structure of the data, a paired-samples t-test was performed comparing each conventional

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vineyard with its corresponding simulated FRGV scenario. The results show a substantial and statistically significant reduction in total phytosanitary management costs following the simulated adoption of resistant cultivars. Average annual costs decreased from €5,095.4 ha$^{-1}$ under conventional management to €2,270.1 ha$^{-1}$ in the FRGV scenario, corresponding to an average reduction of €2,825.3 ha$^{-1}$ (55.4%). The mean paired difference was statistically significant ($t(117) = -21.52$, $p < 0.001$), with a 95% confidence interval ranging from −€3,085.4 to −€2,565.3 ha$^{-1}$. These results indicate that, within the same vineyards and under otherwise comparable production conditions, the simulated adoption of FRGVs is associated with a marked reduction in phytosanitary management costs.

**Table 4.** *Paired-samples comparison of total phytosanitary management costs between conventional and simulated FRGV scenarios*

| Statistic | Conventional | FRGV | Paired difference (FRGV − Conventional) |
|---|---|---|---|
| Observations | 118 | 118 | 118 pairs |
| Mean (€ ha$^{-1}$) | 5,095.4 | 2,270.1 | −2,825.3 |
| Std. Dev. (€ ha$^{-1}$) | 1,955.8 | 1,100.7 | 1,426.2 |
| 95% CI (€ ha$^{-1}$) | 4,738.8–5,452.0 | 2,069.4–2,470.7 | −3,085.4 to −2,565.3 |
| t-statistic | | | −21.52 |
| df | | | 117 |
| p-value | | | <0.001 |

*Source: authors' elaboration from survey data*

With regard to plant protection product costs, the paired-samples t-test confirms a substantial and statistically significant reduction in the simulated FRGVs scenario. Average pesticide expenditures decreased from €2,802.1 ha$^{-1}$ under conventional management to €807.2 ha$^{-1}$ under the FRGV scenario, corresponding to a reduction of approximately 71.2%. The mean paired difference (FRGV − conventional) was −€1,994.9 ha$^{-1}$ (SD = €1,151.6 ha$^{-1}$), with a 95% confidence interval ranging from −€2,204.8 to −€1,784.9 ha$^{-1}$. The difference was highly statistically significant ($t(117) = -18.82$, $p < 0.001$). These findings indicate that, within the same vineyards, the simulated adoption of resistant cultivars is associated with a marked decrease in expenditure on plant protection products.

**Table 5.** *Paired-samples comparison of plant protection product costs between conventional and simulated FRGV scenarios*

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| Statistic | Conventional | FRGV | Paired difference (FRGV − Conventional) |
|---|---|---|---|
| Observations | 118 | 118 | 118 pairs |
| Mean (€ ha⁻¹) | 2,802.1 | 807.2 | −1,994.9 |
| Std. Dev. (€ ha⁻¹) | 1,361.9 | 652.8 | 1,151.6 |
| 95% CI (€ ha⁻¹) | 2,553.8–3,050.4 | 688.2–926.2 | −2,204.8 to −1,784.9 |
| t-statistic | – | – | −18.82 |
| df | – | – | 117 |
| p-value | – | – | <0.001 |

*Source: authors' elaboration from survey data*

## 4. Discussions

The results of this study suggest that the simulated adoption of FRGVs generates substantial economic benefits in table grape production systems, primarily through a marked reduction in plant protection costs and a corresponding improvement in EGM under the assumption of unchanged revenues. These findings are fully consistent with the existing literature on FRGVs, which consistently reports strong reductions in pesticide use and production costs [2, 33, 35]. At the farm level, the simulated reduction of approximately 55% in total plant protection costs confirms the magnitude of savings reported in previous studies, where cost reductions typically range from 46% to 75%, depending on environmental conditions and methodological assumptions. Similarly, the strong decrease in the number of treatments (-36%) and in pesticide expenditures (-71%) is consistent with Eisenmann et al. [33], who document substantial reductions in both treatment frequency and active ingredient use in FRGVs vineyards.

The present study extends these findings by explicitly quantifying cost components in a table grape system under Mediterranean conditions, an area that has been relatively underexplored in the literature. From a profitability perspective, the positive effect on Extended Gross Margin (EGM) observed across all specifications reinforces previous evidence that the main economic advantage of FRGVs stems from reduced variable costs rather than increased revenues (revenues being held constant by assumption in this study). The EGM increase of approximately 7-9% across phenological classes and management systems confirms that cost savings are systematically translated into higher margins, in line with the findings of [2], who report a sharp decline in unit production costs driven mainly by reduced pesticide and labor requirements. Unlike some previous studies focused on wine grapes, the present analysis highlights that similar economic mechanisms also hold in table grape production, where management intensity is typically higher and thus the absolute savings may be even more relevant. In addition, the simulated FRGV scenario shows a lower dispersion of costs across vineyards (Table 1). This should be regarded as a descriptive feature of the simulated scenario

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412 rather than as a tested result, since the paired-samples t-test compares mean values only. While
413 Eisenmann et al. [33] and Dressler [35] emphasize average cost reductions, the present results suggest
414 that FRGVs may also enhance predictability and reduce economic risk at farm level, although this
415 requires confirmation in vineyards actually planted with FRGVs. This lower variability may reflect
416 the reduced dependency on weather-sensitive fungicide applications, which are typically the main
417 source of cost fluctuations in conventional vineyards. From a management perspective, this increased
418 stability may translate into improved planning capacity and reduced exposure to production risk, an
419 aspect that has been highlighted as a key driver of adoption decisions in recent behavioral studies
420 [24]. The consistency of results across phenological classes and production systems (with and
421 without canopy protection) further strengthens the robustness of the findings. It is worth emphasizing
422 that differences in plant protection practices between the two scenarios are assessed by holding the
423 harvest period constant in both the actual and simulated scenarios. Furthermore, no early-ripening
424 fungus-resistant table grape varieties are currently registered, therefore, the potential effects of
425 adopting FRGVs on harvest earliness cannot yet be assessed. Finally, the results contribute to the
426 broader debate on the sustainability of viticulture. In line with Petucco et al. [2], the reduction in
427 pesticide use has clear environmental implications in terms of reduced chemical pressure on
428 agroecosystems and lower operational emissions. However, this study adds an economic dimension
429 by showing that environmental gains are accompanied by statistically significant reductions in mean
430 plant protection costs and, under the assumption of unchanged revenues, higher margins. This dual
431 benefit strengthens the argument for FRGV adoption as a key strategy for reconciling economic
432 viability with environmental sustainability.

433

434 **5. Conclusions, implications, limitations, and future research direction**

435 This study provides empirical evidence that the adoption of FRGVs can improve the economic
436 sustainability of table grape production. By comparing conventional vineyards with a simulated
437 scenario using resistant cultivars under the same production conditions, the analysis demonstrates
438 that FRGVs significantly reduce plant protection costs, primarily by lowering expenditures on
439 pesticides, labor, and machinery. The consistency of these results across different ripening classes
440 and production systems suggests that the economic benefits of resistant cultivars are robust and not
441 limited to specific agronomic conditions. Beyond their direct financial advantages, the substantial
442 reduction in pesticide applications contributes to broader environmental objectives by decreasing
443 chemical inputs and supporting more sustainable viticultural practices in line with the EU Farm-to-
444 Fork strategy.

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From a theoretical perspective, this study contributes to the literature on sustainable viticulture by extending existing research on FRGVs from the wine sector to table grape production, a segment that has received considerably less scholarly attention. While previous studies have mainly focused on consumer acceptance, willingness to pay, or average production cost reductions, the present research provides a detailed farm-level economic assessment based on a sample of commercial vineyards. Furthermore, the findings introduce an additional dimension to the literature by showing that FRGVs not only reduce average production costs but may also increase cost stability, as suggested by the lower cost dispersion observed in the simulated scenario.

The study's practical implications are relevant to multiple stakeholders. For growers, the results provide quantitative evidence that adopting resistant varieties can improve farm profitability by significantly reducing plant protection costs, under the assumption of unchanged revenues. Lower dependence on fungicide applications also reduces labor requirements and machinery use, making vineyard management more efficient and less vulnerable to fluctuations in pesticide prices and labor availability. For policymakers, the findings support promoting FRGVs as an effective instrument for achieving the objectives of the European Green Deal and the Farm to Fork Strategy, particularly those related to reducing pesticide use and improving environmental sustainability. The results suggest that public support schemes, investment incentives, and advisory services aimed at promoting the adoption of FRGVs could generate both private economic benefits and positive environmental externalities. In this regard, although the Italian CAP Strategic Plan 2023–2027 does not include specific measures for research and experimentation on FRGVs in the vine sector, it provides financial support for investments aimed at mitigating climate change and improving the environmental sustainability of agricultural production systems. These measures could indirectly encourage the adoption of resistant varieties by reducing reliance on fungicide applications and promoting more sustainable viticultural practices. The situation varies considerably across Italian regions that have chosen to promote FRGVs. For example, Veneto, which has the largest area cultivated with these varieties, introduced specific requirements in 2019 (Regional Government Resolution No. 1082 of 30 July 2019), mandating the use of resistant varieties for new plantings and replantings near particularly sensitive areas. However, as noted by Maggio and colleagues [39], although such regulatory measures can encourage the adoption of FRGVs, their effectiveness may be limited in the absence of additional financial support and targeted economic incentives for farmers. This reinforces the conclusion that the potential for FRGV adoption also depends on the regulatory framework, which differs significantly between the wine and table grape sectors. In particular, the regulatory debate surrounding the introduction of resistant varieties has focused primarily on wine grapes, whose use remains subject to national legislation and the decisions of individual regions. By contrast, table

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grapes have received comparatively little attention in this debate. However, the introduction of FRGVs may be more readily facilitated in the table grape sector, where varietal identity is generally less closely associated with territorial traditions and appellation regulations [40, 41]. In the table grape sector, consumers are less attached to varietal identity but pay greater attention to product appearance, berry size, crispness, sweetness, and overall fruit quality. Therefore, their successful adoption will depend on their ability to combine disease resistance and environmental sustainability with the quality attributes and commercial appeal required by consumers. Finally, these findings provide useful insights for breeding programmes, policymakers, and extension services seeking to promote innovation and support the sustainable development of the table grape sector.

Despite these contributions, several limitations should be acknowledged. First, the analysis is based on a simulated adoption scenario rather than observations from vineyards already cultivated with resistant table grape varieties. Although the simulation relies on current agronomic recommendations and realistic disease management protocols, actual field performance may vary according to climatic conditions, disease pressure, and growers' management practices. Second, the study focuses exclusively on direct plant protection costs, while other economic dimensions, such as investment costs, vineyard lifespan, maintenance requirements, and marketing considerations, are not included in the analysis. Third, the research is geographically limited to the Apulia region. Therefore, the results may not be directly transferable to other production areas with different climatic conditions, disease incidence, or production systems. Finally, the assumption of unchanged yields and market prices between conventional and resistant cultivars may not fully capture future market dynamics as resistant varieties become more widely adopted.

Future research should address these limitations by evaluating the long-term economic performance of commercial FRGV vineyards under real farming conditions. Longitudinal studies could assess the stability of economic benefits over multiple growing seasons and under varying climatic scenarios. Additional research should also integrate environmental assessment methods, such as Life Cycle Assessment, with economic analyses to quantify the overall sustainability benefits of resistant cultivars.

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