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Meeting Market and Societal Ambitions with New Robust Grape Varietals: Sustainability, the Green Deal, and Wineries' Resilience

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Abstract: This study investigates the sustainability impact of fungus-resistant grape varieties within viticulture, addressing economic, ecological, and social dimensions. Pesticide management is of paramount importance for wineries but causes additional costs, impairs sustainability, and faces societal non-acceptance. Digital monitoring of four German wineries for two consecutive years allowed us to compare treatments of traditional and robust varietals. The results demonstrate that the latter enables a significant reduction in pesticide treatments, can be key for copper reduction, and is of paramount importance for organic winemaking. By reducing pesticide dependency, lowering operational costs, hedging risks, and improving labor efficiency, FRW present a key to sustainable viticulture. The results suggest that robust varietals present a means to comply with societal pressure and to meet EU Green Deal ambitions. This paper contributes new, practice-oriented knowledge on FRW's role in sustainable viticulture, confirming both the ecological and economic advantages in real-world settings, alongside unique insights into social sustainability and market positioning strategies. Sustainability impact is quantified, and a newly introduced productivity metric allows for the orchestration of resilience. The findings contribute to the discourse on sustainable agriculture by validating FRW as a strategic response to climate and regulatory pressures, resilience, and competitive positioning.

Keywords: sustainability; climate change; field observation; digital process observation; cost efficiency; robust varietals; FRW; market opportunities; wine quality; yield management; risk management

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1. Introduction

Vines need care and protection to yield quality grapes and, hence, good wines. Such plant protection in the vineyards encompasses efforts to prevent damage and the resulting reduced yields. A variety of harmful organisms (viruses, bacteria, fungi, nematodes, insects, etc.) can cause considerable damage to plants, resulting in yield losses [1–4]. Comprehensive global estimates quantify agricultural losses at more than one-third to half of the harvest, depending on the crop, the region, and the year [5–8]. Plant protection is, therefore, particularly important to secure the world's food supply [5,9–11]. From an economic point of view, preventing yield and quality losses is most important in intensive crops, such as vegetables, fruit, and grapes. The profitability of an operator can crucially depend on pest management [12,13]. An increasingly effective agriculture to keep pace with population growth and to protect crops against diseases has turned the pesticide market into one of the most lucrative playfields in the world [14].

Phytosanitary treatments are indispensable for wine production, with growing importance in the face of climate change [15–20]. Powdery mildew (PM) is a fungal disease that damages a wide range of crops, especially grapes [21]. Depending on the type of pathological infestation, there are different methods for protecting vines [22]. These belong (chemically) to the pesticide family and include herbicides, fungicides, insecticides, and acaricides. A range of fungicides can help vineyard managers keep the disease in check in most years, but these are costly and may have negative environmental and human health effects [23,24]. The soil suffers from the crossing of agricultural machines, the biodiversity is affected by the application of plant protection products, the winegrowers have to spend time and money, and residues might harm consumers [25,26]. In addition, spraying pesticides can have indirect effects, such as spillovers to neighboring private housing or residues in the water that often travel far distances [27,28]. Indeed, wine cultivation is under scrutiny, as it is a heavy consumer of fungicides [29–32], illustrated by a report that wine required an average of 13 treatments versus 5 for overall crops in France in 2017 [22,33]. Climate change increases the risk of infestations, requiring proactive measures to minimize treatments, whereas, in wine production, reactive measures have prevailed so far [34].

The Federal Environment Agency in Germany recommends robust plant varieties as the most effective measure to reduce pesticide spraying in view of the "like the sand of the sea" portfolio of measures that winegrowers can pursue. (https://www.umweltbundesamt.de/top-ten-der-wirksamsten-pflanzenschutzmassnahmen, accessed on 22 November 2024). Breeders acknowledged the need for new vines that are more robust to phytological pathogens to cope with climate change and the increasing biotic and abiotic stress [21,35–46]. Fungus-resistant grape varieties, also known as disease-resistant or hybrid grape varieties, were specifically bred to withstand fungal diseases, such as powdery mildew, downy mildew, and black rot. The new varietals were marketed according to recommendations for reduced phytosanitary treatments, primarily based on observations of experimental research facilities and trials (e.g., https://www.lwg.bayern.de/weinbau/rebe_weinberg, accessed on 22 November 2024). In Germany, FRW enjoyed attention recently [47], but overall, planting just adds up to about 3% of the vines [48]. Since new robust varietal planting in wine is still limited, it raises the question of whether the varietals do not meet the expectations to better cope with climate change-induced challenges.

The motivation for this study was not only to provide empirical data on treatments and, therefore, wine production but also to cover the market perspective to explore whether, in practice, new robust varietals can fulfill expectations. The wine industry is facing the challenges of increasing competitive pressure alongside rising costs. It is no longer possible to increase profits through cost management while continuing to use the usual business models and processes, as the potential for increasing efficiency and the growing floor space has largely been exhausted [31]. In highly competitive markets, which is the case for the wine industry, (a) innovation, (b) customer-centric offerings [49–51], and (c) increasing sustainability [52–74] are key to successfully compete.

The hereby reported study fills in the gaps in the missing empirical data, which undermine the potential role that fungus-resistant wines (FRW) can have as a core lever for sustainability and value-creation in the wine industry [29,75,76]. Sustainability, in a brief definition, means to not consume at the expense of future generations and has been operationalized as a concept in the parallel pursuit of economic, ecological, and social aspects [64,69,71,77–81]. Given the dependence on climate and ecological factors in agricultural enterprises and wine estates, sustainability draws a lot of scientific attention [54,82–94]. Sustainable practices in viticulture are increasingly critical in the context of climate change, stringent environmental regulations, and evolving consumer expectations. With the EU Green Deal targets aiming for a 50% reduction in pesticide use by 2030, vineyards face mounting pressure to adopt practices that align with these sustainability goals. From a managerial perspective, sustainability turns out to be complex, with a lot of aspects to be considered, such as the contradictory effects of measures and a lack of transparency in the causal effects without neglecting cost implications [89,91,95–99]. Easy but reliable managerial implementation, as well as communication with the consumers, is needed in order for sustainability to become a managerial paradigm.

The purpose of the underlying study was to assess whether and to what magnitude robust wines contribute to cost management, sustainability ambitions, and strategic value for the vintners. Sustainability served as a theoretical foundation, with its three operationalized pillars (economic, societal, and ecologic) orchestrating the empirical study [100–104]. The study's primary objectives were to (1) analyze FRW's capacity to reduce operational costs and stabilize yields, (2) assess reductions in pesticide use and their environmental implications, and (3) explore the social benefits of FRW through improved labor efficiency and work conditions. (See Figure 1) This three-pronged approach provided a comprehensive view of FRW's potential within the context of modern sustainable viticulture. Digital vineyard management monitoring of several wine producers, differing in size and in vineyard management philosophy (i.e., conventional and organic farming), for two consecutive years served to test the claimed potential of FRW for sustainability in viticulture.

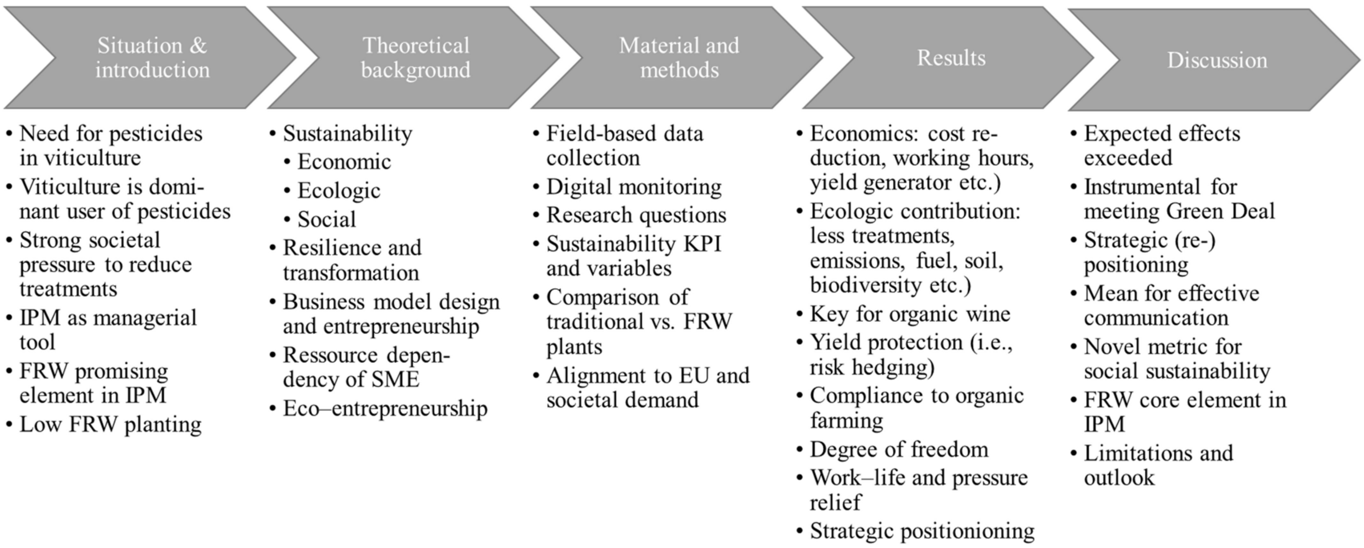

Figure 1. Empirical evaluation of sustainability impact of FRW—overview.

In line with literature-based expectations, the results manifest significant potential to reduce pesticides. Thereby, FRW show great potential to leapfrog in ecological sustainability and can serve to counteract societal pressure and to meet Green Deal EU ambitions. Planting robust varietals fosters the winery's sustainability in all three dimensions. Economic benefits stem from cost reduction but also risk hedging. A reduction of up to 80% of treatments represents a strong ecological lever in viticulture. The reduced pressure to treat robust varietals not only reduces potential harm to employees when spraying pesticides but positively affects work–life balance and relieves pressure from the vintner. New robust varietals represent a unique lever for sustainability, allow for a simplified communication of it, and increase profitability. The results underline the great value that FRW offer for organic wine production.

2. Theoretical Background: Sustainable Viticulture

The implementation of Integrated Pest Management (IPM) is central to modern pest control in viticulture. By combining chemical, biological, and cultural methods, IPM aims to reduce pesticide use and mitigate environmental impacts while ensuring crop protection [13]. Viticulture, however, remains one of the agricultural sectors with the highest pesticide dependency, which entails economic, societal, and environmental costs [14,22,25]. Therefore, for sustainability, combining those three perspectives in one framework fits as a theoretical foundation to explore the value of FRW in IPM.

Sustainability has skyrocketed in relevance for management and business. The short definition of sustainability, that today's living should not be at the expense of future generations [63], can be traced back to Carl von Carlowitz, who managed mining on behalf of the Saxon court in the 17th century. This philosophy limited forest logging with respect to the amount of planting, putting a strain on the Saxonian mining activities, which needed wood for furnaces [105]. In the 1970s, scientifically based concerns about excessive global resource exploitation, the oil crisis, and widespread famine urged a rethinking of a holistic perspective oriented around sustainability (Club of Rome) [106]. A milestone in sustainability conceptualization was the UN publication *Our Common Future* [77]. The report advocated elevating sustainability to the status of a guiding principle in the interest of making the world safe for all human populations and operationalized the concept as a parallel pursuit of economic, ecological, and social aspects. It was also during this period that the managerial principle of corporate social responsibility became a prominent strategic paradigm [107]. In parallel, sustainability developed as a lever for enterprises to gain a reputation and, thereby, a strategic advantage [59,63,108,109]. Consumers are increasingly attaching importance to sustainability, nurturing literature to explore the strategic value of embedding sustainability in design offerings [110–114]. However, sustainable business management is particularly challenging for the agricultural sector. The effort required to implement sustainability in the agricultural industry throughout Germany has been quantified to exceed 100 million Euros, which is four times the total annual value generation of the entire German agricultural production [115]. The European Commission is taking the lead for agricultural sustainability efforts manifested in the "Green Deal" [116].

Sustainability in the wine industry is a transformational phenomenon [86,87,117]. From a theoretical perspective, sustainability meets IPM characteristics of long-term decisions and safeguarding resilience [118]. Indeed, deciding on varietal planting is not short-term, as it takes time for them to come into production, and vines produce for decades [119]. Wine producers' existence is jeopardized as economic profits are scrutinized. In addition, sustainability theory serves to approach the researched matter from a perspective of systematic renewal and transition, thereby addressing the need to overcome the reluctance to reduce pesticide use [120,121]. Sustainability theory embeds grounded ideas into business model recommendations, which is of relevance to IPM in the context of entrepreneurship [101]. For this study, sustainability offers great value in bringing together eco-entrepreneurship and strategic management [100,101,104,109,122–124].

Sustainability in agriculture, and especially in viticulture, encompasses a triad of economic, ecological, and social dimensions, each essential for evaluating the contributions of fungus-resistant grape varieties (FRW) to sustainable agriculture. Brundtland's definition of sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [77], provides a foundational perspective and is particularly relevant given the intensifying environmental pressures associated with climate change. Rising temperatures, fluctuating precipitation, and evolving disease pressures underscore the need for sustainable practices in viticulture [15,20]. FRW have emerged as a promising approach to address these challenges within a structured framework. Economic sustainability pertains to the ability of FRW to reduce operational costs and stabilize vineyard profitability under variable environmental conditions. Ecological sustainability focuses on reducing the sector's heavy reliance on pesticides, particularly for combating diseases like downy mildew (*Plasmopara viticola*), while also preserving soil health and supporting biodiversity. Social sustainability, often less emphasized in agricultural research, highlights improvements in labor conditions, occupational health, and work–life balance through the adoption of practices that decrease labor intensity and chemical exposure. These three pillars collectively serve as a robust framework to assess the comprehensive sustainability impacts of FRW adoption in viticulture.

The wine industry in Germany and other wine-producing countries is characterized by small enterprises [125–128]. As such, wine producers are required to consider resource-based limitations and manage valuable and unique resources [129–131]. Hart [132] explicitly expanded the resource-based view of environmental practices by including a natural resource-based view of strategy. Especially for small enterprises with limited leveraging capabilities and funding, environmental adaptation needs to be reflected in light of resource constraints [133,134]. Economic sustainability in viticulture is increasingly critical as environmental pressures and regulatory demands for reduced chemical use continue to rise. However, a reduction of treatments jeopardizes the needed yields. Hence, FRW as a lever for sustainability should be further researched [48], and this study builds upon sustainability as a theoretical foundation. FRW varieties promise economic advantages by reducing pesticide application costs, lowering labor inputs, and promoting yield stability even under adverse environmental conditions. According to Adnan et al., sustainable agricultural practices that reduce operational costs while stabilizing production are foundational to long-term economic resilience, especially in agriculture sectors vulnerable to climate impacts [135]. Studies indicate substantial savings in plant protection costs and operational expenses [32,136], especially in years with high pathogen pressures. In addition to cost savings, FRW varieties position vineyards favorably within a competitive wine market increasingly driven by consumer demand for sustainability. For wineries, integrating FRW aligns economic sustainability with a strategic market advantage, appealing to environmentally conscious consumers and potentially strengthening their market position.

The need to preserve the environment in the course of business activities is not a new idea [109,137–139]. Natural catastrophes, climate change, pandemics, and the ending of natural resources with extensive lethal impact—e.g., starvation—render environmentalism a guiding managerial principle [64,140,141]. The topic has nurtured immense research with often contradicting findings in regard to the strategic value and performance impact of environmentalism [61]. Agriculture depends on sustainable behavior and needs to contribute. The ecological dimension of sustainability in viticulture emphasizes minimizing the sector's environmental footprint. FRW potentially serve as a key lever in ecological sustainability in meeting the EU's Green Deal objectives to massively reduce pesticide use [116]. Viticulture is crucial given the high pesticide dependency, which poses risks to both biodiversity and soil health [22,25]. Lal et al. highlighted that soil health and reducing the use of chemicals are essential for sustainable agriculture, and there is great hope for FRW adoption to reduce soil contamination and promote biodiversity [142]. If FRW hold up to the expectations of quality production by minimizing pesticide treatments, they provide a unique opportunity for a parallel pursuit of productivity and environmental integrity.

Social sustainability in viticulture encompasses factors such as labor conditions, occupational health, and overall quality of life for vineyard workers. By reducing labor intensity and minimizing chemical exposure, FRW contribute directly to social sustainability. Navarro et al. discuss the importance of reducing hazardous chemical exposure in agriculture to create safer working environments [143]. Furthermore, Duru et al. highlighted that sustainable agricultural practices contribute to improved work–life balance and enhance labor conditions, a significant consideration for labor-intensive industries, such as viticulture, facing future labor shortages [144]. Indeed, the concept of work–life balance increasingly serves as an element but also a measurement for social sustainability, shifting from the original scope of corporate societal responsibility—with a focus on the social impact to employees and external stakeholders—to include entrepreneurs in the scope of employment [122]. If FRW reduce peak labor demands and promote a more balanced workload, stress could be relieved.

3. Materials and Methods

As part of a German research project to nurture healthy vines in organic viticulture by reducing and, in the long term, replacing copper-containing crop protection agents while combatting downy mildew (https://vitifit.de/en, accessed on 22 November 2024), this study monitored and evaluated phytosanitary treatments of traditional versus robust varietals.

The empirical study intended to contribute to existent research by the following:

(a) Evaluating FRW from a holistic sustainability perspective;
(b) Analyzing FRW treatment by assessing real practice;
(c) Comparing FRW versus traditional varietal treatments;
(d) Assessing for a time horizon of more than one year.

3.1. Data Sources and Sample

The data for this research were collected from a sample of operational vineyards from four partnering wine producers in Germany. As a prerequisite, all participating wineries had to substantially produce wine from traditional as well as from robust varietals. The aim was to calculate the operational advantages and sustainability effects associated with the cultivation of robust varietals. Specifically, comparisons were intended between FRW and traditional grape varieties in terms of working hours and operating resources, and the influences on the price and cost structure, as well as on the operational key figures derived thereof. The costs for software and training to use in the monitoring system were borne by the project. In addition, some wineries decided to drop out because of privacy issues concerning the tracking of their employees [145]. All four partnering wineries were monitored for two vegetation periods of two consecutive years (2021 and 2022), with selected plots planted with traditional and FRW varietals. The population of the four wine estates was selected to cover different regions, farming philosophies, varietals, sizes, and business models, as follows:

- Wine growing regions: 3× Rhinehessia and 1× Rheingau;
- Farming philosophy: 2× organic (members of ECOVIN) and 2× conventional;
- Portfolio of varietals: 24 varietals (see Appendix A);
- Business models: 3× production and marketing of bottled wine, and 1× bulk wine;
- Monitored area: approx. 400 hectares, of which 44 hectares were FRW (=11%).

Each vineyard matched plots of both FRW and traditional grape varieties within similar environmental conditions. By using such a paired plot design, the study controlled for external factors (e.g., steepness, vegetation effects, and distance from the farm) to accurately assess differences in pesticide application, labor input, and the yield of grape varieties.

3.2. Data Collection

All of the wineries' processes in the vineyards were tracked by a digital field index and process tracking. The partners were trained in using the tracking software. An initially chosen tracking system turned out not to hold up to its promises [145,146]. All of the experience gained from the first (unsuccessful) data collection run was used to secure reliable data collection for succeeding monitoring. The software provided data on processes performed, time consumed, and materials used.

Digital tracking of the activities in the vineyards allowed for accurate monitoring and documentation of plant protection at the partnering wineries during the observed vegetation period [147]. This minimized potential Hawthorne effects [148], and an eventual bias in the vintners' strive for efficiency was addressed by comparing data within (winegrowers' treatments of their traditional and robust varietals) as well as with peers (cross-winery comparison) [22,31]. Finally, the successful app-based monitoring collected GPS (global positioning system) data and ensured the recording of all measurements (duration, working hours, etc.). Data and results have been validated by all partnering wineries.

3.3. Research Questions and Key Performance Measures (KPI)

The methods for evaluation depended on the dimension of sustainability explored (Appendix B informs about the employed variables and KPI), including:

(a) Economic impact analyses

From an economic sustainability aspect, the research questions were whether FRW allow for reduced costs, to what extent, and what were the yield implications. The observations were tagged with full costs (personnel costs (EUR 35/h for the driver) and machine costs (EUR 42/h for the tractor and sprayer)) [149]. Material costs reflected the farm-specific plant protection products used. In addition, the yields served to also cover the output variable (potential revenues) [2,3,12,13,17,32,150].

(b) Ecological impact analyses

The number of treatments (treatment frequency) served as a key measure to assess the ecological aspect [2,8,22]. More treatments imply more tractor tracks compacting the soil, negatively impacting biodiversity and increasing the risk of erosion. Additional treatments linearly increase pesticides. Expectations from the literature and practitioner reports were that pesticide treatments of new and robust vine varietals oscillate from "no pesticide spraying" up to "covering the varietals to the same extent as conventional varietals". No spraying might sound great from an ecological point of, but given the risk that the varietals lose their robustness, such behavior jeopardizes the positive ecological impact of FRW.

In organic wine production, copper is the remedy to protect the vines [151]. But copper is a heavy metal that pollutes the soil. A reduction in copper application benefits wine producers and the environment [48].

The research questions to explore the value of FRW with respect to ecological sustainability were as follows:

- Are FRW significantly reducing treatments?
- Do you vintners follow the breeders' and expert advice to not refrain from spraying?
- Do vintners treat robust varietals to the same extent as their traditional varietals?
- Are FRW a lever to reduce copper?

(c) Social impact analyses

In order to answer the research question of whether robust varietals have a positive impact on societal sustainability, the study deployed two assessment criteria.

Spraying pesticides potentially causes health problems for the employees as well as the neighboring residents. Hence, the number of pesticide treatments, especially chemical-intensive spraying, serves to measure social sustainability. Fewer treatments reduce the potential harm and enhance occupational health and safety.

In viticulture, particularly during peak seasons like harvest and pest control periods, labor demands can be very high. Vineyard managers and vintners are in stressful situations. Vintners are stressed by cost pressure, anxiety about not harvesting enough grapes, too much work in the field (especially pesticide treatments), endangering themselves, employees, or others (e.g., chemical pesticides), or being blamed or held responsible for side effects. Stress relief and, therefore, work–life balance are important in the wine industry [95,152–155]. Indeed, the increasing dynamism and complexity of environmental changes in combination with acute strain on profitability risk entrepreneurial health and point to a need for positive impacts in work–life balance [122,156,157]. Therefore, less activity (reduced treatments) without jeopardizing the grapes (an attractive yield in quality and quantity) and more flexibility (an urgency to treat the vineyards) are key to stress relief and an increase in work–life balance. Consequently, the hereby introduced KPI measuring yield over time invested serves as a social sustainability metric. A higher yield with reduced labor input signifies less time spent in labor-intensive activities, which can reduce physical strain on workers and free up time for other tasks, directly contributing to a better work–life balance. This newly introduced measure acknowledges claims in the literature to combine both aspects (output and input) when exploring sustainability [150]. In this study, the yield was measured in liters per hectare (output) against time invested (input). Indeed, digital monitoring allowed us to precisely quantify not only the number of treatments but also the time for every activity performed. Usually, pesticide treatments are valued in whether the disease can be defended against or not. The introduction of this efficiency measure allows for a much more sensitive evaluation of sustainability effects since vintners need to spare time—especially in the face of a labor shortage—and appreciate gaining flexibility. The yield-related metric reflects labor efficiency, reduced workload, and lower stress on vineyard workers, aligning with social sustainability by supporting a healthier work environment and improved work–life balance.

3.4. Analyses, Statistics and Methodological Reasoning

The dataset was analyzed using descriptive statistics and variation. The data was primarily used for comparisons within the wineries, across the monitored population, and cross-year assessments.

The methodology applied in this study is essential for producing realistic and reliable insights into the effectiveness of fungus-resistant grape varieties (FRW) in practical vineyard settings. Key reasons for using this methodology were as follows:

1. Field-based data collection to validate theoretical assumptions

Field-based data collection across two growing seasons provides a robust empirical foundation for validating theoretical claims regarding the sustainability benefits of FRW. Previous studies have often relied on experimental or "in vitro" data, which, while controlled, offer limited applicability to real-world conditions. This field-based approach addresses this gap, delivering practical insights that hold direct relevance for vineyard operations.

2. Comparative tracking of traditional vs. FRW treatments

By systematically comparing traditional grape varieties and FRW under similar conditions within the same vineyards, the study assesses the impact of variety choice on sustainability indicators, including pesticide use, costs, and labor demands. This comparative method enables precise conclusions about the extent to which FRW can reduce pesticide application and associated costs, a factor that has not been extensively explored in previous research.

3. Digital process monitoring to minimize bias

Digital monitoring systems enable the objective and continuous tracking of all relevant vineyard activities, including pesticide use and labor time. With GPS data and digital process tracking, the methodology reduces the risk of biases that may arise in manual data collection, such as the Hawthorne effect. This approach enhances accuracy, allowing for detailed evaluations of ecological and economic impacts.

4. Holistic assessment of environmental, economic, and social impacts

The methodology encompasses not only quantitative measures of pesticide reduction and cost savings but also incorporates an analysis of social sustainability, especially regarding the mental pressure in viticulture and increased degree of freedom with a positive impact on work–life balance. This comprehensive evaluation is novel in that it extends beyond conventional ecological and economic indicators, highlighting the potential of FRW to enhance the quality of life for vineyard managers and workers.

5. Alignment with EU goals and societal demand for sustainability

The methodology aims to provide relevant data supporting the EU Green Deal objectives, emphasizing the need for reduced pesticide use. By precisely measuring the treatment frequency and assessing copper application in organic vineyards, the study evaluates the extent to which FRW can contribute to achieving these targets. This is scientifically significant and practically valuable, offering vineyard managers data-driven guidance for optimizing their sustainability strategies.

In summary, the chosen methodology enabled an in-depth, practice-oriented analysis of FRW's potential, supported by precise data collected in operational settings. This strengthens the study's validity and offers valuable insights for advancing sustainable practices in viticulture.

4. Results

Digital monitoring has generated a previously unavailable database for comparing conventional grape varieties and FRW. The digital monitoring confirms that farms (conventional (conv.) and organic (org.)) can massively reduce plant protection treatments for FRW grape varieties (see Table 1):

Table 1. Phytosanitary treatments—results in year one.

KPI	Farm 1 Conv	Farm 2 Conv	Farm 3 Org	Farm 4 Org
Pesticide treatments				
Non-FRW	10	11	14	15
FRW	4	4	3/6	5
Workload (hours/hectare)				
Non-FRW	3.9	7.1	10.7	5.4
FRW	1.6	2.4	2.6	2.4
Costs (EUR/hectare)				
Non-FRW	1494	1438	1232	964
FRW	672	472	311	478
Copper use (kg/hectare)				
Non-FRW	0	0	3.0	3.7
FRW	0	0	0.8/1.75	1.3

For year one, the monitoring demonstrated that conventional as well as organic farming could profit from FRW planting. All FRW plantings needed fewer phytomedical treatments. The robust varietals offered the potential to reduce up to 80% of treatments. The year 2021 turned out to be a year with very high infestation pressure (*Plasmopara viticola* and *Erysiphe necator*) [158]. Whereas one winery had to spray 15 times for their conventional vines and even the winery with the lowest application had to engage 10 times, farm three treated their FRW only 3 times instead.

In the second monitoring year, the vegetative pressure for plant protection treatments was less pronounced than in the previous year [159]. Year two observations confirmed the results from the previous year. All vintners significantly reduced plant protection treatments for FRW but complied with the official recommendation to not refrain from not treating FRW (see Table 2).

Table 2. Phytosanitary treatments—results in year two.

KPI	Farm 1 Conv	Farm 2 Conv	Farm 3 Org	Farm 4 Org
Pesticide treatments				
Non-FRW	9	8	11	10
FRW	3–4	2–3	4	5
Workload (hours/hectare)				
Non-FRW	2.6	3.44	6.9	2.5
FRW	5.6	1.1	1.9	1.6
Costs (EUR/hectare)				
Non-FRW	1002	692	827	477
FRW	541	233	231	233
Copper use (kg/hectare)				
Non-FRW	0	0	3.0	3.7
FRW	0	0	1.6	1.3

While 2021 was an exceptional year for winegrowers due to the high infection pressure, 2022 was a rather “normal” year concerning the danger of pests. The treatments for conventional as well as FRW varied to a lesser extent. While the classic grape varieties required up to 11 treatments in the survey year, FRW required a maximum of 5. FRW thereby enabled a reduction of 5–7 treatments or reduced up to 75% of the treatments.

4.1. Economic Sustainability

FRW reduced phytosanitary costs per hectare for plant protection between 46% and 75%. The costs of plant protection could thus be reduced by up to almost EUR 1000 per hectare (see Table 3). In year one, every winery realized substantial savings in absolute and relative terms by their FRW plantings. New grape varieties make plant protection cheaper for organic as well as for conventional wine growing. As the products used in organic viticulture are less pricy, labor costs account for up to three-quarters of the total costs.

Table 3. Economic effects of FRW: costs for phytosanitary treatments (EUR/ha; FRW vs. traditional plants).

Economic Sustainability	Farm 1 Conv	Farm 2 Conv	Farm 3 Org	Farm 4 Org
Year 1				
Reduction EUR	822€	966€	921€	486€
in %	55%	67%	75%	50%
Year 2				
Reduction EUR	461€	459€	596€	244€
in %	46%	66%	72%	51%

The observations revealed a yield effect in favor of FRW grape varieties. A high infection pressure in year one, particularly due to downy mildew, led to massive yield losses in test Farm 4, for example. Despite extensive treatments with copper, it was not possible for the organic winery to achieve a sufficient economic yield level with the classic grape varieties. The actual yield of only around 3500 kg/ha (9000 kg/ha expected to be economically viable) against their FRW plants with a "normal" yield level of 7000–11,000 kg/ha illustrates that yield losses due to downy mildew in the classic grape varieties can potentially be safeguarded by FRW.

The profitability depends on the business model. For Farm 1, which markets to price-sensitive bulk wine customers, savings of approx. more than EUR 800 or in case of just 450 EUR/ha per year are highly welcomed. However, the cost reductions depend on the infection pressure with lower cost savings in years with less pest danger. The figures apply to average cultivation in flat areas. Irrespective of new or classic grape varieties, as it is expected that labor, machine, and fuel costs will continue to rise, the proportion of the observed savings by reducing treatments is expected to increase in the future.

4.2. Ecological Sustainability

All wineries treated their FRW to a lesser extent. The data illustrate that the farms follow the recommendations for plant protection treatments. FRW were treated significantly less, but plant protection measures were not dispensed, in compliance with recommendations from the breeders and experts to not endanger FRW resistance. In addition, FRW were not treated as part of the "normal" operational treatment, in deviation from previously observed and communicated operational practice. Therefore, the ecological impact could be massively reduced by (a) fewer products applied [14] and (b) fewer applications (soil protection, energy savings, CO_2 reduction, etc.) [151].

The data suggests that organic wine production can profit from FRW varietals. Organic wine production limits plant protection measures. A renunciation of chemical products increases the need for plant protection measures. Indeed, organic winemaking from a phytomedical perspective cannot claim to be more ecological, per se [14,160,161]. Tables 1 and 2 indicate that organic farming requires more treatments in both years compared to conventional farming. But FRW plantings allow organic farms to avoid up to 80% of their treatments and then even outperform conventional farms in ecological sustainability with fewer treatments. FRW varietals enable organic vintners to meet consumers' expectations to be more nature-oriented [53,162–164]. Accordingly, the analyses show an extensive reduction in the copper application by up to two-thirds with FRW plants. New and robust varietals thus contribute to relieving the soil through copper enrichment [165,166]. Farm 4 confirmed that FRW plants were key to complying with the statutory copper application limits.

The ecological advantages of new grape varieties are not only in savings on pesticides and copper but also in a reduction of CO_2 emissions due to fewer passes, and thus, a reduction in soil pollution. The risk of soil compaction is particularly high during prolonged wet periods, which require short spraying intervals. This can be avoided in systems with new grape varieties.

4.3. Social Sustainability

Table 4 illustrates that the introduced proxy to measure work–life balance strongly speaks for a better performance of FRW varietals. Just by looking at the minimal and maximal data points, FRW by length outperforms traditional varietals with significantly higher productivity.

Table 4. Sustainability proxy sustainability: efficiency (kg/hours spent).

Social Sustainability	Farm 1 Conv	Farm 2 Conv	Farm 3 Org	Farm 4 Org
Efficiency trad. variety				
min	1487	870	717	2510
max	4237	2173	1843	7143
Efficiency FRW				
min	1273	1277	1653	5028
max	17,487	12,860	6354	15,109

The data strongly supports that all four wineries were able to strongly increase their productivity since all maximum proxies for the FRW are multiple, compared to their output/input for the traditional varietals. Obviously, Winery Four proved to be highly efficient with their traditional as well as the FRW varietals, but even they tripled their efficiency via FRW. Since pesticide spraying has to be performed in short time periods, a lower proxy speaks for far more measures and the need to invest and act in the field with less wine to market. Hence, the pressure on the vintner dramatically increases.

5. Discussion and Future Research

The results of the digitally based surveys illustrate the far-reaching and weighty potential contribution of FRW varietals in achieving the sustainability goals on all three pillars. In some cases, the vintners were surprised by the considerable effects of FRW, having been informed about the results.

5.1. Results, Expectations and Literature

FRW varietals substantially lower invasive and demanding vineyard work to protect vines, and the often-cited reduction of treatments by 80% characterizes highly infectious years. The claim of the Federal Environment Agency in Germany that the most effective measure in phytosanitary treatments are robust varietals (https://www.umweltbundesamt.de/top-ten-der-wirksamsten-pflanzenschutzmassnahmen, accessed on 22 November 2024), finds strong support in this empirical data. Therefore, FRW varietals become key elements in integrated pest management to leapfrog sustainability effects [14]. The data posit that, against the literature [22], the infectious pressure (vegetation) might have a greater impact on the potential savings than the region.

FRW significantly reduce phytomedical applications and are, hence, of paramount importance to meet the EU and societal demand for fewer fungicides, as vines are heavily dependent on the use of fungicides [29,30,75,76,116,167–169]. Indeed, the hereby reported results underline that FRW are a key lever to meet the quantified ambitions to half plant treatments and in meeting reduced copper application. FRW can, therefore, be the key building block in Integrated Pest Management to fully exploit sustainability potentials [25]. All observations for the monitored wineries meet EU ambitions and even exceed the discussed targets. In addition, vintners can profit from all three dimensions of sustainability: FRW allows them to significantly save costs for plant protection, can serve to harvest enough yield in difficult years, reduce emissions, and provide benefits in the freeing of time when pressure on vintners is high. Indeed, the latter argument is so far neglected in scientific research but more prominent in the press, with articles stating the distress of vintners, the need for psychological help, and even the ruinous effects [170,171]. Still, in regard to the ecological ambition to reduce CO_2 reduction, fewer treatments are welcomed, but the effect is limited. Pesticide treatment only makes up for 1% of carbo-emission in wine [172], so savings of 60% and up to 80% are great but not key levers in the carbon footprint of wineries.

FRW offer great potential to increase social sustainability, as illustrated by work–life balance. The work pressure in summer and during the harvest has increased significantly in recent years due to climate change and is exacerbated by a lack of qualified field workers. As a result, very long working days, night work, and seven-day weeks are already the norm for many years because plant protection requires timely application. During this phase, farm managers and employees are under particular strain [33,150,171]. Burnout syndromes of German vintners are four-point-five times higher, and depression, affecting one-fourth of the vintners and farmers, is three times higher than the population average, with pesticide spraying being mentioned to be one factor for the illnesses and even suicidal events [173,174]. With new grape varieties, phases of high-capacity utilization can be eased. In rainy autumns, especially, the harvest is also eased by a longer harvest window for the new grape varieties, most of which are still healthy, while other grape varieties are already affected by rot. In recent years, the harvest period has shortened considerably, which is why it is becoming increasingly important to reduce pressure and exploit opportunities to diminish pressure. Both in crop protection and harvesting, the time saved can be invested in other areas or used as leisure time to contribute to the work–life balance of the farm manager and employees, which is an important aspect of sustainability management.

For conventional wine growing, in less infectious years and a normal spraying sequence, the phytomedical treatments amount to EUR 0.15 per liter in the premium segment (a yield of 8000 liters per hectare) and EUR 0.08 per liter for basic wine products (a yield of 15,000 liters per hectare) [175]. If the fungal pressure increases, farms react with more frequent applications and special crop protection products (e.g., more systemic crop protection products or botryticides), which are significantly more expensive. In addition, high fungal pressure has an impact on the yield, so the plant protection costs per unit skyrocket. With the cultivation of new grape varieties, plant protection measures can significantly reduce plant protection costs, including labor costs, by 77% in "easy" years and 64% in more difficult years. Savings range from EUR 0.12 for the premium segment to EUR 0.06 for the basic segment per liter. New grape varieties allow organic winegrowers to significantly reduce production costs by up to 80% or up to EUR 1000 per hectare. The savings per bottle show that plant protection costs only determine a fraction of the overall production costs of wine.

The cost benefits of new grape varieties are not limited to savings on pesticides. Other viticultural advantages, such as upright growth or loose-berried fruits that are less susceptible to botrytis, have also been specifically included in breeding and selection [176]. These advantages will become even more relevant from a business perspective due to the increasingly erratic weather conditions caused by climate change and will help to increase profitability and mitigate the impact on profits in challenging years. The profit pressure that winegrowers face asks for an assessment of FRW from an economic sustainability perspective, which has been neglected in academia so far. A global oversupply of wine refrains winegrowers from raising their prices and, given the dramatic increases in costs for materials and services, stresses their economic sustainability. All means to increase efficiency and relieve the vintners need to be seized. Although pesticide treatments only represent a fraction of wine production costs, research has valued the robustness of grapevines from an economic point of view. Binzen et al. quantify the potential cost savings for California grape growers to be as high as USD 48 million per year—a significant economic lever for the wine industry [22,32,136,177]. Prices for pesticides are skyrocketing, and additional labor and machine costs for spraying put further strain on wineries' costs when the profitability of wine estates is already putting wine estates' long-term existence at risk [178,179].

Opportunities to cut costs that are not putting value-creation at risk should be seized by the vintners—robust wines could present such an opportunity. In addition, sustainability gains ground as a fundamental managerial orientation to balance economic, ecologic, and societal goals [180]. Indeed, customers are increasingly considering sustainability in their buying decisions [52,55,57]. The societal shift towards sustainable practices is acknowledged in regulations, for example, the EU Green Deal explicitly addresses a need for a more eco-friendly agriculture with far-reaching targets to be met by the European farmers [116,181]. In order to achieve sustainability goals, agricultural entities, such as wineries, need to minimize their environmental emissions and soil impacts [87,95,167,182]. Consequently, wineries' strategic positioning depends on ecological paradigms with winery business model adaptation and organizational alignment [61,89,92,183,184]. An eco-friendly positioning offers the potential to deliver to one's strategic grouping or to open new market inroads [185,186]. All wine producers and estates, regardless of their strategic grouping, must manage value creation and costs professionally. In this limited field of action, the so-called new grape varieties open up the prospect of increasing added value in the cost and competition-oriented wine market [157,185]. FRW, thereby, can serve in communicating one's sustainability more easily [54,68,89,164].

Monitoring underlines the suitability of FRW for risk hedging and safeguarding resilience [170]. Indeed, FRW might become indispensable for wine to meet consumer expectations, positioning wine as a natural product, and especially for organic wine production [27,28,171]. The pronounced ambitions of the agricultural ministry (e.g., 30% organic wine production in the year 2030 in Germany [187]) in combination with pesticide residues regulated throughout the EU [187] and the Green Deal targets of a 50% reduction in pesticides seem impossible without leaning on FRW. The sustainability effects of FRW and especially its ecological aspects keep with the spirit of the times [188]. Even reputed wine regions suffer from financially distressed wineries, lack of perspectives for handing over estates, or just fallow land. Indeed, suicidal events and strong evidence of a lack of resilience in wine estates illustrate the need to put more emphasis on social sustainability [189–194].

5.2. Interpretation

In this study, an interpretation and analysis of the results is focused on evaluating the sustainability potential of fungus-resistant grape varieties from multiple perspectives.

1. Environmental impact assessment

Pesticide reduction: The data show that FRW significantly reduced pesticide applications, confirmed by a lower treatment frequency compared to traditional varieties. This reduction is critical for aligning viticulture practices with the EU Green Deal targets, specifically the 50% reduction in pesticide use. The findings support FRW as a viable strategy for minimizing environmental impact and meeting regulatory goals.

Copper use in organic viticulture: For organic vineyards, FRW demonstrated a marked reduction in copper application, which is a substantial benefit since copper accumulates in soil, causing long-term environmental damage. By reducing the need for copper, FRW contribute to more sustainable soil management, positioning them as an essential tool for organic wine producers aiming to comply with ecological standards.

2. Economic impact evaluation

Cost savings: The analysis reveals that FRW can lead to substantial cost savings in both conventional and organic vineyards. These savings stem primarily from reduced pesticide use and lower labor requirements for spraying. By quantifying the reduction in costs per hectare, the study provides concrete evidence of FRW's economic advantage, especially in high-disease years where treatment costs can surge.

Yield stability: In years with high infection pressure, FRW maintained stable yields compared to traditional varieties, which experienced significant losses. This yield stability suggests that FRW can function as a risk management tool, protecting against severe crop losses and thus enhancing the economic resilience of wineries.

3. Social sustainability and work–life balance

Labor intensity and stress reduction: FRW reduced the labor intensity associated with pest management, allowing for fewer, more flexible spraying intervals. This reduction not only saves time but also alleviates stress, particularly during peak treatment periods, which are often physically demanding and time-sensitive. By introducing a productivity measure (yield per time invested), the study underscores the positive implications of FRW for work–life balance, an area frequently overlooked in vineyard sustainability research.

Health and safety benefits: Reduced pesticide application also lowers exposure risks for vineyard workers, contributing to safer working conditions. This aspect strengthens the social sustainability case for FRW, addressing occupational health concerns that are critical in labor-intensive sectors like viticulture. Indeed, FRW can, therefore, represent a lever to provision for a shortage of labor in vineyard management.

4. Strategic positioning and market opportunities

Facilitated communication of sustainability: The results support the potential for FRW to enhance wineries' positioning and communication in sustainability-conscious markets. Consumers are increasingly sensitive to environmental and social sustainability, and FRW align well with these values. The study highlights FRW as a core lever to enhance brand image and appeal to eco-conscious consumers, particularly within organic and premium wine segments.

Long-term competitive advantage: By adopting FRW, wineries may gain a competitive advantage as environmental regulations tighten and consumer demand for sustainable products grows. The study suggests that early adoption of FRW can help wineries meet future market and regulatory demands, creating long-term strategic value.

The results indicate that FRW contribute significantly to reducing pesticide dependency and labor intensity, and these findings are consistent with the literature on sustainable viticulture practices and the expectations of FRW. However, unique to this study are (a) the quantified and significant reduction in actually performed pesticide treatments (against posited expectations), (b) the opportunity that FRW offer to hedge yield risks, (c) that FRW in practice have safeguarded an organic winery to comply to the strict pesticide regulations, (d) the documented social benefits (reduced exposure but also stress relief and increased flexibility), and (e) a quantified scenario base on how to meet EU ambitions. Unlike previous research that primarily highlights ecological gains, this study extends the impact of FRW to include social sustainability, a critical yet often overlooked dimension in agricultural sustainability literature.

5.3. Operational Countermeasures

Several practical countermeasures can be implemented to enhance the sustainability of viticulture using fungus-resistant grape varieties (FRW). These measures address key areas of environmental, economic, and social sustainability in alignment with regulatory and market demands. Vintners are well advised to position FRW as a central component within an IPM framework. The real-time monitoring of disease pressures specific to each vineyard and increasingly accurate weather and vegetation forecasts can serve as additional IPM components. Combining FRW with IPM methods, such as beneficial insects or canopy management, further reduces chemical dependencies and builds resilience against pest pressures over time. Such optimized IPM is key to minimizing copper accumulation, particularly in organic vineyards. This can help vintners adjust copper application rates and explore alternative organic fungicides to further reduce soil impact. In addition, alternative fungicides help to transition to environmentally friendly vineyard management.

Robust varietals are a means to increase return on investment (ROI) and, therefore, should be a key in long-term investment and financial planning. FRW allow for hedging against years with high infection pressures, as the stable yields observed with FRW mitigated the financial risks of crop loss. The study might encourage the diversifying plantings of FRW and traditional varieties to balance both market and production risks effectively. Tracing new varietals from a production, sensory, and marketing perspective helps to decide for eventual replanting.

Vintners can exploit the time saved by reduced spraying requirements and implement flexible scheduling for vineyard workers during high-demand periods, thereby decreasing stress and improving work–life balance. This can be achieved by training employees on the unique spraying needs of FRW and scheduling tasks around this reduced demand.

Wine producers evaluating whether to become certified for sustainability can strongly profit from FRW-based production methods. Organic or sustainability labels, which can be communicated to eco-conscious consumers, might strengthen brand positioning and can justify premium pricing in the market. FRW help to leapfrog the meeting of certification requirements [164,195]. Indeed, producers can base their communication or develop educational campaigns to inform consumers about the environmental and social benefits of FRW, such as reduced pesticide use, lower soil impact, and improved working conditions for vineyard staff. This messaging can be incorporated into branding to appeal to consumers who prioritize sustainable and ethical products.

Producers can exploit FRW to establish partnerships with sustainability-conscious retailers. By forming strategic partnerships with distributors or retailers focused on sustainability, they can reach new consumer segments and expand market access for FRW wines [47,196].

These countermeasures offer practical steps for integrating FRW into vineyard operations, enabling vintners to achieve environmental, economic, and social sustainability while meeting market and regulatory demands.

5.4. Limitations and Future Research

The study's limitations include the geographic concentration of vineyard samples, which may not capture the full variability of FRW performance across different climates and disease pressures. [45]. Regional factors significantly influence disease spread and resilience in vineyards, suggesting that future studies should explore a broader range of environments. Additionally, the economic calculations presented here may need adjustment as FRW adoption scales and hybrid varieties evolve, as future hybrids may offer enhanced disease resistance. Continued research on the adaptability and robustness of FRW across regions is essential to validate and expand the study's findings. In addition, this study focused on the production side. FRW varietals depend on market success [30,47,188]. In spite of recent interest from consumers, retailers [196], and producers, FRW planting is still low. A transition towards significant FRW planting requires time and investments—a big challenge considering the current market turmoil of the global wine industry. Furthermore, the impact on wine quality and sensory characteristics needs to be considered, although, in a parallel project, experts and consumers highly valued FRW wines. Since the above-calculated effects of reduced costs only affect a fraction of the overall costs of wine, economic benefit requires that FRG grapes and the wines are reflected in accordance with market prices [149].

Although this study addressed limitations of prior studies, as four wineries have been monitored for two consecutive years with observation of a portfolio of varietals, future research is invited to validate and extend the findings. Every year shows high variability in pathological infestation and its magnitude. Future FRW varietals might show even more robustness and, thereby, more impact. Regional variation needs to be considered, especially examining regions with different climates and different pathological infestations. Costs will change, and therefore the hereby reported results require recalculation in the future. Unlike the monitored vineyards, costs are significantly higher in steep or terraced areas. The partnering wineries were aware of the project, and hence, there is a potential bias that the participants are pioneers in sustainability and also wanted to prove their professionalism in reducing plant protection measures.

6. Conclusions

The contribution of this paper lies in its empirical evaluation of the sustainability impact of fungus-resistant grape varieties (FRW) within real-world vineyard settings, specifically in Germany. While prior research has often relied on experimental or "in-vitro" studies to evaluate FRW's potential, this paper fills critical gaps by offering field-based insights from multiple wineries over two years. The key contributions include:

- Empirical validation of FRW's environmental impact: This study provides concrete data on pesticide reduction achievable through FRW in operational vineyards, quantifying the environmental benefits in terms of reduced treatment frequency and lowered copper use. This real-world evidence supports theoretical claims and regulatory aspirations for more sustainable agriculture, particularly under the EU Green Deal.
- Economic assessment of cost-saving potential: Unlike previous studies that emphasize theoretical or laboratory results, this paper quantifies cost savings in pesticide applications for both conventional and organic vineyards, demonstrating that FRW can substantially reduce operational expenses and increase economic resilience in years with high disease pressure.
- Social sustainability through work–life balance metrics: By introducing a novel productivity measure (yield per time invested), this paper examines FRW's role in enhancing the work–life balance of vineyard managers and employees. This angle contributes to the less-explored social dimension of sustainability by reducing labor demands during peak pest control periods, which can mitigate stress and improve working conditions.
- Bridging sustainability in viticulture and strategic positioning: This study advocates that adopting FRW can enhance wineries' positioning within sustainability-conscious consumer markets. This insight provides a strategic marketing perspective, showing that IPM and FRW can offer wineries competitive differentiation opportunities that align with increasing consumer interest in eco-friendly products.
- The adoption of FRW align with the three core pillars of sustainable agriculture: economic, ecological, and social sustainability, positioning these varieties as central to the evolution of sustainable viticulture. Economically, FRW reduce costs and enhance resilience. Ecologically, they lower environmental impact and contribute to regulatory goals. Socially, they foster better working conditions and occupational health. This comprehensive theoretical framework highlights FRW's role as a sustainable response to the challenges of climate change and regulatory pressures, reinforcing their value as a resilient approach to modern viticulture.

In summary, this paper contributes new, practice-oriented knowledge on FRW's role in sustainable viticulture by confirming both ecological and economic advantages in real-world settings, alongside unique insights into social sustainability and market positioning strategies. FRW are key for sustainable viticulture and climate change adaptation. They appear indispensable in meeting the high expectations of the European Commission to massively reduce pesticide spraying and also copper application. FRW are by no means intended to abandon phytosanitary treatments. For organic wine production, FRW can be of paramount importance in meeting consumer expectations, complying with statuary copper application limits, ensuring resilience, and constituting convincing sustainability communication. Wineries are well advised to consider FRW in their production portfolio to hedge yield risks.

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Data Availability Statement: Data generated during the study complied with MDPI ethical standards. Since the data is proprietary to the monitored entities, further data requests require individual contact with the author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Varietals Observed

Traditional Varietals	FR Varietals
Acolon	Accent
Chardonnay	Cabernet blanc
Dornfelder	Cabertin
Gewürztraminer	Calardis blanc
Merlot	Johanniter
Müller-Thurgau	Muscaris
Riesling	Pinotin
Ruländer	Prior
Sauvignon Blanc	Regent
Scheurebe	Sauvignac
Pinot noir	Solaris
Pinot blanc	Souvignier gris

Appendix B. Explanation of Variables and Key Performance Indicators (KPI)

Treatment Frequency

The variable treatment frequency counts the number of pesticide applications per hectare per calendar year. This KPI has developed into a common measurement for pesticide treatments in the form of the Treatment Frequency Index (TFI). Fewer treatments, hence a lower FTI, indicate a lower impact on the ecologic environment (e.g., fewer tractor miles with reduced CO_2 emissions and fuel consumption) and less workload in the vineyards.

Yield per time (kg/h):

This key performance indicator measures the amount of grape yield harvested per hour of pesticide treatments. It reflects (a) labor efficiency, indicating how much can be produced in a given time frame, and (b) yield as the key to profitability since it determines having enough wine to market. Higher values suggest greater labor productivity and are an indicator of social sustainability, as they imply reduced labor intensity and potentially less physical strain on workers but also the vintners.

Pesticide reduction (%):

This metric represents the percentage decrease in pesticide usage when using fungus-resistant grape varieties (FRW) compared to traditional varieties. A higher percentage indicates greater ecological sustainability by reducing environmental contamination and protecting biodiversity.

Labor cost savings (€):

This variable calculates the reduction in labor costs resulting from fewer pesticide applications and less intensive management practices with FRW. Lower labor costs contribute to economic sustainability by improving profitability and reducing operational expenses for vineyard managers.

Copper use (kg/ha):

Specifically relevant for organic vineyards, this variable measures the amount of copper applied per hectare. Copper is a common organic fungicide but can have long-term adverse effects on soil health. Therefore, copper spraying is limited. Lower values indicate ecological sustainability by reducing soil contamination and promoting healthier soil ecosystems.

Yield stability (yield variance):

This variable represents the consistency of grape yields across different growing seasons. Low yield variance indicates stability, meaning the vineyard is less vulnerable to environmental stresses and disease pressures. This consistency contributes to economic resilience by providing reliable output.

Workload intensity (hours per hectare):

This key performance indicator tracks the number of labor hours required per hectare for vineyard management. Lower values signify a reduced workload, reflecting social sustainability by lowering labor intensity and supporting a healthier work–life balance.

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