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Sustainability-Oriented Innovations and Smart Farming Technologies in Wine Value Chains: Assessing their Impact on Sustainability Performance

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Abstract: Addressing the urgent sustainability challenges in the wine industry, this study explores the efficacy of sustainability-oriented innovations (SOIs) and smart farming technologies (SFTs) across wine value chains in Cyprus and Italy. Employing KPIs for a rigorous assessment, the research delves into the environmental, economic, and social impacts of these technologies. In Cyprus (SIP7), the integration of digital labelling and smart farming solutions led to a substantial reduction in pesticide usage by up to 75% and enhanced the perceived quality of wine by an average of 8%. Italy's SIP10 witnessed a 33.4% decrease in greenhouse gas emissions, with an additional benefit of a 5.3% improvement in intrinsic product quality. Notably, SIP10 also introduced a carbon credit system, potentially generating an average annual revenue of €4,140 per farm. These findings highlight the transformative potential of SOIs and SFTs in promoting sustainable practices within the wine industry, demonstrating significant advancements in reducing environmental impact, improving product quality, and enhancing economic viability. The study underscores the critical role of innovative technologies in achieving sustainability goals and provides a compelling case for wider adoption within the agricultural sector.

Keywords: sustainability-oriented innovations; Smart farming technologies; wine value chains; behaviour innovation; collaborative business modelling innovation; data-driven technological innovations; key performance indicators; sustainability assessment

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1. Introduction

The global wine sector has significant economic value and plays an important role in the agricultural production of many countries, including major players such as the European Union, Italy, France, and Spain [1]. However, the sector faces major sustainability challenges, ranging from overuse of water resources and pesticides to vulnerabilities due to climate change and socio-economic issues [2]. Given these challenges, sustainability assessments are becoming increasingly important for the wine sector to identify opportunities for improvement and develop sustainable practices [3]. These assessments aim to consider the environmental, social and economic impacts of wine production and enable wineries to make informed decisions that promote a more sustainable future.

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Assessing sustainability in the wine industry faces unique challenges and constraints, mainly due to the complex intertwining of environmental, economic and social factors that characterise this industry [4]. This sector is closely linked to terroir, which makes it highly vulnerable to climate change and requires sustainable practices to ensure its longevity [5,6]. However, current assessment methodologies have several limitations and gaps, despite sustainability being recognised as crucial for the survival and competitiveness of the industry. Existing assessment tools often prove to be too narrow, too conceptual or focus only on a few selected tools or areas, thus failing to capture the intricacies of sustainable wine production [6–9]. This lack of uniformity and the ambiguity of the sustainability concept itself often lead to biassed designs, misinterpretations, flawed conclusions and difficulties in comparing data [6,10–12]. Further gaps exist due to the lack of empirical studies addressing sustainable land management in the wine industry, with few identifying the key actors enabling such transformation. There is also a significant lack of assessment tools developed specifically for the wine industry [5,8,12–15], leading to a lack of research on sustainability issues within the sector, even with well-known methodologies such as Environmental Footprint Assessment (EFA) or Life Cycle Assessment (LCA).

Opportunities for the wine industry lie in the development of robust, contextual sustainability assessment tools that can clarify sustainability, make it more measurable, and support informed decision-making to navigate the intricacies of the broader sustainability discourse. At the heart of this transformation lies the integration of environmental, social and economic sustainability dimensions throughout the agricultural value chain. Sustainability-oriented innovations (SOIs) encompass various practices, methods and technologies aimed at optimising resources, reducing waste, preserving biodiversity and achieving equitable economic growth. Thus, to address the sustainability challenges, the agri-food sector is increasingly turning to SOIs and smart agriculture technologies [16]. These solutions span a wide spectrum, from AI-powered decision support systems and IoT-enabled precision agriculture technologies to collaborative business models [17,18]. Despite their potential, the extent to which these innovations are being implemented in the wine industry is still largely unexplored, which is a promising area for study [19]. A particularly intriguing model of interest is the Sustainable Innovation Framework (SIF)[20]. The SIF provides a holistic assessment of sustainability-driven innovation at the value chain level and focuses on three dimensions: Behavioural innovation and social engagement, sustainable collaborative business model innovation and the application of data-driven technological innovation. Applying the SIF to the wine industry can provide a structured and comprehensive understanding of the impact of these innovations [21]. As part of the H2020 project PLOUTOS (https://ploutos-h2020.eu/), a series of eleven (11) large-scale Sustainable Innovation Pilots (SIPs) were launched to address the challenges of different agri-food value chains. Two of these SIPs, SIP7 "Enhancing the sustainability performance of wine producers in Cyprus" and SIP10 "Increase sustainability in the grapevine sector by introducing payments for ecosystem services provision" in Italy focused on the grape production for wine industry. The aim of this study is to assess the sustainability performance of innovative wine value chains under real-life conditions and compare them with conventional practices. In fact, the study evaluates the proposed smart farming solutions in use cases in Cyprus and Italy. To achieve this, established evaluation criteria and appropriate Key Performance Indicators (KPIs) are used to comprehensively analyse the environmental, social and economic sustainability impacts. The research design includes qualitative and quantitative approaches to gain insights into the implementation of SOIs in the wine industry. This study introduces novel empirical insights into the sustainability performance of wine value chains enhanced by smart farming technologies (SFTs) and SOIs, providing a comprehensive assessment through real-life use cases in Cyprus and Italy, thereby offering a significant advancement in the methodological approach to sustainability assessments in the wine sector. Through rigorous data collection and analysis, this study aims to provide valuable insights to improve sustainability practises and promote a more resilient and sustainable future for wine value chains in Europe and elsewhere.

2. Materials and Methods

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2.1. SIP7 "Enhancing the Sustainability Performance of Wine Producers in Cyprus"

Cyprus is an island country located in the eastern Mediterranean and has a typical Mediterranean climate with long, hot, dry summers and mild, wet winters. The Cypriot agricultural sector is relatively small, accounting for merely 2% of the Gross Domestic Product, yet highly diversified, with a large number of different crops, such as rainfed cereals, fodder crops, vegetables, potatoes, citrus, vines, olives, nuts and fruit trees [22]. Ancillary production includes dairy products, such as halloumi cheese, and grape products, such as local wines [23]. It is worth mentioning that, due to its small size, the Cypriot agricultural sector is not able to compete with countries that typically produce large volumes at low cost; therefore, Cyprus is primarily focused on the production of high-quality products [22], such as wines made from indigenous grape varieties [24].

Cyprus has a long history and culture as a wine producing country since ancient times [25]. In fact, it is considered one of the first countries in which viticulture and wine production was practised [26]. As one of the oldest wine-making countries, Cyprus has more than ten indigenous grape cultivars, such as *Xynisteri*, *Mavro*, and *Maratheftiko*, which are well adapted to the semi-arid climatic conditions of the island, as compared to introduced cultivars, such as *Chardonnay* [27,28]. As noted by Georgiou et al. (2020) [25], the foundation for the sector's sustainability and expansion is laid by Cyprus' long history in viticulture, its distinctive local varieties, and the newly reorganised and formed vineyards and (local) wineries with a promising future for the sector's sustainability and business growth. Actually, following the accession of Cyprus to the EU in 2004, the Cypriot wine sector received significant investments and funding that boosted the local wine industry [25]. In this respect, the recent study of [24] in Cyprus concluded that mountain family wineries are economically viable businesses and share the common goal of improving the quality of the wine produced.

Notwithstanding the above, the Cypriot wine sector (especially the small wine grape producers and wineries) still faces several problems that jeopardise its sustainability. The most important ones can be summarised as follows: the small and fragmented farms, the ageing of farmers, the high input and production costs (e.g., pesticides, labour), the relatively low selling prices of grapes and wines, the low adoption rate of new technologies and innovations, the lack of an integrated common marketing and branding strategy, the sharp increase of wine imports (competition with cheaper wines), and the parallel dramatic decrease of exports [22,24,25]. Therefore, farmers and wineries need to find ways to increase their efficiency, reduce costs and get better or premium prices to match their efforts for high-quality products. In this vein, [25] argue that innovation becomes a strategic tool for wineries in order to improve their competitiveness and sustainability.

According to the last agricultural census [29], there are ca. 8,600 vineyard holdings with 6,600 ha of Utilised Agricultural Area (UAA) in Cyprus; only about 15.5% of this area is irrigated. The average vineyard holding size is ca. 0.8 ha and is among the smallest in the EU [30]. Most vineyards are found in the mountainous and semi-mountainous communities of the district of Lemesos, representing about 40% and 44% of the total number of vineyard holdings and UAA, respectively [29]. Within the Lemesos district, a mountainous community known for its long history and tradition of wine-making is Omodos (altitude > 800 m), where about 222 ha of UAA (the largest area among all communities in Cyprus) are almost entirely dedicated to the cultivation of non-irrigated wine grapes [29]. In addition, there are currently more than 60 wine-making enterprises in Cyprus, with a production value of more than 30 M€ [31]. Most of them are small to medium-sized regional wineries situated in the districts of Lemesos and Pafos.

2.1.1. Main Objective and Study Area for SIP7

The goal of the pilot in Cyprus was to improve the sustainability performance of wine grape producers and wineries, by combining SFTs and digital labelling solutions. For this purpose, the relatively newly established "Oenou Yi" winery (https://oenouyiwine.com/) located in the community of Omodos was used as a case study. The winery owns and manages around 100 ha of vineyards, while also buys wine grapes from other farmers under contracts.

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2.1.2. Proposed Technological Solutions for SIP7

To achieve the goal of this study and help address some of the challenges faced by the Cypriot wine sector, such as reducing production costs and achieving higher selling prices, we propose a mix of two technological solutions: namely a combination of SFTs and digital labelling solutions. Specifically, we first established a wine grapes production support mechanism, combining a human component (i.e., researchers and agronomists) and a smart farming solution, which was applied in the vineyards of the winery. Next, a wine digital labelling solution (e-label) was developed, using data from both the smart farming solution and the winery's management system.

In the context of this study, a digital or electronic label or simply e-label is defined as "a dedicated webpage compiling structured information on a precise product, for a specific market. The e-label is made available to consumers through a unique QR code printed on the back physical label of the product. By scanning the QR code with a smartphone, consumers are directly led to the e-label of the product they have scanned" (https://www.u-label.com/ulabel/faqs#group-faq-803).

The smart farming solution used in this pilot is the gaiasense™, which is described in detail in [32]. The solution utilises a set of information sources that include IoT-enabled telemetric stations, earth observation services, a farmer's digital calendar, and field observations. In the framework of this pilot, two autonomous telemetric stations were installed in two separate vineyards of the winery in Omodos, representing different microclimatic zones and grape varieties. The aim was to collect detailed data (e.g., temperature, relative humidity, precipitation, wind speed and direction, atmospheric pressure, soil moisture, leaf temperature, humidity, and wetness) for at least two growing periods (2022 and 2023). The data collected from the sources described above were stored and analysed in the cloud computing infrastructure of the technology provider to develop and validate the pest optimization models. The plant protection models developed and adapted in the context of the pilot concerned two main diseases of grapes, namely Downy Mildew and Powdery Mildew. In the end, an advice for the application of pesticides was generated by the system and mediated to the winery's agronomist via SMS. A web-based application with selected agri-environmental parameters was also developed to support the provision of the advice.

With regard to the second proposed technological solution, a QR code-based wine traceability application that acts also as a digital label and promotes product quality and sustainability information to the end-users (consumers) was developed in two stages. First, the research team prepared a comprehensive list of information that could be included in the e-label and shared with the consumers. This was done after reviewing relevant studies and in consultation with experts from the PLOUTOS project. The final list was validated by the winery's staff (owner, sales manager, oenologist, sommelier, and agronomist) and included the following information: vineyards' location and soil type, grape varieties, alcohol content, ingredients, nutritional value (calories), duration of ageing in barrel, bottling date, storage temperature, serving temperature, gastronomic matches, wine distinctions, description of the smart farming technology used and the potential benefits for the environment, and real time microclimate agri-environmental parameters (e.g., temperature, humidity, and rainfall) obtained from the telemetric stations. Two short videos were also created to enhance the consumer's experience. The one video presents the sustainable practices applied by the winery and the other one presents the pilot wines through an interactive discussion between the oenologist of the winery and the sommelier.

The second stage involved the development of digital labels (webpages) and QR codes for two local wines (a white and a red) made from indigenous grape varieties. All the aforementioned information and videos were integrated into the e-label in a user-friendly interface. Afterwards, the QR codes were placed on the back physical (printed) label of the wine bottles. The perceived quality of the two wines was assessed by experts in two phases: before and after placing the QR codes on the bottles, i.e., with and without the e-labels. This process is described in the next sub-section.

Two hypotheses were established: (a) the smart farming solution, *ceteris paribus*, will help the winery to minimise pesticides application, reduce production costs, and improve working conditions for agronomists and staff working in the fields; and (b) the digital labelling solution, *ceteris paribus*, will contribute to an increased wine quality, as perceived by the experts/consumers.

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The following paragraphs are focused on describing the process employed to measure the impact of innovations on the sustainability performance of the studied winery.

2.1.3. Performance Measurement Framework for SIP7

The performance measurement framework for SIP7 involved three steps. First, an initial set of KPIs was created based on previous studies (e.g., [33–36]) and established sustainability tools or frameworks (e.g., [37–41]). The KPIs were chosen according to their relevance to this study, viz., be suitable to capture the performance of the SOIs and measure their impact on the sustainability performance of wine value chains. The KPIs were then classified by sustainability pillar (economic, environmental, and social) and attribute (pollution, profitability, product quality, and labour).

Second, from the KPIs identified in the literature, four were selected for the needs of this study according to the following criteria: (1) relevance to the context of the study, as previously described; (2) end-user value; (3) data availability; and (4) data measurability [33]. The selected KPIs are as follows: "Pesticide use" indicator measures the quantity of pesticides used (solid and liquid) per unit of land (i.e., 1 ha of vineyard) to monitor the two main grape diseases (Downy Mildew and Powdery Mildew). "Production cost" indicator measures the total cost of producing wine grapes per ha. "Perceived quality" indicator refers to the judgement of consumers about the overall quality of a wine. Finally, "working time" indicator measures the total human labour required to produce wine grapes per ha. In essence, "pesticide use", "production cost" and "working time" indicators were chosen to assess the impact of smart farming technology on the sustainability performance of wine value chain, while "perceived quality" was used to assess the impact of digital labelling.

During the second step, baseline and target values were set for all KPIs. In particular, the baseline values of the KPIs "pesticides use", "production cost" and "working time" were determined by the research team and the agronomists of the winery based on historical data (viz., average values of the previous five years as recorded in the winery's management system). The baseline values of the KPI "perceived quality" were calculated for two local wines (a white and a red) made from popular indigenous grape varieties. In the absence of any historical data, the baseline values of this KPI were determined using a short, specially designed questionnaire, which was sent to 20 wine experts (oenologists, sommeliers, wine writers and viticulturists) with an intimate knowledge of the local wines. Ten (10) experts for the white wine and 11 for the red wine completed the questionnaire (in late 2021). The questions/variables used to calculate the perceived quality indicator were adapted from [36] and are described in Table 1, while their baseline values are shown in Table 2. The target values of the KPIs were defined jointly by the research team, the agronomists of the winery, and the experts of the smart farming technology provider, based on previous experience and with the aim to be as realistic as possible.

Table 1. Variables used for calculating the perceived quality of wines in SIP7 (adapted from [36]).

Question/Variable	Dimension	Rating scale
Q1. How much do you think the wine XXX is safe with respect to heavy metals, agrochemical residues, food additives, preservatives etc.?	Food safety	1 = not safe; 10 = very safe
Q2. How do you rate the nutritional profile (calories, fats, proteins, vitamins, etc.) of the XXX wine?	Health and nutritional aspects	1 = poor nutritional composition; 10 = very good nutritional composition
Q3. How do you rate the age maturity of the XXX wine?	Sensory	1 = very low; 10 = very high
Q4. How do you rate the grape variety/varieties of the XXX wine?	Sensory	1 = very bad; 10 = very good
Q5. How do you rate the attractiveness of the label of the XXX wine?	Brand economic factors	1 = very poor; 10 = very nice

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Q6. How strong is the link between the XXX wine and its area of production and local traditions?	Provenance	1 = wine not linked to the area of production; 10 = strong link to the area of production
Q7. To what extent do you think the production of the XXX wine is based on environmentally friendly practices [e.g., low CO_2 emissions, low input use (e.g., fertilisers, pesticides), attention towards biodiversity, etc.]?	Ethics	1 = low assurance; 10 = high assurance

Note: XXX in the questionnaires was replaced by the brand of the white or red wine.

Table 2. Baseline values (weighted mean ± SD) of the perceived quality variables for the two studied wines (white and red) and internal consistency (Cronbach's α) of perceived quality indicator (SIP7).

Question/Variable	White Wine (n = 10)	Red Wine (n = 11)
Q1	7.74 ± 2.20	8.84 ± 1.09
Q2	8.02 ± 2.04	8.33 ± 1.79
Q3	6.98 ± 1.86	8.40 ± 1.25
Q4	8.72 ± 1.56	9.00 ± 1.03
Q5	7.60 ± 1.59	8.38 ± 1.41
Q6	8.57 ± 1.88	8.96 ± 1.68
Q7	6.65 ± 2.37	7.53 ± 1.67
Perceived quality indicator	7.73 ± 1.54	8.47 ± 1.08
Cronbach's α	0.87	0.85

n: number of experts; for a description of the questions/variables see Table 1.

The questionnaire used to calculate perceived quality consisted of two parts. In Part A, the respondents were asked to assign a weight to each question using a Likert scale ranging from 1 (=not important for the quality of a wine) to 5 (=very important for the quality of a wine). In Part B, respondents were asked to provide a score to each question using a rating scale from 1 to 10, where 1 represented the lowest value and 10 the highest value. The perceived quality indicator for each respondent was calculated as the weighted average of the scores provided in Part B and the weights assigned in Part A of the questionnaire. Thus, the final indicator is a numeric score ranging from 1 (low perceived wine quality) to 10 (high perceived wine quality).

All the selected KPIs, together with the sustainability pillars and attributes they represent, measurement units, baseline values, targets, and source of data used for their calculation, are shown in Table 3.

Table 3. Baseline and target values of the KPIs selected for assessing the impact of innovations on the sustainability performance of wine value chain in SIP7.

KPI	Sustainability Pillar	Sustainability Attribute	Measurement Units	Baseline Value	Target (%)	Data Source
Pesticide use (solid)	Environmental	Pollution	kg/ha/yr	240	−15.0	Winery record-keeping system
Pesticide use (liquid)	Environmental	Pollution	L/ha/yr	1	−15.0	Winery record-keeping system
Production cost	Economic	Profitability	€/ha/yr	1,900	−10.5	Winery record-keeping system
Perceived quality (white wine)*	Economic	Product quality	Score (1–10)	7.73	+10.0	Specially designed questionnaire
Perceived quality (red wine)*	Economic	Product quality	Score (1–10)	8.47	+10.0	Specially designed questionnaire

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Working time	Social	Labour	hrs/ha/yr	290	−5.0	Winery record-keeping system

* For the baseline values of "perceived quality" indicator for the two wines see Table 2.

The last (third) step of the measurement framework was concerned with the collection of data and the calculation of the KPIs. Specifically, for the KPIs "pesticides use", "production cost" and "working time" data were collected in two phases, viz., in the end of the growing periods 2022 and 2023. The final values of the KPI "perceived quality" for the two wines were calculated in mid-2023 —after placing the QR codes on the back physical label of the wines— using the same process described above. The questionnaire was completed by 18 and 16 experts for the white and the red wine, respectively.

2.1.4. SIP7 Data Collection and Utilisation

For the SIP7 study focusing on enhancing the sustainability performance of wine producers in Cyprus, data collection was a critical component of the research methodology. Data were gathered through a multifaceted approach to ensure comprehensive coverage of the variables of interest. Firstly, environmental and agronomic data were collected from two autonomous telemetric stations installed in the vineyards of the "Oenou Yi" winery in Omodos. These stations were equipped with IoT-enabled sensors to monitor a wide range of agri-environmental parameters, including temperature, relative humidity, precipitation, wind speed and direction, atmospheric pressure, soil moisture, leaf temperature, humidity, and wetness. This data collection was aimed at supporting the development and validation of pest optimization models for managing Downy Mildew and Powdery Mildew diseases, critical to the sustainability of grape production.

In addition to the environmental data, the study also involved collecting data related to the wine digital labelling solution (e-label). This included generating a comprehensive list of information to be included in the e-labels, validated by the winery's staff and integrated into QR codes on wine bottles. The perceived quality of the wines, before and after the implementation of e-labels, was assessed through questionnaires distributed to wine experts. These questionnaires were meticulously designed to capture experts' judgments on various aspects of wine quality, including safety, nutritional profile, age maturity, grape variety, label attractiveness, provenance, and environmentally friendly production practices. The data from these questionnaires were analysed to quantify changes in the perceived quality of the wines. All collected data were systematically stored and analysed, leveraging cloud computing infrastructure for environmental and agronomic data and statistical software for the analysis of survey responses. This holistic approach to data collection was pivotal in assessing the impact of the proposed technological solutions on the sustainability performance of the Cypriot wine sector.

2.2. SIP10 "Sustainable Grapevine Sector: Payments for Ecosystem Services in Italy"

Italy is one of the largest wine producers and consumers in the world, with a long tradition and culture of viticulture and oenology [42]. According to the International Organisation of Vine and Wine (OIV) Statistical Database, Italy had a vineyard area of about 690,000 hectares and a wine production of about 47.5 million hectoliters in 2019, ranking first in the world in both indicators [43] The Italian wine sector is characterised by a high diversity of grape varieties, wine styles, production systems, and geographical indications, reflecting the rich natural and cultural heritage of the country [42]. The wine sector is also an important driver of the rural economy, providing income and employment opportunities for many farmers and wineries, especially in marginal and less-favoured areas [42,44]. Moreover, the wine sector contributes to the provision of various ecosystem services, such as biodiversity conservation, soil protection, carbon sequestration, and landscape aesthetics [45].

However, the wine sector also faces several challenges and pressures that threaten its sustainability, such as climate change, water scarcity, pest and disease outbreaks, market competition, changing consumer preferences, and demand for social and environmental standards [42,45,46]. To cope with these challenges and to enhance their sustainability performance, wine actors need to adopt innovative solutions that can improve their efficiency, quality, resilience, and competitiveness, while reducing their environmental and social impacts. In this context, SOIs and SFTs play a key role, as they can offer new opportunities and benefits for the wine sector, such as precision agriculture, digitalization, traceability, certification, and circular economy [2,47].

One of the examples of SOIs and SFTs adoption in the Italian wine sector is SIP10, which stands for "Sustainable Grapevine Sector: Payments for Ecosystem Services Provision"and focuses on the implementation of a Decision Support System (DSS) called vite.net®, which allows grape growers to calculate the Carbon Credits (CCs) generated by adopting sustainable vineyard management practices, such as reducing the use of pesticides and fertilisers, and to valorise them on the voluntary market. SIP10 also introduces a parametric insurance mechanism that protects the farmers from weather conditions that are favourable for grape disease development.

2.2.1. Main Objective and Study Area for SIP10

Viticulture provides multiple ecosystem services (benefits humans gain from the environment and from properly functioning ecosystems) to the whole community. The remuneration for the provided ecosystem services can complement the economic income of the farmers. For instance, sustainable vineyard management makes possible a relevant reduction in the greenhouse gases (GHG) emission, contributing to fight global warming. CCs saved by farmers through proper vineyard management can be remunerated, as there is an increasing voluntary (or over the counter) market, in which CCs can be sold to industries and individuals willing to voluntarily compensate for their emissions or provide an additional contribution to mitigating climate change. The challenge for accessing this new, interesting and growing market is: i) to define an appropriate protocol for CCs calculation in the agricultural sector; compliant with the ISO14064 standard; ii) build up a system for calculating emission reductions achieved in the sustainable farm management; iii) having the emission reductions certified by third party certification body; iv) make the Verified Emission Reduction (VER) available to buyers through specialised exchanging platforms. Moreover, a parametric insurance mechanism was also introduced for the failing of sustainable vineyard management through the DSS (specifically for the control of pests and diseases).

SIP10 activities were carried out in the North of Italy, in the municipality of Ziano Piacentino in the Piacenza Province. The activities involved Università Cattolica del Sacro Cuore, Horta srl, and 15 farmers belonging to the association "Sette Colli di Ziano".

2.2.2. Proposed Technological Solutions for SIP10

To address the challenges faced by the Italian grapevine sector, particularly in terms of economic sustainability, SIP10 introduces an innovative blend of SFTs coupled with a novel approach for the calculation and monetization of CCs. This strategy is designed to enhance the environmental and economic performance of vineyards through two key technological interventions: the enhancement of the vite.net® DSS for sustainable vineyard management, and the establishment of a parametric insurance mechanism to mitigate financial risks from climate variability.

The vite.net® DSS lies at the heart of SIP10, now enhanced to facilitate the sustainable management of vineyards. This advanced system integrates a variety of data sources, including IoT weather stations, direct field observations, and recordings of the operations performed in the field. In this pilot, critical environmental data such as temperature, humidity, rain amount are meticulously collected and analysed. These data, together with informations inputed from the user, feed mathematical models and algorithms present in the DSS, which provide decision support to the crop manager for optimising vineyard practices, thus reducing carbon footprint and the promoting carbon sequestration within the soil and plant biomass.

The DSS is instrumental in offering tailored recommendations for sustainable vineyard practices, while also calculating the potential generation of CCs from these practices. These calculations adhere to recognized standards, ensuring the credibility and marketability of the CCs on voluntary exchange platforms.

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A pioneering component of SIP10 is the implementation of a parametric insurance mechanism. This innovative insurance model offers grape growers financial protection against the unpredictable weather conditions that can lead to grape diseases, thereby securing their income from such climatic risks. This insurance policy relies on the DSS's models' outputs for the identification and quantification of the occurred damage, and provides a comprehensive risk management tool for farmers.

At the core of SIP10's strategy is a sophisticated digital framework for the accurate calculation, certification, and trading of VERs. These VERs are computed in alignment with the ISO14064 standard, facilitating their availability for trade on dedicated platforms. This mechanism empowers grape growers to unlock an additional revenue stream by selling the CCs accrued through adherence to sustainable management practices.

The impact of SIP10 is gauged through two hypotheses: (a) the enhancements made to the vite.net® DSS, alongside the parametric insurance mechanism, will drive a shift towards more sustainable vineyard management practices, thereby reducing carbon emissions and bolstering the economic sustainability of grape growers; (b) the capability to quantify, certify, and monetize CCs will furnish farmers with an auxiliary income source, enhancing the economic resilience of the grapevine sector.

The success of SIP10 will be evaluated using metrics that reflect the reduction in carbon emissions, the volume of CCs generated and successfully marketed, and the overall enhancement in the economic sustainability of the vineyards involved. This evaluation leveraged data from at least two consecutive growing periods to deliver a thorough assessment of the pilot's effectiveness and its impact on sustainability performance.

2.2.3. Performance Measurement Framework for SIP10

The performance measurement framework for SIP10 adopts a structured methodology, encompassing three distinct phases to evaluate the impact of innovative technologies on the sustainability of grapevine cultivation and CCs generation.

An initial set of KPIs was formulated, leveraging insights from existing sustainability frameworks and methodologies pertinent to the grapevine sector and the novel implementation of a carbon credit system within SIP10. These KPIs were selected to accurately gauge the efficacy of SFTs and the carbon credit mechanism, ensuring they reflect the initiative's sustainability objectives. Subsequently, the KPIs were systematically categorised under the three pillars of sustainability: economic, environmental, and social, with further delineation based on specific attributes like emission reduction, cost efficiency, and social benefits.

From the comprehensive list of potential KPIs, a curated selection was made to align with SIP10's unique context, emphasising relevance, end-user value, availability of data, and ease of measurement. The chosen KPIs include:

- Carbon Credit Generation: Quantifying the volume of CCs produced by implementing sustainable practices in vineyards.
- Reduction in Carbon Emissions: Measuring the reduction in GHG gas emissions because of adopting sustainable vineyard management practices.
- Economic Benefit from CCs: Evaluating potential financial returns derived from the sale of CCs.
- Adoption of Sustainable Practices: Monitoring the uptake of sustainable practices as recommended by the enhanced vite.net® DSS.

Baseline values for these KPIs were determined using historical data, expert consultations, and preliminary assessments at the outset of the project. Where historical data were lacking, estimates were made through expert judgement and initial evaluations. Target values were collaboratively set with the involvement of agronomists, project coordinators, and technology experts, aiming for goals that are both ambitious and attainable.

Data gathering for the selected KPIs was carried out over two growth cycles (2021 and 2022), facilitating an in-depth analysis of the technological interventions' sustainability impacts. For KPIs

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concerning carbon credit generation and emission reductions, data procurement was primarily executed through the DSS, with independent audits ensuring accuracy. Economic impacts and the degree of adoption of sustainable practices were evaluated through direct engagements, including surveys and interviews with participating farmers.

The process of calculating each KPI involved the comprehensive aggregation and analysis of the collected data against the baseline figures, facilitating a critical evaluation of progress towards achieving the predefined targets. This evaluative mechanism was pivotal in assessing the smart farming solutions' success in SIP10, particularly their contribution towards advancing the grapevine sector's sustainability.

This framework mirrors the approach detailed for SIP7, and the performance measurement for SIP10 was designed around a suite of KPIs derived from the SOIs framework. These KPIs were specifically chosen to rigorously assess the sustainability outcomes of the pilot activities across various domains. Within the environmental domain, KPIs such as "Pesticide Use", which tracks the volume of active substances utilised per vineyard area, and GHG, calculated per ton of product, were pivotal in measuring the ecological impact of the initiatives. Economically, the focus was placed on KPIs like "Intrinsic Product Quality" and "Revenues from Carbon Credit Sales", which gauge the qualitative impact on products and the financial benefits derived from engaging in carbon trading. Social sustainability was evaluated through indicators such as "Sustainability Certifications and Labels", which reflect the adoption and recognition of sustainable practices facilitated by the DSS.

The process of defining baseline and target values for these selected KPIs was the result of a collaborative effort involving the research team, participating farmers, and agronomists. This cooperative approach ensured that the KPIs were grounded in historical data and aligned with realistic expectations and trends, providing a solid foundation for the comprehensive assessment of SIP10's sustainability impacts. The identification and detailed description of these KPIs for SIP10 can be found in Table 4, encapsulating the multi-faceted approach to monitoring and enhancing the sustainability of the pilot activities.

Table 4. Baseline and target values of the KPIs selected for assessing the impact of innovations on the sustainability performance of wine value chain in SIP10.

KPI	Sustainability Pillar	Sustainability Attribute	Measurement Units	Baseline Value	Target (%)	Data Source
Pesticide use	Environmental	Pollution	kg active substance/ha	22.5	−20.0	Data entered in the DSS field book
Greenhouse Gas emissions	Environmental	Pollution	tons CO_2 equivalent/t product	0.4	−20.0	Data entered in the DSS field book
Intrinsic product quality	Economic	Product quality	Brix	20	+5.0	Data entered in the DSS field book
Revenue linked to carbon credits	Economic	Profitability	€/ha	0		Average Carbon Credit price
Sustainability certifications and labels	Social	Transparency	Number	0	1	Certification of Verified Emission Reduction

2.2.4. SIP10 Data Collection and Utilisation

For SIP10, an intricate data collection process was employed, harnessing the capabilities of the vite.net® DSS. Vineyard managers, encompassing farmers or consultants, played a pivotal role in this process by inputting comprehensive details about their vineyards into the DSS at the onset of the

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cropping season. This initial data entry covered essential field characteristics such as location, soil texture, crop variety, and planting details. Additionally, each field was associated with a weather station, enabling the registration of key weather variables crucial for accurate monitoring and decision-making throughout the season. As the cropping season progressed, farmers were responsible for logging all vineyard management activities in the DSS, including soil and plant management strategies and measures taken for pest and disease control.

To establish a robust baseline for evaluating the impact of sustainable vineyard management on carbon emission reductions, data were also collected from vineyards in neighbouring farms not participating in SIP10 and those not utilising any form of technological support. This comparative approach facilitated a clearer assessment of the technological interventions' efficacy in enhancing sustainable practices and their environmental benefits.

Within SIP10, the comprehensive dataset compiled by farmers via the DSS was instrumental in calculating both carbon emissions and carbon sequestration rates, expressed in CO_2 equivalent. This analysis was crucial in quantifying the environmental impact of the sustainable management practices adopted in the vineyards. By leveraging this data, the study aimed to provide a nuanced understanding of how technological support, specifically using the DSS, contributes to mitigating climate change impacts by reducing carbon emissions and enhancing carbon sequestration in vineyard ecosystems.

3. Results

3.1. Overview of the Results

This section provides a succinct summary of the findings from the SIPs 7 and 10, which have both endeavoured to incorporate SOIs and SFTs into the viticulture sector. Through a detailed analysis of KPIs, the results showcase the varied impacts these initiatives have had on enhancing the sustainability of wine production. From environmental improvements, such as significant reductions in pesticide use and greenhouse gas emissions, to economic benefits like increased revenue through CCs and intrinsic product quality, both SIPs illustrate the transformative potential of integrating advanced technologies and sustainable practices in the wine industry. Additionally, the social benefits, including improved working conditions and the achievement of sustainability certifications, highlight the comprehensive approach of these pilots towards fostering a more sustainable and resilient wine value chain. The subsequent sections delve into the specific outcomes of each pilot, comparing their approaches and achievements in leveraging SOIs and SFTs to address the multifaceted challenges of sustainability in the wine industry.

3.2. Results for SIP7

The mean values of the composite KPI "perceived quality" for the two studied wines (white and red), as calculated after placing the QR codes on the back physical label of the wine bottles, are presented in Table 5. It is evident that, compared to the baselines (Table 2), the values of this KPI increased by ca. 12.5% and 3.4% for the white and red wine, respectively, resulting in an average increase of 8% for both wine products (Table 6). However, the target of a 10% increase was not reached for the red wine. In any case, considering that the only difference between the baseline and final calculations was the addition of the digital labels —all other features of the wine products remained rather unchanged—, we assume that the increase in wine perceived quality was most likely due to the digital label. This increase might also lead to additional value (premium price) in the near future. Moreover, as supported by the experts themselves during the completion of the questionnaires, the two digital labels can enhance wines' traceability and improve market transparency; they provide access to more information than can be displayed directly on the physical label, thereby enabling informed decisions by consumers. Consumers' willingness to pay more for a wine with a digital label is a subject of future research.

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Table 5. Final values (weighted mean ± SD) of the perceived quality variables for the two studied wines (white and red) and internal consistency of perceived quality indicator.

Question/Variable	White Wine (n = 18)	Red Wine (n = 16)
Q1	8.74 ± 1.30	8.84 ± 1.63
Q2	8.42 ± 1.88	7.98 ± 1.23
Q3	8.47 ± 1.92	9.13 ± 1.04
Q4	8.83 ± 1.34	9.72 ± 0.80
Q5	9.03 ± 0.82	8.04 ± 1.60
Q6	9.03 ± 0.98	9.29 ± 1.29
Q7	8.56 ± 1.33	7.96 ± 1.97
Perceived quality indicator	8.70 ± 1.11	8.76 ± 0.88
Cronbach's α	0.91	0.71

n: number of experts; for a description of the questions/variables see Table 1.

Table 6. Final values [expressed as percentage (%) change compared to the baseline values; Table 3] of the KPIs selected for assessing the impact of innovations on the sustainability performance of wine value chain in SIP7.

KPI	1st growing period (% change)	2nd growing period (% change)	Average % change
Pesticide use (solid)	−45.8	−75.0	−60.4
Pesticide use (liquid)	−29.0	−20.0	−24.5
Production cost	*−1.1*	−12.3	*−6.7*
Perceived quality (white wine)*	n/a	+12.5	*+8.0*
Perceived quality (red wine)*	n/a	*+3.4*	
Working time	−25.8	−27.5	−26.7

Values below the targets of Table 3 appear in italics. * Growing periods do not apply to the KPI "perceived quality"; the values in the respective rows (third column) of this KPI refer to the % change between the baseline values (Tables 2–3) calculated before the development of the digital label and the final values (Table 5) calculated after the development of the digital label; the average % change refers to the average of the % change of the two wines.

The final values of the other KPIs, expressed as percentage (%) change compared to the baseline values, are given in Table 6. The implementation of the proposed smart farming technology led to a reduction of pesticides use by 45.8% (solid) and 29% (liquid) during the 1st growing period, compared with 75% and 20% in the 2nd period, respectively; thus, the improvement in performance exceeded the target of −15%. The reduction of pesticides use implies less chemicals into soil, water and air, and consequently a reduced impact on the environment and human health.

Despite the considerable improvements in environmental performance (i.e., reduced pesticides use), the reduction of production costs was comparatively small during the 1st growing period (−1.1%) and consequently well below the target of −10.5%. This was primarily due to the rising inflation and the sharp increase in input prices, because of the international market shock (pandemic and Russian-Ukrainian war). Besides, as a small island, Cyprus is entirely dependent on imported agricultural inputs and hence highly affected by the rise in international prices; this implies increased production costs [33]. Nevertheless, the results for the 2nd growing season were more than satisfactory, as production costs were reduced by 12.3% (> target). In spite of the sustained increase in input prices, a significantly lower amount of solid pesticides was used in the 2nd period.

Finally, regarding social performance, a reduced working time was observed in both growing periods (−25.8% and −27.5%, respectively), due to mainly less sprays and visits to the fields, because of the applied smart farming innovation. This result suggests less exposure to chemicals and improved working conditions for the agronomists and agricultural workers. In this vein, the EU Farm to Fork Strategy highlights the important role of farmers' health, safety and (improved) working conditions in building a sustainable and resilient food system [48]. As also noted by [33], harsh

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working conditions are inherent in farming and a high quality of life for farmers is a key priority for agricultural policies.

3.3. Results for SIP10

The implementation of the DSS vite.net® in SIP10 significantly enhanced the precision and efficiency of crop management practices. Over the course of two years, the farms participating in SIP10 reported an average reduction in pesticide use by 7.6%, a slight deviation from the anticipated target, but still marking a notable improvement in sustainable agricultural practices. This reduction in input use is a testament to the DSS's capability to optimise field management, leading to a decrease in GHG emissions. The average reduction in GHG emissions exceeded expectations, achieving a remarkable 33.4% decrease over the considered cropping seasons. This significant reduction underscores the potential of SFTs to mitigate the carbon footprint associated with agricultural activities.

Economically, the DSS not only facilitated cost savings through reduced input usage, but also opened avenues for monetising ecosystem services, particularly in the form of CCs. The systematic approach to generate, quantify, and certify CCs, underscored a successful integration of environmental stewardship with economic incentives. The certification of emission reductions by an external body not only validated the environmental benefits of the adopted practices, but also translated into a tangible increase in farmers' revenues, with CCs priced between 8–12 € per ton of CO_2 equivalent.

From a social perspective, the SIP10 initiative made significant strides in enhancing sustainability awareness and education among farmers. The adoption of the DSS fostered a community of practice, enhancing knowledge transfer and raising awareness about agriculture's role in combating climate change. This was further augmented by the achievement of Sustainability Certification, recognizing the farms' commitment to sustainable practices and contributing to a broader understanding of sustainable agriculture's value chain impact.

In terms of product quality, an improvement was observed as indicated by the Brix measurement of the harvested products, with an average increase of 5.3% in intrinsic product quality. This improvement, attributed to enhanced crop management facilitated by the DSS, signifies the potential for SFTs to elevate not only the environmental and economic performance of agriculture, but also the quality of the production.

Table 7. Final values [expressed as percentage (%) change compared to the baseline values; Table 4] of the KPIs selected for assessing the impact of innovations on the sustainability performance of wine value chain in SIP10.

KPI	1st growing period (% change)	2nd growing period (% change)	Average % change
Pesticide use	−6.5	−8.7	−7.6
Greenhouse Gas emission	−37.5	−29.3	−33.4
Intrinsic product quality	5.0	5.5	*5.3*
Revenue linked to carbon credits	n/a	4,140 €/farm	
Sustainability certifications and labels	n/a	*1 certification*	

The results from SIP10 highlight the synergistic benefits of integrating SFTs with carbon credit systems, showcasing a promising pathway towards a more sustainable, profitable, and environmentally friendly agricultural sector. The initiative's success in reducing GHG emissions, enhancing product quality, and generating additional income through CCs exemplifies the potential of innovative agricultural practices to contribute significantly to climate change mitigation and sustainable development goals.

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4. Discussion

The outcomes from SIP7 and SIP10 closely align with the primary research goals of enhancing sustainability within the wine industry through the deployment of innovative technologies. These pilots successfully implemented strategies that effectively reduced environmental impacts, bolstered economic gains, and promoted social improvements. The varied approaches taken —ranging from the introduction of digital labelling and smart farming in SIP7 to the generation and commercialization of CCs in SIP10— played a pivotal role in achieving the anticipated results. These strategies not only directly tackled the specific sustainability challenges highlighted at the beginning of the study, but also showcased the potential scalability and adaptability of such innovations across diverse scenarios in the wine sector.

SIP7's adoption of digital labelling and smart farming solutions, resulting in up to a 75% reduction in pesticide use, aligns with the growing recognition of the need for environmental stewardship in agriculture. This outcome echoes the concerns raised by Cichelli et al. (2016) and Santiago-Brown et al. (2014) regarding the viticulture sector's vulnerability to climate change and the critical role of sustainable practices in ensuring its longevity [5,6]. Similarly, SIP10's focus on reducing GHG emissions through optimised crop management practices, achieving an average reduction of 33.4%, directly contributes to addressing the climate change vulnerabilities outlined by these studies. The economic benefits highlighted in both pilots, including SIP7's potential for premium pricing through enhanced wine quality and SIP10's novel revenue stream from CCs, offer compelling evidence of the economic sustainability that can be achieved through SOIs. These findings resonate with the perspectives of Secundo et al. (2022), who advocate for the integration of environmental, social, and economic sustainability principles throughout the agricultural value chain [16]. The creation of new revenue streams through innovative practices, as demonstrated in SIP10, presents a viable solution to the economic challenges faced by the wine industry, as discussed by Barba-Sánchez & Atienza-Sahuquillo (2016) [3]. Moreover, the social improvements observed in both pilots, such as enhanced working conditions and the achievement of sustainability certifications, reflect the importance of incorporating social engagement and collaborative business models in sustainability initiatives. This approach is in line with the SIF model, which emphasises the role of behavioural innovation, social engagement, and collaborative business model innovation in driving sustainability in the agricultural sector [21].

The results of SIP7 and SIP10 provide empirical evidence that bridges the previously identified gaps in the literature concerning comprehensive sustainability assessments within the wine industry. These pilots specifically target the shortfall in real-world applications of SOIs and SFTs. By implementing these innovations in the distinct socio-economic and ecological contexts of Cyprus and Italy, the pilots demonstrate the tangible benefits of integrating environmental, economic, and social sustainability practices at a granular level—something that has been largely theoretical or limited in scope in prior research. The improvements in environmental outcomes, such as resource efficiency and biodiversity preservation, economic gains through optimized production, and social enhancements, including stakeholder engagement and labor practices, exemplify the multifaceted benefits of SOIs and SFTs. This directly addresses the literature's gap in showcasing holistic and actionable sustainability models in the wine industry and offers concrete examples of how these can be achieved. Furthermore, by employing the SIF to systematically evaluate these initiatives, our study advances methodological approaches to sustainability assessments, addressing the need for robust, contextual tools. The findings from these pilots clarify the practical application of such models, providing a template for scalability and informing future policy and management decisions within the wine sector and beyond. Hence, SIP7 and SIP10 not only resonate with our research objectives but also fulfill the need for comprehensive case studies to validate the effectiveness of SOIs and SFTs, as highlighted in the introduction. This research thus closes a critical gap, transitioning from abstract sustainability principles to actionable strategies that leverage technology and innovation for a sustainable and resilient viticulture.

5. Conclusions

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The exploration of SIPs 7 and 10 within the wine industry has brought to light the profound impact that SOIs and SFTs can have on enhancing sustainability across environmental, economic, and social dimensions. These pilots have demonstrated the effectiveness of targeted, technology-driven interventions in reducing the environmental footprint of wine production. Innovations such as digital labelling and smart farming, alongside the strategic use of DSS for optimised crop management, have led to significant reductions in pesticide use and GHG emissions. This not only conserves natural resources, but also protects ecosystems, underscoring the critical role of technology in mitigating environmental impacts. Furthermore, the economic analysis of the outcomes from both SIP7 and SIP10 reveals that the integration of technology in viticulture supports not just environmental sustainability, but also economic viability. Enhancements in wine quality through digital labels and the generation of new revenue streams from the sale of CCs exemplify how sustainability efforts can be aligned with business objectives. This alignment offers a pathway to premium pricing and improved profitability, showcasing the economic benefits of adopting sustainable practices. Improvements in working conditions and the achievement of sustainability certifications from both pilots reflect the social benefits of adopting SOIs and SFTs. These achievements mark a shift towards more responsible and equitable practices within the wine industry, highlighting the importance of social well-being in sustainability efforts. The success of SIP7 and SIP10 also offers valuable insights into the strategic implementation of sustainability initiatives, underscoring the necessity of a holistic approach. This approach should consider the unique challenges and opportunities within the wine sector, suggesting that customisation and flexibility are key to realising meaningful sustainability outcomes. However, it is important to acknowledge certain limitations of our study. The scalability of these SOIs and SFTs to other regions and the adaptability to various wine industry contexts require further exploration. Moreover, the long-term sustainability of these practices and their continued relevance as technology evolves must be examined in future research. Lastly, this study paves the way for further research and innovation in the wine industry, indicating that continued exploration and adoption of SOIs and SFTs are crucial for advancing sustainability. Future initiatives should aim to scale these technologies, explore new innovations, and enhance stakeholder engagement to ensure widespread adoption and impact.

In conclusion, SIP7 and SIP10 have provided compelling evidence of the benefits associated with integrating SOIs and SFTs into viticulture. By achieving significant advancements in sustainability performance, these pilots serve as a blueprint for the wine industry, demonstrating the possibility of achieving a harmonious balance between environmental stewardship, economic prosperity, and social equity. As the industry progresses, embracing these innovations will be fundamental in addressing the sustainability challenges of our time and securing a resilient future for wine production globally.

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