

Artificial Intelligence in Precision Viticulture: A pathway to sustainable and smart vineyard management

By Luciano Wehrli DipWSET

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OBJECTIVES OF THIS THESIS

The global wine industry faces increasing pressure to adopt sustainable practices amidst climate change, resource scarcity, and consumer demand for environmentally responsible products.

This thesis explores the potential of **Artificial Intelligence (AI)** in **precision viticulture** to transform vineyard management, emphasizing sustainability and environmental impact reduction. By leveraging AI-driven technologies such as remote sensing, machine learning, and predictive analytics, viticulturists can optimize resource use, including water, fertilizers, and pesticides, while enhancing biodiversity and soil health.

The study examines how AI can monitor vineyard conditions in real-time, predict disease outbreaks, and enable site-specific interventions, thereby minimizing chemical inputs and conserving natural resources. Additionally, it evaluates case studies of successful AI integration in viticulture, highlighting best practices and technological innovations that balance productivity with ecological stewardship.

The findings aim to establish a practical method or roadmap for wine producers seeking to embrace AI as a tool for sustainable vineyard management as well as other winemaking practices.

Chapter 1: Introduction

1.1 Context and Relevance:

Sustainability Challenges in Modern Viticulture

The viticulture sector faces major sustainability challenges, with climate change posing the greatest threat to the long-term viability of wine production. Viticulture is highly sensitive to climate, as temperature and moisture define terroir and wine quality. Projections estimate that climate change could reduce suitable viticulture areas by 25–73% in major regions by 2050 under high-emission scenarios. [1]. These shifts are evident in increased temperatures, altered precipitation, and more frequent extreme weather, directly impacting grapevine physiology and fruit development. [2].

Drought is a severe challenge as water becomes scarcer in traditional wine regions. Extended dry periods stress vines, reduce yields, and increase irrigation demands. In water-scarce areas, this creates a cycle where climate change raises water needs as availability declines. Soil erosion and increasing salinity further restrict productivity in regions historically known for high-quality grape production [1].

Climate change also alters pest and disease dynamics, shifting the range of grapevine pathogens and insect vectors. Previously stable regions now face new pest pressures or increased disease severity, requiring adaptation. These stresses weaken vine resistance, potentially increasing reliance on chemical interventions at a time when sustainability demands reduced inputs [3] [4].

Environmental and regulatory pressures also challenge the wine sector. Key impacts stem from intensive pesticide use, variable fertilizer rates, and high energy consumption. EU regulations increasingly restrict conventional inputs, such as copper-based fungicides, to minimize soil accumulation and protect non-target organisms, reflecting broader expectations for responsible agriculture [4].

Resource scarcity, especially in Mediterranean zones, compounds these challenges. Global warming may render large areas unsuitable for quality grape cultivation. Rising temperatures, unpredictable rainfall, and water shortages threaten the viability and

characteristic styles of established wine regions, making adaptation essential to preserve distinctive sensory attributes [4] [3].

The Importance of Technological Innovation in Viticulture

Technological innovation is essential for addressing modern viticulture's challenges. Advanced technologies help maintain grape quality and productivity while reducing environmental impact through precise resource management, collectively transforming viticultural practices for greater sustainability.

Precision Viticulture (PV) uses technology and data from satellites, drones, and sensors to support site-specific decision-making and optimize production. **PV** enables more accurate and efficient vineyard management than conventional methods, providing detailed insights into soil variability, vine health, and microclimates. This allows for targeted interventions, optimizing resources and minimizing ecological impact [30].



Fig. 1. Precision Viticulture and Automation. Vinescapes

Artificial intelligence (AI), i.e: **machine learning**, is central to sustainable vineyard management. AI analyzes large datasets to identify patterns and generate actionable insights beyond human capability, helping predict grape ripeness, optimal harvest timing, and disease outbreaks before symptoms appear.

Modern wireless **field monitoring systems** continuously collect data on weather, plant status, soil moisture, and irrigation. These platforms transmit real-time data to cloud analytics, enabling rapid decision support and precise water management through smart irrigation that adjusts delivery based on actual plant needs. [6].



Fig. 2. Monitoring atmospheric conditions and soil moisture within a vineyard using a weather station. LODI Wine Growers.

Autonomous and robotic systems, such as **AI-equipped tractors**, map vineyard conditions with high precision, enabling targeted input application. Companies like John Deere have developed AI-driven technologies that reduce waste, environmental impact, and address labor shortages.



Fig. 3. Autonomous Robotic Systems. The Androver II robotic test platform

Biotechnology and **genomics**, including gene-editing (e.g., CRISPR), are used to develop grape varieties with greater resistance to pests, diseases, and environmental stressors. These advances can reduce chemical inputs and improve adaptation to climate change [7] [31].

These technological advances enable sustainable wine production that balances economic and environmental goals. Australian and Californian vintners using precision viticulture and advanced monitoring have improved resource **efficiency**, vineyard **vigor**, **health** metrics and maintained or enhanced **grape quality** within two years, demonstrating the dual benefits of innovation [5] [6].

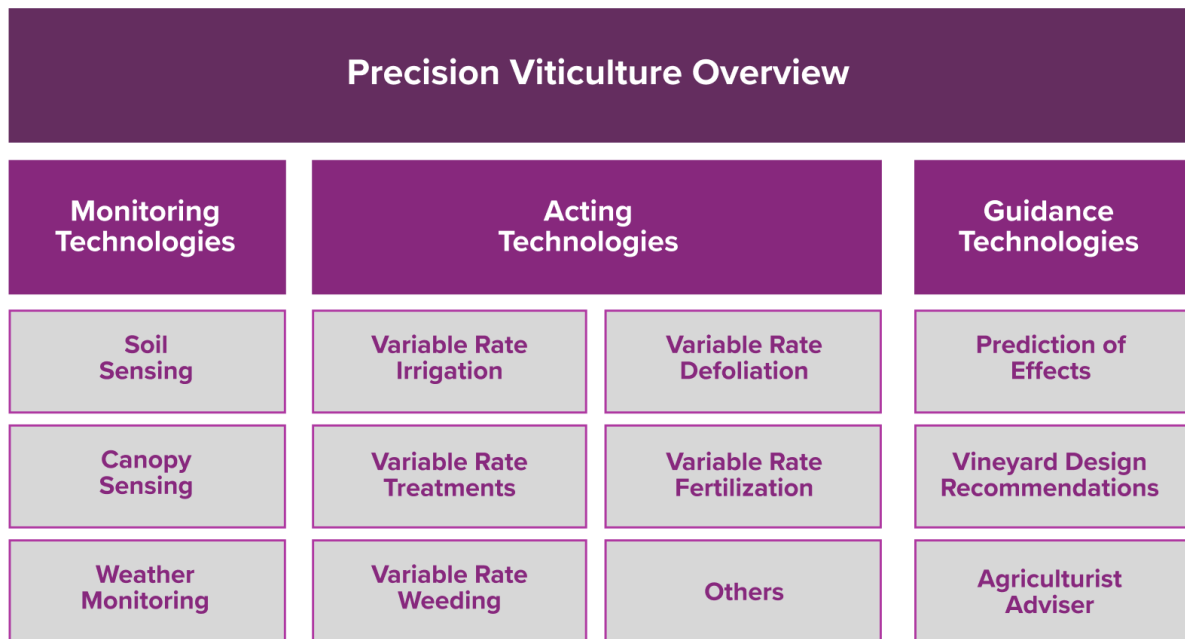


Fig. 4. Precision viticulture technologies overview

The Technological Transformation of Viticulture

The wine industry's shift to **technology-enabled sustainability** marks a major departure from centuries-old practices. Climate change is altering growing conditions, making traditional knowledge insufficient. Unpredictable weather and rising temperatures challenge winegrowers to maintain quality, requiring transformative management approaches [3].

AI plays a core role in this transformation, offering capabilities that extend beyond human observation and analysis, identifying patterns, predicting biological responses, and optimizing multiple variables.

Chapter 2: Challenges in Sustainable Viticulture

2.1 Environmental Impact of Traditional Viticulture

Traditional viticulture practices have significant environmental consequences that threaten the long-term sustainability of wine production. Conventional vineyard management typically involves intensive machinery use, frequent tillage operations, and substantial chemical applications that collectively degrade soil health and ecosystem functioning. These intensive practices decrease soil porosity, aeration, aggregation, and organic matter content while simultaneously increasing toxicity to beneficial soil organisms [8]. The adverse impacts on soil biodiversity lead to degradation of biological fertility, with harmful consequences for the ecological services that soils provide [8].

Soil degradation in vineyard systems is particularly concerning because these agricultural landscapes are among the most intensively managed and erosion-prone [8]. Conventional practices often involve keeping soils bare both below and between vine rows through frequent tillage and herbicide applications, creating conditions that accelerate erosion processes and diminish water retention capacity. Additionally, the regular application of mineral fertilizers and fungicides further compromises soil biological communities that are essential for sustainable viticulture [8].

The environmental consequences extend beyond the vineyard ecosystem itself. The intensive water use in traditional viticulture is increasingly problematic as climate change exacerbates water scarcity in many wine-growing regions. Attempts to maintain wine grape productivity and quality amid warming conditions may be associated with increased irrigation demands, creating potential freshwater conservation impacts [9]. These practices collectively negatively impact not only the ecological sustainability of vineyards but also the distinctive terroir characteristics that define premium wine production [10].

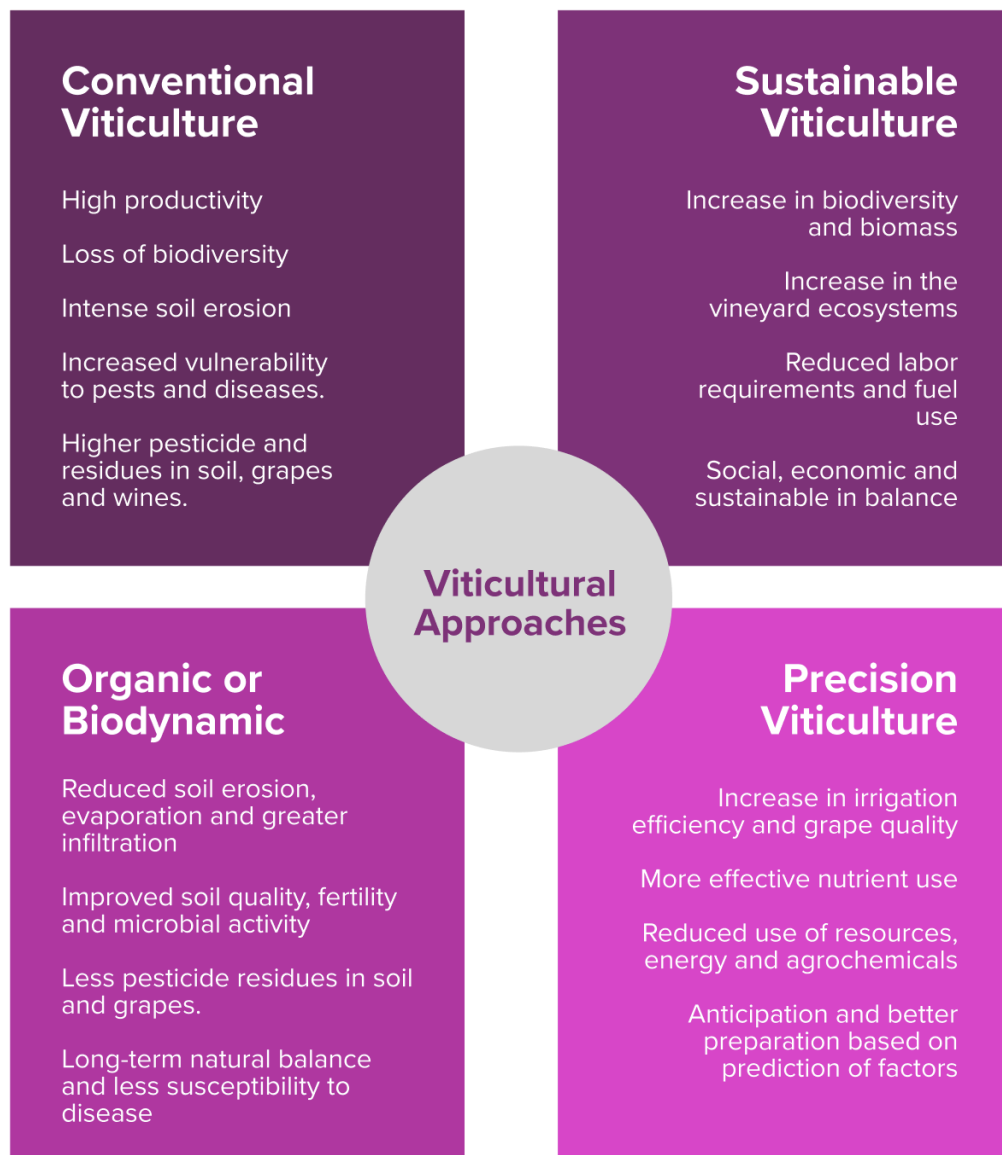


Fig. 5. Viticultural approaches

2.2 Effects of Climate Change on Vineyards

Climate change represents an existential threat to global viticulture, with profound implications for vineyard geography, grape composition, and wine quality.

Temperature increases are already manifesting through **earlier phenological development** and **harvest dates**. Harvesting in most vineyards now begins two to three weeks earlier than four decades ago, significantly affecting grape composition and resulting wine styles [11]. These thermal changes can alter wine sensory profiles through reduced

acidity, increased alcohol content, and modified aromatic signatures, fundamentally changing the character of wines from established regions [11].

Weather extremes associated with climate change pose additional challenges. The unpredictable pattern of rainfall, more frequent heat waves, and sudden frost events disrupt the delicate balance of grape ripening processes [12]. Wine quality depends on achieving appropriate balance between sugar accumulation, acid preservation, and secondary compound development, all of which are highly sensitive to climatic conditions [12]. When regional climate patterns shift, they can disrupt these balances by altering the rate at which different compounds develop in the fruit, potentially compromising wine quality and regional typicity.

2.3 Need for Technological Solutions

The convergence of environmental sustainability challenges and climate change impacts necessitates innovative technological approaches to viticulture. While traditional sustainable practices like organic and biodynamic farming provide important foundations, they may be insufficient alone to address the complex challenges facing modern wine production. Advanced technologies, particularly those utilizing **AI**, can complement these approaches by enabling more precise resource management and adaptive responses to changing conditions.

Smart vineyard technologies are emerging as powerful tools for sustainable management. **Robotic platforms utilizing 5G connectivity** can perform precision operations such as defoliation and weed removal on difficult terrain, reducing the need for chemical controls while improving operational efficiency. These systems represent critical support for traditional winegrowing practices, particularly where manual labour reaches its limits. Similarly, **AI-based vineyard information management systems** help winegrowers optimize fertilizer and spray applications, reducing environmental impact while maintaining productivity [13].



Fig. 6. Lumo smart irrigation valve in a Cabernet Sauvignon vineyard



Fig. 7. LiDAR technology. Intelligent Spray Control System

The integration of multiple technological systems creates comprehensive management platforms that drive sustainability. The **VitiGEOSS** platform exemplifies this approach by combining **artificial intelligence**, **internet of things**, **remote sensing**, **drone** technology, **satellite** observation, and **in-field sensors** to deliver actionable insights for vineyard managers [14]. This system enables early disease detection, generates alerts for targeted preventive treatments, and provides long-term weather forecasts and phenological predictions to optimize resource use [14]. Such platforms support informed decision-making that enhances sustainability while building resilience to climate volatility.

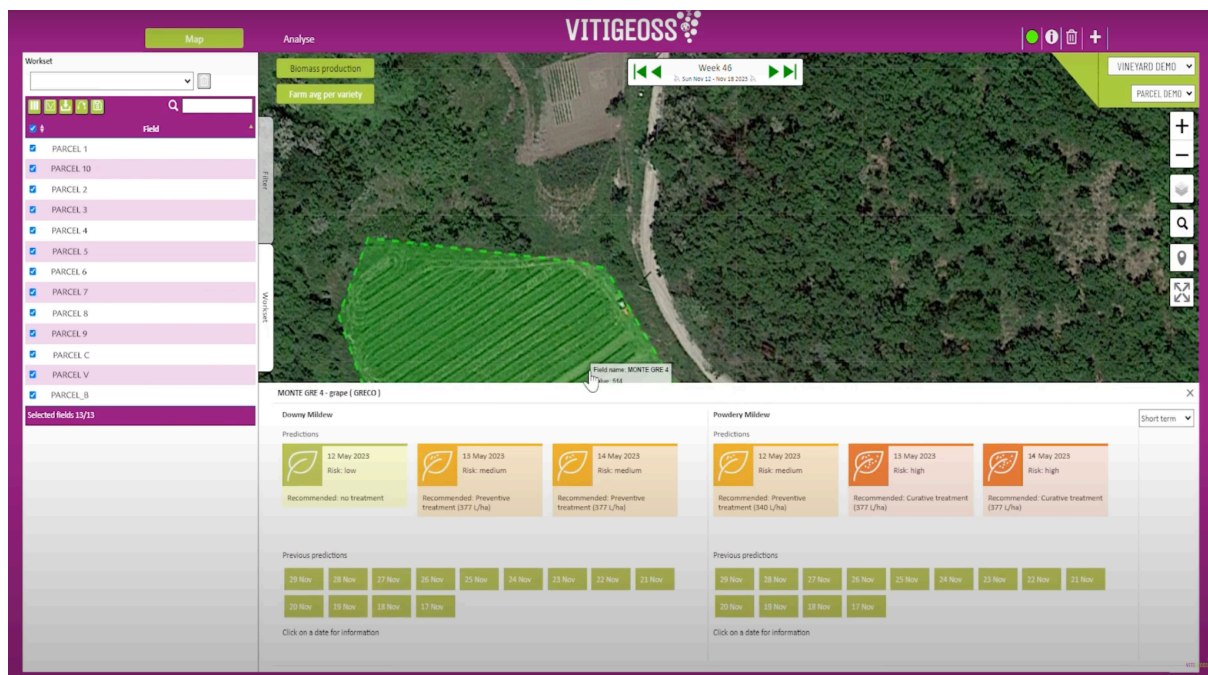


Fig. 8. Vitigeoss Platform showing mildew auto-detection vineyard areas

By leveraging **AI** to analyze complex datasets from multiple sources, vineyard managers can better anticipate extreme weather events, optimize water use during drought conditions, and adjust practices to maintain quality despite changing growing conditions [14]. These capabilities position technology as an essential component of future sustainable viticulture, complementing traditional ecological approaches with precision management capabilities that can respond dynamically to environmental challenges.

Chapter 3: AI Applications in Precision Viticulture

3.1 Definition of AI and Its Relevant Components

Artificial Intelligence (AI) in viticulture encompasses interconnected technologies that enable data-driven decision-making for vineyard optimization. At its core, AI systems process environmental and biological data through advanced computational methods, creating actionable insights that surpass human observational capabilities. Four key components form the technological foundation of modern precision viticulture:

Machine Learning (ML):

A subset of AI where algorithms iteratively improve their performance through exposure to agricultural data. Unlike rule-based systems limited to predefined scenarios, ML models **analyze historical and real-time vineyard data to identify patterns** in disease progression, water stress indicators, and nutrient deficiencies [15]. For instance, **deep learning models** process multispectral imagery (from satellites) to detect early signs of fungal infections before visual symptoms appear [19].

Remote Sensing

Multispectral imagery, typically captured twice a year in flowering and veraison, helps understand the variability within a vineyard, for instance, to locate the boundaries between different quality grapes to show where viticulturists can safely reduce inputs without compromising the quality of the fruit, making the vineyard considerably more profitable [32]. Advanced platforms combine **thermal infrared sensors** with **computer vision** technology to map vineyard microclimates at 5 cm resolution.

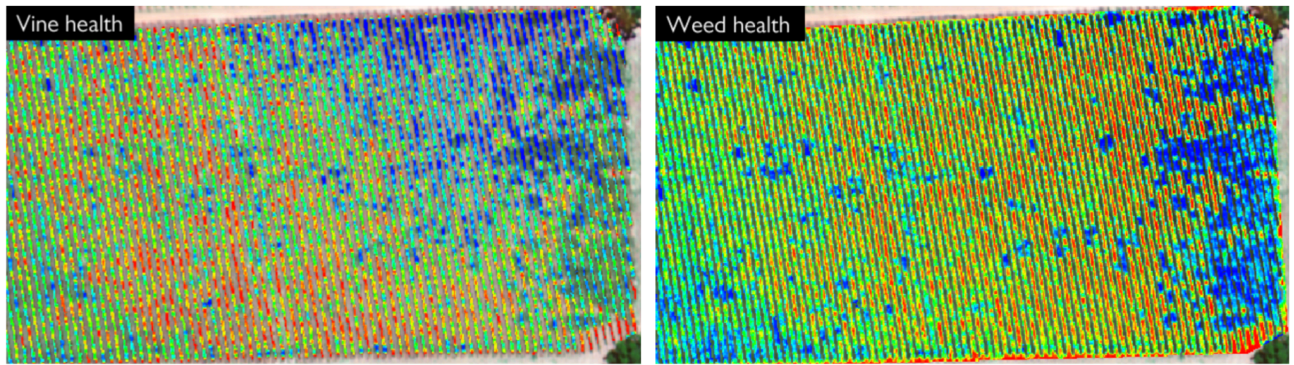


Fig. 9. Vine Health and Weed Health of same vineyard by Multispectral Imagery

Parameter	How it is measured?	Use in viticulture
NDVI (Normalized Difference Vegetation Index)	Difference between NIR (near-infrared) and red reflectance.	Indicates vine vigor, canopy density, and overall plant health.
NDRE (Normalized Difference Red Edge Index)	Uses NIR and Red Edge bands.	Detects chlorophyll content and stress earlier than NDVI.
CIR (Color Infrared)	Combines visible and infrared bands.	Visualizes vine vigor zones and water stress areas.
Canopy Temperature	From thermal infrared sensors or coupled datasets.	Identifies heat stress, water stress, or disease risk.
Leaf Area Index (LAI)	Derived from multispectral reflectance models	Estimates canopy density and photosynthetic potential
Plant Water Status (CWSI)	Combines thermal and multispectral data.	Detects water stress and irrigation needs.

Table. 1. Key vineyard data collected through multispectral imaging typically includes

Additional data is combined with multispectral results to generate a more complete understanding of the vineyard situation such as:

- Soil electrical conductivity (EC) maps
- Elevation and slope (from LiDAR or drone mapping)
- IoT sensor data (soil moisture, leaf wetness, temperature)
- Historical yield maps
- Weather station data

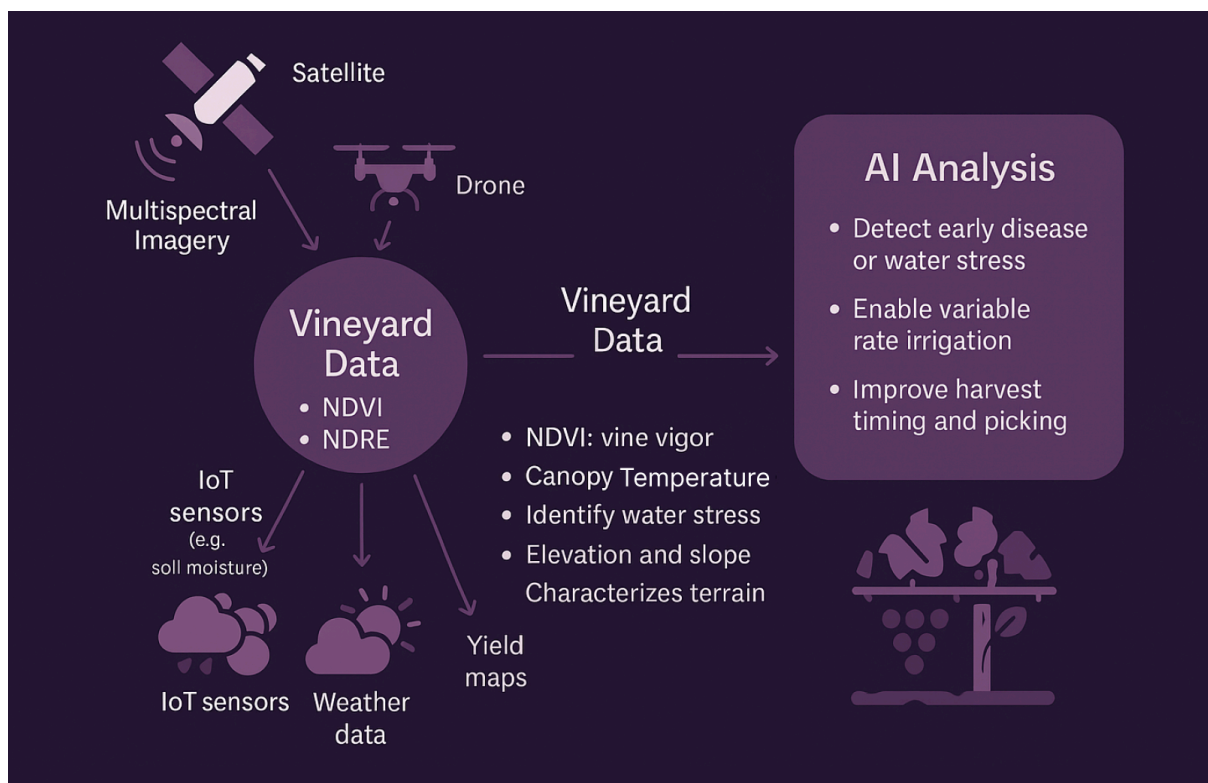


Fig. 10. Multispectral and complemented vineyard data system

Predictive Analytics:

AI models integrate weather forecasts, soil sensor data, and historical growth patterns to simulate vineyard responses under various climate scenarios. These systems **predict optimal harvest windows with 97% accuracy 60 days pre-harvest** in trials, enabling proactive logistics planning [16] [20].

Time-series forecasting models integrate weather data, soil moisture trends, and phenological observations to simulate vineyard responses under various climate scenarios. The VitiGEOSS platform demonstrates 93% accuracy in predicting botrytis outbreak risks 72 hours pre-symptom through multimodal data fusion [21]. These systems enable dynamic adjustment of management practices in response to predicted conditions.

Internet of Things (IoT):

Networked sensor arrays monitor soil moisture (0-100 cm depth), **trunk diameter fluctuations** (indicating water stress), and **sap flow rates** in real time, using i.e.: **thermal dissipation**, by sticking a couple of needles in a vine, heating one of them, and measuring how quickly sap carries that heat away. Wireless sensors transmit data to cloud-based AI

platforms that adjust irrigation schedules dynamically, reducing water waste by 25-52% compared to conventional systems. [22]

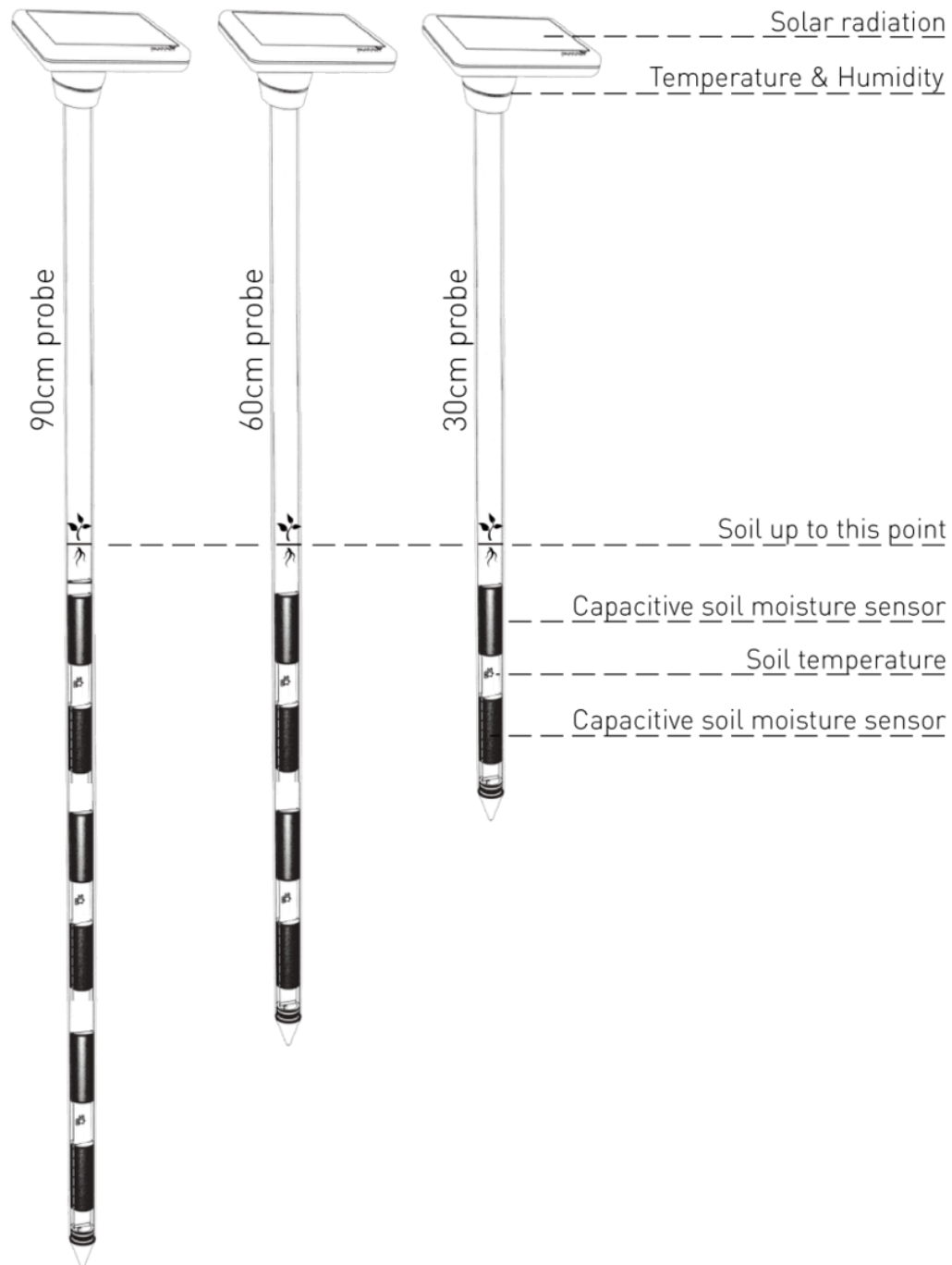


Fig. 11. Example of PYCNO sensor probe length which allows soil moisture and temperatures and different depths (PYCNO, 2020). Vinscapes

3.2 AI Technologies and Tools Used in Vineyards

Remote Sensing & Spectral Analysis

Modern vineyards deploy multi-layered remote sensing systems:

Orbital Monitoring: Satellite constellations (Sentinel-2, Landsat 8) provide weekly **NDVI** updates at 10m resolution, tracking canopy development across entire appellations. Also Modified Chlorophyll Absorption Ratio Index **MCARI** to better estimate chlorophyll content and Leaf Area Index (LAI) [15].



Fig. 12. Sentinel-2 Satellite

Hyperspectral Drones: Drones, also known as **unmanned air vehicle (UAV)**, equipped with LiDAR map vineyard topography, identifying drainage issues.

By equipping an **UAV** with a normal camera and a long-range infrared camera set up to work as a temperature sensor it is possible to measure the temperature of vines, grapes, buds and the ground itself.



Fig. 13. Hyperspectral Drone

As UAVs also make a very distinctive noise, by measuring this and converting it to sound speed between the ground sensors and the UAV, 3D snapshots of **temperature** and **wind velocity** can be created up to a height of 500 metres. When

joining all the bits together it allows to monitor and assess temperature and wind conditions at the meso- and micro-scale without needing masses of very expensive equipment. As a result, **evapotranspiration maps** and **crop stress indices** are generated at the micro-scale level. [29]

Ground-Based LiDAR:

Ground-based hyperspectral scanners use lasers to detect subtle biochemical changes (e.g., anthocyanin accumulation) with 2nm spectral resolution, enabling precision harvest scheduling.



Fig. 14. LiDAR Sensor

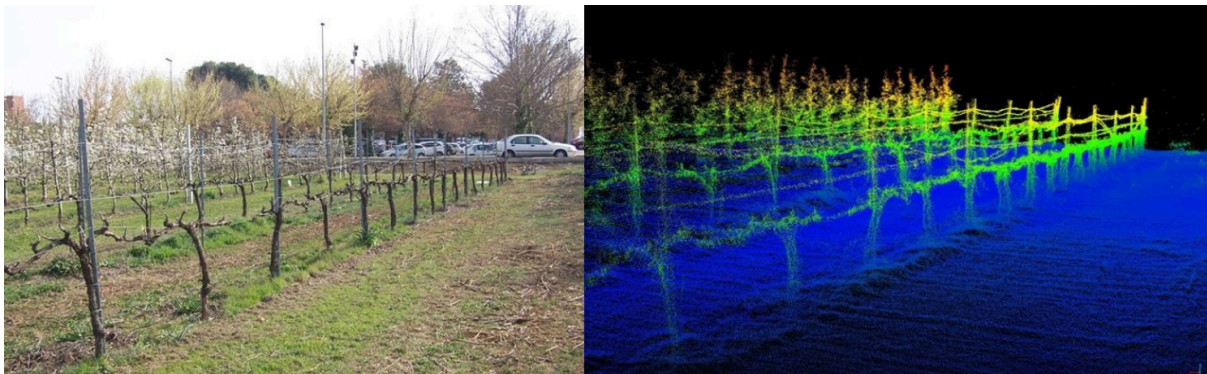


Fig. 15. experimental plot scanned with a mobile terrestrial scanner based on LiDAR technology

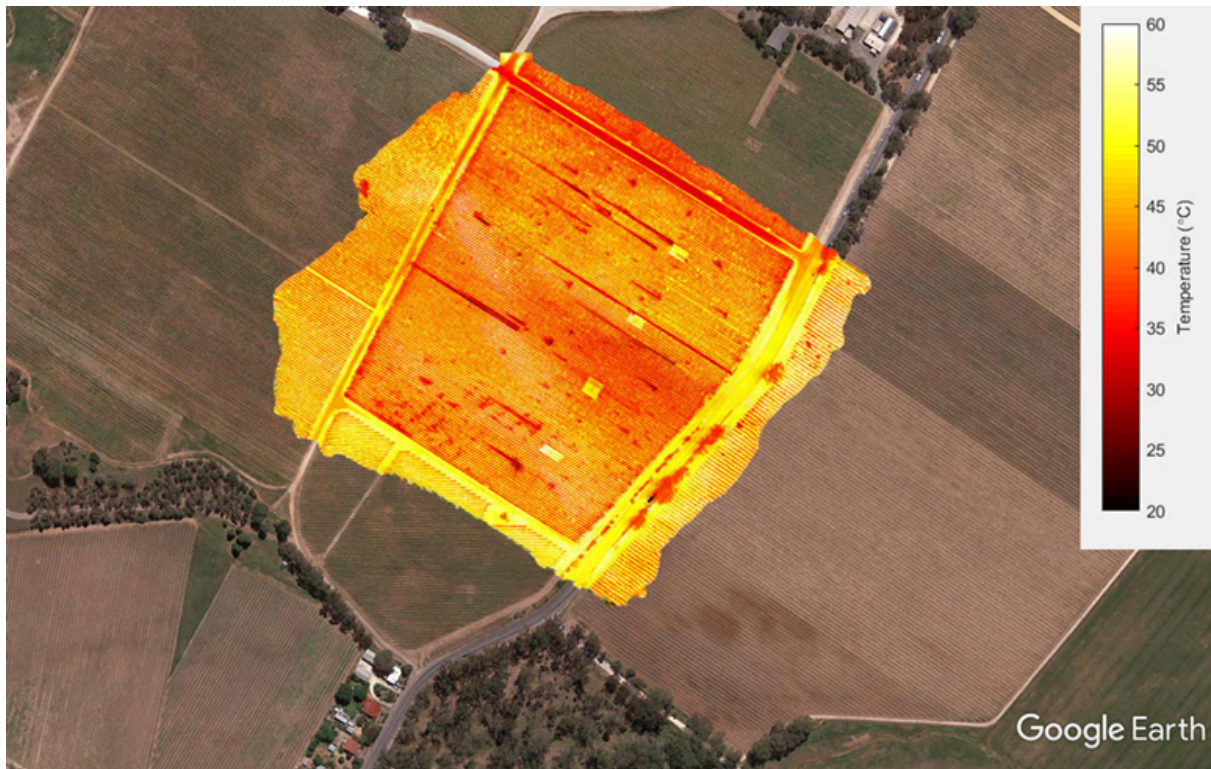


Fig. 16. Drones showing their value in vineyards. Aerial image showing the vine/ground temperatures at approximately 2pm. The vines (which transpire) are significantly cooler (~40°C) than the ground temperatures (> 50°C); and the darker (cooler) areas along the vine rows show areas where irrigation pipes have burst.

Predictive Disease Models

Deep learning architectures process multimodal inputs for disease forecasting:

- **Convolutional Neural Networks (CNNs)** analyze time-series images to detect i.e. powdery mildew infection probabilities 14 days pre-symptom. [21]
- **Recurrent Neural Networks Model** detect spore dispersion patterns using weather station data (temperature, humidity, wind vectors). Spores are reproductive cells produced by fungus or bacteria.
- **Ensemble models** combine satellite thermal data with IoT soil probes to predict botrytis outbreak risks with 93% accuracy [15].

Smart Irrigation Systems

AI-driven irrigation integrates multiple data streams:

- **Soil moisture tensiometers** monitor root zone water potential
- **Sap flow sensors** measure real-time vine transpiration rates
- **Evapotranspiration models** calculate water needs at a fine spatial resolution of 10 m² grids for more precise irrigation.

A Jordanian pilot using **AI Convolutional Neural Networks** (CNNs) to analyze drone imagery achieved 52% water savings through precision irrigation scheduling [17]. California vineyards report 30% yield increases with AI-optimized irrigation that maintains stem water potential in balance during berry maturation [18]. AI-based systems can reduce water consumption by up to 30% compared to traditional irrigation methods, making it very valuable in increasing drought conditions [17].

3.3 Representative Case Studies

Autonomous Vineyard Robots

The TED (Technical Environmental Drone) by Naïo Technologies demonstrates AI's physical implementation:

- Computer vision guides mechanical weeding arms with 2cm positioning accuracy
- LiDAR mapping creates 3D vineyard models for path planning [24]
- Yield prediction algorithms estimate crop loads 90 days pre-harvest with <5% error margin. [19]

Deployed in Bordeaux, TED reduced herbicide use by 92% while maintaining weed coverage below 15% [18].



Fig. 17. TED. Battery powered, autonomous robot designed to reduce or eliminate the need for herbicides in vineyards.



Fig. 18. TED. Weed removal is one of the most time consuming and costly vineyard operations and it usually involves the use of a tractor burning fossil fuels to trail an herbicide sprayer or mechanical weeder.

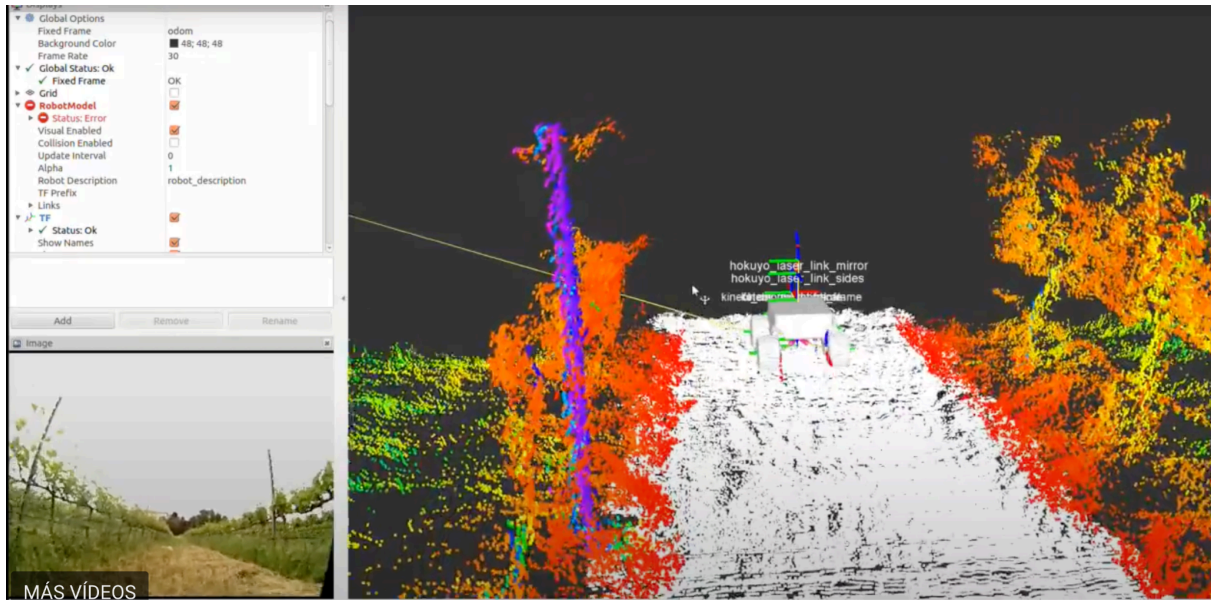


Fig. 19. VinBot - Autonomous vineyard robot mapping the environment to predict yield and quality.

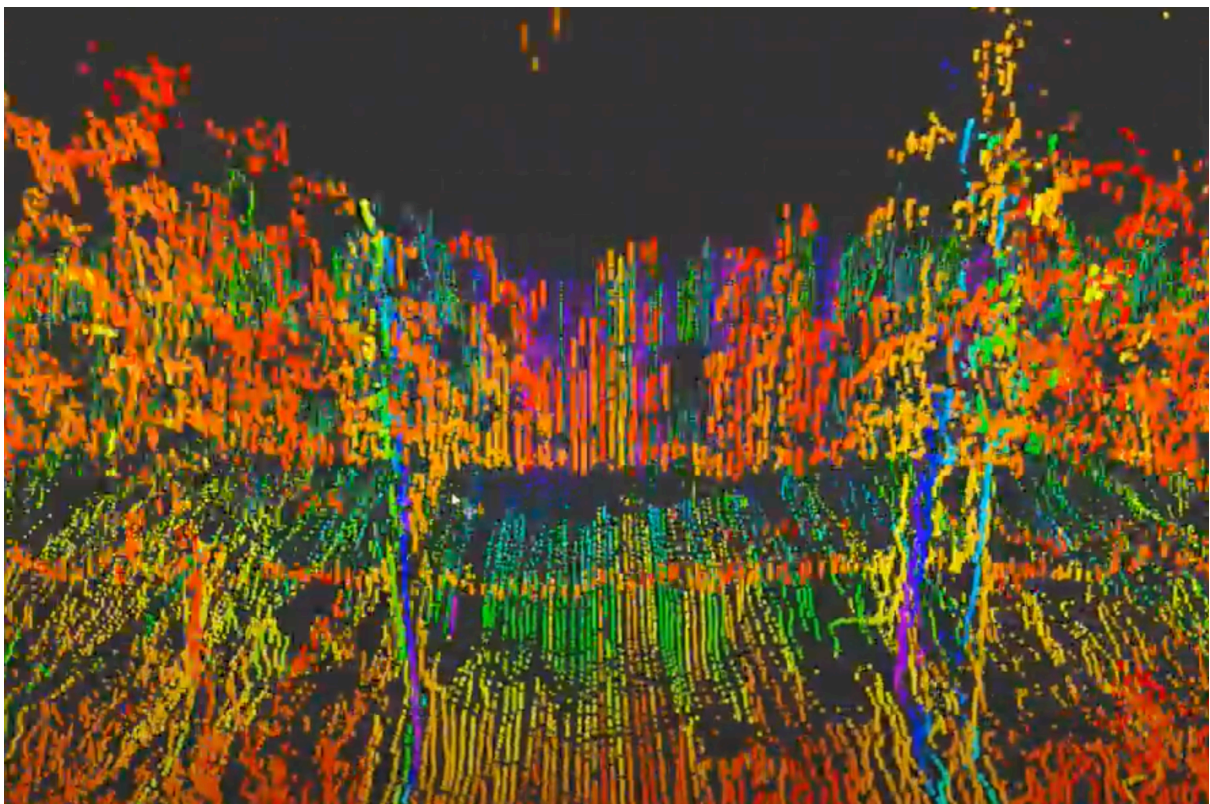


Fig. 20. VinBot - Front view to vineyard



Fig. 21. VinBot

AI-Enhanced Disease Management in Rioja

The DOCa Rioja's AI platform integrates:

- Multispectral drone imagery (5-band analysis)
- Weather station networks (150 units across appellation)
- Historical pest incidence records (15-year database)

Machine learning models provide growers with:

1. Mildew risk alerts 72 hours pre-infection
2. Custom spray plans reducing copper applications by 35%
3. Yield forecasts ($\pm 7\%$ accuracy) for production planning [\[16\]](#).

Napa Valley Autonomous Tractors

Tom Gamble's vineyard employs AI-enhanced tractors featuring:

- **Autonomous Tractors:** Self-driving navigation with 5cm positional accuracy, enables precise inter-row operations, reducing soil compaction through optimized path planning [19]
- **Canopy density mapping.** Time-of-flight cameras quantify leaf layer numbers, informing pruning strategies that improve fruit zone sunlight exposure by 40% using RGB-D cameras [21]
- **Nutrient Recommendation Engines:** Machine Learning models analyze soil sensor data with foliar nutrient assays to generate variable-rate fertilization plans and recommendations, decreasing nitrogen inputs by 25% while maintaining grape quality parameters.[18]

The system also generates vineyard health maps that inform pruning strategies, improving sunlight penetration by 40% in trial blocks [18].

Concha y Toro Smart Systems - Chile

In an interview for this thesis with **Daniela Chacón**, researcher of **Viña Concha y Toro, Chile**, she highlighted their implementation of AI in Precision Viticulture through three platforms: **Smart Agro**, **Smart Winery**, and **Smart Maintenance**. AI-based yield prediction models now outperform human estimations, improving harvest logistics and winery operations.

Concha y Toro's precision tools like **NDVI imaging**, soil and foliar analysis, and AI-guided irrigation optimize their vineyard performance. In the winery, AI monitors fermentation and predicts wine quality based on must composition and phenolic development.

3.4 Observed Benefits

Resource Efficiency Improvements

- **Water conservation:** CNN-based (Convolutional Neural Networks) irrigation systems achieve 52% reduction in water use versus conventional methods [17].
- **Chemical input reduction:** Predictive models lower fungicide applications by 40-60% through targeted treatments [18].
- **Energy savings:** Autonomous electric tractors decrease diesel consumption by 75% per hectare [18].

Quality and Yield Enhancements

- **Sugar content prediction:** Machine Learning models estimate Brix levels with $\pm 0.3^\circ$ accuracy 30 days pre-harvest
- **Yield optimization:** AI-driven canopy management increases yields 20-30% through improved light interception [17]
- **Disease incidence reduction:** Early detection systems maintain infection rates below 2% in monitored vineyards [15]

Soil and Biodiversity Monitoring

AI systems analyze:

- **Microbial Community Analysis:** Microbial DNA sequences to assess soil health (Shannon diversity index >3.5)
- **Earthworm Activity Sensors:** Earthworm activity sensors tracking bioturbation rates, which is the frequency and extent of soil disturbance and redistribution caused by biological activity.
- **Cover Crop Optimization:** Cover crop analytics optimizing species mixtures for nitrogen fixation

By processing vineyard data at unprecedented scales, AI systems enable precision interventions that maintain production quality while radically reducing environmental impacts. [21]

Chapter 4: Challenges & Limitations of AI in Viticulture

The integration of AI in precision viticulture faces technical, economic, and cultural barriers that demand careful evaluation. While AI offers transformative potential, its adoption requires overcoming significant challenges tied to costs, expertise, and systemic limitations inherent to agricultural AI systems.

4.1 Barriers to Adoption

High Initial Investment Costs

Deploying AI-powered systems in vineyards involves substantial upfront costs for sensors, drones, and autonomous equipment. Smaller vineyards often lack the capital for these investments, exacerbating inequalities between large and small producers. Beyond hardware, recurring expenses for software updates and data storage further strain budgets, extending **ROI** (Return of the Investment) timelines to multiple growing seasons.

Need for Technical Expertise

AI implementation demands interdisciplinary skills in data science, agronomy, and systems integration, a challenge for traditionally trained viticulturists. Training existing staff or hiring specialists adds operational complexity, particularly for legacy vineyards. Educational gaps persist in interpreting AI-generated insights, with many growers lacking the literacy to validate algorithmic recommendations or troubleshoot errors.

Resistance to Change

Cultural attachment to traditional practices hinders adoption, as many winemakers prioritize experiential knowledge over data-driven inputs. Concerns about AI homogenizing terroir-driven wines amplify skepticism, despite evidence that AI enhances, rather than replaces, artisanal decision-making. Transitioning workflows to accommodate AI also disrupts labor dynamics, requiring vineyard teams to adapt to new roles in system monitoring and data validation. [\[25\]](#) [\[26\]](#)

4.2 AI's Limitations in Precision Viticulture

Human-AI Synergy

AI cannot replicate the contextual intuition developed through decades of vineyard interaction. While algorithms excel at analyzing soil moisture or disease patterns, they lack the sensory acuity to assess grape phenolic maturity or nuanced microclimatic shifts. Successful systems, like those used at **Gamble Family Vineyards (Napa Valley)**, position AI as a decision-support tool, with viticulturists overseeing final harvest or irrigation calls.

In the interview done for this thesis in May 2025 with **Daniela Chacón**, researcher of **Concha y Toro** in Chile, she shared their different systems to apply precision viticulture and AI-driven insights for better decision making, as well as highlighting the relevance of including cultural change initiatives to increase adoption.

Data Reliability Challenges

AI performance hinges on high-quality, unbiased datasets. Sensor inaccuracies, calibration drift, and regional data gaps (e.g., underrepresented emerging wine regions) limit model generalizability. Training datasets often fail to account for climate volatility, risking outdated recommendations during extreme weather events. For example, AI models trained on pre-drought California data may misprescribe water use in aridified conditions. [\[27\]](#) [\[28\]](#)

Ethical and Privacy Risks

Data ownership disputes arise when third-party platforms collect proprietary vineyard metrics, such as soil health maps or yield projections. Over 60% of vineyard managers express concerns about corporate exploitation of aggregated agricultural data. Additionally, drone-based surveillance systems risk worker privacy, while cybersecurity vulnerabilities in farm IoT networks expose operational data to breaches.

The viability of AI in viticulture depends on resolving cost barriers through subsidized technologies, improving user-friendly interfaces for non-experts, and establishing ethical data governance frameworks. While AI augments precision in irrigation, disease detection,

and yield forecasting, its limitations underscore the irreplaceable role of human expertise in preserving viticultural artistry. Future development must prioritize hybrid systems that harmonize algorithmic efficiency with enological wisdom. [28]

4.3 Survey study to industry leaders

This inception study was conducted in spanish language with a select group of leading wine producers from Spain (*sample size 25, anonymous completion was allowed to encourage engagement*), including renowned wineries such as *Frontonio*, *La Rioja Alta*, *La Rioja Alta*, *Bodegas Trenz* and *Pares Balta*. The participants represent a cross-section of respected industry professionals actively involved in viticulture and winemaking, providing valuable insights into the current awareness, application, and future potential of artificial intelligence within the Spanish wine sector. Online survey:

<https://forms.gle/3EN2DxFwo1E634TB8>

Key Findings

Awareness of AI in Viticulture and Winemaking

- **80%** of respondents have heard about AI applications in wine.
- **60%** claimed to have *detailed knowledge* about AI in the industry.
- **40%** admitted having barely or no awareness, showing an educational opportunity.

Perceived Value of AI for the Industry

- **100% of participants** believe AI could benefit wine production:
 - **80%** consider it will have a *major impact*.
 - **20%** are unsure how it would work but recognize potential.

Current Application of AI

- **60% are already using AI** in some form:
 - **Viticulture monitoring, yield prediction, disease alerts** were the most common uses.
 - Others applied AI for **logistics optimization, sales forecasts, and predictive pricing**.
- The remainder are either exploring tools or facing knowledge/resource barriers.

Barriers to AI Adoption

- Main challenges:
 - **Lack of knowledge (60%)**
 - **Lack of budget or resources (20%)**
 - Some indicate missing **digital infrastructure** for historical data management.

Data Readiness

- **80%** have relevant historical data:
 - Climate, fermentation, and vineyard yield records are the most available.
 - However, data digitalization and structuring remain incomplete in some wineries.

Future Outlook

- **60% believe AI will be essential within 5 years**, especially for:
 - **Sustainability impact reduction**
 - **Operational efficiency**
 - **Cost optimization**
- **Predictive viticulture** and **precision irrigation** also emerged as frequent expectations.

Interest in Further Involvement

- **100% expressed interest** in participating in AI research or studies.

- Respondents suggested more *training programs, case sharing, and pilot projects* would be valuable.

Ubicación de la bodega (País, región)

25 respuestas

España
Haro, La Rioja
Cataluña
España, Penedes
Yecla
Alpartir, Aragon

Fig. 22. Google Forms Survey Results

¿Has escuchado hablar sobre Inteligencia Artificial (IA) aplicada a la viticultura o enología?

[Copiar gráfico](#)

25 respuestas

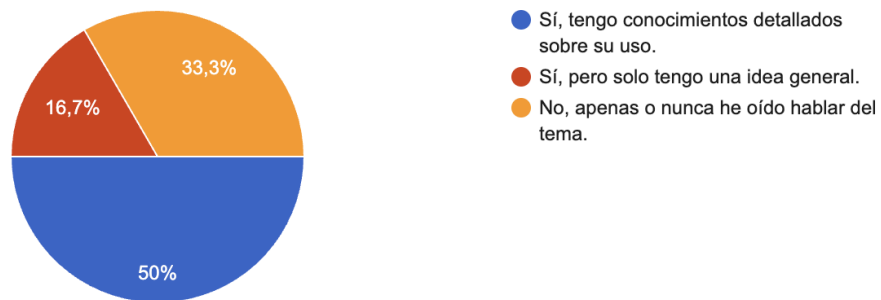


Fig. 23. Google Forms Survey Results

¿Consideras que la IA podría aportar beneficios a la producción de vino?

 Copiar gráfico

25 respuestas

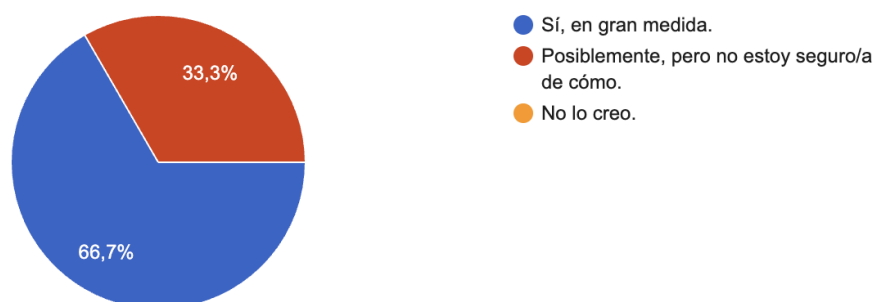


Fig. 24. Google Forms Survey Results

¿Has participado en alguna charla, curso o evento sobre IA aplicada al vino?

 Copiar gráfico

25 respuestas

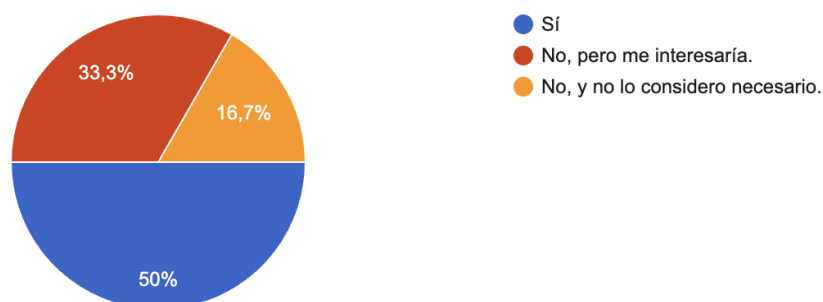


Fig. 25. Google Forms Survey Results

Actualmente, ¿se utiliza alguna herramienta de IA en la bodega?

 Copiar gráfico

25 respuestas

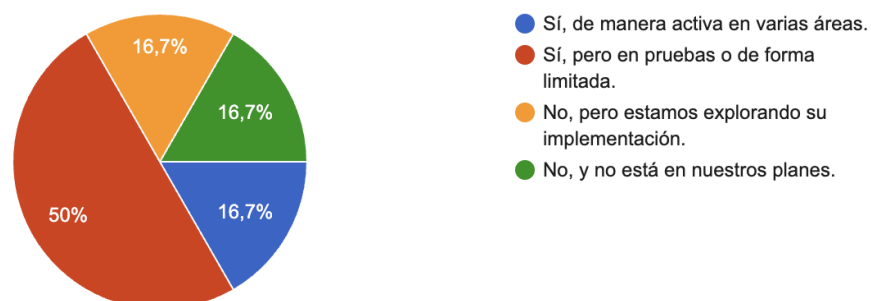


Fig. 26. Google Forms Survey Results

Si aún no aplican IA, ¿por qué razón?

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25 respuestas

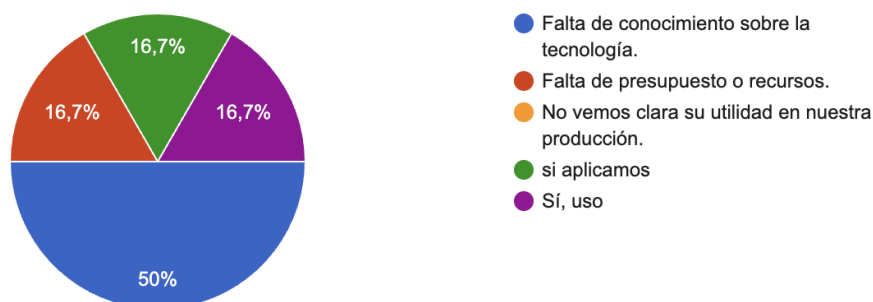


Fig. 27. Google Forms Survey Results

¿Crees que la IA será una herramienta clave para la vitivinicultura en los próximos 5 años?

 Copiar gráfico

25 respuestas

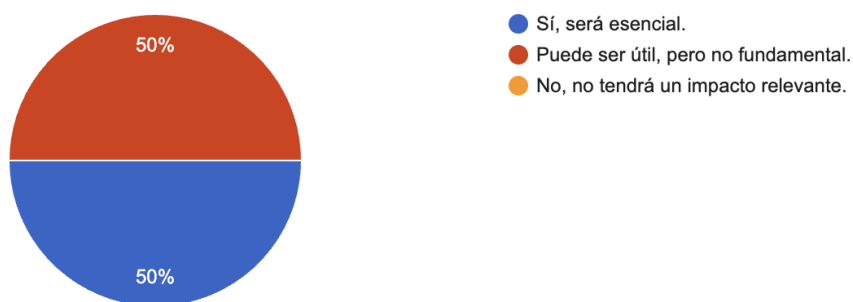


Fig. 28. Google Forms Survey Results



Fig. 29. Google Forms Survey Results

Reflexions from the survey

The results reflect a **growing awareness and early-stage implementation of AI in wine production**, with clear consensus about its future importance, particularly for **sustainability, predictive viticulture, and operational optimization**. Despite interest, **knowledge gaps and digital infrastructure limitations** remain key adoption barriers. Strategic efforts in **education, pilot programs, and data management support** are essential to accelerate AI integration in the wine sector.

While producers express awareness of AI's potential, there **remains uncertainty around where and how to apply it effectively**. These findings reinforce the need for a practical, accessible work model that guides wineries in identifying relevant AI use cases, evaluating technological feasibility, and prioritizing AI-driven interventions as part of precision viticulture and the entire value chain.

Chapter 5: New Innovative Working Model for AI Implementation in Wine Value Chain

5.1 Proposal for a Scalable Implementation Model:

Strategic Framework for AI Adoption in the Wine Industry

The adoption of Artificial Intelligence (AI) in the wine industry requires a structured and strategic approach to ensure that technological innovations align with business objectives and create tangible value. This thesis proposes this innovative **AI Framework for Wine Businesses** named “**AI&WINE**”, fully created and designed by Luciano Wehrli, to systematically identify AI opportunities across the entire wine value chain. By mapping key ecosystem components and categorizing AI use cases according to their functional areas, this framework serves as a practical tool to guide wineries seeking to integrate AI in a purposeful and effective manner.

This innovative **AI&WINE Framework** tackles sustainability and precision viticulture challenges and beyond. It was created to holistically analyse the wine business and, through hands-on workshops, help winery stakeholders adopt **artificial intelligence** as a strategic empowerment for efficiency, accuracy, prediction, market penetration, wine experience, education, among others.

An extensive physical and digital hands-on **AI&WINE Toolkit with one hundred and fifty (150) cards** was also designed to facilitate work sessions. These cards serve as a tangible and interactive resource which enhances collaborative thinking, accelerates problem-solving, and promotes a more practical and actionable approach to AI integration.

This physical and interactive methodology ensures that AI adoption is not merely a theoretical exercise but a dynamic, stakeholder-driven process, enabling wineries to systematically explore technological innovations that align with their strategic goals.



Fig 30. Complete set of 150 AI&WINE Cards

STEP 1: Mapping the Wine Ecosystem to Identify AI Opportunities

The wine industry operates as a complex ecosystem, where processes in viticulture, winemaking, logistics, marketing, and sales are highly interconnected. **AI&WINE Framework** employs **system thinking**, by visually mapping **wine ecosystems** to ensure that AI applications are assessed comprehensively across all critical areas.

For instance, AI opportunities can be hit the following business ecosystem spots:

- **Viticulture:** AI-driven remote sensing and predictive analytics enable optimized irrigation, disease forecasting, and resource efficiency, minimizing chemical inputs while improving vineyard sustainability.
- **Winemaking:** AI-powered fermentation monitoring and quality control enhance production consistency, optimize temperature management, and reduce spoilage risks.

- **Supply Chain & Logistics:** AI-based predictive inventory management and distribution optimization can reduce operational costs and improve efficiency in wine delivery networks.
- **Marketing & Consumer Insights:** AI-driven personalization engines and sentiment analysis can refine e-commerce recommendations and enhance direct-to-consumer strategies, increasing customer engagement and brand loyalty.

The **AI&WINE Toolkit** contains **36 Ecosystem Cards** categorized in the following groups covering the wine value chain.



Fig 31. Wine Business Ecosystem Cover Cards representing wine industry areas where AI can intervene to add value. These are used in practical workshops with wine company owners to help them identify most appropriate areas where AI can impact their business.



Fig 32. Each card contains the wine ecosystem spot on one side and the explanation on the other side, being useful to run practical workshops with wine business owners to prioritize key strategic AI intervention areas for their companies.

STEP 2: Find AI Use Cases for Wine Value Chain Challenges With AIW-FIT Cards.

This is a key stage where AI applicability is discovered. There are **111 AIW-FIT Cards** that function as a strategic tool designed to systematically match specific challenges or inefficiencies identified across the wine value chain with appropriate **AI use cases** and technologies. Each card represents a validated AI application contextualized for viticulture, winemaking, business operations, wine tourism, and others.

During **collaborative hand-on workshops**, stakeholders select cards that address specific challenges within the selected ecosystem spot in the previous step, such as operational efficiency, agronomic or commercial needs, yield prediction, fermentation optimization, or consumer engagement analytics. This process not only accelerates the ideation of relevant AI solutions but also ensures alignment with business objectives, technological feasibility, and return on investment potential, providing a tangible and practical bridge between sector-specific problems and AI-driven opportunities.



Fig 33. AIW-FIT Cards are numbered and categorized. AIW means Artificial Intelligence in Wine.

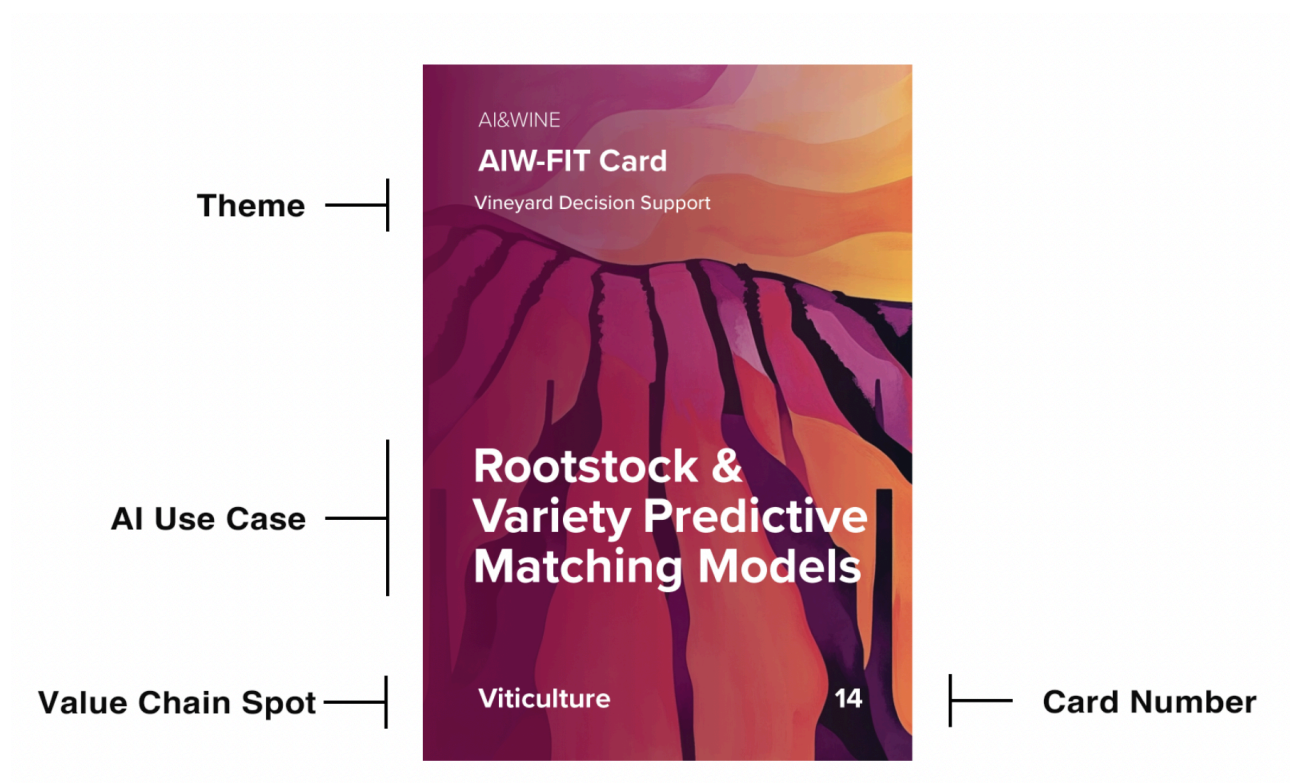


Fig 34. Front side of AIW-FIT Card

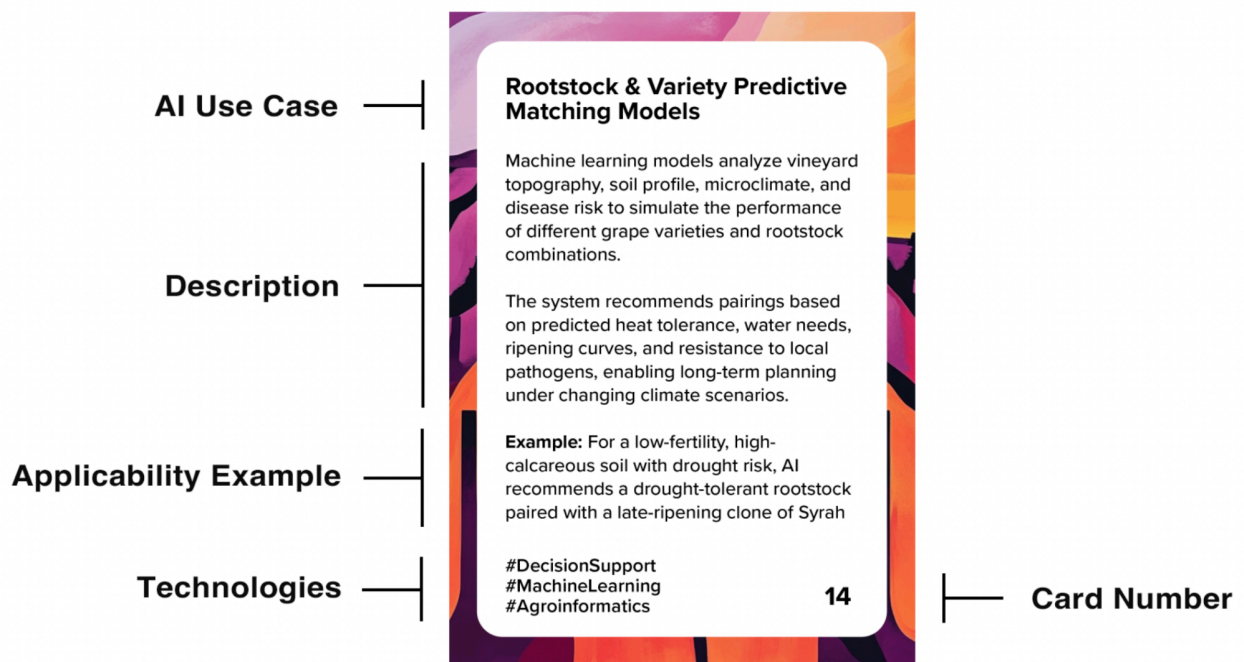


Fig 35. Back side of AIW-FIT Card



Fig 36. Luciano Wehrli running practical workshops to find AI use cases in wine industry

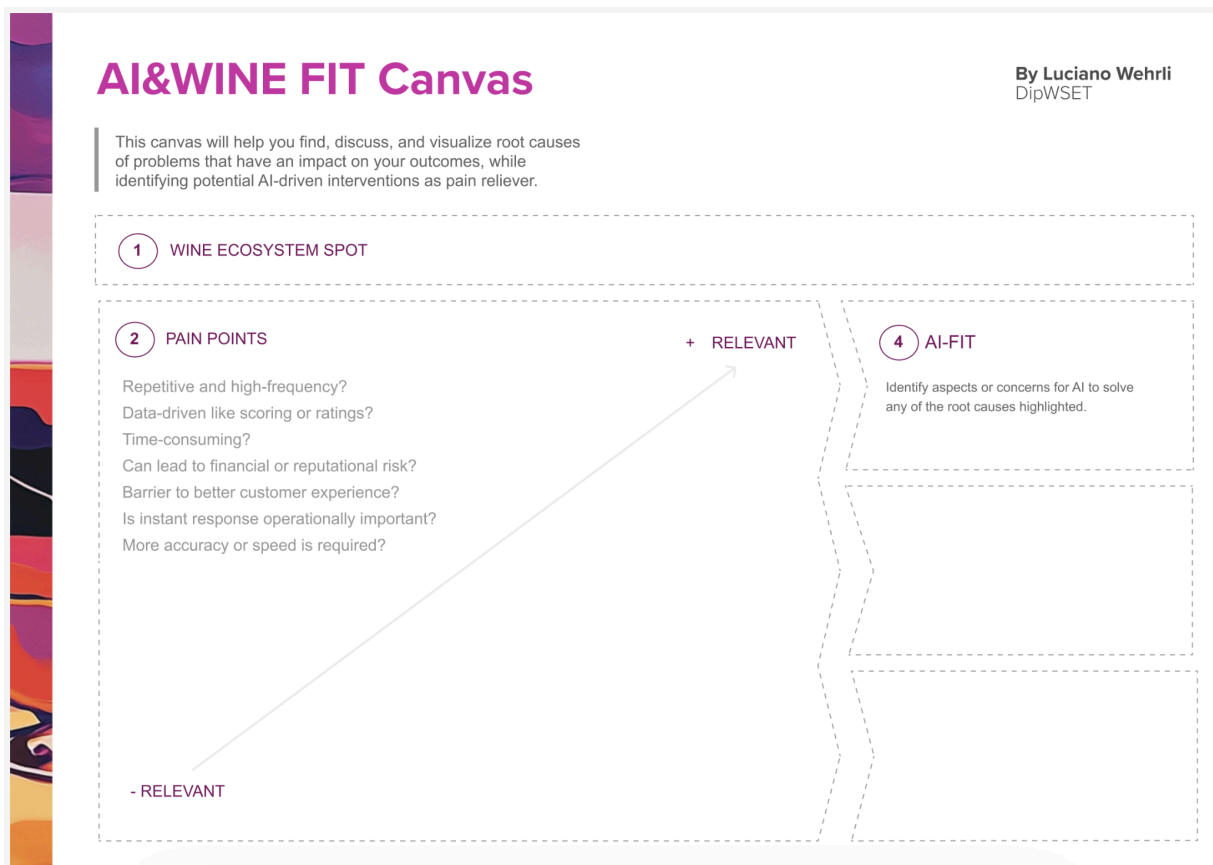


Fig 37. Canvas that is used in practical workshops with wine business owners. AIW-FIT Canvas helps detect wine value chain obstacles, friction points, challenges and associate Artificial Intelligence Use Cases in the “AI-FIT” blocks by using AIW-Cards.

STEP 3: Expand the AI Solution description with AI&WINE Solution Canvas

AIW Solution Canvas is applied as a strategic tool to structure and detail the proposed AI solution for each identified use case. The canvas guides the evaluation of required data sources, data quality considerations, and the potential presence of biases that could affect the model’s accuracy or fairness.

It also outlines the proposed AI architecture whether leveraging machine learning models, computer vision systems, IoT-integrated sensors, or natural language processing and anticipates the technological infrastructure needed for implementation as well as preliminary assessment of the expected ROI, operational feasibility, and alignment with the winery’s strategic priorities



Fig 38. Canvas that is used in practical workshops with wine business owners. AIW-SOLUTION CANVAS helps describe the AI solutions identified from the previous step in the AIW-FIT Canvas. In this canvas more technical and implementation descriptions are shown.

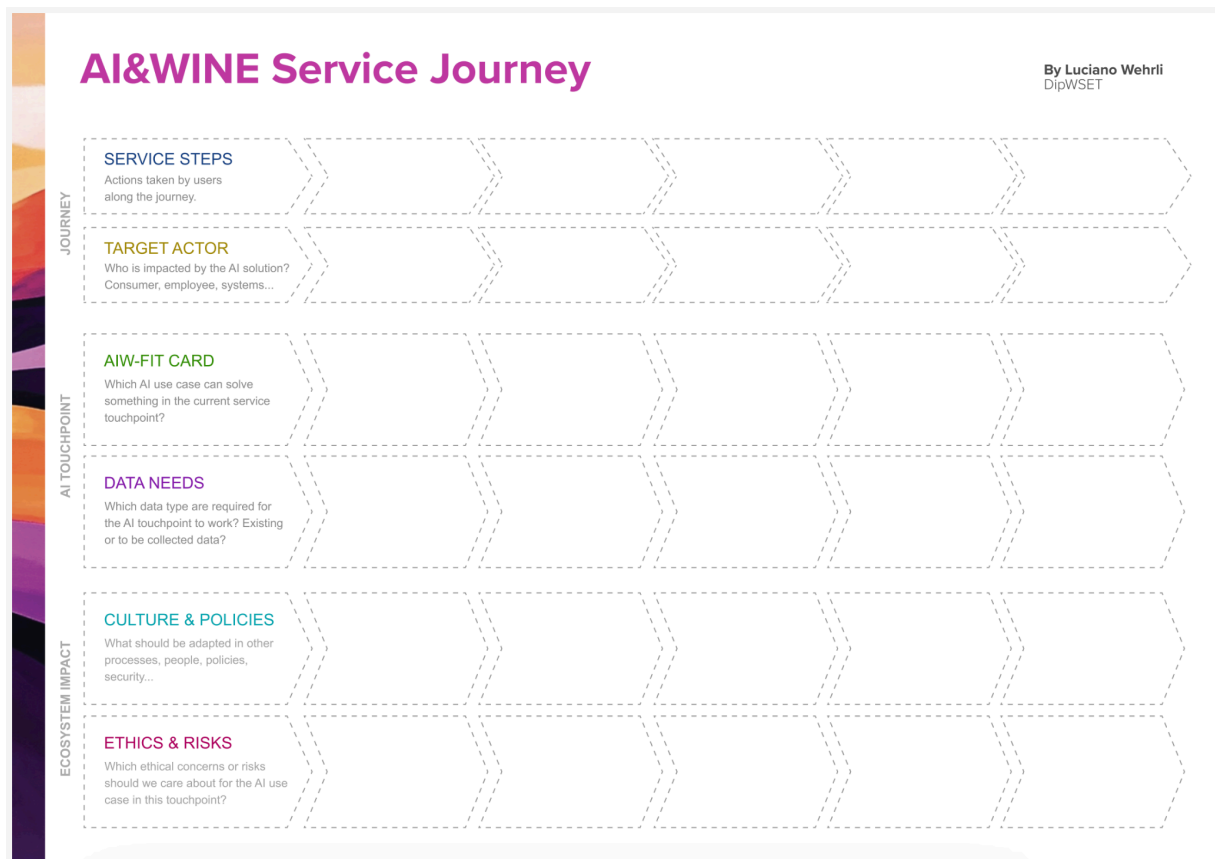


Fig 39. Canvas that is used in practical workshops with wine business owners. AIW-Service Journey helps map an entire wine experience or service and to associate AI solutions along the journey, data considerations, cultural shifts and ethical concerns.

STEP 4: Aligning AI Adoption with Return of the Investment

One of the key barriers to AI implementation in the wine industry is the lack of clear ROI and the perception that AI adoption is driven primarily by technological trends rather than strategic necessity. The proposed framework addresses this challenge by ensuring that AI investments are directly linked to business objectives such as:

- Operational efficiency, reducing vineyard input costs and improving production processes.
- Product quality enhancement, through AI-driven blending optimization and fermentation control.
- Sustainability objectives, including AI-powered soil health monitoring and carbon footprint reduction.

- Market differentiation, leveraging AI for consumer insights, predictive analytics, and digital engagement strategies.

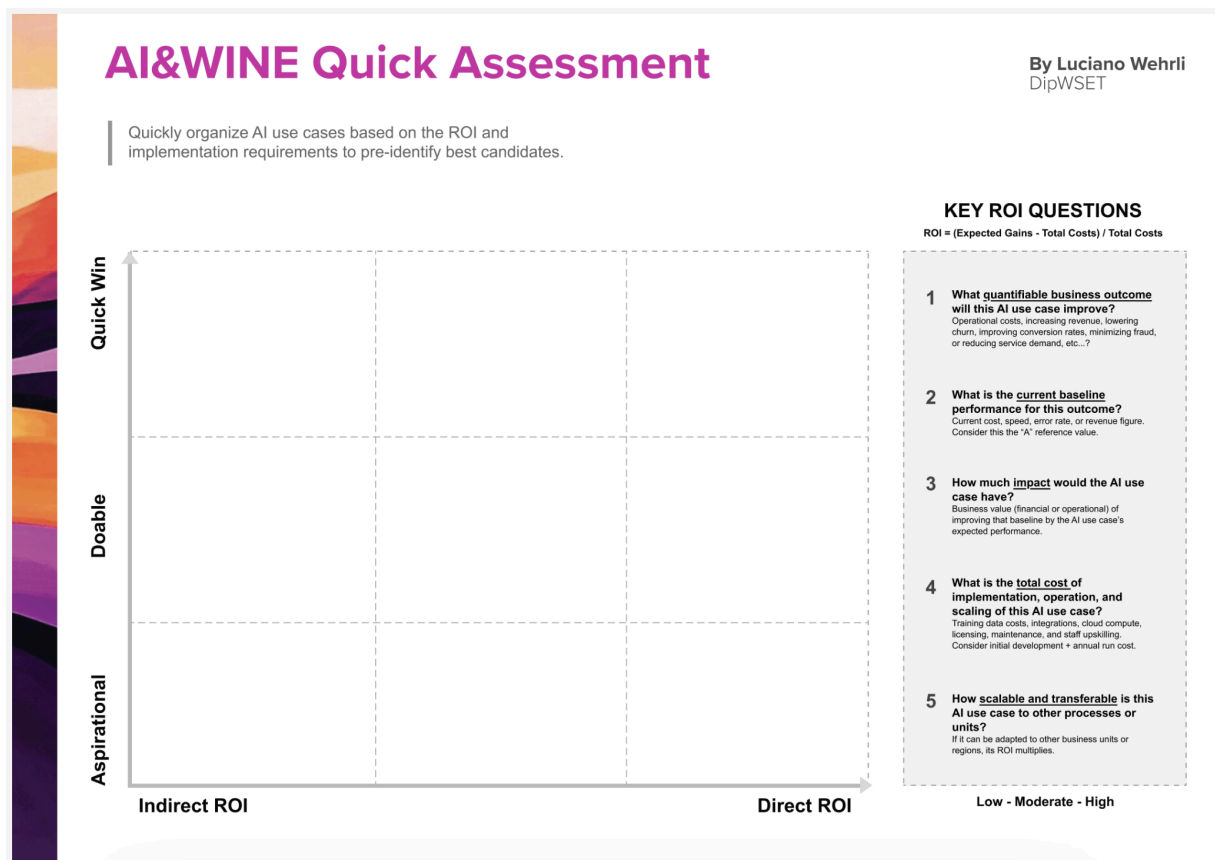


Fig 40. Canvas that is used in practical workshops with wine business owners. AIW-Quick Assessment Canvas helps prioritize the AI interventions based on a rapid analysis of technical feasibility and return of the investment.

By structuring AI implementation around these key business drivers, wineries can prioritize AI initiatives that deliver measurable impact, thereby maximizing both short-term efficiency gains and long-term strategic value.

A Practical For a Scalable AI Adoption Roadmap

The framework also serves as a roadmap for wineries, guiding them in the phased adoption of AI solutions based on feasibility, investment requirements, and technological maturity. Wineries can adopt AI incrementally, starting with low-cost, high-impact solutions such as AI-powered vineyard monitoring, before scaling up to more advanced applications like robotics and automation in production and logistics.

This structured approach positions the framework as a new and innovative resource for wineries, enabling them to navigate the complexities of AI integration with clarity and strategic focus.

Chapter 6: Conclusions

This thesis explored the growing role of artificial intelligence (AI) in addressing the critical sustainability and operational challenges facing modern viticulture. Climate change, resource scarcity, and evolving consumer expectations are reshaping the wine industry, making the adoption of advanced, data-driven technologies not only valuable but essential.

The study identified how AI technologies, including machine learning, remote sensing, IoT systems, and predictive analytics, are already transforming precision viticulture practices, improving resource efficiency, yield forecasting, disease prevention, and wine quality management. Insights from leading international case studies and a dedicated industry survey of Spanish wine producers revealed strong awareness of AI's potential, alongside persistent barriers such as knowledge gaps, budget limitations, and digital infrastructure constraints.

In response, the **AI&WINE Framework** was developed as a practical, scalable methodology to guide wineries in systematically identifying, evaluating, and implementing AI solutions aligned with their strategic priorities, positioning wineries to lead this transition, fostering a resilient, intelligent, and sustainable wine sector for the decades ahead.

This research ultimately concludes that AI, applied with intention and respect for viticultural tradition, offers the wine industry a vital pathway to improve sustainability, resilience, and competitiveness in a rapidly changing global environment.

Appendices & References

Glossary

Wine Terms

- **Viticulture:** The science and practice of growing grapes for winemaking.
- **Precision Viticulture (PV):** Use of technology (sensors, drones, satellites) and data analysis to manage vineyard variability and optimize grape growing practices at a localized scale.
- **Terroir:** The unique combination of climate, soil, topography, and viticultural practices that shape the sensory profile of a wine.
- **Phenology:** The study of periodic plant life cycle events, such as flowering and ripening, and how they are influenced by environmental conditions.
- **Brix:** A measure of sugar content in grape must, used to estimate potential alcohol and harvest timing.
- **Canopy Management:** Techniques used to control vine foliage density and exposure to optimize grape ripening and health.
- **Evapotranspiration:** The combined water loss from soil evaporation and plant transpiration.
- **Cover Crop:** Plants sown between vineyard rows to improve soil health, reduce erosion, and promote biodiversity.
- **Yield Forecasting:** Estimating the quantity of grapes a vineyard will produce in a given harvest, important for logistics and resource planning.
- **Botrytis (Botrytis cinerea):** A fungal disease affecting grapes, causing rot under certain conditions, though desirable for sweet wine production in controlled cases.

Technological Terms

- **Artificial Intelligence (AI):** The capability of machines to imitate intelligent human behavior, including learning, problem-solving, and decision-making.
- **Machine Learning (ML):** A subset of AI that uses algorithms to identify patterns and improve predictions through data analysis without being explicitly programmed for specific outcomes.
- **Deep Learning:** A specialized area of machine learning using multi-layered neural networks, effective in image and pattern recognition.
- **Convolutional Neural Networks (CNNs):** A type of deep learning model particularly effective for image analysis, such as detecting diseases from drone imagery.
- **Recurrent Neural Networks (RNNs):** AI models designed for sequential data analysis, like time-series weather and pest spread prediction.
- **Remote Sensing:** The acquisition of information about an object or area from a distance, typically via satellite or drone-based multispectral and thermal imagery.

- **Multispectral Imagery:** Imaging technology capturing data at multiple specific wavelength bands, used for assessing plant health, vigor, and stress.
- **Hyperspectral Imaging:** A more advanced remote sensing method capturing hundreds of wavelength bands, allowing for detailed biochemical analyses.
- **NDVI (Normalized Difference Vegetation Index):** A vegetation index derived from multispectral data to measure plant health and canopy density.
- **NDRE (Normalized Difference Red Edge Index):** An index sensitive to chlorophyll content and stress levels, detecting vine issues earlier than NDVI.
- **IoT (Internet of Things):** A network of connected sensors and devices that collect and exchange data in real-time, such as vineyard weather stations and soil moisture probes.
- **LiDAR (Light Detection and Ranging):** A remote sensing method that uses laser pulses to create detailed 3D models of terrain and plant structures.
- **Predictive Analytics:** The use of statistical algorithms and AI to forecast future events, such as disease outbreaks or yield volumes.
- **Time-Series Forecasting:** Predictive modeling of sequential data points collected over time, commonly applied to vineyard climate and crop data.
- **GIS (Geographical Information Systems):** Systems for capturing, storing, and analyzing spatial and geographic data, used in mapping vineyard variability.
- **Autonomous Robots / Drones:** AI-powered machines performing tasks like weeding, spraying, or imaging without human intervention.
- **Decision Support Systems:** AI-integrated platforms that assist human decision-making by providing data-driven insights.
- **Data Bias:** Systematic errors in AI models due to unrepresentative or incomplete training data, affecting model accuracy and fairness.
- **ROI (Return on Investment):** A measure of the profitability or value gained from an investment, applied in assessing AI adoption outcomes.
- **AI-FIT Canvas:** A practical framework tool from this thesis used to match wine business challenges with appropriate AI use cases.
- **VitiGEOSS:** A real-world AI-powered viticulture platform combining AI, IoT, and remote sensing for vineyard management.

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FIGURES

Fig. 1. Precision Viticulture and Automation. Vinescapes.

Fig. 2. Monitoring atmospheric conditions and soil moisture within a vineyard using a weather station. Lodi Wine Growers.

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Fig. 3. Autonomous Robotic Systems. *The Androver II robotic test platform*

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Fig. 4. Precision viticulture technologies overview.

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Fig. 5. Viticultural approaches.

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Fig. 6. Lumo smart irrigation valve in a Cabernet Sauvignon vineyard

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Fig. 7. LiDAR technology. Intelligent Spray Control System

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Fig. 8. Vitigeoss Platform showing mildew auto-detection vineyard areas.

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Fig. 9. Vine Health with Multispectral Imagery

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Fig. 10. Multispectral and complemented vineyard data system

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Fig. 12. Sentinel 2 Satellite

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Fig. 13. Hyperspectral Drone

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Fig. 14. LiDAR Sensor

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Fig. 15. experimental plot scanned with a mobile terrestrial scanner based on LiDAR technology

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Fig. 16. Drones showing their value in vineyards.

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Fig 18. TED Weed Removal Robot

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Fig. 19. *VinBot - Autonomous vineyard robot mapping the environment to predict yield and quality*

<https://robotnik.eu/es/projects/vinbot/>

Fig. 20. *VinBot - Front view to vineyard*

<https://robotnik.eu/es/projects/vinbot/>

Fig. 21. *VinBot*

<https://robotnik.eu/es/projects/vinbot/>

Fig. 22 to 29. Google Forms Survey Study

<https://forms.gle/19667ezPD6to15bS8>

Fig 30. Complete set of 150 AI&WINE Cards

Fig 31. Wine Business Ecosystem Cover Cards

Fig 32. Each card contains the wine ecosystem spot on one side and the explanation on the other side

Fig 33. AIW-FIT Cards are numbered and categorized. AIW means Artificial Intelligence in Wine.

Fig 34. Front side of AIW-FIT Card

Fig 35. Back side of AIW-FIT Card

Fig 36. Luciano Wehrli running practical workshops to find AI use cases in wine industry

Fig 37. AIW-FIT Canvas

Fig 38. AIW-SOLUTION CANVAS

Fig 39. Canvas AIW-Service Journey

Fig 40. Canvas that is used in practical workshops with wine business owners. AIW-Quick Assessment Canvas

TABLES

Table. 1. Key vineyard data collected through multispectral imaging typically includes.