Journal of Engineering Science *Vol. XXXII, no. 4 (2025), pp. 137 - 149*
Fascicle *Food Engineering* *ISSN 2587-3474*
Topic *Food Industry and Management* *eISSN 2587-3482*

https://doi.org/10.52326/jes.utm.2025.32(4).10
UDC 663.25:634.8:004.8:004.738.5

SMART TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE IN VITICULTURE

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Received: 11. 15. 2025
Accepted: 12. 22. 2025

Abstract. Every technological innovation is a step forward in the development of human society. Almost all areas of life have been affected by the digital industry, including winemaking. The digitization process is widely implemented in order to obtain high-quality products, increase crop yields, verify counterfeit wine products, and automate the work process. Any digital technology can be used for the benefit of mankind, and the use of drones in winemaking is already accepted and recognized. The International Organization of Vine and Wine (OIV) has launched a new digital monitoring center with the aim of identifying key trends in digitalization and how new technologies can be applied in the vine and wine sector. The initiative aims to provide updates on digital/technological trends in the vine and wine sector. This paper analyzes various digital technologies used throughout the value chain: vineyard, winery, and distribution. Artificial intelligence, robotics, satellite imaging, the Internet of Things (IoT), and blockchain are some of the technologies included. For each of these, a definition has been included, as well as their application in the wine sector and their future prospects. Digital transformation offers the wine sector an opportunity to gain efficiency, transparency, productivity, open up to new business models/value propositions, and improve sustainability.

Keywords: *digitization in winemaking, modern wineries, digital technologies, viticulture, robotics, blockchain.*

Rezumat. Fiecare inovație tehnologică este un pas înainte în dezvoltarea societății umane. Aproape toate domeniile vieții au fost afectate de industria digitală, printre care și domeniul vinificației. Procesul de digitalizare este implementat pe larg în cadrul obținerii unor produse de înaltă calitate, majorării volumului de recoltă, verificarea produselor vitivinicole contrafăcute și automatizarea procesului de muncă. Orice tehnologie digitală poate fi folosită în folosul omului, iar utilizarea dronelor în domeniul vinificației este deja acceptată și recunoscută. Organizația Internațională a Viei și Vinului (OIV) a lansat un nou centru de monitorizare digitală cu scopul de a identifica principalele tendințe în digitalizare și modul în care noile tehnologii pot fi aplicate în sectorul viei și vinului. Se propune inițiativa de a oferi actualizări privind tendințele digitale/ tehnologice din sectorul viei și vinului. În lucrarea dată s-au analizat diferite tehnologii digitale utilizate pe parcursul etapelor lanțului de valoare: vie, cramă și distribuție. Inteligența artificială, robotica, imagistica prin satelit, Internet of Things (IoT) și blockchain sunt câteva dintre tehnologiile incluse. Pentru fiecare dintre acestea a fost inclusă o definiție, precum și aplicația lor în sectorul vinicol și perspectivele lor viitoare. Transformarea digitală oferă oportunitate sectorului vinicol de a câștiga eficiență, transparență, productivitate, de a se deschide către noi modele de afaceri/propuneri de valoare și de a îmbunătăți durabilitatea.

Cuvinte cheie: *digitalizare în vinificație, crame moderne, tehnologii digitale, viticultură, robotica, blockchain.*

1. Introduction

The wine industry is undergoing a profound transformation due to the adoption of digital technologies and process automation, which are necessary for producing high-quality wines while reducing operational costs and energy consumption. In many wine-producing countries, conceptual projects have been launched to address the challenges of an increasingly complex and fast-paced global market. The Italian project Vino 4.0 is dedicated to integrating the latest technologies in the wine industry with new models of organization and promotion of the wine business. Advanced technologies, such as infrared spectroscopy integrated with artificial intelligence (AI), offer extensive possibilities for analysis and optimization. Spectroscopy detects and analyzes the chemical parameters of grape varieties, and AI processes this data by comparing it with existing databases to identify deviations or opportunities for improvement. Based on historical and predictive analyses, AI enables an assessment of grape quality over several years, providing winegrowers with strategic information on evolutionary trends and harvest quality.

Technologies such as the Internet of Things (IoT), Laser Imaging Detection and Ranging (LIDAR), satellite imaging, and geographic information systems (GIS) contribute significantly to the digitization of agricultural processes in viticulture. IoT integrates high-precision sensors for continuous monitoring of essential parameters such as soil moisture, air humidity and temperature, and wind speed. Complex, integrated analysis of these parameters, correlated with decision-making models based on effective practices tested over many years, allows for the optimization of irrigation, reduction of water consumption, and identification of the nutrients needed by the vines.

The intelligent recommendations of the digitized system are adapted to variable weather conditions and other impact factors. LIDAR scanning technology is a remote sensing method used to assess the characteristics of a specific area in detail, such as studying the terrain, vegetation, and obstacles, and recording this information.

This method is already being used in viticulture, including to prevent accidents in vineyards, namely through the use of a detailed 3D map of the terrain and satellite images are used to map and analyze vineyards, providing detailed data on terrain topography, crop conditions, and areas with high productivity potential. In wineries, sensors monitor critical fermentation and storage parameters, contributing to precise adjustments and ensuring consistent quality of the final product [1-3].

The main objective of digitization in the wine industry is the complete integration of data and processes to create an agile, sustainable production system capable of consistently delivering high-quality wines, regardless of fluctuations in various important factors. According to the report by International Organization of Vine and Wine (OIV) experts [4], digitization in the wine sector focuses on the following key components: efficiency, productivity, transparency, proposing new values and business models, and sustainability.

In order to effectively achieve this goal in the field of production and storage, the following basic trends of the digital revolution are evident: IoT/sensorisation, AI, robotics, satellite imaging/ GIS, LIDAR systems, blockchain, e-label, e-certificate, smart storing.

The economic, social, and environmental benefits of implementing these components can only be relevant if all stages of product realization—raw material production, processing, distribution, and marketing—are integrated into the digitized system in order to optimize the organization and management of the wine-producing entity [5]. Certain digital technologies and techniques are present at all stages of production and distribution, while others are specific to certain stages (Table 1) [6].

Table 1

Digital Transformation of Production and Distribution Processes [5,6]

Production	Transformation	Distribution	Consumption
Field sensors, technology and equipment. Drones. Satellite imagery. Decision support systems (DSS).	Quality control sensors. Big Data Analytics. Dematerialization systems. Integrated traceability.	Logistics optimization systems. E-commerce platforms. Blockchain in food delivery.	Smart labels. Sensors for waste reduction. Food sets. Big data analytics.

In fact, DSS must be present at all stages of the production-distribution chain as an indisputable tool for analyzing data and recommending executive decisions, free from human error.

2. Smart Technologies in Vineyards

During the grape production stage, real-time data acquisition provides winegrowers with an overview of the phytosanitary status of the plantation, temperature and water conditions, light radiation, vegetative development, nutrient sufficiency, chlorophyll content, wind direction, and wind speed. The data provided (input) feeds various predictive models and, as a result, is reflected in relevant conclusions about the risk of the occurrence and development of various pathogenic diseases (downy mildew and powdery mildew), the activity phases of pests, and the course of biochemical processes that impact grape quality [7]. In this context, the oenologist also has a priority of information about the potential quality of the grapes, enabling them to organize the winemaking process appropriately.

Precision viticulture (PV) is closely linked to smart technologies and depends on their level of development and implementation. Smart technologies can already become a reliable aid to winegrowers in establishing vineyards by providing comprehensive training at all essential stages: mapping with geodetic positioning (satellite, aerial, and drone imagery), LIDAR, physical and chemical soil analysis, assessment of water reserves, nutrients, etc.

Planting a vineyard cannot be successful unless all the impact factors that will determine the quality of the grapes are taken into account: soil quality, exposure, slope, wind rose, composition, granulometry, water retention capacity, organic matter, erosion risk, etc. Data on these essential parameters can be obtained using remote monitoring techniques (satellites, aircraft, drones), assisted by intelligent equipment and sensors. The dedicated software can also be fed with the primary information collected without the involvement of operators, thus excluding possible errors caused by human factors. In conclusion, reports are obtained on the feasibility of planting, as well as recommendations on the suitability of the land for the intended varieties or the most suitable varieties for planting. If in-depth soil studies of the land already exist, they can be digitized and made available for consultation on web-based platforms using geographic information system, such as the one developed by the Agricultural Institute of the Edmund Mach Foundation (S. Michele all`Adige, Trentino, Italy) [8]. Formation on water requirements for irrigation can also be consulted, providing sufficient data for calculations according to the Irri4web mathematical model based on soil characteristics [8,9]. Other useful information is also available, processed in QGIS software—shading, exposure, slope, hours of sunlight, potential global radiation.

All forms of real-time agricultural imaging provide information about plant vigor, development trends, and possible nutrient deficiencies. Images taken from lower altitudes (airplanes and drones) (Figure 1) are more suitable for this topic, as the sectors between rows can be individualized to exclude them from the estimation of vine vigor [10,11].

Figure 1. Low-Altitude Drone-Based Agricultural Imaging System for High-Resolution Monitoring of Vine Vigor, Growth Dynamics, and Nutrient Stress Indicators [11].

Projects such as Chianti and Bolgheri [12], launched in this context in Tuscany, Italy, in vineyards of 15 and 3 ha respectively, using drones equipped with multispectral and thermal cameras, have demonstrated their effectiveness and the importance of information for tactical decisions appropriate to precision viticulture. Thus, thermal and multispectral images, processed using various specialized programs (PIX4D, NDVI-Normalized Difference Vegetation Index, and CWSI, Crop Water Stress Index), enabled the creation of 3D maps of temperatures, four classes of water insurance, and vegetative vigor (Figure 2).

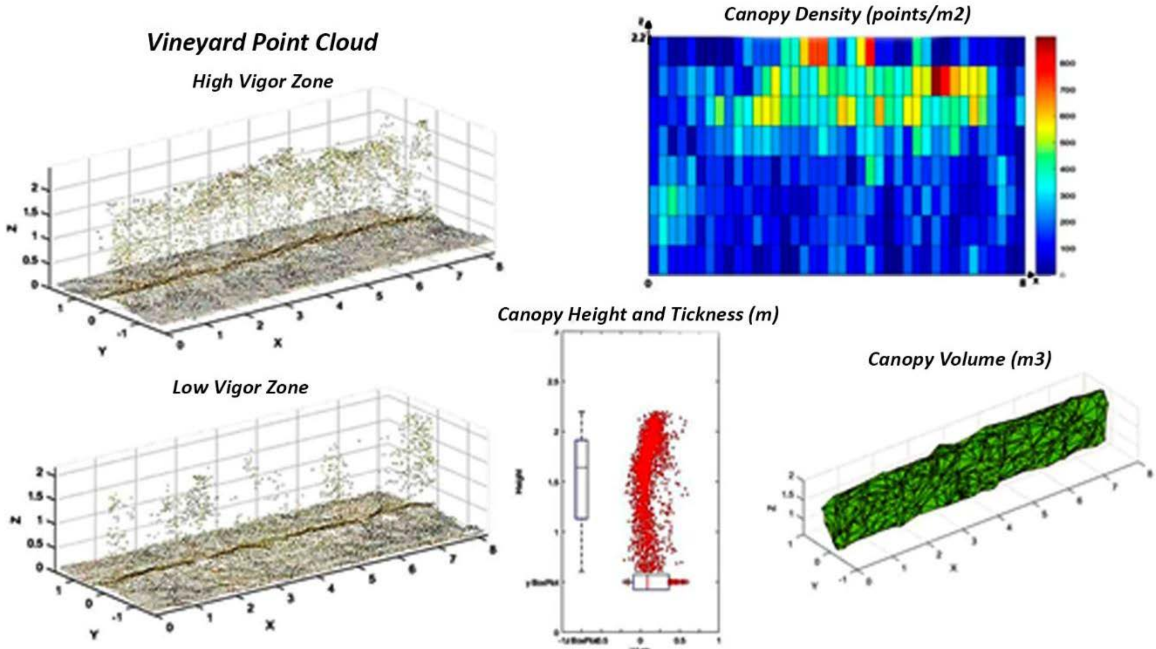

Figure 2. Vine vigor map, created in 3D based on multispectral images captured using drones [12].

The image resolution ranged from 1.76 to 8.6 cm/pixel, which ensured accurate details. Based on these results, schemes were developed for differentiated irrigation and staggered harvesting according to grape quality.

3. Precision Viticulture and Robotics

Determining the geographical coordinates of plants showing symptoms of certain diseases or nutritional deficiencies can be integrated into the decision-making system by programming the executive machine for local processing and fertilization according to the specific situation, without the need to treat the entire vineyard excessively. This results in significant savings in pesticides and fertilizers and ensures increased sustainability, with particular care for environmental organisms, pollinating insects, flora diversity, and soil quality [13]. Artificial intelligence is responsible for managing each stage of vineyard work, including harvesting, given that automated systems have already been developed for the operational sorting of grapes by quality during mechanized harvesting [14,15]. The labor shortage is forcing builders and IT specialists to develop robots to efficiently replace humans, even in the most complex operations. Similar technologies are being progressively implemented in large companies in the field. For example, Bouchaine Vineyards (California, USA) has secured its production throughout the wine-making chain with IoT sensors from Cisco, not only to optimize the quality of grapes and wines, but also to avoid wasting any resources and ensure care for the environment [15]. To emphasize sustainability, together with researchers from Oregon State University's Wine Research Institute, they are studying and developing smart technologies to combat pests without harming pollinating insects. To do this, they use robotic devices powered by solar energy to generate vibrations of a certain frequency and intensity to capture and destroy harmful insects (Figure 3). The frequency of the vibrations coincides with that used by insects to meet and mate.

Figure 3. The Pied Piper robot (prototype) for selective pest control in vineyards [15].

Robots are also welcome when it comes to performing complicated and responsible tasks to replace professional operators, such as cutting and shaping the crown of grapevines. In New Zealand, the Maara Tech project has been launched with the involvement of researchers from the Universities of Auckland and Ontago, focusing on virtual pruning and correct crown formation. Virtual reality headsets are also being designed to teach the principles of dry and green pruning. Continuous training of the curriculum takes place with the help of Artificial Intelligence. Initially, the rows are scanned using a robot [17].

Although fully automated cutting has not yet been achieved, numerous robots, including those already in industrial production, are available for other maintenance tasks—chipping removed wood material, loosening soil, mowing grass between rows and between plants, spraying pesticides and fertilizers, and the trend toward replacing scarce labor with robots is steadily increasing. The automation of vineyard work can also be achieved by towing various equipment with autonomous tractors equipped with sophisticated positioning and monitoring systems, with multiple video cameras, radars, and LiDARs. Increasingly, these are powered by electric motors rather than combustion engines. AI ensures instantaneous response to deviations from the planned route - 0.1 s [17]. Communication platforms already allow remote control of multiple executive units. For example, six tractors can be controlled simultaneously via a smartphone in Android or iOS environments.

4. The era of Drones in Viticulture

The global market for agricultural drones (Unmanned Aerial Vehicles – UAVs) is experiencing rapid growth, reaching an estimated value of USD 1.92 billion in 2024 and projected to expand to approximately USD 10.46 billion by 2034 [18]. According to additional sources, the European agricultural drone market alone was valued at around USD 5.8 billion in 2024, with expectations of growth to USD 7.62 billion in 2025 and a long-term forecast indicating an increase to approximately USD 55.72 billion by 2033 [19]. A substantial share of this market is attributed to drones designed for crop health management, particularly those employing aerial spraying technologies, commonly referred to as unmanned aerial spray systems [20].

A major challenge is the use of drones for phytosanitary treatments and vineyard fertilization (Figure 4). Industrial technologies are advancing rapidly, and agricultural drones are now being proposed, specialized for various operations, assisted by complex software, cameras, GPS localization, and impressive technical features.

The well-known Chinese company DJI (global leader) recently launched its top-of-the-range Agras T100 model, which has a 75-liter pesticide tank and a 100-liter fertilizer tank, with a takeoff weight of 150 kg and lifting capacity of 85 kg, a 360° horizontal and 180° vertical viewing system consisting of five cameras, LiDAR, radar, and AI. These features allow the Agras T100 to be used even at night, and to increase the efficiency of treatments, the droplet size can be adjusted by adjusting the spray nozzles accordingly [21].

While EU legislation is slowly evolving, with many reservations in drone regulations, including for security reasons, in some countries - the US, China, Japan [22], drones are increasingly being used for these important tasks, generating a number of advantages [23,24]:

- ✔ the ability to intervene when traditional techniques cannot be applied, at any phenological stage, regardless of soil moisture, without compacting it;
- ✔ savings in pesticide consumption of up to 30%, with the prospect of reducing the amount of pesticides needed by 5-10 times;
- ✔ reduced water consumption (more than 10 times);
- ✔ operational efficiency—about 5 times faster than traditional methods [23];
- ✔ possibility of localized treatments, with mapping and exact GPS positioning.

To overcome excessive regulatory constraints, facilitate the adoption of drones in agricultural practices, and support the integration of emerging technologies, several countries, including Poland and Germany, have been compelled to approve official derogations from existing European Union regulations [25].

At the same time, the problems that need to be solved are also highlighted, including uncertainties regarding the effectiveness of drone-based treatment, possible drift of sprayed preparations from target objects and damage to the ecological system, including pollinating insects, potential phytotoxic effects caused by active ingredient concentrations that are much higher than in traditional treatments, etc.

Work safety for operators is no less important. As tests carried out in Lombardy (Italy) have shown, when treating vineyards with drones in weather conditions that meet the requirements, the operator (pilot) is not at risk of contamination except when filling the tank with the necessary preparations [26].

Figure 4. Drone-Based Phytosanitary Treatment System for Precision Protection of Vineyards [26].

Another limitation is the development of an appropriate legal framework, which in the EU requires a complex approach, as well as the certification of pilots in accordance with European Regulations 2019/945 and 2019/947.

A pragmatic, rational approach to the use of drones in plant protection is demonstrated by Switzerland, a country that has developed concise, precise, and intuitive scenarios for the application of drones (Figure 5) [27]. Drones can be used at a maximum wind speed of 3 m/s, with a maximum flight speed of 7 m/s. The maximum flight altitude is 30 m above ground level, with spraying possible up to 6 m above ground level. The distance to the buffer zone (10 m) and its width are specified. In this way, the Swiss have omitted excessive bureaucracy from the permissive documents, which hinders the application of drones in agriculture.

In recent years, a severe and incurable disease capable of compromising entire vineyards has been identified, namely grapevine yellows, commonly referred to as Flavescence dorée [28,29]. The disease is caused by a phytoplasma—a unicellular pathogenic organism—transmitted by the insect vector Scaphoideus titanus (grapevine leafhopper).

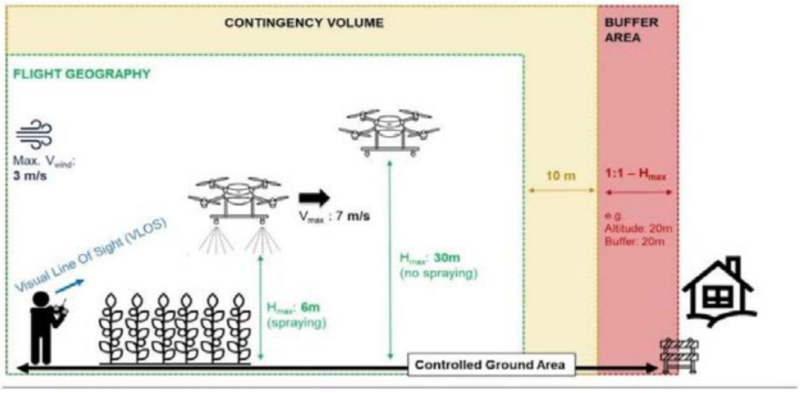

Figure 5. Example of a scenario sheet for the use of drones for phytosanitary treatments in Switzerland [27].

The manifestation of the disease in vineyards is well defined and exhibits distinct symptomatology depending on grape variety, particularly between white and red cultivars. Based on a comprehensive set of physiological and phenotypic parameters, the disease can be reliably identified, allowing for an accurate assessment of infection severity and the subsequent development of vineyard sanitation and containment measures. A critical step in the monitoring of phytoplasmosis is the determination of infection rates, which is essential for establishing effective control strategies. However, this task becomes particularly challenging in large-scale vineyards, especially considering the highly active but temporally limited phenophases during which vector insects exhibit peak activity. To facilitate the detection of disease symptoms, identify outbreak hotspots, and monitor disease spread over extensive areas within short timeframes, drone-based technologies equipped with multispectral and hyperspectral imaging systems have been developed. A key contribution to the advancement of these technologies was made by researchers at NASA, whose findings were subsequently commercialized by the Canadian–French–American consortium SkySquirrel Technologies. With proven field experience in vineyards across France, Switzerland, and Romania, SkySquirrel Technologies demonstrated the operational effectiveness of this approach in 2017 through the pilot project FlaveDor. The project was conducted in the vineyards of Sălcuța LLC (Căușeni district), with full involvement of the National Office of Vine and Wine and support from international partners, including USAID and the Government of Sweden [30]. The drone-based system achieved a detection accuracy of 95%, surveying 20 ha of vineyards in just 24 min. In addition to Flavescence dorée, the integrated sensor suite successfully identified another highly destructive disease - Black Wood (Bois noir). Following the demonstrated high efficiency of this technology, the role of specialized drones in monitoring vineyard health is expected to expand significantly in the near future, becoming an essential component of precision viticulture and sustainable plant protection strategies.

5. Evaluating Grape Ripeness

During the grape ripening stage, it is crucial to estimate the optimal harvest period, using not only sugar and acid content as reference parameters, but also polyphenol concentration and their extractability from the berries. To this end, several laboratory methods have been developed, but they require special equipment and are time-consuming and laborious. To overcome these drawbacks, mobile methods have been developed to instantly assess phenolic ripeness [31,32], based on the principle of global radiation absorption in a specific spectral range (Figure 6).

a) b)

Figure 6. Hand-device Spectron (a) and Multiplex (b) for grape quality proximal quality [32].

Phytosanitary status assessment and grape maturation monitoring can be fully automated through robotic and drone-based systems (Figure 7) [33], incorporating advanced technologies for data acquisition, transmission, integration, and intelligent interpretation.

Figure 7. Robotic monitoring of phytosanitary status and grape ripeness [33].

Assessing the phenolic maturity of red grapes is an essential criterion for obtaining quality wines. To quantify this parameter, equipment based on the interaction of waves with grapes is proposed. These can be waves in the infrared range or the fluorescence effect (Pellenc Spectron and Multiplex Terrain portable devices) [32].

Prof. E. Celotti et al. from the University of Udine (Italy) [34] developed an instrumental photometric method for easy, instant assessment of ripeness directly in the vineyard, comparing the results with those obtained by traditional methods in laboratory conditions, but also with the color intensities of vineyard plots, obtained by satellites using cameras with different spectral filters (Figure 8) [34,35].

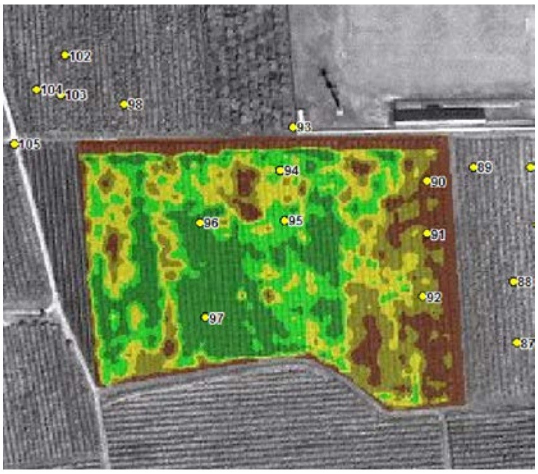

Figure 8. Satellite image of a vineyard and elaboration of spectral information into vigor indices [34].

For vineyards, a satisfactory correlation was established between the abstract values obtained in the vineyard and satellite spectral analysis. For vineyards in the Valpolicella area, a high correlation was determined between vine vigor and anthocyanin content (R^2=0.8997), while the correlation between vigor and carbohydrate content (°Brix) is much lower (R^2=0.3244) (Figure 9). The evolution of drone technology can make this procedure very efficient for plantations of all sizes and for the most diverse grape varieties.

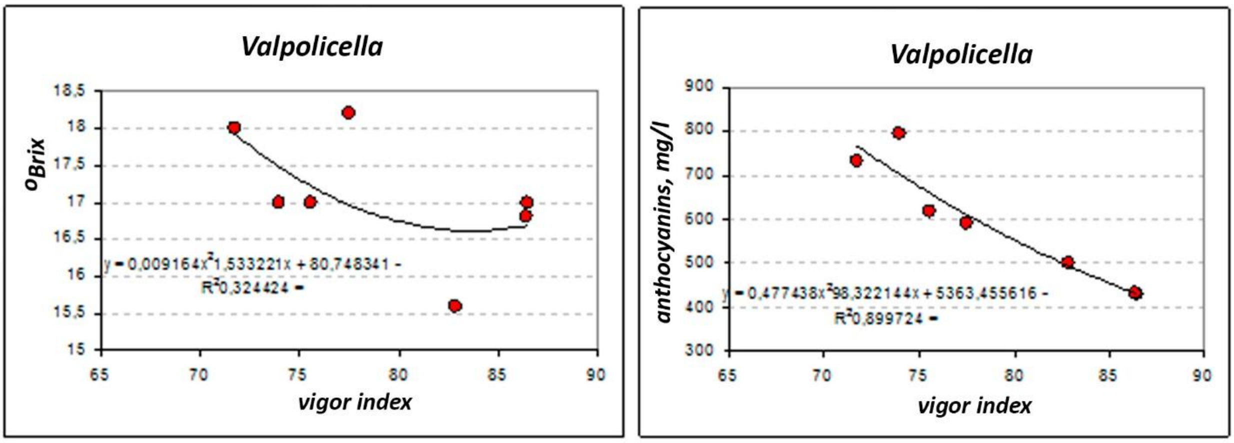

Figure 9. Correlations between vine vigor, determined using satellite imagery, and various grape parameters [35].

Regenerative agriculture, based on accurate data, improves soil quality and vineyard productivity, helping to mitigate the impact of climate change. In this context, digitization not only reduces the risks associated with harvesting and production, but also allows processes to be customized to meet market demands and consumer preferences. Through automation, smart monitoring, and advanced analytics, the wine industry is building a modern future focused on excellence and sustainability [36,37].

From exotic to widespread implementation, with the full involvement of wine industry specialists, through their training and involvement in the adjustment and development of smart technologies—this is their natural path in the face of multiple challenges—climatic, economic, ecological, and social. Familiarization with the latest smart technologies and their use in successful economies is no longer an option but a necessity, as confirmed by numerous dedicated events, such as the robotics and digitization festival in viticulture in Italy, organized on the platform of the University of Pisa with the participation of numerous national and international producers, researchers, and consumers of such products [38,39].

6. Conclusions

The implementation of smart technologies in viticulture represents a fundamental change in the mechanization, automation, and optimization of wine grape production, bringing tangible benefits at both the operational and strategic levels.

Although the adoption of smart technologies is currently at an early stage, they promise undeniable valuable potential.

The main task of developing smart technologies in the wine sector, associated with artificial intelligence, is to help wine growers throughout the entire production chain to:

- ✔ identify areas suitable for growing grape varieties;
- ✔ monitor the vegetative state of plantations, climatic conditions, and the plants' water and fertilizer needs;

- ✔ optimize irrigation and fertilization of vineyards;
- ✔ detect pests and diseases of vines and optimize phytosanitary protection;
- ✔ simplify and automate quality control of grapes to optimize their harvesting.

Acknowledgment: The research was funded by Institutional Project 020405„Optimizing food processing technologies in the context of the circular bioeconomy and climate change, Bio-OpTehPAS", running at Technical University of Moldova.

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

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Citation: Scutaru, I.; Sclifos, A. SMART technologies and artificial intelligence in viticulture. *Journal of Engineering Science*. 2025, XXXII (4), pp. 137-149. https://doi.org/10.52326/jes.utm.2025.32(4).10.

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