

# Economics and barriers of precision viticulture technologies: A comprehensive systematic literature review

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## ABSTRACT

Precision farming technologies are revolutionising the wine-growing sector thanks to their ability to manage crop variability, increase economic benefits, reduce the environmental impact, and improve grape yields and quality. Most earlier studies focused on the effects of precision technology adoption on plant health and canopy development—and therefore grape quality—neglecting the profitability impact. This study aims to fill this gap by presenting a systematic literature analysis discussing advancements in the economics of precision viticulture technologies. The results show how technologies such as unmanned aerial vehicles, precision irrigation, and robotics can increase efficiency in resource management, helping to reduce costs and improve vineyard profitability. However, the findings also emphasise the need for tailored approaches to integrate these advances. Furthermore, the analysis highlights the main barriers related to the cost of adopting precision technologies and the skills required to read and interpret the data. The results of this study hold interest to academics, vine growers, and farmers, providing a basis for future research into the cost-effectiveness of adopting precision technologies.

## 1. Introduction

Precision agriculture (PA) has revolutionised farms globally by managing spatial and temporal variability and contributing to enhancing crop performance, reducing costs, minimising environmental impact, and improving food production quality [1,2,3]. PA has evolved into a digital-centric approach that is increasingly adopted worldwide. One of the areas in which PA has found wide application is viticulture. Through the adoption of sensors, data analytics, and automation, precision viticulture (PV) enables sensing and comprehending variability in production systems, allowing growers to better match inputs to desired outputs [4], thus elevating grape quality [5]. The operational goals of PV encompass various aspects, including differentiated vineyard management through variable-rate fertilisation, variable-rate pesticide spraying resulting in reduced costs and environmental impacts, and tailored pruning and canopy management based on vigour and microclimatic needs [6].

Adopting Precision Agriculture Technologies (PATs) in viticulture could enable addressing environmental and climate change challenges. According to the World Meteorological Organization (WMO), there has been an increase in global temperature of about 1.1 degrees Celsius above pre-industrial levels, affecting grapevine cultivation areas and insect populations, thereby influencing grape production [7]. For instance, in 2023, global production plummeted to 244.1 million hectolitres, marking the lowest output in the past 60 years. The World

Organization of Vine and Wine (OIV) reported a 7 % decrease compared to the previous harvest on a global scale. Europe was significantly affected by the unfavourable weather conditions, experiencing a 6 % decline in production, totalling slightly over 150 million hectolitres [8]. As mentioned in the OIV report: “Once again, extreme climatic conditions – such as early frost, heavy rainfall, and drought – have significantly impacted the output of the world vineyard”. In addition, in 2023, at the European level, substantial rains between April and May caused significant challenges for wine-growing companies (i.e. fungal pressure, storms, hail, severe droughts), resulting in damages to vine health (i.e. hydric stress, vigour level, defence response of plants in the presence of pests or disease), ranging from 10–20 % to 70–80 % of loss of grape harvest volume [8].

In this scenario, employing predictive models is crucial in minimising these damages, highlighting the importance of defensive management strategies. Specifically, predictive models are the dynamic result of a mathematical and mechanistic analysis driven by weather data, soil characteristics, and biological information. These models can signal the probable onset of disease or infestation spread that could compromise production by the end of the crop year [9]. These tools provide valuable real-time information for vineyard management through alerts, as seen in the models for primary infections by mildews in Caffi et al. [10], back rot disease in Rossi et al. [9], and plant hydric stress levels in Cola et al. [11].

Many empirical studies have focused on optimising resources with

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PATs, improving overall vineyard management. In particular, these technologies provide detailed data on soil moisture, plant health [12], and canopy development [13], allowing for targeted interventions such as precise irrigation, tailored nutrient application, and timely pest or disease management, reducing environmental impact and enhancing the quality of grapes harvested [14,15,16]. However, despite these technologies' increasing adoption, studies on PV come from various research fields, losing sight of the profitability of adopting these innovative tools as the main priority for winegrowers. In the context of PV, understanding economic profitability can be approached using different terminologies based on the methodological perspective as (1) a valuable metric for decision-making, particularly when assessing the productivity of technology implementations in the field of viticulture over a historical timeframe [17]; (2) a measure of economic performance that considers not only explicit or accounting costs but also implicit or opportunity costs [18]; and (3) a concept used to assess the profitability of a business by considering the total economic costs involved, including the cost of capital or the return that could have been earned on alternative investments [19]. Recent studies on PV explore technology adoption's farm benefits and barriers. Studies such as Maynard et al. [20] and Schimmelpfennig and Ebel [21] showcase increased profits due to increased yield or reduced operating costs, notably in pesticide and fertiliser usage. However, while precision tools offer savings in vineyard management costs [22], the results fluctuate [23] because the profitability of PATs in viticulture varies across technologies, crops, and farm sizes [24,25]. For example, due to socio-economic barriers and higher investment costs, smaller farms often face obstacles in adopting PATs [26]. In this scenario, it is interesting to identify the potential applications of different precision farming tools in the vineyard, their relative profitability, and factors that might hinder their adoption. Consequently, the following two research questions (RQs) have been formulated:

RQ1. Does the integration of PATs in viticulture improve the wineries' economic performance?

RQ2. What are the main barriers associated with adopting PATs in viticulture, and why might these risks arise?

This work aims to review the extant literature to gather knowledge on how academics have addressed the economics of PATs in the wine industry to date, as well as ascertaining potential barriers hindering its rapid spread, including technological issues and the learning resistance from winegrowers.

This study is distinctive and contributes to the state of the art of literature on precision technology adoption by summarising the knowledge accumulated about the economics of PATs applied to wine-growing companies and outlining the effects of implementing different precision technologies on the profitability of wine-growing companies. A clear picture of the economics of investing in precision technologies is important to guide future research and encourage growers and wine industry decision-makers to invest in innovative and sustainable solutions, especially in the face of looming socio-economic and environmental challenges. Profitable precision technologies are more likely to be widely adopted, especially if they contribute to achieving environmental benefits. Furthermore, this work aims to propose new perspectives to scholars and wine managers on exploiting the potential offered by precision technologies from an ecological perspective.

## 2. Methodology

### 2.1. Articles' selection

A systematic literature review was chosen for its ability to summarize knowledge on a specific research field, like the profitability in the adoption of PATs in vineyards, by adopting well-defined criteria in a comprehensive and transparent manner. In addition, to conduct a comprehensive literature review on the adoption of PATs, a broad search of these technologies in the viticulture field was carried out.

Following the guidelines from Moher et al. [27], the following economic keywords such as 'Economic Feasibility', 'Economic Profitability', 'Economic Performance', and 'cost analysis' were considered. For the Precision Technologies, the following keywords: 'precision technologies', 'Proximal sensors', 'remote sensors', 'robots', 'Unmanned Aerial Vehicle (UAV)', 'precision farming', and 'precision agriculture'. For the viticulture topic, keywords such as 'precision viticulture', 'viticulture', 'Vitis vinifera L.', 'Grapevine vigour', 'grape', and 'wine' were included.

Consequently, the search formula employed for the research was: ('Economic Feasibility' OR 'Economic Profitability' OR 'Cost analysis') AND ('Precision viticulture' OR 'Viticulture' OR 'Grape' OR 'Wine' OR 'Precision technologies' OR 'Proximal sensors' OR 'Remote sensors' OR 'UAV' OR 'Robots' OR 'Precision farming' OR 'Precision agriculture') AND ('Vitis vinifera L.' OR 'Proximal sensors' OR 'Viticulture' OR 'UAV' OR 'Wine').

### 2.2. Coding

The search formula was applied to academic databases, namely Science Direct, Web of Knowledge, and Scopus, obtaining a list of 1,995 articles (1,524 results for Science Direct, 301 articles for Web of Knowledge, and 170 articles for Scopus). Specifically, key terms were sought within manuscript titles, keywords, and abstracts in all databases. In the first phase, articles were systematically screened in relation to the exclusion and inclusion criteria described in Table 1 to identify only studies closely associated with the theme of this article. Specifically, only peer-reviewed articles strictly adhering to the study objectives were included. Other research—including empirical research on books and/or conference proceedings, or grey literature articles—was excluded because these documents do not clearly specify review standards.

The authors carried out data extraction from the aforementioned databases from December 2023 to February 2024, which included checking the information for each of the extracted items in relation to the inclusion and exclusion criteria and resolving any discrepancies through discussion.

In the initial phase, no specific time frame was defined, whereby the search conducted and the inclusion and exclusion criteria specified did not identify any scientific articles published prior to 2005. Subsequently, a timeframe from 2005 to October 2023 was set. Following the screening, the total number of articles was reduced from 1,995 to 679, in line with the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [28,29].

In alignment with the goals of the systematic literature review, the coded data were recorded and categorized into different sections,

**Table 1**  
Inclusion and exclusion criteria.

INCLUSION criteria	EXCLUSION criteria
Peer reviewed articles with a particular focus on the costs and returns associated with the implementation of precision viticulture technologies, considered in the search equations, whether theoretical perspectives and real profit indicators, were included	Articles on financial indicator analysis to observe the productivity of company with the precision technologies applied in other type crops were excluded
Peer reviewed articles that focused exclusively on economic aspects of innovative real wine-growing company real life to optimize vineyard management considering the different types of technologies applied in different phases of vineyard lifecycle	Other types of articles like gray literature or literature review, extended abstract, book chapters, and series found in open access journals were excluded
Research Articles with only English language published in scientific journal were included	Other articles with the same main research topic written in other languages were excluded

including publication details, paper type, definitions related to the research questions, unit of analysis, main findings, and authors' suggestions for future research in each study. This step was taken to minimize the chance of errors and ensure that the process is clear and repeatable. Duplicate references were searched for, and article titles and abstracts were reviewed, resulting in 354 selected articles. Subsequently, following a screening based on article abstracts, 47 articles were identified and included. After completing the abstract review and selection process, the papers underwent thorough reading to ensure alignment with the review's objectives. All the authors conducted

stringent screenings based on agreed-upon criteria, emphasizing original research on agricultural precision technologies and economic analysis methods.

The last phase involved reading the full texts of the selected papers, serving as a definitive assessment to include only the most relevant ones. Throughout this stage, papers that did not precisely address the research topics were excluded. Additionally, we considered those focusing primarily on economic profitability if they contributed to the broader research area under review. The selection of full papers relied on the presence of economic analysis, encompassing basic cost descriptions to

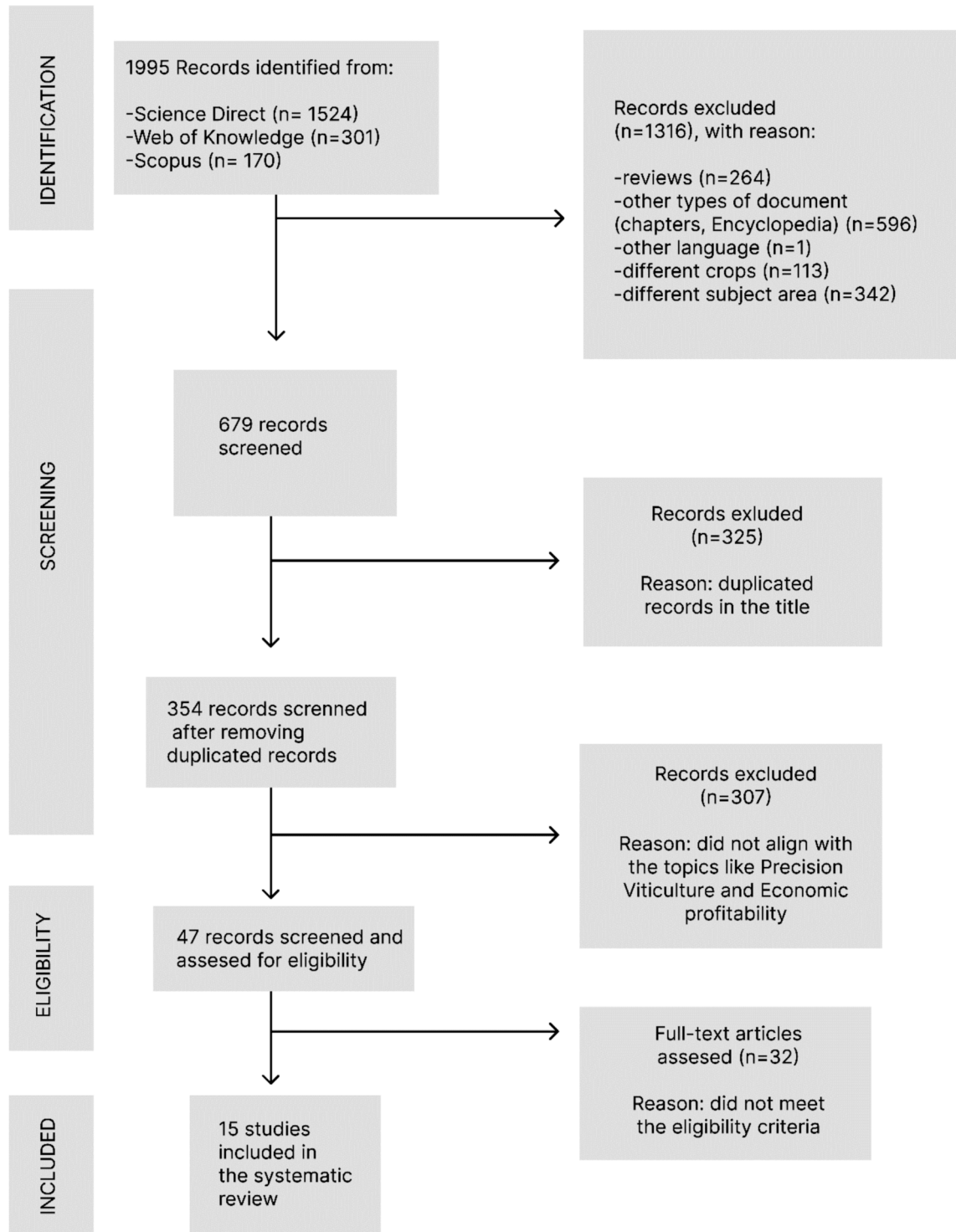


Fig. 1. PRISMA flowchart, overview of the article selection process.

comprehensive cost–benefit analyses applied in various PATs in viticulture. Stringent procedures were in place to ensure a comprehensive assessment of full papers, minimizing the risk of excluding relevant articles. Extracting, documenting comprehensive data from papers allowed thorough evaluation, offering insight into current research in the field. Ultimately, after conducting a final assessment meeting the predefined eligibility criteria, 15 articles were ultimately selected. The entire process is illustrated in Fig. 1. Analyses were performed with the systematic software Rayyan, a powered tool for Systematic Literature Reviews and visual keywords networks [30].

2.3. Research questions formulation and search strategy

First, we described each of all studies under review with categorical variables, including information such as authors, title, publication year, journals, publication type (theoretical/conceptual or empirical), methodology applied, and managerial context of empirical studies. The procedure in line with the PRISMA statement, allowed us to identify the key themes, codes, and relationships under the ‘application of Precision technologies effect on productive level of wineries’ framework, which encompassed three major aspects: (1) the application of PATs in viticulture (including various types of precision technologies and their applications); (2) the economic viability of these technologies (encompassing the reduction of operational cost, increase in gross margin profit or net revenue, increases in yield, enhancements in production quality, price competitiveness, and the attainment of a positive net benefit); (3) the presence of barriers according to different perspectives of figure involved with the application of PVTs. Subsequently, this information was used to address our research questions (RQs). The formulation of these RQs was carried out allowing for a systematic report of results and facilitating comparisons between different articles within the same category. In our final review, we documented practical implications and delved into suggestions for further research. Our aim is to present a straightforward and clear framework aligned with research questions, facilitating the development of a comprehensive line of inquiry.

3. Results and discussion

3.1. Descriptive analysis

3.1.1. Paper trends and distribution over time among selected scientific journals

The distribution of publications over time (Fig. 2) reflects a growing interest of scholars towards the economic feasibility of PV. The first article selected for this review, was published in 2005, is a study on the inclusion of vineyard variability into experimental designs, focusing on maximizing the benefits of vineyard experimentation through the use of satellite applications in South Australian wine regions [31]. While, the most recent selected article, published at the beginning of 2023, explores the potential of robots in viticulture, highlighting cost reductions and efficiency gains in cross tasks within the field on greek vineyards [22]. This growing attention aligns with the necessity of pinpointing the strengths of precision technologies to monitor vineyards that are increasingly difficult to manage in present landscape due to the climate changes, wars, market instability leading to price hikes, and the need for natural resource rationalization because of their continuous reduction [19,32].

The review activity showed that several journals published articles on profitability analyses of the adoption of PATs in viticulture (Table 2). Two journals called “Computers and Electronics in Agriculture” and “Precision Agriculture” accounts for 4 articles among those selected for

Table 2  
List of journal and number of matching articles (N = 15).

No.	Journal titles	No. of articles found
1	Computers and Electronics in Agriculture	2
2	Precision Agriculture	2
3	Science of The Total Environment	1
4	Front. Plant Sci.	1
5	Remote Sensing.	1
6	Sustainability	1
7	Journal of Applied Geophysics	1
8	IFAC-PapersOnLine	1
9	Water	1
10	Journal of Agricultural Engineering	1
11	European Journal of Remote Sensing	1
12	Horticulturae	1
13	ECPA-Eur Conf on Precision Agriculture	1

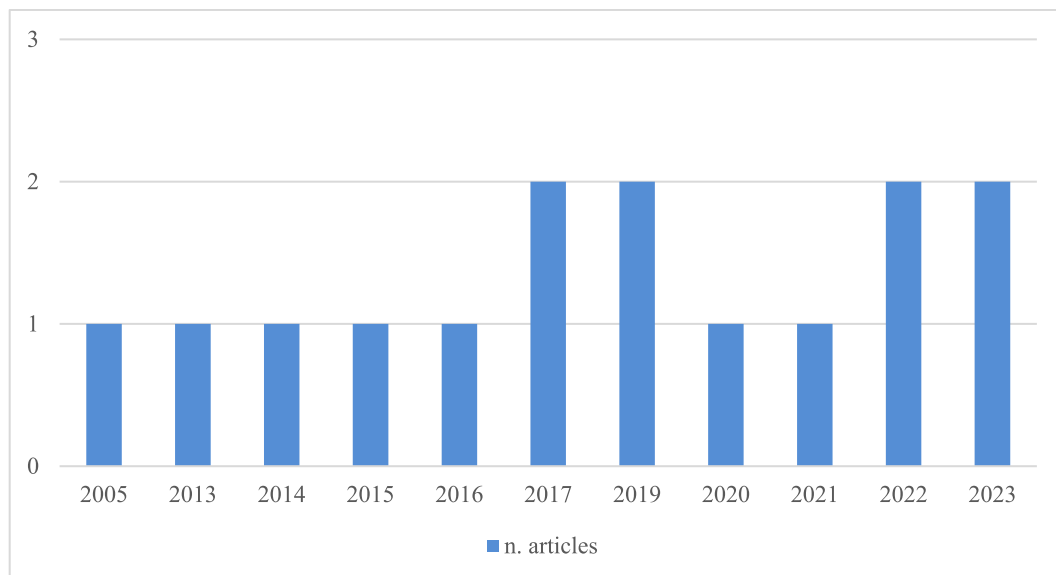


Fig. 2. Temporal distribution of selected articles.

this review. Looking at the journal subject categories our findings reveal that articles were published in journal that mainly fall under the subject categories Agricultural and Biological Sciences (5 articles), Environmental Science (2 articles), Earth and Planetary Sciences (2 articles), Geography, planning and Development (1 article), Water Science and Technology (1 article), Bioengineering (1 article), Technical Advances in Plant Science (1 article), Agricultural Sciences (1 article) and Agronomy and Crop Science (1 article). In contrast, any article is featured in a journal with Management or Economics, Econometrics and Finance subject categories.

More detailed information about the studies under review is available in the Table 3 of this review. It provides a comparison based on the number of citations for the final articles and includes bibliography information.

**Table 3**  
Characteristics of all articles found related to our study.

c	Year	Authors	Article title	Journal title	Country	Fields of journals	Total Citations In Scopus
1	2023	Allegro, G., Martelli, R., Valentini, G., Pastore, C., Mazzoleni, R., Pezzi, F. Filippetti, I.	Effects of Mechanical Winter Pruning on Vine Performances and Management Costs in a Trebbiano Romagnolo Vineyard: A Five-Year Study	Horticulturae	Italy	Agricultural and Biological Sciences	2
2	2023	Tziolas, E., Karapatzak, E., Kalathas, I., Karampatea, A., Grigoropoulos, A., Bajoub, A., Pachidis, T., Kaburlasos, V.	Assessing the Economic Performance of Multipurpose Collaborative Robots toward Skillful and Sustainable Viticultural Practices	Sustainability	Greece	Geography, planning and Development	2
3	2022	Finco, A., Bentivoglio, D., Chiaraluca, G., Alberi, M., Chiarelli, E., Maino, A., Mantovani, F., Montuschi, M., Raptis, K., Semenza, F., Strati, V., Vurro, F., Marchetti, E., Bettelli, M., Janni, M., Anceschi, E., Sportolaro, C., Bucci.	Combining Precision Viticulture Technologies and Economic Indices to Sustainable Water Use Management	Water	Italy	Water Science and Technology	4
4	2022	Casson, A., Ortuani, B., Giovenzana, V., Brancadoro, L., Corsi, S., Gharsallah, O., Guidetti, R., Facchi, A.	A multidisciplinary approach to assess environmental and economic impact of conventional and innovative vineyards management systems in Northern Italy	Science of The Total Environment	Italy	Environmental Science	6
5	2021	Bellvert, J., Mata, M., VallverdÀ, X., Paris, C., Marsal, J.	Optimizing precision irrigation of a vineyard to improve water use efficiency and profitability by using a decision-oriented vine water consumption model	Precision Agriculture	Spain	Agricultural and Biological Sciences	26
6	2020	Sarri, D., Lombardo, S., Pagliai, A., Zammarchi, L., Lisci, R., Vieri, M.	A technical–economic analysis of telemetry as a monitoring tool for crop protection in viticulture	Journal Of Agricultural Engineering	Italy	Bioengineering	1
7	2019	Di Gennaro, S.F., Toscano, P., Cinat, P., Berton, A., Matese, A.	A Low-Cost and Unsupervised Image Recognition Methodology for Yield Estimation in a Vineyard	Frontiers in Plant Science	Italy	Technical Advances in Plant Science	48
8	2019	Andújar, Di., Moreno, H., Bengochea-Guevara, J., de Castro, A., Ribeiro, A.	Aerial imagery or on-ground detection? An economic analysis for vineyard crops	Computers and Electronics in Agriculture	Spain	Agricultural and Biological Sciences	36
9	2017	Borgogno Mondino, E, Gajetti, M	Preliminary considerations about costs and potential market of remote sensing from UAV in the Italian viticulture context	European Journal of Remote Sensing	Italy	Environmental Science	3
10	2017	Tona E, Calcante R., Roberto O.	The profitability of precision spraying on specialty crops: a technical–economic analysis of protection equipment at increasing technological levels	Precision Agriculture	Italy	Agricultural and Biological Sciences	36
11	2016	McCorkle D. A., Dudensing, R. M., Hanselka, D., Hellman, E. W.	Economics of robotic technology in texas wine grape production.	Southern Agricultural Economics Association paper.	USA	Agricultural Sciences	5
12	2015	Matese, A., Toscano, P., Di Gennaro, S.F.; Genesio, L., Vaccari, F.P., Primicerio, J., Belli, C., Zaldei, A., Bianconi, R., Gioli, B.	Intercomparison of UAV, Aircraft and Satellite Remote Sensing Platforms for Precision Viticulture	Remote Sensing	Italy	Earth and Planetary Sciences	685
13	2014	Rossi, V., Salinari, F., Poni, S., Caffi, T., Bettati, T.	Addressing the implementation problem in agricultural decision support systems: the example of vite.net®	Computers and Electronics in Agriculture	Italy	Agricultural and Biological Sciences	126
14	2013	Andrenelli, M.C., Magini, S., Pellegrini, S., Perria, R., Vignozzi, N., Costantini, E.A.C.	The use of the ARP© system to reduce the costs of soil survey for precision viticulture	Journal of Applied Geophysics	Italy	Earth and Planetary Sciences	20
15	2005	Bramley R.G.V., Lanyon D.M., Panten K.	Whole-of-vineyard experimentation – An improved basis for knowledge generation and decision making.	ECPA-Eur Conf on Precision Agriculture	Australia	Agronomy and Crop Science	27

### 3.1.2. Publications categorized by geography, topics studied and methodologies used

Mapping the geographical locations of studies carried out on economics of PATs in viticulture revealed that among all selected studies ten have been conducted in Italy, two, respectively in Spain, while single articles were focused on profitability analysis in, Greece, USA and Australia.

Studies under review are characterized by two main topics: the challenges associated with PATs for sustainable resource management and their economics. With reference to the PATs adopted in vineyards, from the studies analyzed, it is possible to identify and classify it in four main categories: i) Monitoring technologies with remote/proximal sensing equipped with sensors and cameras (6 articles); ii) Guidance technologies controlled traffic farming, machine guidance, driver

assistance (1 article); iii) Acting technologies with Variable Rate Application (VRA) technologies and autonomous robots (6 articles); iv) Decision Support Systems (DSSs) (2 articles). As shown in Fig. 3, acting technologies and DSSs are equally studied (6 studies), highlighting their crucial role in the implementation and management of vineyard operations. Monitoring technologies also play a significant role (6 studies), emphasizing data-driven decision making, while guidance technologies attracted less interest (one study). A closer look at the monitoring technologies shows that sensors such as the RGB (Red Green Blue) camera supported by unmanned aerial vehicles (UAVs) are the most studied technologies in viticulture (4 studies), followed by precision soil surveying (one study) and satellite monitoring (one study). UAVs are preferred for plant health monitoring research because of their ability to provide high resolution data in real time.

Regarding the methodological approaches used in the articles under analysis in order to assess the viability and profitability of the adoption of PATs in viticulture, four distinct evaluation methods can be identified: Cost-Benefit Analysis (CBA), analysis of operational costs related to the PATs adoption; Gross Margin analysis and Net Present Value. Fig. 4 highlight that Cost Benefit Analysis (CBA) and Cost Analysis are the most commonly used assessment methods, constituting 13 articles of the all selected articles. Specifically, the analysis of the operational costs associated to the adoption of PATs in viticulture has been employed in nine out of the fifteen studies, related to precision technologies like UAVs [33,34] and robots for management applications [22,35]. The CBA approach has been used in four articles, in which the authors evaluate the impact of both monitoring technologies such as UAVs [20,36] and acting technologies like Precision irrigation [19] on the economic viability. More in detail, there has been a notable rise in attention towards CBA in the precision viticulture field, with a peak of four articles from 2019 to 2022. This increased attention be due to a heightened awareness of the need to evaluate investments and returns associated with these technologies. Improved data and advanced tools

allow for more precise assessments, meeting the growing demand to understand their practical and economic impact [37,38]. In contrast, in the context of Net Present Value (NPV), limited attention has been given, as evidenced by its low inclusion in this review's theme appearing in only one case study that applied precision acting methods using robots in vineyards. Similarly, Gross Margin analysis is less explored, each represented in only one out of the fifteen case studies for their respective methods, likely due to its intricate structure, posing challenges in practical economic analysis [25,39]. Specifically, Gross Margin analysis has been applied emphasizing the gross return obtained from applying drones in the different irrigation water supply systems and fertilizer management strategies [40]. By outlining four key areas of analysis, aligned with different evaluation methodologies, this framework facilitates a comprehensive assessment of the economic feasibility and management implications of PAT implementation.

### 3.2. Thematic analysis

The majority of scholars who focused on the economics of PATs on vineyards, paid attention, as previously emphasized, on two distinct research areas, closely related to each other, that enable the research questions formulated to be answered. One the one hand, the economic viability and profitability of PATs adopted in the field of viticulture, and on the other hands the main barriers to their adoption examining how winegrowers can effectively uses the identified solutions.

#### 3.2.1. Economic viability of precision technologies adoption in viticulture

Empirical investigations on the adoption of PATs in the wine-growing field demonstrate the cost-effectiveness of implementing these innovative tools in terms of both increased yields, grape quality, and above all efficiency and effectiveness of vineyard operations. The authors explored the advancement of innovation in the viticulture field, showcasing the economic viability of precision tools as UAVs

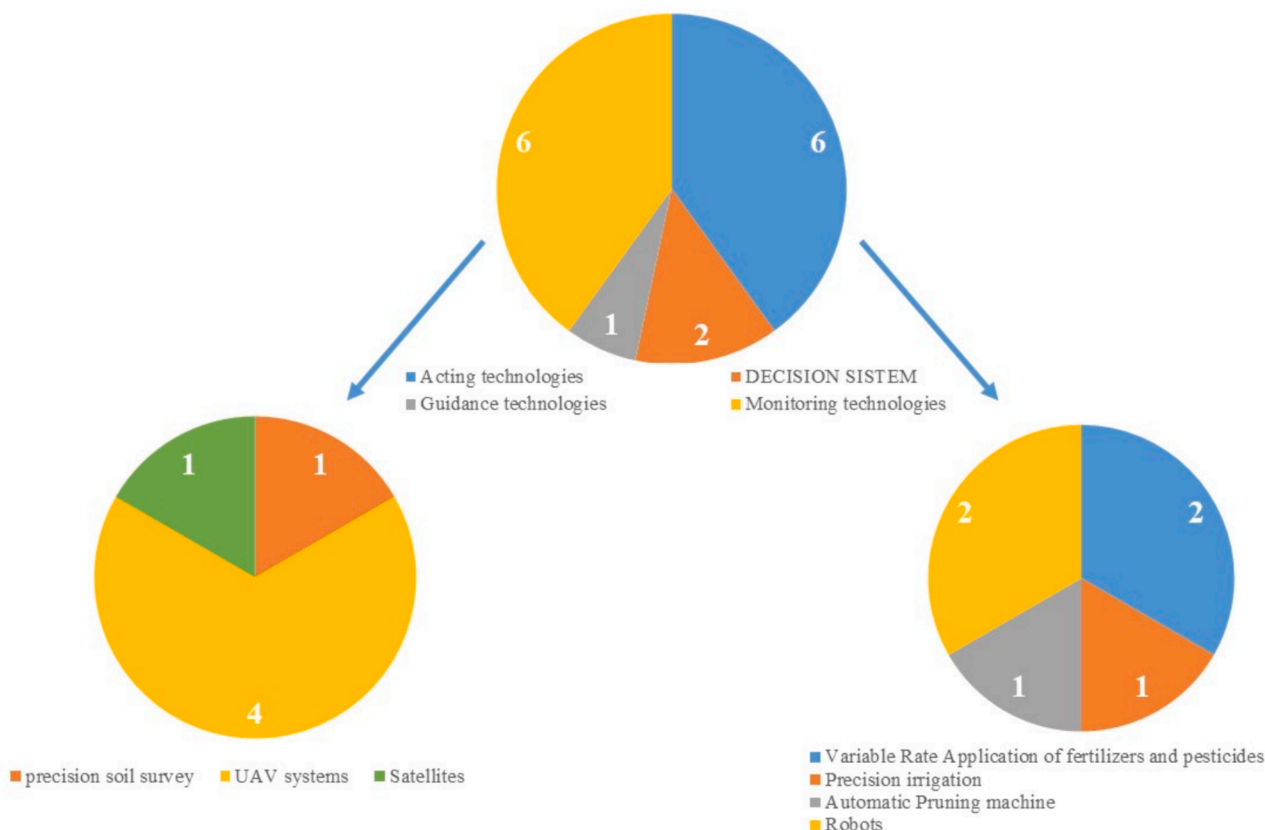


Fig. 3. Number of articles according to the types of PATs in viticulture.

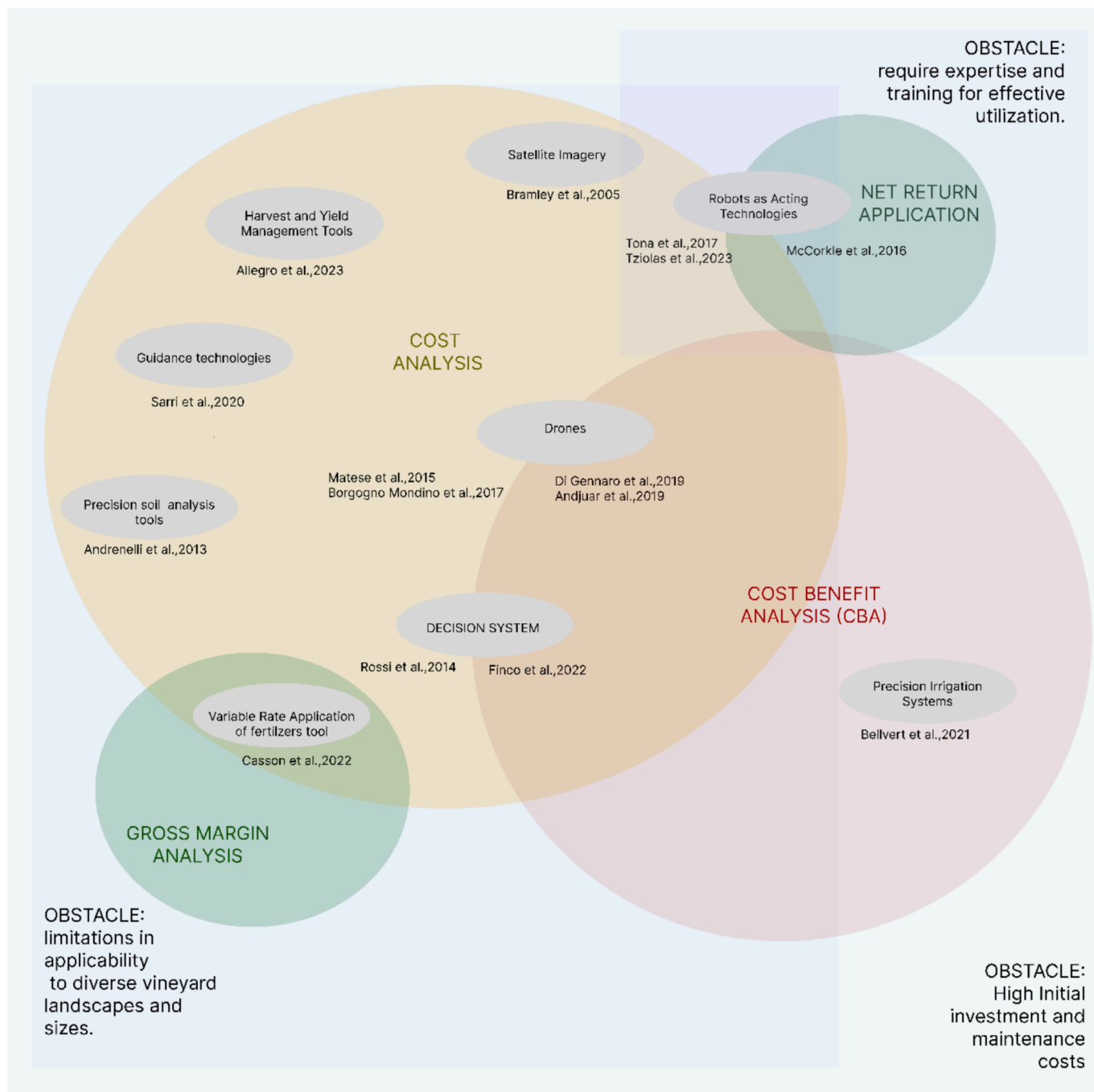


Fig. 4. Overview of the feasibility analysis of PATs implementation in viticulture.

[20,33,36], precision irrigation and fertilization techniques [19,40], precision pruning technique [40] and robotics [22]. These early studies emphasize the importance of considering the operational costs associated with the adoption of PATs in viticulture, particularly those related to the use of inputs and natural resources (such as water, electricity, fuel, fertilizers, etc.), looking at a short period [22,42] or long-term financial implications [19,41]. Fig. 4, underscores the multifaceted nature of feasibility studies on the implementation of PATs in viticulture. In this figure, each study has been positioned according to the methodology used (depicted by red and green circular areas) pertaining to the specific type of precision technology. Indeed, it's possible to observe in this figure that within the category of Acting technologies as Harvest and Yield Management tools, there are various studies with specific economic analyses belonging to cost analysis approach, cost-benefit

analysis, profitability analysis and net return calculation. Comparative studies of economic viability vary in their focus, methodology and economic indicators. While some studies focus on specific technologies such as UAVs or precision irrigation, others provide a broader perspective by examining multiple tools and economic sustainability in the face of climate change. Moreover, each study has been scrutinized for the current barriers encountered during their respective field experiments (represented by blue squares), underling the necessity for tailored decision-making when adopting these technologies for vineyard management. For instance, high initial and maintenance costs are a significant financial barrier, particularly for technologies such as precision irrigation, drones and autonomous robots. Wineries must carefully assess the payback period and true economic return of these investments before adopting them. The need for specialised training and

expertise is another constraint, as many PATs require advanced knowledge of digital systems, data interpretation and equipment calibration. Therefore, successful large-scale adoption will depend on overcoming economic and educational challenges, promoting financial support mechanisms and ensuring that farmers have access to user-friendly decision-making tools. This conceptual framework is an essential resource for researchers, agronomists and policy-makers seeking to improve the sustainability and efficiency of viticulture through technological innovation.

The cost-benefit analysis proves the most effective in justifying the adoption of various technologies such as drones and precision irrigation systems. A number of empirical studies estimated the costs of adopting technologies such as UAVs, aircraft, and satellite remote sensing in order to verify whether they are consistent with the vineyard revenues [33,34]. For example, Borgogno and Gajetti [34] develop a cost simulation model that considers technical and economic aspects as well as vineyard spacing. The results show that the cost of using UAVs decrease from 99 €/ha to 27 €/ha in the case of a common drone with rotating wings in line with the gradual increase in survey area (from 10 ha to 100 ha). However, the authors emphasize that the adoption is only worthwhile if technical skills related to image processing and maintenance are developed in-house. Furthermore, Di Gennaro and co-authors [20] add that, compared to traditional survey systems, the use of UAVs leads to a reduction in monitoring times and costs, of \$15.5 on an area of 5 ha, and 152.5\$ on an area of 50 ha, only in the case in which the cost due to the purchase of the UAVs and RGB camera is not considered. These results contrast with the findings of Matese and colleagues [33] who, comparing the costs of using three different technologies (UAVs, Aircraft and Satellite remote sensing) related to technology acquisition, image obtaining and image processing, find that UAVs are the most effective solution for small vineyards (5 ha), while for large areas (50 ha) satellite imagery is the most cost-effective solution. As these studies show, using drones in viticulture offers benefits like low operational costs, high-resolution imagery, and versatile support for tasks throughout the crop year. Andrenelli and co-authors [43] also highlighted the relationship between the cost of adopting PATs in viticulture and vineyard size. The authors estimate the costs of using precise Automatic Resistivity Profiling systems to create maps adopted for soil sampling, pointing out that the adoption of precision surveying tools is a cost-effective solution for large-area surveys with a cost ranging from 206€/ha for 15 ha areas to 734€/ha for 60 ha areas.

In contrast, only a few studies have assessed the economic feasibility of PATs considering the impact on overall vineyard management costs. For instance, Andújar and colleagues [36] evaluate the cost saving associated with the introduction of UAV, on-ground systems (LiDAR) and depth camera for vineyard fertilization. The results show that UAVs are the most profitable solution, contributing to a reduction in fertilization costs of 6.1€/ha, compared to the other systems studied. In particular, the adoption of precision farming tools makes it possible to reduce the margin of error in the execution of operations through targeted treatments. In line with this, the Sarri and co-authors [44] study's estimates vineyard management costs using telemetry tools to assess operational errors in the execution of operations. The results show that the use of telemetry systems can support winegrowers during operations such as treatments and irrigation, reducing pesticide distribution errors and related costs per linear meter of pesticides and fuel ranging between 0.01 € m<sup>-1</sup> and 0.03 € m<sup>-1</sup>. PATs have also proved to be cost-effective for the execution of other cultivation operations in the vineyard. For example, Bramley and colleagues [31] uses remote sensing to assess vineyard responses to treatments like ripping and mulch application. Considering operation costs (\$185/ha for ripping vs. \$2,500/ha for mulch), the manager favored ripping and aimed to use mulch only where its benefits outweighed those of ripping, optimizing cost allocation for maximum impact. The authors found substantial yield variations, aiding vineyard managers in determining optimal treatment locations with the assistance of PA tools, which pinpoint where the

benefits justify their costs. Instead, Allegro et al. [41] estimates the winter pruning treatment costs by using precision mechanized tools and comparing them with manual pruning techniques. The authors highlighted a 58 % cost reduction for vineyards of 5 ha and of 80 % for vineyards of 30 ha. The results indicate the suitability and success of precision pruning machines for small vineyards, aiming to address labor shortages on farms.

PATs find wide application in particular in the field of irrigation and crop treatments in viticulture where they make it possible to reduce the waste of resources with a positive impact on the environment. Specifically, Bellvert and colleagues [19] showed that the precision regulated deficit irrigation showcase substantial net benefits in terms of cost-saving, compared to a conventional irrigation system, ranging from 70,9€/ha (2016) to 99,6€/ha (2017), compared to non precision irrigation, alongside conserving 0.14 hm<sup>3</sup> of water in 2017, thereby reducing energy use by 27,677 kWh. This underscores how precision techniques not only increase profitability but also foster resource conservation, aligning viticulture with sustainable practices. However, as pointed out by Finco and co-authors [42] the costs of precision irrigation through the use of remote and proximal sensors to monitor the level of water stress in the vineyard reach 30 % of fixed costs and 12 % of variable costs. This is reflected in the benefits of adopting precision technology, which is strongly influenced by the yields obtained. The study by Casson et al. [40] comparing six different irrigation scenarios from traditional to variable-rate irrigation systems confirms the findings of previous studies. In particular, the authors note that variable-rate irrigation systems entail higher costs related in particular to water management. However, the increased yields and quality of the harvested grapes result in higher income and consequently a higher gross margin. It starkly outlines the economic challenges influenced by drought, leading to negative returns due to decreased yields and increased costs. The dependence of viticulture on climatic conditions, prone to fluctuations resulting in variable annual yields, is underscored by the adverse outcomes outlined in the OIV-World Wine Production Outlook [8]. Technological advancements serve as instrumental contributors, mitigating the shifting returns attributed to factors such as drought, impacting both yields and expenses, as evidenced by Finco et al. [42] and Bellvert et al. [19]. These economic benefits to farmers, factoring in water and energy savings, affirm the financial viability of precision irrigation in vineyard management. Precision viticulture's broader application includes mitigating environmental impacts, notably through an eco-design approach for automatic solutions in vineyards to secure an economic sustainability in the future of the wineries. PATs can play an important role in disease control in vineyards. Tona and colleagues [35] compared three precision spraying technologies, highlighting that if, on the one hand, the costs of the equipment increase with the sophistication of the technology used, on the other hand, more sophisticated technologies lead to a reduction in pesticide costs, although they represent a cost-effective solution only for large companies. Consistent with this, Rossi et al. [45] found that the use of DSSs, like [vite.net](http://vite.net), for monitoring vineyard components (soil, pests, plants) and data analysis to provide information on effective vineyard management, resulted in a reduction in copper consumption and cost savings estimated at €195/ha compared to traditional management practices.

In the case of cutting-edge technologies such as robotics, the CBA were used in order to verify the economic viability for winegrowers to implement an innovative technology. Specifically, Tziolas et al. [22] revealed, through Life Cycle Cost analysis, an average operational cost saving ranging from -11,53 % for *Tempranillo varietis* to -2.23 % for *Cabernet Sauvignon* varieties due to the adoption of robotics. This innovation leads in particular to a reduction in costs related to typing, pruning and herbiciding that can be performed by the use of the cabot. However, as the authors themselves point out, the convenience of using robots increases as their useful life increases by at least 15 years. Similarly, McCorkle and co-authors [46] also underscored positive economic returns notably in pruning and topping, mirroring the findings of Tziolas

et al. [22]. However, certain tasks in field, notably defoliation and tying, have proven to be time-intensive for robots, resulting in increased operational time and elevated capital service costs when compared to manual practices, due to the difficult to involve identifying objects like leaves and tying vine shoots. Additionally, as demonstrated in this case study, the size of vineyard significantly influences revenues and costs of adoption of robots in field. For instance, the 50-acre vineyard yielded higher of the net present value per acre (\$15,807 vs. \$13,641 for the 100-acre vineyard) due to the higher cost of finish spur prune and hoeing/Hand Pulling in 100 acres vineyards. These results underline the need to study the cost-effectiveness of adopting PATs in viticulture under different conditions. These researchers caution about the need for more economic studies and practical experiences, highlighting the limitations in analyzing robots' integration into viticultural practices following the concept of "learning by doing" [47] derived from accumulated experience in producing goods or services.

In recent years, the landscape of vineyard management has been transformed by the integration of PATs. These cutting-edge advancements have not only revolutionized traditional practices but have also ushered in a new era of efficiency, sustainability, and quality within viticulture [48]. In addition to the benefits and costs identified in the adoption of precision technologies in vineyard management, the latest selected studies further enhance several advantages, which can be summarized in four categories:

- "Sustainability Boost": PATs streamline operations, by reducing environmental impact through optimized resource utilization and minimized waste [41,45];
- "Risk Mitigation": These technologies offer early detection of issues such as diseases or stress in vines, allowing proactive measures that mitigate potential risks to vineyard health enhancing grape quality [20,34];

- "Labor Efficiency": By automating certain tasks and providing targeted insights, PATs can streamline operations, potentially reducing labor requirements while improving productivity [22,36,40];
- "Market Competitiveness": Implementing these technologies can enhance the market position of wineries by ensuring consistent quality, meeting evolving consumer demands, and showcasing a commitment to innovation and efficiency [44,46].

Fig. 5 shows the interrelationship between different precision technologies and their various positive effects in the short and long term, depending on the size of the area of intervention or the size of the farm. At the farm level, DSSs and robotic technologies optimise macro-level management by improving operational efficiency and strategic planning. At the field level, precision interventions are implemented through advanced vineyard applications, including UAVs, precision irrigation systems, automated guidance technologies and variable rate fertilization. At the plant level, individual vine performance is optimised through high-resolution soil analysis and data-driven yield management strategies, ensuring site-specific agronomic decision-making. Specifically, within the figure, these connections are highlighted by the numerical abundance of case studies that address and highlight the positive effects following the introduction of PVTs. The size of each arrow corresponds to the exact number of articles that address the core themes within the review. The Figure shows the strength of the correlations through the thickness of the arrows, with thicker arrows indicating stronger evidence (4–5 articles) and thinner arrows reflecting weaker associations (1 study). Fig. 5 provides an opportunity for practitioners to review which PATs are most effective in achieving business objectives such as increasing yields, reducing operating costs and improving labor efficiency, with a view to reducing risk and improving grape quality.

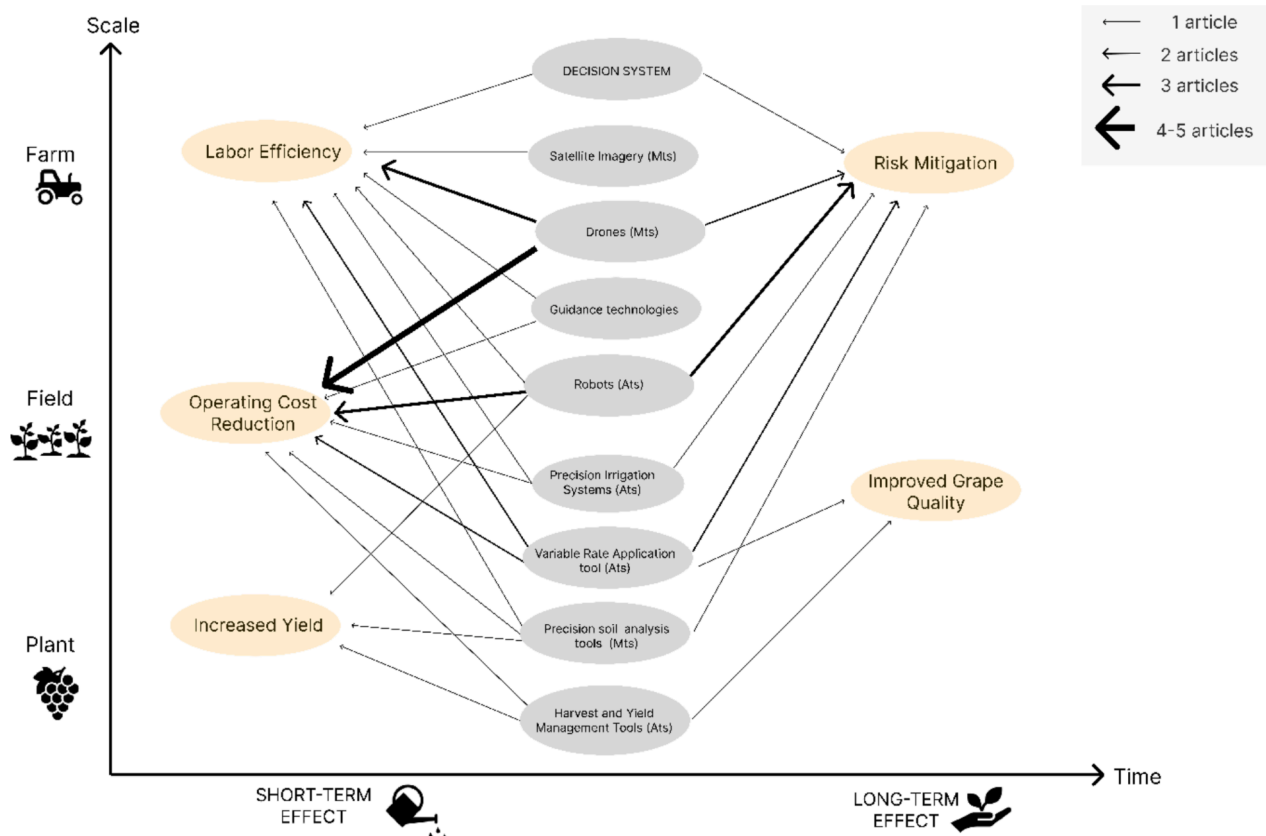


Fig. 5. Interconnectedness and positive effects of PATs in viticulture management.

3.2.2. Exploring the landscape of precision Viticulture: Barriers and strategies in the adoption of PVTs

Adopting PATs in viticulture involves upfront investments in equipment, sensors, data management systems, and skills, which are considered primary barriers. This is especially true in the adoption of innovative technologies such as robots, which leads to a reduction in the time required to carry out operations and resource inputs [22,35], although the acquisition costs pose a challenge for wine growers due to the high market prices and maintenance costs, as emphasised by McCorkle and colleagues [46]. The authors suggest tailored awareness for winegrowers operating small-sized farms, emphasising the specific advantages of precision instruments to help overcome financial barriers through well-informed investment strategies. While acknowledging current challenges, McCorkle et al. [46] and Bellvert et al. [19] suggest that as technology advances and the severe labour shortage on farms worsens [49], autonomous systems in the “acting technologies” category such as VRA technologies and autonomous robots could become more economically viable. Other studies [22,41] emphasise that these barriers encompass uncertainties about long-term impacts, heightened initial costs for implementing these technologies (e.g. training specialised workers for managing these technologies), potential performance variations, and concerns regarding adaptability to different grape varieties or vineyard conditions depending on farm size. Specifically, small farms (<5ha) face financial constraints that hinder investment in costly precision equipment, such as the feasibility of collaborative agricultural robots in small vineyards in the case of Tziolas et al. [22], being reliant on factors such as the robot’s weight and price. These findings shed light on the complexities of adopting emerging technologies, potentially

influencing their widespread acceptance among wine growers. As a result, adoption rates tend to be higher for larger farms that can better bear additional costs and recoup initial investments within a few years thanks to their robust financial resources, allowing them to stay ahead in PV. In some cases, these farms benefit from dedicated personnel and integrated management systems, ensuring the effective implementation of advanced tools. In light of this, according to, Borgogno and Gajetti [34], “future scenario for technology transfer should necessarily consider and drive farmers to aggregate in consortiums” (p.317) for small wineries (see Fig. 6, in the perspective presented in the “Company’s economic balance sheet” circular area). In summary, cultivating innovation in viticulture through strategic incentives and collaborative partnerships fosters the widespread adoption of PATs, heralding a sustainable future for vineyards.

Despite the benefits obtained from advancements in PATs, some studies note that the complexity of certain technologies might present challenges for vineyard managers and workers who are unfamiliar with advanced agricultural technologies, underlining a resistance to change among vineyard managers [22,34]. For example, Borgogno and Gajetti [34] emphasise that the operator plays an important role in data interpretation when using UAVs which cannot be completely automated. This indicates the necessity of digital skills for operators in each winery to understand vineyards’ biometric information based on UAVs images. The authors highlight challenges including the abundance of data generated by precision tools and compatibility issues when incorporating these innovations into existing traditional systems. Smart farming and PA are currently underutilised, with only 25 % of EU farms adopting related technologies due to the previously emphasised obstacles

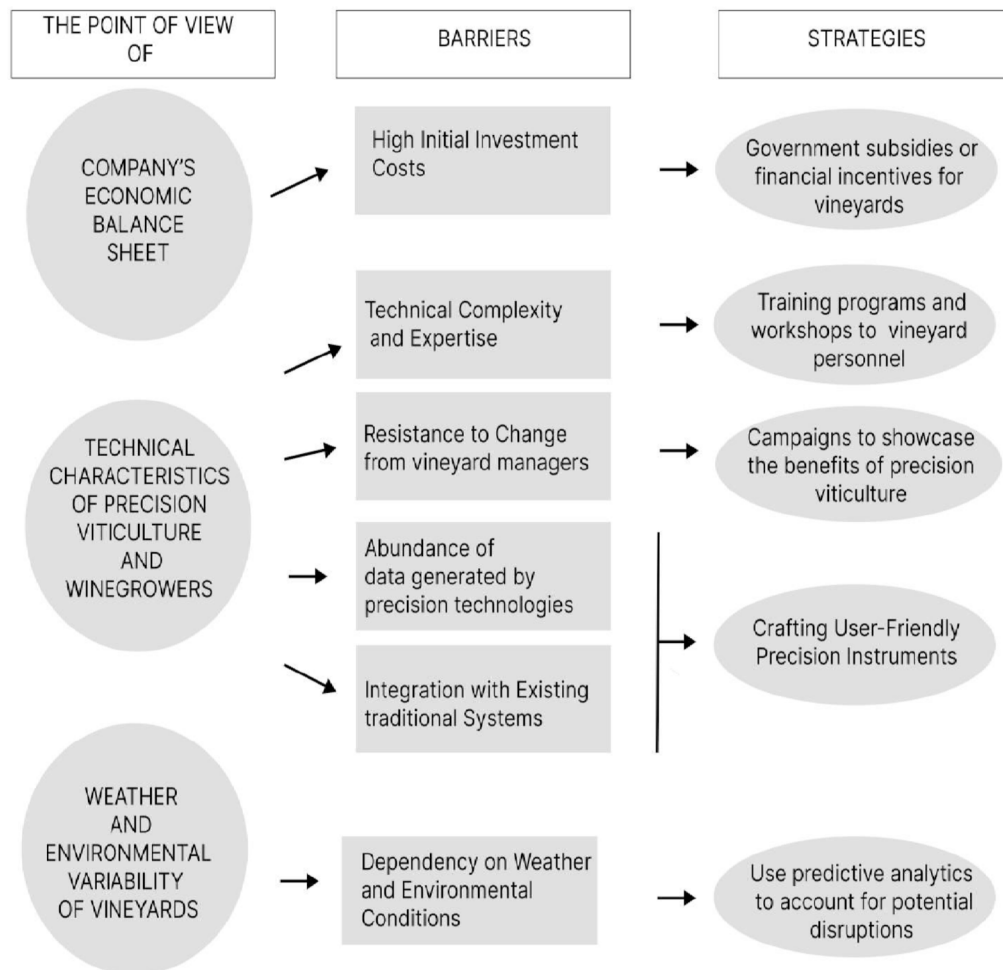


Fig. 6. Concept scheme of possible barriers and strategies applied.

[50,51]. To address the aforementioned barriers, winegrowers can invest in training programmes aimed at enhancing their skills in interpreting data from precision tools and remaining updated on new technologies within data processing, particularly concerning easy-to-use software available in the market. Collaborating with analytics experts to develop simplified, user-friendly precision instruments can further streamline the decision-making process and ensure that actionable insights are derived from the wealth of data generated. Rossi et al. [45] and Finco et al. [42] highlight that through improved collaboration among professionals, researchers, and winegrowers, it is possible to create innovative DSSs tailored to meet the specific needs of local winegrowers, facilitated by European financial resources. Finco et al. [42] highlight a DSSs called SMART-VITIS that efficiently manages and monitors water usage by incorporating precision instruments such as proximal and remote sensing to provide real-time data from the vineyards involved, offering innovative services and support systems to local farmers. According to Rossi et al. [45], during the presentation of the [vite.net](#) DSSs developed within a European research project, positive feedback was collected during the development, testing, and practical use of this digital platform. In addition, awareness campaigns are crucial for showcasing PV benefits, overcoming industry resistance, and addressing barriers to new technology adoption. The studies discussed highlight the potential of PV and emphasise the need for tailored strategies based on vineyard size, technological complexity, and the socio-economic context (see Fig. 6, in the perspective presented in the “Technical characteristics of precision viticulture and winegrowers” circular area).

Furthermore, PV faces specific challenges, notably a dependence on accurate real-time weather and environmental conditions, as well as the carbon footprint of vineyard management. Disruptions caused by adverse weather events can impede the effectiveness of these technologies. Several studies have shown that using PATs in viticulture helps to improve sustainability through the rational and efficient use of natural resources such as water, fuel, fertilisers, and pesticides [52]. Bellvert et al. [22] underscore precision irrigation’s pivotal role in overcoming spatial variability challenges. Its successful implementation involves navigating challenges related to spatial variability in soil properties and topography, which can hinder consistent water stress levels across subzones. Precision irrigation—with reduced hours and lower energy costs—offers significant water and energy savings, significantly reducing the environment impact. Similarly, the adoption of PATs for fertiliser application offers significant benefits. Casson and colleagues [40] find that adopting a variable-rate fertiliser application system results in a 58 % reduction in global warming compared to conventional fertiliser application systems. However, the carbon footprint of using precision tools also varies by grape variety. In a case study in northern Greece, Balafoutis et al. [53] found that the use of variable-rate irrigation and fertilisation systems in vineyards contributed to a reduction in greenhouse gas emissions ranging from 25 % in the case of Sauvignon Blanc to 28 % in the case of Syrah, compared to conventional practices. These results provide useful insights for vine growers on the appropriateness of implementing precision technologies to reduce costs and carbon footprint, thus meeting society’s expectations and in line with the ecological transition process at the global level.

Meanwhile, each precision technology possesses unique limitations, as evidenced by Matese et al. [33] stating that each instrument has its specific maximum effective size range of measurements in the vineyard due to its technical characteristics. Consequently, while each tool captures certain key information about plant health, it might overlook other aspects. This limitation highlights how these tools might prove inadequate when used individually for comprehensive vineyard management. Using diverse platforms to monitor vineyard status throughout the crop year and to offer valuable crop insights for farmers proves a valuable strategy in anticipating potential disruptions and harnesses technologies capable of accurately identifying the spatial complexities within vineyards due to various inherent factors [33]. Overcoming challenges

through proactive measures, embracing eco-design principles, and continuous improvements in technology contribute to the sustainable and effective adoption of PV practices in the dynamic context of viticultural operations (see Fig. 6, in the perspective presented in the “Weather and environmental variability of vineyards” circular area).

Each study aims to provide theoretical insights and offer tangible, actionable information for vineyard management. Their research does not exist in a vacuum but rather aims to address tangible challenges that vineyard stakeholders face. Accordingly, our review systematically delineates various challenges (barriers) while concurrently proffering potential strategies, encapsulated within a comprehensive concept scheme (Fig. 6).

In conclusion, as already highlighted, the analysis allowed the identification of three levels: the perspectives of the field relevant to adoption (economic balance of the company, technical characteristics of precision viticulture and winegrowers, weather and environmental variability of vineyards), the challenges of adoption and mitigation strategies. Specifically, from a conceptual point of view, the three different fields of observation are framed as follows: The Economic balance sheet assesses a winery’s financial health and investment viability; the Technical characteristics of precision viticulture and winegrowers encompasses the tools, methodologies and expertise necessary for optimal vineyard management; and Weather and environmental variability refers to the climatic and environmental factors that affect vineyard productivity. All of these elements are essential for evaluating and implementing precision viticulture strategies. Key barriers to the adoption of PATs include significant initial investment costs, which pose a significant challenge for small and medium sized wineries. In addition, the technical complexity of PATs requires specialised expertise, while resistance to innovation among traditional winegrowers further hampers adoption. In addition, the processing and interpretation of large data sets, the integration of PATs into existing farming systems, and the impact of climatic variability on the effectiveness of the technology are critical constraints limiting widespread adoption. To mitigate these challenges, the Figure outlines six strategic approaches: economic incentives and subsidies to reduce the financial burden, specialised training programmes to improve technological skills, awareness campaigns to demonstrate the benefits of PATs, user-friendly tools to facilitate technology adoption, predictive systems for climatic risk management, and improved integration with traditional viticultural systems. The Figure shows that while financial and technical constraints are the main barriers to adoption, targeted policies, improved accessibility and advanced data management can significantly facilitate the adoption of PATs. A comprehensive approach that integrates economic support, technological innovation and capacity building is essential to promote a more sustainable, efficient and technologically advanced wine sector.

#### 4. Conclusions, limitations and future research directions

The systematic literature analysis has shown the growing interest in the economic aspects of PV. This study aimed to analyse the economic feasibility of corporate investments in precision vineyard management technologies and identify the main barriers and strategic solutions that can be adopted by companies in the wine-growing sector. The articles reviewed highlighted the many technologies currently available on the market and the potential of adopting PATs in viticulture to improve the efficiency of production processes and in relation to the financial capacity of companies. The studies highlight the economic feasibility of investing in precision technologies that enable companies to reduce the waste of resources, such as water, fertilisers, pesticides, energy, and time spent on operations, which are reflected in wine-growing companies’ operating costs and profitability. Key performance indicators identified in the review offer valuable metrics for evaluating the economic success of PV practices.

Some theoretical and practical implications can be envisaged. At a

theoretical level, this study enriches the literature on the economic and environmental sustainability of adopting PATs in viticulture. In detail, we have sought to demonstrate that the adoption of these innovative technologies constitutes a cost-effective solution for companies in the wine-growing sector by helping to reduce operating costs and thus increase profitability depending on the precision technology and the winery's characteristics. In addition, the systematic literature review shows that using PATs reduces the carbon footprint of vineyard management, thereby reducing greenhouse gas emissions and the impact on global warming. Furthermore, the study has enabled systematising the barriers to the adoption of precision technologies and the potential strategies that companies can adopt in relation to their varying circumstances.

From a managerial perspective, wine growers can leverage these key insights to make informed decisions, ensuring sustainable, efficient, and economically viable viticulture practices across diverse operational scales. Although the principle of economic viability is the basis on which businesses survive, agribusinesses must increasingly respond to the expectations of society and various stakeholders regarding environmental sustainability. From this perspective, PATs offer numerous environmental benefits, depending on the socio-economic and environmental conditions in which the wineries operate. PV presents tailored solutions for vineyards of all sizes, addressing challenges and unlocking opportunities. However, in many cases, some of the PATs are the preserve of large companies capable of bearing the high implementation and management costs. For small wineries, the transition towards the adoption of PATs for managing growing operations is only possible by acting on the intricate economic, socio-cultural, technological and environmental variables [54]. The high initial costs and the need for specific skills represent major challenges especially for small and medium-sized farms. Financial support in the form of subsidies or low-interest loans from governments for the implementation of precision technologies can help overcome the initial investment barrier. These subsidies could be complemented by aid under agricultural and rural development policies, which might serve to compensate for the environmental benefits produced following the adoption of technological innovations contributing to saving natural resources and other inputs (pesticides, fertilizers, energy, water, etc.). Nevertheless, providing financial incentives to farmers is not enough if the complexity of precision farming tools hinders their use. In other words, it is not sufficient to collect data if farmers do not have the capacity to analyse it and use it to support decision-making processes. This is why it is necessary to develop a digital culture and skills among farmers, i.e. it is necessary to qualify and upgrade human resources in the digital technologies field. In this sense, educational programs on the precision technologies, their potential use, and their environmental and economic impacts could increase the reliability of the technology, reduce the risk perception, and encourage its adoption. The development of digital skills and increased knowledge of digital technologies could in fact enable farmers to choose which technology is best suited to their specific farming conditions. In other words, the diffusion of precision technologies goes through farmers' literacy. Promoting networking and thus knowledge sharing among farmers, especially with those who have already implemented precision technologies and with potential adopters, is another strategy that could help to reduce perceived uncertainty and facilitate the digital transition among farms. This peer-to-peer exchange could also enable potential adopters not only to become more aware of the benefits of adopting precision technologies, but also to identify the most appropriate form of investment for their business. However, it is important to acknowledge that the issue of high initial investments remains. From this perspective, cooperation between the public sector, especially universities and research centers, and private companies is essential to identify technological solutions that are more accessible in terms of cost and able to meet the specific needs of farms. In the case of very small wineries experiencing difficulties in accessing subsidies or financing, there is a possibility that the use of such innovative tools could be explored

through consortia forms, with the support of technology companies that can assist companies in managing, reading and analysing data. Ultimately, overcoming financial barriers, embracing innovative technologies, and adopting collaborative models are key strategies. Collaborating with analytics experts and conducting awareness campaigns are suggested strategies to highlight the benefits of adopting PATs in viticulture and overcome resistance to change among winegrowers. In other words, cultivating innovation through strategic incentives and collaborative partnerships fosters the widespread adoption of precision technologies, ensuring a sustainable future for vineyards.

However, this study shows some limitations related to the databases used—which may have excluded some works—and the methodological approach employed, which did not allow a clear comparison and generalisation of the results. Studies might be context-specific, limiting the generalizability of findings to different regions or emerging technologies. Furthermore, the review might have failed to capture recent advancements or anticipate future developments in PATs as economic conditions and practices evolve. However, this sufficiently comprehensive and data-rich review opens the possibilities for future empirical research in PV. Future research should focus on evaluating economic viability and conducting cost-benefit analyses associated with adopting different precision farming technologies. Furthermore, it could be insightful for research to focus on the environmental and social impacts of PATs adoption through life cycle analysis and social life cycle assessment, which could provide a clear picture of the benefits and/or criticalities of precision technologies adopted in strategic sectors such as viticulture. In addition to offering useful information to wine growers, these insights would also enable defining technological and strategic solutions for companies depending on their distinguishing factors.

#### CRedit authorship contribution statement

**Antonino GALATI:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Serena SOFIA:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Maria CRESCIMANNO:** Writing – original draft, Formal analysis.

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#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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