

REVIEW

Open Access



Grapes production and its management with emphasis on plant protection, fertilizer application, harvesting, and residue management: a comprehensive review

Abhijit Khadatkar^{1*}, Chetankumar Prakash Sawant^{1*}, Deepak Thorat¹, Swapnaja Jadhav¹, Ajita Gupta^{1*}, Ashutosh Pandirwar¹, Yukti Verma² and Dhananjay Gawande³

*Correspondence:

Abhijit Khadatkar
abhijitkhadatkar18@gmail.com
Chetankumar Prakash Sawant
chetankumarsawant@gmail.com

Ajita Gupta
ajitagupta2012@gmail.com
¹ICAR-Central Institute of
Agricultural Engineering, Bhopal,
Madhya Pradesh 462038, India

²ICAR-Indian Institute of
Horticultural Research, Bengaluru,
Karnataka 560 089, India

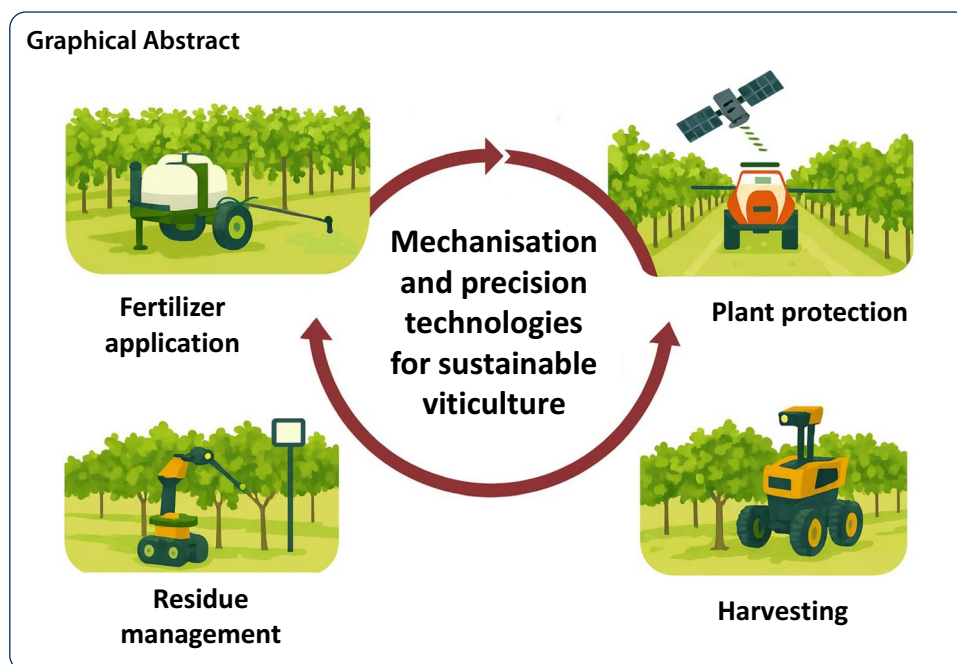
³ICAR-National Research Centre for
Grapes, Pune, Maharashtra
412307, India

Abstract

Grapes (*Vitis vinifera*) are a globally important high-value crop produced for fresh consumption, wine, and processed derivatives. Growing pressure from labor shortages, climate variability, and sustainability demands has intensified the need for mechanization and precision agriculture in viticulture. This review synthesizes current practices, technological advancements, and research gaps across major operational domains, including nutrient management, plant protection, canopy operations, harvesting, and post-pruning residue handling. Advances such as sensor-integrated fertigation systems, machine-vision and AI-assisted sprayers, autonomous and semi-autonomous harvesters, and mechanized residue management tools are critically examined in terms of performance, applicability, and suitability for diverse vineyard scales. A comparative assessment of conventional versus emerging technologies highlights potential benefits, including 20–45% reductions in input use, improved operational efficiency, and significant labor savings, particularly in large commercial vineyards. However, widespread adoption remains limited by high capital costs, fragmented landholdings, inadequate technical support, low digital literacy, and weak policy incentives. The review integrates interdisciplinary research, technological trends, and field-level experiences to identify key barriers and priority areas for innovation. Overall, this work provides strategic insights and a forward-looking framework to guide the development, scaling, and adoption of sustainable, efficient, and resilient viticultural systems, especially for growers in resource-constrained regions.

Keywords Fertigation, Grapevine cultivation, Post-pruning biomass utilization, Precision viticulture, Robotic harvesting, Sustainable viticulture, Variable-rate technology





1 Introduction

Grape (*Vitis vinifera*) is a high-value fruit crop cultivated extensively across the globe, primarily for wine production, but also for consumption as table grapes, raisins, juice, vinegar, and other processed products. Its adaptability to both tropical and temperate climates, along with compatibility with a wide range of soils, has facilitated its global cultivation. As of 2020, global grape production stood at approximately 77.8 million tonnes across 7.4 million hectares, with the majority (57%) designated for wine production, followed by table grapes (36%) and dried grapes (7%) [1]. China, Italy, the United States, Spain, France, Turkey, and India are among the major producers, with over half of the global vineyard area concentrated in Spain, China, France, Italy, and Turkey [2]. The growing demand for wine and fresh table grapes continues to drive the expansion and intensification of grape production, particularly in emerging regions such as India and across the Mediterranean basin [2–4].

Despite rapid technological progress in global viticulture, grape production across many countries particularly developing regions continues to face persistent challenges such as labor scarcity, rising wage rates, climate variability, declining soil health, and the environmental impacts of excessive agrochemical use. While mechanization and precision agriculture technologies have been widely adopted in developed viticulture systems, their uptake in small and medium vineyards remains limited due to cost, infrastructural, and knowledge barriers [5, 6]. Moreover, there is a growing concern over the sustainability of current practices, particularly regarding the overuse of synthetic agrochemicals, high labor costs, and reduced resource-use efficiency [7, 8].

Nutrient management is a critical factor influencing grapevine health, yield, and fruit quality, but existing practices remain highly variable and often inefficient. Grapevines are known to extract substantial quantities of macro and micronutrients, necessitating balanced and timely fertilizer applications [9]. Although integration of chemical, organic, and bio-fertilizers is commonly recommended, site-specific nutrient management

supported by sensor-integrated fertigation, automated applicators, and real-time monitoring has yet to be realized at scale in many production systems [10, 11]. Advances in fertigation and sensor-integrated fertilizer applicators have enabled more precise, efficient, and environmentally sound nutrient delivery [12, 13]. Emerging solutions such as fertigation and sensor-based fertilizer applicators hold promise but remain underutilized in commercial settings due to lack of awareness, cost, and technical support [12, 14, 15].

Similarly, plant protection is another domain where existing technologies are often suboptimal. Grapevines are highly susceptible to fungal infections, insect pests, and weeds, necessitating frequent agrochemical application. [16]. However, conventional spraying methods result in high levels of pesticide waste, environmental pollution, and operator exposure [17]. Modern tools such as LiDAR-based canopy sensing, variable-rate sprayers, and AI-integrated detection systems have shown significant potential in reducing chemical use and improving targeting precision, yet their adoption remains limited in many production regions [18]. Weed management, often overlooked, also plays a significant role in vineyard productivity, with unmanaged weeds capable of causing 29% to 45% yield losses [19, 20]. In temperate climates, dense weed cover can contribute to frost damage by reducing soil heat radiation. While herbicide use remains the primary control method, integrated weed management strategies combining mechanical and biological techniques are increasingly favored in sustainable viticulture [21–23].

Harvesting has seen considerable evolution, particularly in wine grape production, driven by the need to reduce labor dependence and operational costs. Since the introduction of the first mechanical grape harvester in the 1960s, innovations have resulted in increasingly sophisticated systems capable of selective harvesting, canopy manipulation, and real-time sorting [24–26]. However, harvesting of table grapes remains predominantly manual due to strict quality standards and fruit sensitivity to damage during handling.

The increasing global demand for grapes, combined with labor shortages, climate challenges, and sustainability imperatives, underscores the importance of integrating advanced technologies into grapevine production systems. Innovations in robotics, machine vision, and artificial intelligence have the potential to revolutionize vineyard operations by improving efficiency, reducing input use, and minimizing environmental impacts [27–30]. Despite this, their implementation remains limited due to economic and technical constraints, particularly in smallholder contexts.

Although numerous studies address individual components of grape production such as fertigation scheduling, precision spraying systems, robotic harvesting mechanisms, or post-pruning residue management there remains a clear gap in the literature for an integrated, cross-domain assessment of vineyard mechanization and precision technologies. Existing reviews typically examine technologies in isolation, with limited emphasis on their comparative performance, operational compatibility, scalability, or economic feasibility across diverse vineyard conditions. Moreover, the rapid emergence of sensor networks, AI-driven decision-support systems, machine vision platforms, and autonomous robotic tools has outpaced the availability of synthesized research that evaluates their combined potential to transform vineyard operations. Most published work also focuses on large-scale vineyards in high-income regions, leaving significant gaps in understanding how these technologies translate to smallholder, fragmented, or resource-limited viticulture systems, particularly in developing countries. As a result, stakeholders lack a

unified framework to judge which technologies are relevant, adoptable, and cost-effective under varying production scales and agroecological constraints.

Based on the systematic literature review and thematic synthesis presented above, it is evident that despite substantial advancements in vineyard mechanization and precision technologies, several critical research gaps persist. A key limitation of the existing body of work is the fragmented nature of research, where most studies focus on individual operational domains such as nutrient management [12, 34], plant protection [18, 60], or harvesting systems [24, 72] in isolation, with limited efforts toward integrated, system-level assessments. Furthermore, there is a notable lack of comprehensive comparative analyses, as conventional practices and emerging mechanized, sensor-based, and AI-driven technologies are seldom evaluated using consistent performance indicators such as efficiency, precision, environmental impact, labor requirements, and cost [5, 27, 30]. In addition, while several studies acknowledge constraints to technology adoption, these are often addressed in isolation; a holistic understanding of cross-cutting barriers including technical, economic, infrastructural, policy, and socio-cultural factors remains insufficiently developed [5, 7, 8].

To address the above-identified gaps, this review presents an integrated assessment of vineyard mechanization and precision technologies across key operational domains, including nutrient management, plant protection, harvesting, and residue management. It compares conventional and emerging mechanized, sensor-based, and AI-enabled systems using a consistent evaluation framework based on efficiency, precision, environmental impact, labor, and cost. The review also provides a consolidated analysis of cross-cutting adoption barriers and highlights key research priorities, with emphasis on autonomous systems, multi-sensor integration, and AI-driven decision support for sustainable and scalable viticulture.

2 Literature search strategy and review framework

This review was conducted using a structured and systematic approach to identify, evaluate, and synthesize published research related to grape production mechanization, precision viticulture, plant protection technologies, harvesting systems, and post-pruning residue management. A comprehensive literature search was carried out using major scientific databases including Scopus, Web of Science, ScienceDirect, Springer-Link, Wiley Online Library, and Google Scholar. The search primarily covered studies published between 2000 and 2025, with particular emphasis on recent developments reported after 2012, reflecting rapid advancements in automation, sensing, robotics, and artificial intelligence in viticulture. Relevant literature was identified using combinations of keywords such as grape production, viticulture mechanization, precision viticulture, fertigation, sensor-based spraying, LiDAR sprayers, robotic grape harvesting, variable-rate technology, vineyard automation, and post-pruning residue management. Boolean operators (AND/OR) were used to refine the search and improve relevance. Reference lists of selected articles were also screened to identify additional relevant studies. Studies were included if they (i) addressed grapevine production systems, (ii) focused on mechanization, automation, sensing, or precision agriculture technologies, and (iii) were peer-reviewed journal articles, conference papers, or authoritative technical reports. Articles dealing exclusively with grape genetics, wine chemistry, or unrelated horticultural practices were excluded. Duplicate publications and non-English articles were also omitted.

Priority was given to studies providing quantitative or qualitative performance indicators such as operational efficiency, input savings, labor reduction, environmental impact, or economic feasibility. The selected literature was analyzed using a thematic and systems-based synthesis framework. Studies were grouped according to major operational domains of vineyard management, including fertilizer and nutrient application, plant protection technologies, harvesting systems, and post-pruning residue management. Within each domain, conventional practices were compared with emerging mechanized, sensor-based, and AI-enabled technologies using common evaluation criteria such as precision, labor requirement, resource-use efficiency, environmental impact, scalability, and adoption potential. Cross-cutting challenges related to technical limitations, economic constraints, and barriers to adoption were synthesized to identify research gaps and future research priorities. This integrative approach enabled a holistic assessment of vineyard mechanization and precision technologies and facilitated comparison across diverse production scales and agro-ecological contexts.

3 Fertilizer application

Grapevines (*Vitis vinifera*) are nutrient-demanding perennial crops that extract substantial quantities of essential elements from the soil throughout their growth cycle. Therefore, the development of well-structured fertilization strategies is critical for maintaining soil fertility, supporting optimal vine growth, and maximizing yield and fruit quality [9]. Grapevines generally require about 100–500 kg/ha of nitrogen, 80–400 kg/ha of P_2O_5 , and 100–600 kg/ha of K_2O , along with 50–150 kg/ha of calcium, 10–50 kg/ha of magnesium, and 10–50 kg/ha of sulphur annually, supplemented with micronutrients such as 25–50 kg/ha zinc sulphate, 5–10 kg/ha borax (boron), 25–50 kg/ha manganese sulphate, 5–10 kg/ha copper sulphate, and 100–200 kg/ha iron sulphate as needed based on soil and leaf analysis [31]. Apart from the chemical fertilizers, 8–12 tonnes/ha of organic manure is recommended to improve soil health and nutrient availability. Effective vineyard fertilization practices are aimed at replenishing nutrient reserves in the soil and ensuring the availability of macro and micronutrients vital for physiological and metabolic processes such as vegetative growth, flowering, fruit set, and berry ripening [32]. Fertilizer application in grape vineyards should be timed to match key growth stages basal application before pruning, follow-up doses during vegetative growth, flowering, and berry development. Chemical fertilizers are typically applied through soil placement in bands or fertigation near the root zone to ensure efficient uptake, while organic fertilizers such as FYM, compost, or vermicompost are incorporated uniformly in the basin around the vine before the season starts. Placement should be 30–45 cm from the trunk and 15–25 cm deep to target active feeder roots.

An efficient nutrient management plan integrates the selection of appropriate nutrient sources (synthetic, organic, or bio-fertilizers), precise application rates, correct timing, and optimal placement. This holistic approach maximizes nutrient uptake efficiency while minimizing losses and environmental impact. Typically, vineyard fertilization is performed twice annually, usually at pruning, with supplemental foliar sprays applied periodically to address micronutrient deficiencies [14]. The nutrient regime in many vineyards includes approximately 40% organic sources and 60% inorganic fertilizers [15], promoting both short-term productivity and long-term soil health. Advancements in precision agriculture and fertigation technologies have revolutionized vineyard

nutrient management. Fertigation where nutrients are delivered via drip irrigation has gained popularity, particularly in water-scarce or high-value grape-producing regions, allowing for targeted and uniform nutrient delivery [15]. Despite these developments, the direct application of solid synthetic, organic, or bio-fertilizers to the soil remains an essential practice, contributing to improvements in soil structure, microbial activity, and nutrient-holding capacity. Foliar fertilization offers a rapid means to correct deficiencies, especially of micronutrients like zinc, boron, and iron. However, literature indicates that foliar application is generally ineffective for supplying macronutrients in quantities sufficient to meet vine demands and is best used as a supplementary practice [33]. Given the scale and labor requirements of fertilization in commercial vineyards, mechanization has become increasingly important. A variety of specialized fertilizer applicators ranging from rotary tillage-based trench applicators to precision injectors and sensor-integrated robotic systems have been developed to enhance accuracy, reduce labor costs, and improve operational efficiency [12, 34]. These technologies are particularly vital in large-scale vineyards and high-value production systems where input optimization and sustainability are paramount. Table 1 in this review provides an overview of various fertilizer application technologies, outlining their operational principles, advantages, and limitations.

Given the inherent spatial and temporal variability within orchards, implementing differential or site-specific nutrient management strategies will be essential for optimizing vineyard productivity in the future. According to [35], plant nutrient concentration is a more stable and reliable tool than soil nutrients concentration. In a recent advancement, an intelligent self-navigating orchard trenching and fertilization machine was developed that performs unmanned driving, automatic trenching, mixed organic–chemical fertilizer application, and soil covering in a single cycle. It demonstrated high operational consistency, maintaining over 90% stability for both trenching depth and fertilizer distribution [36].

3.1 Synthetic fertilizer application

The application of chemical fertilizers is a critical component in the nutritional management of grapevines, especially in intensive production systems aiming for high yields and fruit quality. To achieve an average yield of 30–35 tonnes per hectare, it is generally recommended to apply approximately 700–900 kg of nitrogen (N), 400–600 kg of phosphorus (P_2O_5), and 750–1000 kg of potassium (K_2O) annually [14]. During the active vegetative growth phase, about 40% of N, 50% of P_2O_5 , and 33% of K_2O need to be applied, with the remainder distributed during the fruiting stage to meet the crop's evolving physiological requirements.

The nutrient requirement of grape vines varies during the total growth cycle particularly, two distinguishable growth phases is given in Table 2.

In specific soil conditions, particularly in heavy, calcareous soils or when using saline irrigation nutrient uptake efficiency may be hindered, requiring adjusted fertilizer doses. For example, table grape orchards grafted on Dogridge rootstock may require significantly lower inputs, estimated at 266 kg N, 177.5 kg P, and 266 kg K per hectare [37].

To enhance the efficiency of fertilizer delivery and reduce labor demands, various mechanized and semi-automated application systems have been developed. A variety of mechanized fertilizer application systems have been developed to address the challenges

Table 1 Summary on fertilizer application in vineyard automation

Method/technology	Details/working principle	Advantages	Drawbacks	References
Chemical fertilizer application	Uses rotary tillage knife opens furrow and then applies fertilizer into it	Improved production efficiency in fertilizer application	High tillage resistance and easy tree roots damage in ditching operation, fertilizers unevenly distributed in trench	[39]
	Uses ditching device, plough for furrow cutting and fertilizer application device	Suitable for grape vineyard specially	–	[38]
	Uses high pressure gas to shock soil body and then injects liquid fertilizer deep in the soil	Improved automation degree and reduced intensity of labor operations	Equipment set up is complex compared to conventional machines	[110]
Organic or manure fertilizer application	It is mainly composed of a traction frame, fertilizer box, fertilizer box opening size adjusting component, fertilizer conveying component, ditching depth adjusting device, two fertilizing devices	Machine is compact, flexible in adjustment of ditching depth, dose, row width, etc	–	[44]
	Uniform slurry band application with inputs on slurry total nitrogen content and target application rate in the control unit was applied based on metering pump rotational speed as a function of machine forward speed	Even distribution of slurry into two application bands, Low environmental impact as a result of reduced ammonia emissions	Low field efficiency due to high application rate of slurry and low spreader tank capacity	[111]
	It consists of chain conveyor metering device, cross belt conveyor, hydraulically-driven spinning plate, Uses proximity sensor with electronic control system	More uniform application of slurry solid fractions as application rate in accordance with machine forward speed	Low field efficiency i.e. 19.5–32.8% (for N application rate of 50 and 25 kg.ha ⁻¹)	[46]
	Tractor-powered (PTO) spray equipment with slurry tank, venturi pump, mixing equipment and hoses	Applies biochar slurry in the root zone of grape vines	The effect of biochar application on crop yield and quality not validated	[47]

Table 2 Relative Nutrient Requirement of Grapes at Different Stages of Growth (Adapted from [37])

Nutrient	N	P	K	Mg
	<i>Days after back pruning</i>			
0–30	High	Medium	Nil	Nil
32–60	Low	High	Low	Medium
61–90	Nil	Medium	High	Medium
91–120	Nil	Nil	Low	Nil
	<i>Days after forward pruning</i>			
0–40	High	Low	Low	Low
41–70	Medium	Medium	Medium	Low
71–110	Low	Low	High	Medium
111–140	Nil	Nil	Medium	Nil

of labor-intensive and inefficient nutrient delivery in vineyards. Among the earliest innovations are rotary-type ditching and fertilizing machines, such as the model designed by [38], which use mechanical tillage to open trenches and deposit fertilizers directly into the root zone. These systems are particularly effective during vineyard establishment and for periodic nutrient replenishment. Two-stage rotary tillage fertilizer injectors, proposed by Ye et al. [39], offer a more refined approach by combining a front-mounted tillage blade with an integrated fertilizer injection unit. This setup enables precise placement of fertilizers in furrows approximately 500 mm deep and 200 mm wide, making it especially suitable for vineyards organized in row-crop layouts. For precise and optimum fertilizer placement, a site-specific fertilizer applicator equipped with a mechanical sensing mechanism was developed by [12].

More recently, gas explosion-based fertilizer injection systems have emerged, offering deep subsoil nutrient delivery through high-pressure gas release, which fractures the soil and allows for deeper infiltration of liquid fertilizers [40]. While such systems improve nutrient placement and root uptake efficiency, their operational complexity and equipment costs pose challenges for widespread adoption, particularly in resource-constrained settings. In parallel, robotic applicators integrated with artificial intelligence (AI) and real-time sensing technologies have gained prominence as advanced tools for site-specific nutrient management. These autonomous systems such as leverage canopy vigor indices, historical growth data, and sensor feedback to precisely dispense liquid nitrogen or other nutrients at the trunk level, reducing over-application and improving fertilizer use efficiency [41, 42]. A comparative assessment of these emerging technologies relative to conventional practices highlighting resource savings and operational efficiency is presented in Table 3.

In addition to fully automated systems, semi-automated site-specific applicators have also shown promise in improving nutrient management in vineyards. For instance, the system developed by Jyoti et al. [12] utilizes mechanical sensors to detect spatial variability and modulate fertilizer output accordingly. [13] used prescription map for variable rate fertilization with a tractor and fertilizer spreader in olive orchards. The variable rate application of nitrogen fertilizer resulted in a 31% reduction in the amount to be applied in the olive orchard compared to the standard dose. Such innovations offer cost-effective alternatives to conventional broadcasting, especially in medium- to large-scale vineyards where uniform nutrient application is critical for maintaining productivity. Collectively, these technologies represent significant advancements in vineyard fertilization, enabling precision, sustainability, and labor efficiency. However, future research must address the economic feasibility, system integration with other vineyard

Table 3 Comparative evaluation of conventional vs. emerging nutrient management technologies in vineyards

Parameter	Conventional nutrient practices	Emerging precision technologies
Application method	Broadcasting / manual fertigation	Sensor-based, automated variable-rate fertigation
Spatial precision	Low	High (zone-specific or vine-specific)
Data use	Limited soil/leaf testing	Continuous multi-sensor, remote, and AI data
Labor requirement	High	Low (automation, IoT, robotics)
Environmental impact	Higher runoff & leaching	Reduced losses through targeted placement
Cost efficiency	Moderate to low	High in long-term, though initial cost is higher
Suitability	Small vineyards, low investment	Medium-large vineyards, technology-ready systems

operations, and adaptability to varied topographies and soil conditions. These emerging technologies not only enhance nutrient use efficiency and minimize environmental impact but also offer promising solutions for the automation of fertilizer application in commercial viticulture.

3.2 Organic or manure fertilizer application

The efficiency of organic fertilization in vineyards is strongly influenced by the inherent characteristics of the organic material used. Factors such as nutrient composition, C:N ratio, degree of decomposition, and overall stability determine the rate at which nutrients are mineralized and released into the soil. Consequently, different organic sources can exhibit highly variable nutrient-release patterns, which may affect their ability to meet crop demand at specific growth stages. Therefore, proper selection and characterization of organic amendments are essential for optimizing nutrient availability and improving vineyard nutrient management. The application of organic fertilizers, including farmyard manure (FYM), compost, and slurry, is a key practice in sustainable viticulture, offering numerous agronomic and environmental benefits. Organic amendments enhance soil structure, microbial activity, nutrient retention capacity, and long-term fertility, thereby supporting the physiological health and productivity of grapevines [43]. In integrated nutrient management systems, organic sources typically contribute 40% of the total fertilizer input, complementing the chemical fraction to ensure both immediate and residual nutrient availability [15].

In practice, organic fertilizer application schedules vary by vineyard age, vine vigor, and soil fertility status. For newly established vineyards, 50 kg of FYM per vine is recommended during the first two years, increasing to 100 kg per vine in subsequent seasons [36]. Application is usually carried out twice annually post-pruning and during active growth stages either by broadcasting or banding near the root zone. Due to the bulkiness and labor-intensive nature of organic materials, several mechanized systems have been developed to streamline the process and improve distribution efficiency. Several mechanized solutions have been developed to improve the efficiency, precision, and labor economics of organic fertilizer application in vineyards. Ditching and fertilization machines, such as the integrated system developed by Chang et al. [44], combine trenching, fertilizer dispensing, and soil covering into a single operational pass (Fig. 1). This multifunctional approach significantly reduces labor demands and enhances application uniformity, especially in structured vineyard rows. A tractor operated fertilizer applicator was developed to dispense FYM along both sides of the crop row. Studies reported that this machine significantly reduced operational costs, labour requirements, and time, while also ensuring uniform FYM application in vineyards [34]. For liquid organic inputs, slurry spreaders offer viable options. The prototype presented by Gioelli et al. [45] features band application nozzles and metering systems that synchronize slurry discharge with the machine's forward speed (Fig. 2). These systems have shown potential in reducing ammonia volatilization and improving nitrogen use efficiency; however, their effectiveness is often constrained by limited tank capacity, which hampers field coverage and necessitates frequent refills.

In the context of semi-solid amendments, solid fraction slurry applicators have demonstrated enhanced precision and operational control. The model introduced by Balsari et al. [46] integrates cross-belt conveyors, precision metering devices, and electronic



Fig. 1 Double ditches fertilizing device operating into the soil [44]



Fig. 2 Prototype slurry spreader with band application distribution system [45]

control systems to ensure consistent and uniform distribution of composted manure solids. Despite these advantages, the reported field efficiency of such machines remains modest ranging from 19.5% to 32.8% and is heavily influenced by application rate and field conditions. Meanwhile, attention has also turned to the use of biochar as a soil amendment in vineyards. Husk [47] designed a venturi-based slurry injector capable of applying biochar in liquid suspension directly into the root zone (Fig. 3). Biochar has been shown to improve soil carbon levels, nutrient retention, and microbial activity; however, the technology for its application in vineyards remains in the early stages and requires extensive validation across diverse vineyard environments and soil types.

In terms of solid organic matter, farmyard manure (FYM) applicators provide effective mechanized alternatives to manual broadcasting. Khadatkar et al. [34] developed a side-dispensing auger-based FYM applicator that achieved a field efficiency of 71% and a coverage rate of 0.2 hectares per hour. This design significantly reduces operational time and manual labor requirements while ensuring even manure distribution along grapevine rows. These mechanized systems collectively support a shift toward more sustainable and scalable organic nutrient management in viticulture. Nonetheless, there remains a need to enhance their precision, automate plant-detection capabilities, and



Fig. 3 Biochar slurry applicator for grape vines [47]

improve adaptability to varied vineyard terrains and canopy architectures to optimize their full potential.

Despite these advancements, limitations persist. Organic fertilizers are inherently heterogeneous in nutrient composition and moisture content, complicating dose precision. Furthermore, many applicators are designed without the ability to detect plant presence or variability in canopy size, which may result in inconsistent application across rows.

Nonetheless, integrating electronic sensors and control systems into organic fertilizer applicators holds substantial promise for improving accuracy and reducing wastage. In the context of sustainable viticulture, the use of organic amendments is not only aligned with ecological goals but also provides a resilient foundation for long-term soil fertility and vineyard productivity. Future research should focus on real-time nutrient release monitoring, site-specific organic application, and compatibility with precision agriculture systems. While efficient nutrient management strengthens vine growth and improves overall vineyard performance, maintaining crop health also depends on timely and precise plant protection interventions. As vineyards advance toward greater sustainability and precision, innovations in spraying technologies become equally important.

4 Plant protection technologies

Effective pest and disease management remains a core challenge in viticulture, particularly in intensive production systems where grapevines are susceptible to a wide range of fungal diseases (e.g., powdery mildew, downy mildew, botrytis), insect pests (e.g., mealybugs, thrips), and weed competition. Traditionally, vineyards have relied on frequent and broad-spectrum pesticide applications, which, while effective, have raised concerns regarding environmental degradation, groundwater contamination, human health risks, and chemical residues on produce [22]. Tamagnone [48] reported chemical saving up to 80% with developed mechanical prototype for herbicides application as against conventional practice. Consequently, the viticulture sector is increasingly moving toward sustainable, precision-based, and automated plant protection systems that maximize efficacy while minimizing resource use and off-target effects. An overview of key plant protection technologies used in vineyards is provided in Table 4.

Table 4 Summary on plant protection technologies used in vineyards

Method/technology	Details/ Working principle	Advantages	Disadvantages	References
<i>Conventional sprayers</i>				
Airblast	The agrochemicals get released by nozzles in air stream produced by centrifugal blower	More coverage; better canopy penetration	Course droplets; High drift; low deposition on abaxial leaf surface; about 50–85% spray losses from drift	[49, 112]
Tunnel	Designed with shields for canopy enclosure and basins at the bottom each shield to reduce loss of agrochemicals by drift and recycling of non-retained spray on canopy	High spray deposition efficiency; reduced drift; reduced pesticide dose by 15–50%; Spray recovery of 34–75%	High machine cost; low working speed; uneasy maneuverability; chances of contamination due to recycled spray; Non-uniform spray deposition; low penetration inside the canopy	[52, 112–117]
Electrostatic	Compressed air and spray liquid get converged together and passed through electrode having positive electric field	Very fine droplet (< 50 µm); better deposition on both adaxial and abaxial surfaces of leaves; reduced pesticide dose; high spray retention	Costly method; requires awareness while handling	[53, 54]
<i>Sensing technology</i>				
Infrared sensor based canopy sprayer	Measures infrared light emitting from an object having absolute temperature above zero degree	Detect plant canopy; low cost; robust; least affected by environmental factors	Affected by plant characteristics and intensity of illumination; low range of detection; unable to measure plant canopy volume	[53]
Ultrasonic sensor based canopy sprayer	Measures distance between sensor and object by transmitting ultrasonic waves from transmitter and receiving returned echo at receiver	Detect plant canopy affordable; wide range 0–3 m; 10–35% pesticide gets saved;	Unable to measure plant canopy characterization with suitable algorithm; large angle of divergence; requires numbers of sensors;	[56, 57]
LIDAR sensor based canopy sprayer	Measures time of flight taken between transmitted pulsed laser beam and returned signal after striking on an object	Able to measure plant characterization with suitable algorithm; real time measurement; 25–45% pesticide gets saved;	Limited accuracy;	[60, 65]
Computer stereo vision based canopy sprayer	Stereo vision gives range of distance between object and camera, which helps to form 3D scan point cloud using monocular cameras such as CCD and CMOS	Provides 3D image of plant canopy including its characterization; 30% pesticide gets saved;	Less accurate	[27]

4.1 Conventional spraying systems

Conventional spraying technologies continue to be widely adopted, particularly in low-to-medium mechanized regions. These systems apply agrochemicals uniformly across vineyard plots without accounting for canopy variability, often leading to excessive chemical usage and environmental waste. The primary sprayer types include:



Fig. 4 MITRA Storm (info@mitraweb.in) [51]



Fig. 5 Tunnel sprayer during operation in vineyards [52]

Airblast sprayer: Airblast sprayers are widely employed in vineyard operations and are equipped with air-assisted systems that enhance the penetration of spray material into dense canopies. These sprayers uniformly distribute agrochemicals across tree canopies through fine droplet swaths [49]. The field capacity of an airblast sprayer is approximately 1.7 ha/h at a forward speed of 1.5 km/h, with an application rate that can be adjusted between 100 and 400 L/ha [50]. Compared to manual spraying, this technology can reduce operational costs by 28.5%. Several tractor-mounted airblast sprayers designed for orchard and vineyard use are available commercially. For instance, the MITRA Storm [51] is a compact, lightweight tractor-mounted sprayer (Fig. 4) suitable for applying pesticides in vineyards, particularly for managing powdery mildew, downy mildew, and mites.

Tunnel sprayers: Tunnel sprayers are used in vineyards to mitigate soil contamination and airborne diseases. These sprayers (Fig. 5) are designed to minimize the loss of agrochemicals to the environment and soil through the use of canopy-enclosing shields and collection basins at the bottom of each shield. This structure effectively contains drift and non-retained spray [52].

Electrostatic sprayer: Electrostatic sprayers utilize a shearing action where highly compressed air and spray liquid collide at the tip of an air-shear nozzle, atomizing the liquid into ultra-fine droplets. These droplets are then exposed to a high-voltage

electrode with a positive field and become negatively charged before exiting the nozzle [53]. Salcedo et al. [54] evaluated electrostatic sprayers in trellised vineyards at forward speeds of 1.3 and 1.6 m/s, volume rates of 60 and 75 L/ha, and an operating pressure of 200 kPa. They compared systems with and without electrostatic activation against conventional sprayers. Results showed that the activated electrostatic system achieved the highest spray retention (75%), outperforming the airblast sprayer (55%) and the deactivated electrostatic system (45%). The smaller droplet size ($< 50 \mu\text{m}$) in electrostatic spraying diminishes the influence of inertia and gravity, allowing surface tension and viscosity forces to dominate, which helps reduce drift and off-target spray deposition.

4.2 Sensor-based spraying technology

Variable-rate spray technology utilizes real-time sensing systems and offers substantial potential for improving precision in plant protection. Because canopy density and structure vary spatially within vineyards, accurate measurement of plant morphological characteristics is essential for optimizing agrochemical delivery, minimizing chemical losses, and preventing both over- and under-application, thereby reducing environmental impacts. Plant geometric parameters are particularly critical inputs for variable-rate application systems. Plant height reflects vine vigor and structural development, influencing nutrient dynamics and spray deposition patterns. Canopy width defines the lateral spread of foliage and directly affects spray coverage and airflow penetration. Canopy density, which captures the compactness and thickness of vegetative growth, regulates light interception, intra-canopy microclimate, and the ability of sprays to reach interior leaf layers. The leaf area index (LAI), the total one-sided leaf area per unit ground surface area, is widely used to assess photosynthetic capacity, evapotranspiration, and overall canopy performance.

Accurate, real-time quantification of these geometric parameters is therefore essential for refining nutrient delivery, adjusting spray volumes, and enabling truly site-specific management in heterogeneous vineyard environments. However, there remains a pressing need to enhance real-time measurement capabilities for parameters such as plant height, canopy width, canopy density, and LAI, given their central role in guiding variable-rate application technologies. While the complete elimination of agrochemicals is unlikely in the near future, their judicious and site-specific use will be essential to ensure environmental protection and sustainable viticulture. In view of the above, the sensor based advanced spraying system are being developed.

Infrared sensor-based sprayers: Infrared (IR) sensors are transducers that detect infrared radiation emitted from objects within their field of view. While relatively cost-effective, processing IR signals remains complex, limiting commercial deployment. He et al. [53] developed an electrostatic sprayer integrated with an IR canopy detection system that achieved pesticide savings of 50–75%. This technology performs best in dense canopies with high leaf reflectivity and adequate illumination. However, IR signal quality may be slightly affected by temperature and humidity and significantly influenced by plant appearance, illumination intensity, operating speed, and plant spacing [55].

Ultrasonic sensor-based detection technology: Ultrasonic sensors consist of a wave emitter, receiver, and a chronometer. They function by emitting sound waves and measuring the time it takes for the echo to return after reflecting off a surface. Sawant et al. [13] developed an ultrasonic sensor-based canopy detection and spraying system

for young orchards. In a related study, a microcontroller-based site-specific spray module was optimized using RSM and RBFNN-PSO, with the derived optimal parameters enhancing spray performance and delivering substantial environmental and economic benefits, including a 46.2% reduction in operational cost and a 72% reduction in chemical use. Gil et al. [56] developed an ultrasonic-based variable-rate sprayer for vineyards, featuring three sensors mounted at different heights on one side of an airblast sprayer to assess canopy volume along the tree row. The system included a compact field point controller, a laptop with dedicated LabView® software, and wireless routers for real-time monitoring and control. The spray volume was modulated based on canopy dimensions, achieving pesticide savings of 21.9%. Other studies reported pesticide savings ranging from 10 to 35% using airblast sprayers fitted with ultrasonic sensors compared to conventional systems [57–59].

LiDAR sensor-based spraying technology: Light Detection and Ranging (LiDAR) sensors operate by emitting laser pulses and measuring the time taken for the pulse to return after hitting an object. These pulses form a highly precise, narrow beam capable of generating two-dimensional point clouds used to analyze canopy structure. Cabre and Landers [60] developed an axial fan-type canopy spraying system for vineyards, incorporating GPS, four ultrasonic sensors, four anemometers, and a louvre system to adjust air volume from 0 to 100%. The study examined the relationship between ultrasonic echoes and air flux absorption, hypothesizing that both are proportional to canopy density. Zhongyi et al. [61] developed a stratified variable-rate spraying system that integrates a LiDAR sensing module with independently controlled multi-channel nozzles. In this system, spray volume is adjusted according to canopy structure, which is segmented into longitudinal layers for precise dose regulation (Fig. 6). Similarly, Baltazar et al. [62] combined a two-dimensional LiDAR sensor with a canopy boundary detection algorithm and achieved a 28% reduction in pesticide use, demonstrating the strong potential of LiDAR-based systems to improve spray efficiency and reduce chemical inputs. Reported pesticide savings with LiDAR-equipped airblast sprayers ranged from 25 to 45% compared to conventional systems [63–65].

Computer stereo vision-based detection technology: Computer stereo vision systems capture video images of plant canopies using monocular cameras (e.g., CCD or

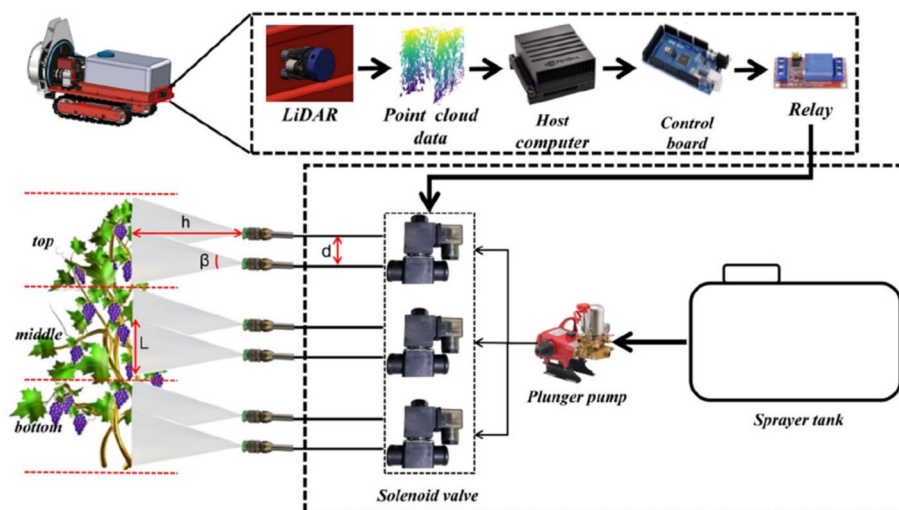


Fig. 6 LiDAR Stratified variable spraying system [61]

CMOS), creating 3D models of plant structural parameters such as height, width, volume, and leaf area index. These parameters are extracted using image processing based on color coding. Stereo vision provides distance ranges between the object and camera, allowing for 3D point cloud generation. Berenstein et al. [27] developed a variable rate spraying robot equipped with an algorithm capable of detecting and targeting grape bunches with 90% accuracy, achieving 30% pesticide savings. Although conventional spraying technologies such as airblast, tunnel, and electrostatic sprayers are crucial for pest and disease control in vineyards, they often lack precision and result in higher spray losses. Modern technologies such as infrared, ultrasonic, LiDAR, and stereo vision-based systems offer promising alternatives for variable-rate agrochemical application, enhancing input efficiency and minimizing environmental contamination.

4.3 Autonomous and AI-driven systems

The next generation of plant protection in vineyards leverages robotics, GPS, artificial intelligence (AI), and real-time data analytics to enable autonomous spraying platforms. These systems can detect grape clusters, identify pest-infested zones, and modulate spray accordingly. Zaidner and Shapiro [66] demonstrated that such platforms could dramatically reduce labor inputs while maintaining high levels of operational accuracy and chemical efficiency. Advanced systems now combine LiDAR, stereo vision, AI algorithms, and machine learning to recognize diseases, assess canopy vigor, and differentiate between healthy and affected zones [44]. For example, AI-powered robotic sprayers such as the GUSS (Global Unmanned Spray System) and Vitibot Bakus integrate autonomous navigation with sensor-guided precision spraying, reducing pesticide use and improving safety by removing human operators from hazardous environments [30, 67]. Drone-based spraying systems are also emerging as a viable solution for hilly or inaccessible vineyards. Equipped with multispectral cameras and variable-rate nozzles, these unmanned aerial vehicles (UAVs) offer rapid deployment, reduced labor, and minimal soil compaction. Though still limited in payload and regulatory approval, drone spraying has shown potential for spot treatments and vineyard surveillance [68, 69]. To illustrate their advantages, Table 5 presents a detailed comparison of emerging technologies and traditional practices, focusing on resource use efficiency and performance gains.

Advances in precision spraying and disease management enhance canopy health, fruit uniformity, and yield stability. With these upstream operations optimized, attention shifts to harvesting technologies, where mechanization and robotics play a critical role in ensuring quality retention and operational efficiency.

Table 5 Comparative evaluation of conventional vs. emerging spraying technologies in vineyards

Parameter	Conventional sprayers	Precision / emerging technologies
Spray pattern	Uniform, constant volume	Variable-rate, canopy-adaptive
Drift & wastage	High	Low (20–60% reduction)
Canopy adaptation	Poor	High (sensor-guided, map-based)
Labor requirement	High	Low (autonomous or semi-autonomous)
Monitoring	Visual inspection	AI-based detection, UAV imaging
Environmental impact	High	Lower due to targeted delivery
Cost	Low initial, high recurring	Moderate/high initial, lower recurring
Suitability	Small farms with limited technology	Medium and large vineyards; adaptable over time

5 Harvesting

Grapes are harvested only when all the berries are of unique colour and desired TSS of the cultivar. Time of harvest is an important and challenging viticultural decision for grape growers due to the trouble in assessing maturity of grape in vineyard and predicting wine quality. The time of harvesting of grapes depends upon several factors like maturity, variety (mainly TSS), availability of skilled labours, size of the crop, appearance of berries, winery requirement etc. Harvesting is done by repeated pickings since bunches do not ripen at one time. The adoption of grape harvesters depends on many factors including value of crop, vineyard location, availability and cost of manual labour, fruit removal efficiency and transportation of harvest [70, 71].

The hand picking is mostly done for table purpose grapes grown in India. The pickers pick only healthy grape bunches. Manual harvesting is slower and labour intensive while skilled worker availability during harvesting season is limiting factor. However, hand picking permits for a selection of the mature grapes from vines; unripe or rotten grapes can be left on the vine or discarded. The bunch is harvested as whole which causes less damage to the grapes. The bunches are usually plucked with secateurs very close to the canes. During harvesting, bunches need to be placed in the baskets very gently. Hand pickers use small containers for temporary field storage of the grapes which help in reducing the grape damage. Some of the developed grape harvester was summarized in Table 6.

5.1 Mechanical harvesters

Traditionally, grape harvesting has been conducted manually using hand tools. However, due to rising labor costs, limited time windows for harvesting during peak seasons, and increased competition both locally and globally, commercial vineyard operators have been compelled to adopt mechanized alternatives. The primary objective of introducing mechanical grape harvesters is to reduce labor dependency and lower annual operational costs. Nonetheless, the initial investment required for acquiring mechanical harvesters remains significantly high [72–75].

Over time, several advanced grape harvester models have been developed. Presently, two principal types dominate the market: one that detaches berries by beating and shaking the vines using staves or rods, and another that generates impulses to shake the trunk or cordon. In both cases, detached berries fall onto conveyors that carry them past blowers, which remove leaves before the grapes are temporarily stored in collection bins [24, 76]. Grape harvesters are further categorized based on their power source: self-propelled harvesters (Fig. 7) and towed or tractor-mounted harvesters (Fig. 8). Notable manufacturers of these harvesters include Oxbo International Corporation (USA), Pellenc Australia Pty Ltd (Australia), PFG Australia (Australia), ERO-Gerätebau GmbH (Germany), and New Holland (USA). While self-propelled harvesters require high capital investment, they offer large harvesting capacities and may be utilized in custom-hiring models, making them commercially viable for large-scale growers. In contrast, tractor-mounted units offer a more affordable alternative, requiring only a conventional tractor to provide traction and power via the power take-off (PTO). Some models also feature hydrostatic drives that facilitate operation on sloped terrains. Modern grape harvesters offer several enhanced features such as automatic grape sorting and cleaning. These features allow for the removal of foreign material, sorting by grape color and ripeness, and

facilitate easy cleaning and maintenance. The effectiveness of mechanization depends significantly on the ease of maintenance and the precision with which grapes are harvested. Most contemporary models are designed to ensure high detachment efficiency with minimal mechanical damage to the fruit. Furthermore, many harvesters now incorporate continuous harvest bin systems, enabling uninterrupted harvesting operations over long rows. Side-discharge conveyors enable efficient grape transfer to larger trailers. Some advanced self-propelled harvesters are equipped with position sensors for automatic row alignment and active systems that adjust the vibration frequency of the harvesting head, thereby optimizing detachment while protecting vines and trellising systems. The motion of the harvesting head is dynamically controlled in proportion to the forward speed.

The mechanical harvester typically consists of several key components: harvesting arms, linear berry separators, de-stemmers, screen rollers, and integrated sorting and cleaning systems (Fig. 9). Harvesting arms (Fig. 9a) secure the berries, while high-frequency linear berry separators (Fig. 9b) gently detach them. Screen rollers (Fig. 9c) eliminate petioles and other green waste. An optional sorter (Fig. 9d) can further segregate berries, leaves, and bunches using feeder rollers and grid belts, with the berries and juice collected in storage bins. Numerous empirical studies have assessed the performance of both self-propelled and towed grape harvesters. Findings generally confirm that mechanical harvesting does not compromise grape quality [73, 77, 78]. Modern harvesters can achieve an average cleanliness rate of 99.82% in the collection bin, 82% of usable berries, and removal of 100% of leaves and 95% of stalks [34]. Novak and Burg [79] compared two self-propelled harvesters Gregoire G-152 and New Holland VL-6060 and found them comparable in product quality. Total losses, including slump and non-harvested yield, ranged from 2 to 4% and 2–3.7% respectively, with both harvesters.

Domingues and Aguila [80] reported that manual harvesting costs were 133.3% higher than mechanical alternatives and found that mechanical harvesting was economically justifiable for vineyard areas exceeding 41.92 ha. Jobbágy et al. [5] evaluated a towed harvester and observed an effective field capacity of 0.32 ha/h at a speed of 2 km/h and 65% field efficiency. Grape losses across the entire field area were 470 kg/ha. For 100 ha of vineyards, the total annual mechanical harvesting cost was USD 8,597.84, with an operating cost of USD 28.66 per hour. Pezzi and Martelli [74] compared the self-propelled Holland Braud VL660 and the towed ERO LS harvesters. Both straddle-type machines employed horizontal detachment units. The self-propelled harvester exhibited 45% and 40% higher capacity in flat and hilly vineyards, respectively, and had lower fruit losses. However, it was cost-effective only for areas larger than 45–51 ha. Break-even points were estimated at 7–8 ha for towed and 12–14 ha for self-propelled harvesters, in comparison to manual methods. Multiple studies conclude that, when correctly adjusted, mechanical harvesters can deliver fruit quality on par with manual harvesting [76, 78, 80].

Thus, both towed and self-propelled mechanical grape harvesters equipped with advanced automation, berry sorting, and cleaning capabilities provide a comprehensive solution for modern viticulture. The choice between the two depends on factors such as vineyard topography, area under cultivation, and available machinery. Moreover, the observed yield losses are within acceptable ranges for sustainable commercial operations.

Table 6 Summary on grapes harvesters with their different types of harvesting systems, conveying and cleaning mechanisms

Machine/technology	Advantages		References
	Harvesting head and detachment mechanism	Conveying and cleaning mechanism	
Self-propelled harvesters			
New generation optimum	ACTIV head automatic row-tracking sensors; low-frequency shaking system	Flexible sorting conveyor starts sorting process soon after grape falls; de-stemmer removes the stems and sort harvested grapes; Sorting rollers permits sorted berries to pass through while removing leaf stems and other waste from variable screen sorting table	[24]
Oxbo 6030 Multi-function grape harvester	Soft-touch bow rod picking system for minimal canopy impact	High capacity bucket conveyance for conveying the grapes; Unique three fan cleaning system removes debris and M.O.G.; Cleaning system with on-board destemming and sorting	http://www.oxbocorp.com/Products/Grape
Gregoire (G 152)	Prolonged banana shaped shakers	Catching area equipped with catcher trays pivoted by the integrated stiffeners	[79] https://www.gregoire.fr/en-oc/ http://www.ero-viti.com/
ERO-Grapeliner 6000	Square section beaters operated by a direct drive hydraulic motor; single elevator system allows the machine to be split into 2 halves, one side for fruit, juice etc. and other for engine fuel, and all hydraulics	Single elevator system split the machine into 2 halves, one for fruit and juice while other for engine fuel, and all hydraulics, de-stemmer has a brush system which clean the de-stemmer basket while in use, discharge conveyor with a de-stemmer	
NEW HOLLAND (NH VL 6060)	Harvesting mechanism has arched shaking rods cambered in a direction to row axis	Two pocket conveyors do catching and simultaneous transport of the product	[79]
Towed type harvesters			
ERO-LS traction	Detachment system consist of an oscillatory shaker having bow rods on both sides of the frame	Grapes are collected by a series of overlapping spring-loaded plates, which carry the grapes on two lateral conveyor belts which unload in two lateral hoppers; cleaning system has two lateral suction fans at the end of catching surface and at discharge point into hoppers	[72] http://www.ero-geraetebau.de/
Oxbo 316XL Grape Harvester	Soft-touch bow rod picking system for minimal canopy impact	Effective three fan cleaning and a bucket conveyance system; A high capacity, full-sized picking tunnel to allow it to efficiently handle even high tonnage crops	http://www.oxbocorp.com/Products/Grape
Pull type grape harvester G3.220	Automatic row following system; Picking tunnel self-alignment sensors gives automatic alignment over the row; two shakers support system uses ARC shaped shakers with low shaking frequency and high work speed	Conveying system has Supply belt driving system; bottom cleaning fans and vertical cane extractors performs cleaning and wood extraction just after grapes are picked	https://www.gregoire.fr/en-oc/

Table 6 (continued)

Machine/technology	Advantages		References
	Harvesting head and detachment mechanism	Conveying and cleaning mechanism	
GRAPES'LINE towed harvester	Harvesting head has 'ACTIV' auto-guidance system	Conveyor opens at back to remove foreign material and avoid clogging, de-stemmer removes the stems and sort harvested grapes, sorting rollers permit sorted berries to pass through and also removes leaf stems and other waste from variable screen sorting table	https://pellen.com.au/



Fig. 7 Self-propelled grape harvesters; **a**) Gregoire G7.200 (<https://www.gregoire.fr/en-oc/>); **b**) ERO-Grapeliner 6000 (<http://www.ero-viti.com/>)



Fig. 8 Towed-type grape harvesters; **a**) G3.220 (<https://www.gregoire.fr/en-oc/>); **b**) Grapes'Line (<https://pellenc.com/au/>)

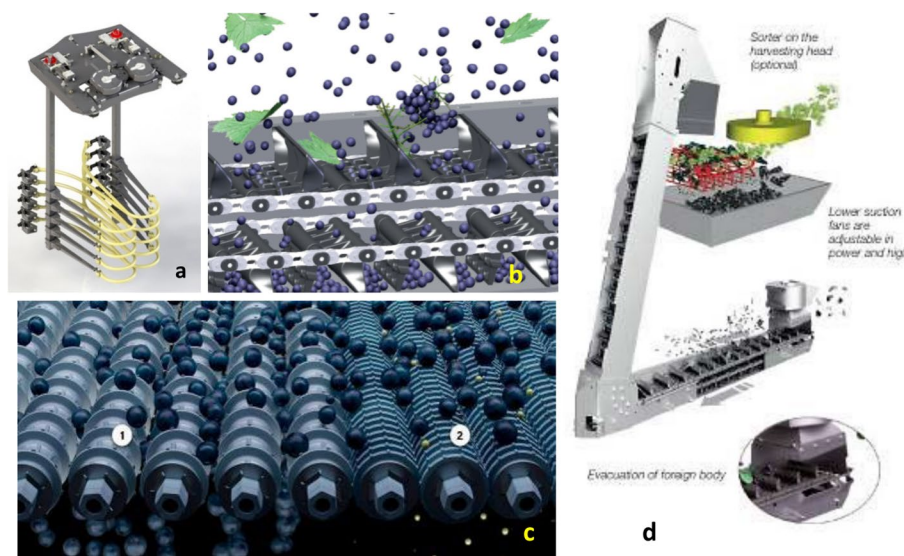


Fig. 9 Component of mechanical grape harvester; **a**) harvesting arms; **b**) linear berry separator de-stemmer; **c**) screen rollers; **d**) Sorting and cleaning system (Source: <https://pellenc.com/>)

5.2 Automated grape harvesters

It is well established that grape quality is strongly influenced by viticultural practices such as defoliation, lateral shoot removal, and green harvesting [81]. For high-value crops like wine grapes, canopy management along with pre-harvest, harvest, and post-harvest operations plays a significant role in determining the final wine quality. Agrobots are increasingly expected to support modern viticulture by reducing labor requirements and performing these operations with a level of precision comparable to that of skilled workers [82]. Jiang et al. [83] developed a dual-arm rapid grape-harvesting robot to overcome the low efficiency and high fruit damage seen in multi-joint robotic harvesters (Fig. 10). The system incorporates several high-speed technologies, including a sequential mirroring method for deciding harvest order, a “one-eye–dual-arm” visual servo system, optimized dual-arm coordination, and an enhanced visual end-effector suited for natural field conditions. Field tests showed an average harvesting cycle of 9 s per bunch, with an 88% identification rate and 83% harvesting success rate significantly outperforming existing grape-harvesting robots. Vrochidou et al. [82] presented integrated system architecture of an Autonomous Robot for Grape harvesting (ARG) consisting of three interdependent units namely an aerial unit, a remote-control unit and the ARG ground unit specially built to carry out three viticultural operations, namely

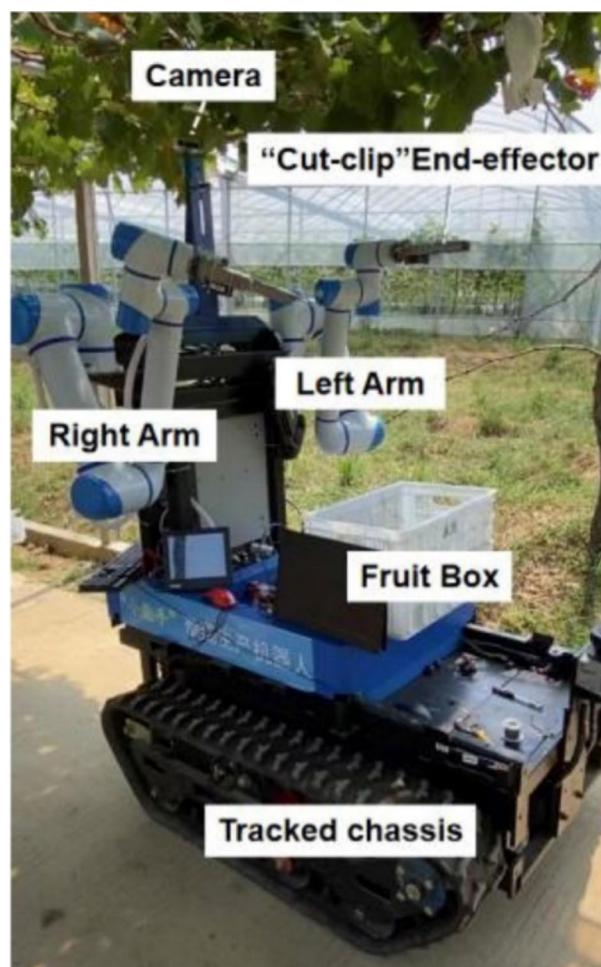


Fig. 10 Dual-arm rapid grape-harvesting robot [83]

harvest, green harvest and defoliation (Fig. 11). Lytridis et al. [84] demonstrated cooperative grape harvesting task involving two heterogeneous robots, where one robot (i.e., the expert) is assigned the grape harvesting task, whereas the second robot (i.e., the helper) is tasked with supporting the harvesting task by carrying the harvested grapes (Fig. 12). The proposed cooperative harvesting methodology ensures safe and effective interactions between the robots.

Agrobots for grape harvesting are still in their early stages of development, and their applications are expected to expand steadily as new technologies along with the required hardware mature. Outlining detailed design principles and system architectures for these robotic harvesters is essential for identifying the key challenges that researchers must address. Highlighting the technical hurdles, different design options, and alternative approaches will support the transfer of advanced robotic techniques for grapes harvesting. Table 7 summarizes how these technologies compare with conventional practices in terms of resource savings and overall efficiency.

Once harvesting is completed, vineyards enter a renewal phase where pruning and residue handling become essential for maintaining field hygiene and preparing vines for the next season. Effective management of post-harvest residues is therefore a critical step toward sustaining vineyard health and long-term productivity.



Fig. 11 Autonomous grape-harvester robot [82]



Fig. 12 Helper robot followed by expert robot, ready to support harvesting [84]

Table 7 Comparative evaluation of conventional vs. emerging harvesting technologies in vineyards (Source: Authors’ synthesis based on reviewed literature)

Parameter	Manual harvesting	Advanced systems
Labor requirement	Very high	Low-moderate
Fruit damage	Low	Moderate
Speed	Low	High
Selectivity	High	High (AI-enabled)
Initial cost	Low	High
Long-term cost	High	Low–moderate
Suitability	Small vineyards	Large vineyards

6 Plant residue management

Post-pruning residue management is an essential but often overlooked component of vineyard operations. Grapevine cultivation generates substantial biomass in the form of pruning residues, typically produced during the dormant season and influenced by regional climatic conditions and cultivation practices [85, 86]. Pruning methods vary and include pre-pruning, spur pruning, cane pruning, Guyot pruning, box pruning (Fig. 13b), head, and cordon training systems. The choice of pruning method depends on labor availability, mechanization level, and the specific vine architecture. Tools used range from hand pruners, loppers, and pruning saws to mechanical pruners with manual finishing (Fig. 13a), pole pruners, shoot removers (Fig. 13c), and advanced pruning machines.

Mechanized pruning significantly improves operational efficiency, reducing time to 4.56 h/ha compared to 71–79 h/ha for manual pruning [87]. Moreover, canopy management operations such as leaf removal (Fig. 13d) are essential to ensure adequate exposure of grape clusters for subsequent treatments. Vineyard pruning residues typically range from 1,850 to 5,360 kg/ha depending on the grape variety, vine age, climate, and agronomic practices [88, 89].

Traditionally, these residues are burned to prevent the spread of pathogens from infected vines to healthy shoots [90]. However, alternative sustainable practices such as composting [91], and bioenergy production are increasingly gaining traction. Vineyard

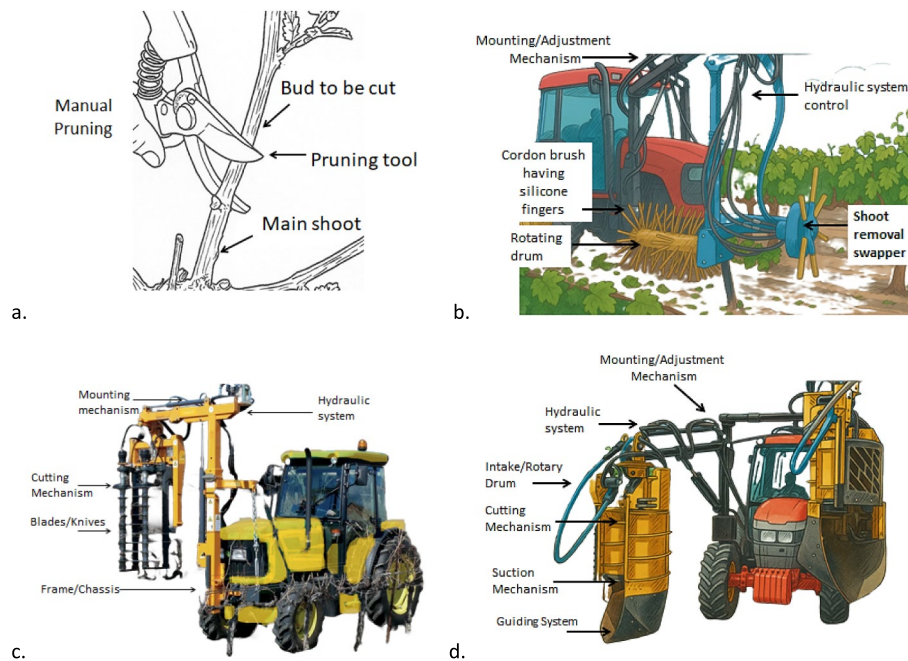


Fig. 13 **a** Mechanical pruning with manual finishing [109], **b** Box pruning operation, **c** A shoot removing machinery equipped with cordon brush having silicone fingers on a rotating drum and the shoot removal swapper in the front **d** A suck-and-cut type Fruit-zone leaf removal machine [85]

prunings represent a valuable bioenergy resource, with an energy potential ranging from 13.67 to 19.20 MJ/kg [92–94]. Mechanized systems enable efficient collection, processing, and transportation of pruning residues for bioenergy production [95, 96]. Some of the residue management techniques was summarized in Table 8.

6.1 Mulching, in-situ management, and chipping

Mulching vineyard residues can enhance soil organic matter, improve water retention, and positively influence grape juice quality. To support this, Adamchuk et al. [90] developed a pick-up wood chopper (Fig. 14a) that collects pruned residues using a pick-up mechanism, feeds them into a chopping chamber, and spreads the mulch over the vineyard floor. KUHN Agricultural Machinery [97] offers various shredders suited for row spacing from 960 to 2,090 mm, with offset widths ranging from 1,080 to 2,070 mm, requiring power inputs between 26 and 48 kW. Ongoren and Sessiz [98] evaluated vineyard shoot shredders and reported that blade rotational speed significantly influenced fuel consumption, ranging from 0.918 to 1.535 kg/h for a 15 hp shredder. Commercial reversible-blade mulchers (Fig. 14b), suitable for 90–140 hp tractors, can process residues up to 50 mm in diameter [99]. For improved in-situ decomposition, pulverization of mulched residues can be achieved using disc harrows or rotavators in successive passes. To recover residues as chips, mechanized units such as the MAREV Alba 150 (Fig. 14c) or PC 50 chipper can be used, both of which can be operated with 50 kW tractors at a fuel consumption of approximately 3.64 L/h [100, 101]. Utilization of these chips in winery boilers can reduce fuel and transportation costs by 60% and cut carbon emissions by 98% during transport, offering an economically and environmentally viable solution [102]. Additionally, chipping enables integration into circular economy models via pellet production, biochar, or syngas conversion [103].

Table 8 Summary on pruning residue management in vineyards

Method/technology	Details/ working principle	Advantages	Drawbacks	References
Mulching	Pick up wood chopper collects pruned grapevine residue from ground using pick-up attachment, and convey the material to chopping chamber and spread from rear end of machine	Suitable for in-situ management; works at low power consumption about 15 kW	–	[90]
	Collects pruned vineyard residue followed by shredding and mulching	Suitable for wide range of spacing and offset width; designed for vineyard residue management	–	[97]
	Tractor operated machine having hydraulically powered pick up roller which convey the residue to reversible blade for mulching	Uniform sized residue mulching	Suitable for tractors of higher power (90 to 140 hp)	[99]
Chipping	Tractor operated pruning harvester which pick up residue convey it to chipper and store it in attached bin	Reduces transport cost and manpower required to collect the chips	–	[101, 118]
	Pruning residue harvester-chipper and continuously stores chips in the attached bag	It is reduces cost of bin or trolley; reduces transport and laborers cost	–	[100, 108]
Baling	Modified baler for pruning residue	High field capacity (0.615 ha/h) with 31.3% of losses; reduce manpower by 50%	–	[104]
	Tractor operated square and round balers for baling of pruning residue	Round balers have higher densification and productivity than square balers	Square balers required higher turning time	[105]
	Tractor operated round baler pick up residue and produce round bales and drop it on the ground	Higher field capacity (1.25 ha/h) and reduced losses	–	[106]
	Tractor operated round baler can pick up residue, produce bales and also have optional accumulator to store bales up to 8 number during operation	Reduced stoppage time required for discharging bales and hence increases its field capacity	–	[107]

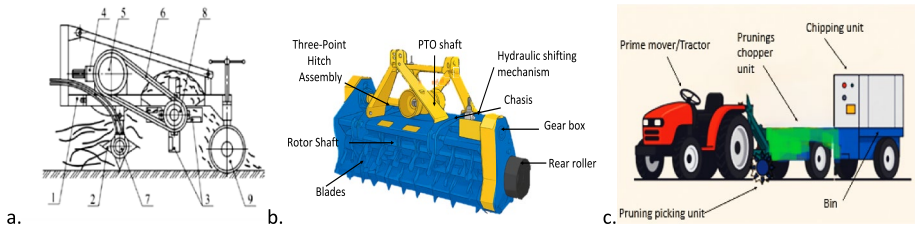


Fig. 14 **a** Schematic diagram of the grape vine pruning residue pick up chopper (1-frame; 2-pick-up system; 3-chopping chamber; 4,5-drive and intermediate gear; 6-belt; 7- hydraulic motor; 8- clutch for chopping unit; 9-gauge wheel [90]; **b** Reversible blades mulcher [55]; **c** Pruning harvester with bin [101]

6.2 Baling

Baling is an increasingly adopted method for collecting pruning residues efficiently. Modified balers such as the Lerda T110 (Fig. 15a) have achieved field capacities of 0.615 ha/h with a 31.3% reduction in labor input, although residue losses can reach up to 31.3% [104]. Silvestri et al. [105] compared square balers (Lerda 900 L) and round balers (CAEB MP 400 S), both powered by 40 kW tractors, and found round balers to be more productive due to reduced turning times and better compaction.

Another study on the PRB 1.75 baler (Fig. 15b) recorded a field capacity of 1.25 ha/h and residue losses of 24.3% [106]. CAEB International [107] offers balers for different row spacing configurations (Quickpower 1230, 930, and 730), compatible with 850–1,600 mm spacing. Some models (Fig. 15c) are equipped with transporters capable of storing 4–8 bales, allowing uninterrupted collection over distances up to 240 m. The average bale weight is around 27.7 kg with a density of 367.6 kg/m³ [108]. For smaller vineyards, mechanized systems that produce compact (450 mm) round bales, allow natural drying in stacks, and later chip the biomass using a PTO-powered mill have proven effective [108]. These systems reduce handling time and enable seasonal stockpiling of pruned biomass for year-round energy use. Considering the adverse environmental and health impacts of open burning, alternative residue management technologies such as shredders, mulchers, and balers offer promising sustainable pathways. Machines with storage bins or conveyors minimize power consumption while enabling the residue's reuse as mulch, compost, biofuel, or input for value-added products. Among these, round balers with transport attachments have demonstrated high efficiency and cost-effectiveness, reducing reliance on external wood pellets and transport logistics. Adoption of these mechanized practices represents a significant step toward sustainable and circular vineyard management.

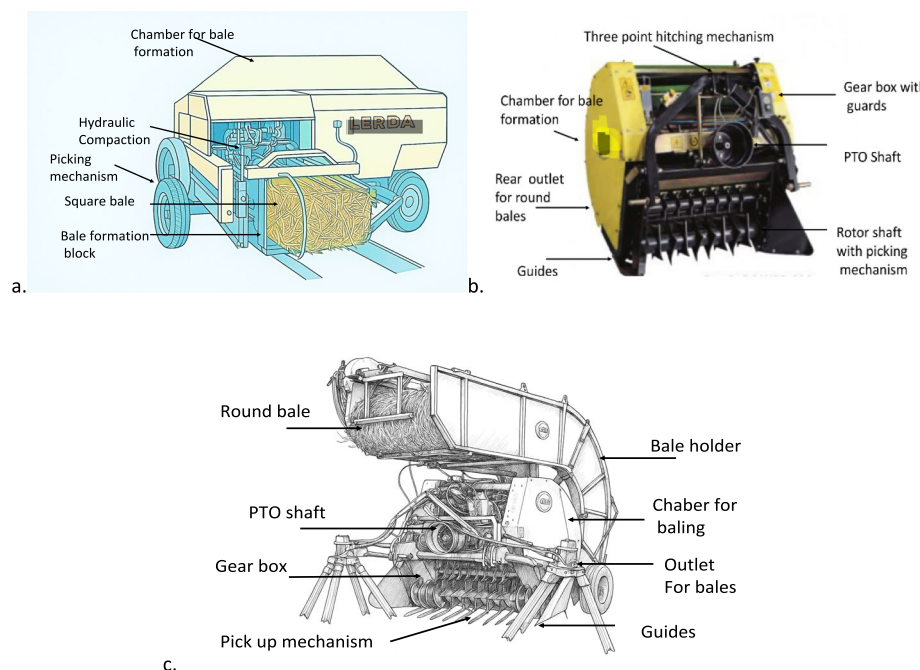


Fig. 15 **a** Square baler (Lerda 900 L); **b** Round baler [106] **c** Round baler with transporter/accumulator having capacity of 8 bales [107]

Table 9 Comparative evaluation of conventional vs. emerging harvesting technologies in vineyards

Parameter	Conventional residue practices	Modern mechanized/automated systems
Labor requirement	High (manual collection & hauling)	Low (shredders, automated collectors)
Environmental impact	High (burning, smoke, nutrient loss)	Low (mulching, biomass recycling)
Disease suppression	Inconsistent	High (fine shredding reduces inoculum)
Operational efficiency	Slow	Fast and uniform
Equipment cost	Low initial	Moderate-high
Soil health impact	Limited	Improved due to organic matter incorporation
Suitability	Small farms, low mechanization	Medium-large vineyards; tech-ready farms

Table 9 provides a comparative evaluation of these technologies against conventional approaches, with emphasis on resource savings and improvements in operational efficiency.

Although significant progress has been made across all stages of vineyard management from nutrient application and plant protection to canopy operations, harvesting, and residue handling the adoption and impact of these technologies are shaped by broader structural challenges. Understanding these cross-cutting limitations and identifying opportunities for advancement are essential for guiding the future direction of viticulture, as discussed in the following section.

7 Challenges and future prospects

7.1 Technical challenges

The adoption of advanced mechanization and precision technologies in grape vineyards is constrained by several technical limitations. Current sensor-based spraying, fertigation systems, and canopy monitoring tools require higher accuracy under variable environmental conditions such as fluctuating light, humidity, and dense canopy structures. Many autonomous systems rely heavily on stable GNSS signals, which may be unreliable in hilly or obstructed vineyards. Compatibility issues between modern sensors and older machinery, high maintenance requirements, and limited durability of electronics under field conditions further restrict adoption. Continued improvements in AI algorithms, multi-sensor fusion, rugged field hardware, and low-power autonomous platforms are essential to overcome these technical barriers.

7.2 Economic constraints

Despite offering significant agronomic and labor-saving advantages, advanced vineyard technologies involve substantial capital investment. Precision sprayers, AI-enabled monitoring systems, and robotic harvesters remain unaffordable for many small and medium growers. Operational costs including repair, calibration, software updates, and the need for skilled operators add further financial burden. Limited access to credit, insufficient subsidies, and lack of custom-hiring centers exacerbate economic constraints. Economic feasibility studies, cost–benefit analyses, and cooperative machinery-sharing models will be crucial in making mechanization more accessible.

7.3 Barriers to adoption

Multiple structural, social, and policy-related challenges hinder the widespread adoption of modern vineyard technologies. One of the most critical constraints is the high initial investment required for autonomous platforms, advanced sprayers, AI-based monitoring systems, and other precision tools, making them inaccessible for many small and

medium growers. Adoption is further limited by inadequate technical support and weak service networks, particularly in developing or remote grape-producing regions where skilled technicians and maintenance facilities are scarce. Low levels of digital literacy also present significant obstacles, as many farmers lack familiarity with data interpretation, sensor interfaces, and software-driven decision-support platforms. Vineyard fragmentation adds another challenge, as small and irregular landholdings reduce the efficiency and economic viability of using large or sophisticated machinery. Policy limitations such as insufficient subsidy mechanisms, weak institutional incentives, and limited recognition of precision viticulture within government programs also restrict technological uptake. In addition, the lack of awareness and structured training programs means many growers remain uncertain about the potential benefits of automation, sensing systems, and AI-driven tools. Finally, concerns regarding the reliability of emerging technologies persist due to limited field validation across diverse vineyard environments. Addressing these barriers will require coordinated efforts involving researchers, manufacturers, policymakers, extension agencies, and farmer organizations to build supportive infrastructure, improve training, and enhance confidence in modern viticulture technologies.

7.4 Future prospects

The future research directions outlined in this section are derived from the research gaps identified through the literature synthesis. These include the lack of integrated system-level assessments, limited comparative evaluation of emerging technologies, and insufficient understanding of cross-cutting barriers to adoption. Accordingly, future research should focus on addressing these key limitations through the following priority areas.

To address the identified gap in site-specific and data-driven nutrient management, future research should emphasize the development and adoption of advanced precision fertilization tools and data-driven nutrient management systems. The development of multi-sensor feedback platforms, AI-enabled variable-rate applicators, and UAV-based nutrient monitoring systems will enable real-time assessment of crop nutritional needs. Autonomous ground robots equipped with nutrient sensors can support site-specific micro-dosing, while improved subsurface injectors and side-band applicators will ensure targeted delivery to the active root zone. Integrating soil, leaf, weather, moisture, and growth-stage data through advanced machine-learning models will further refine nutrient scheduling and enhance fertilizer use efficiency.

7.4.1 Precision spraying and chemical use reduction

In response to the gap in efficient and targeted agrochemical application, future research should focus on precision spraying technologies. Machine vision-guided sprayers and sensor-based platforms allow site-specific chemical application, reducing ecological impact while improving efficacy. Combining selective chemical control methods with mechanical weed management systems offers a sustainable approach that reduces both manual labor dependence and environmental damage. Continued research should focus on creating robust and scalable tools for real-time canopy characterization and dynamic spray control to minimize chemical wastage.

7.4.2 Mechanization of intercultural operations

Full mechanisation of intercultural practices, such as shoot thinning, berry thinning, leaf removal, and bunch positioning, requires modifications to the trellis architecture. Future vineyard systems should be designed to be compatible with robotic tools equipped with machine vision, enabling selective and high-precision execution of these labor-intensive tasks. These technologies can provide higher accuracy and consistency compared to manual methods, particularly for table grape production.

7.4.3 Mechanized and robotic harvesting

To overcome limitations related to labor dependency and scalability, future research should focus on mechanized and robotic harvesting solutions. The need for time-efficient and labor-saving harvesting solutions reinforces the adoption of self-propelled and tractor-mounted grape harvesters, especially in large commercial vineyards. Future research must address issues related to fruit quality, detachment efficiency, and mechanical damage. The integration of modern fruit detection algorithms, multispectral imaging, and spatial mapping tools will help optimize harvest timing and reduce damage. Autonomous robotic platforms capable of navigating vineyard rows may eventually enable real-time data collection, yield estimation, and selective harvesting, supporting comprehensive site-specific decisions.

7.4.4 Integrated smart viticulture systems

The long-term vision for vineyard technology revolves around seamless integration of autonomous robots, sensor networks, remote sensing tools, and AI-driven decision-support systems. These systems will facilitate continuous monitoring of canopy, soil, and climatic conditions and support real-time management of irrigation, fertilization, pest control, and harvesting. Coupled with policy support, training programs, and cooperative machinery-sharing models, these innovations have the potential to make advanced mechanization accessible to small and medium vineyard owners, promoting sustainable and efficient grape production.

Addressing these research priorities will help bridge the gaps identified in current literature and support the transition toward sustainable and technology-driven viticulture systems.

8 Conclusions

Mechanization and precision agriculture technologies are rapidly transforming global viticulture, offering substantial opportunities to improve efficiency, reduce labor dependence, enhance fruit quality, and minimize environmental impacts. This review synthesizes the full spectrum of vineyard operations—from nutrient management and plant protection to canopy operations, harvesting, and post-pruning residue handling—and highlights both the advancements achieved and the persistent gaps that remain. Across all operational domains, emerging tools such as sensor-integrated fertigation systems, AI- and machine vision-based sprayers, robotic canopy manipulators, autonomous harvesting platforms, and mechanized residue processors demonstrate clear advantages over conventional approaches. These technologies collectively offer 20–45% input savings, improved uniformity, enhanced worker safety, and greater resilience to labor shortages. However, adoption remains uneven, particularly in fragmented and

resource-limited vineyards, due to high initial investment, limited technical support, digital literacy constraints, and inadequate policy incentives.

The analysis also underscores the need for integrated, multi-sensor decision support systems capable of combining soil, canopy, weather, and crop phenology data to guide precision interventions across the vineyard lifecycle. Further research is required to develop low-cost, scalable versions of emerging tools, enhance the robustness of AI models under diverse conditions, and design mechanization-friendly trellis structures suited for both commercial and smallholder systems.

Overall, the future of grape production will be shaped by continued advancements in sensing, automation, robotics, data analytics, and electrification. A coordinated effort among researchers, equipment manufacturers, policymakers, and growers is essential to accelerate the transition toward smart, sustainable, and resilient viticulture systems that can meet the increasing global demand while safeguarding environmental and economic sustainability. This review provides a comprehensive foundation for guiding future innovation, investment, and adoption strategies across the viticulture sector.

Author contributions

All authors have equally contributed to the preparation of the manuscript. The first draft of the manuscript was written by [A.K., C.P., D. T., S. J., A.P., A. G., Y. V., D. G.] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

No funding was received for conducting this research.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 17 June 2025 / Accepted: 1 April 2026

Published online: 29 April 2026

References

1. OIV. Statistical report on world vitiviniculture, 2021. Retrive on May 2025
2. FAO (Food and Agriculture Organization of the United Nations) FAOSTAT: crops and livestock products Grapes. 2020. Retrieved from <http://www.fao.org/faostat>
3. Anderson K, Pinilla V. Annual database of global wine markets, 1835 to 2016. University of Adelaide Press, 2020. <https://doi.org/10.20851/wine-data-2020>
4. NHB. National Horticulture Board. Indian horticulture database 2019. Ministry of agriculture and farmers welfare, Government of India, 2019. Retrieved from <http://nhb.gov.in/>
5. Jobbágy J, Koloman K, Schmidt A, Krizan M, Urbanovicova O. Evaluation of the mechanized harvest of grapes with regards to harvest losses and economical aspects. *Agron Res.* 2018;16(2):426–42. <https://doi.org/10.15159/AR.18.056>.
6. Torregrosa A, Verdu AMC, Company RS, Ortiz C. Mechatronic solutions for the automation of canopy management in vineyards. *Span J Agric Res.* 2017;15(1):e0203. <https://doi.org/10.5424/sjar/2017151-9988>.
7. Proffitt T, Malcolm AA. Protocol for precision viticulture in Australia. Australia: CSIRO and Grape and Wine Research and Development Corporation (GWRDC); 2005.
8. Romero Azorín P, García García J. The productive, economic, and social efficiency of vineyards using combined drought-tolerant rootstocks and efficient low water volume deficit irrigation techniques under Mediterranean semiarid conditions. *Sustainability.* 2020;12(5):1930. <https://doi.org/10.3390/su12051930>.
9. Khadatkar A, Sawant CP, Thorat D, et al. A comprehensive review on grapes (*Vitis* spp.) cultivation and its crop management. *Discov Agric.* 2025;3:9. <https://doi.org/10.1007/s44279-025-00162-2>.
10. Imran. Integration of organic, inorganic and bio fertilizer, improve maize-wheat system productivity and soil nutrients. *J Plant Nutr.* 2024;47(15):2494–510.

11. Chivenge P, Zingore S, Ezui KS, Njoroge S, Bunquin MA, Dobermann A, et al. Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crop Res.* 2022;281:108503.
12. Jyoti B, Thorat DS, Singh KP, Kumar M, Magar A, Parmar BS. Design and development of site-specific grape vineyard fertilizer applicator prototype. *J Sci Ind Res.* 2022;81:402–7.
13. Sawant CP, Jyoti B, Gaikwad BB, Gaikwad N, Kumar N, Kumar M. Optimization of operational parameters of site-specific pesticide spray module for young pomegranate orchards using RSM and RBFNN-PSO techniques. *J Biosyst Eng.* 2023;48:225–41. <https://doi.org/10.1007/s42853-023-00185>.
14. IndiaAgroNet. Tropical & sub-tropical fruits: grapes, 2020. Available on <https://www.indiaagronet.com/horticulture/CONTENTS/grapes.HTM>. Retrieved on April 2025
15. Shikhamany SD. Grape production in India, 2018. Retrieved in June 2024. Available on <http://www.fao.org/3/x6897e/x6897e06.htm#TopOfPage>
16. Pennington T, Reiff JM, Theiss K, Entling MH, Hoffmann C. Reduced fungicide applications improve insect pest control in grapevine. *Biocontrol.* 2018;63:687–95. <https://doi.org/10.1007/s10526-018-9896-2>.
17. Petrot M, Dhananjayan V, Jayakumar S, Ravichandran B. Conventional methods of pesticide application in agricultural fields and fate of the pesticides in the environment and human health. In: *Controlled release of pesticides for sustainable agriculture*. Berlin: Springer; 2016. p. 1–39.
18. Azghadi MR, Olsen A, Wood J, Saleh A, Calvert B, Granshaw T, et al. Precision robotic spot-spraying: reducing herbicide use and enhancing environmental outcomes in sugarcane. *Comput Electron Agric.* 2025;235:110365.
19. Hussein FA, Wafaa MH, Hamed ME, Eman AA. Safe methods for weed control in fruit crops: challenges, and opportunities: review. *Der Pharm Lett.* 2016;8(5):325–39.
20. Khadatkar A, Sujit PB, Agarwal R, Viswanath K, Sawant CP, Magar AP, et al. WeeRo: design, development and application of a remotely controlled robotic weeder for mechanical weeding in row crops for sustainable crop production. *Results Eng.* 2025. <https://doi.org/10.1016/j.rineng.2025.105202>.
21. Bochtis DD, Sørensen CGC, Busato P. Advances in agricultural machinery management: a review. *Biosys Eng.* 2014;126:69–81.
22. Maghsoudi H, Minaei S, Ghobadian B, Masoudi H. Ultrasonic sensing of pistachio canopy for low-volume precision spraying. *Comput Electr Agric.* 2015;112:149–60.
23. Xing Y, Wang X. Precise application of water and fertilizer to crops: challenges and opportunities. *Front Plant Sci.* 2024;15:1444560. <https://doi.org/10.3389/fpls.2024.1444560>.
24. Cristescu AC, Popa L, Ștefan V, Rotaru A, Anghel Ț A, Zaița A, et al. Study on new mechanized harvesting technologies in vineyards. *Acta Tech Corviniensis Bull Eng Tome XII Fasc.* 2019;12:39.
25. Morris JR. Commercialization of the Morris-Oldridge Vineyards mechanization systems, Justin R. Morris Vineyard mechanization. *Symposium proceedings-midwest grape and wine conference*, 2008, pp 9–30, Osage Beach, Missouri/USA
26. Tardáguila J, Diago MP, Martínez de Toda F, Poni S. On-the-go assessment of vineyard canopy porosity, bunch and leaf exposure by image analysis. *Aust J Grape Wine Res.* 2010;16(2):209–15. <https://doi.org/10.1111/j.1755-0238.2009.00087.x>.
27. Berenstein R, Shahar OB, Shapiro A. Grape clusters and foliage detection algorithms for autonomous selective vineyard sprayer. *Intelli Serv Robot.* 2010;3(4):233–43. <https://doi.org/10.1007/s11370-010-0078-z>.
28. Brainy A, Smith J, Lee K. A perspective study for the assessment of field robots in agriculture: an enhanced fuzzy MADM approach. *Comput Electron Agric.* 2023;214:107000. <https://doi.org/10.1016/j.compag.2023.108296>.
29. Foglia MM, Reina G. Agricultural robot for radicchio harvesting. *J Field Robot.* 2006;23:363–77.
30. Scholz M, Seele-Dilbat C, Engelmann RA, Kasperidus HD, Kirsten F, Herkerlath-Bley A, Vieweg M. Die Elster-Luppe-Aue eine wertvolle Auenlandschaft: Ergebnisse der wissenschaftlichen Begleitung aus dem Projekt Lebendige Luppe. *UFZ-Bericht 2/2022*. <https://www.researchgate.net/publication/366617044>
31. Wang H, Wang X, Liu C, Shi X, Ji X, Wang S, et al. Nutrient diagnosis and precise fertilization model construction of ‘87-1’ grape (*Vitis vinifera* L.) cultivated in a facility. *Plants Basel.* 2025;14(21):3345. <https://doi.org/10.3390/plants14213345>.
32. Keller M. *The science of Grapevines: anatomy and physiology*. 2nd ed. London: Academic Press; 2020.
33. Christensen LP. Fertilization and nutrition. In: *Wine grape production guide for eastern North America*. New York: Cornell University Press; 2020. p. 145–66.
34. Khadatkar A, Sawant CP, Magar AP, Modi RU. Development and application of a tractor-operated side dispensing type farmyard manure applicator for organic fertilizer application in vineyards. *Agric Res.* 2024;13(1):160–8.
35. Serrano J, Silva J, Shahidian S, Silva LL, Sousa A, Baptista F. Differential vineyard fertilizer management based on nutrients spatio-temporal variability. *J Soil Sci Plant Nutr.* 2017;17(1):46–61.
36. Sun J, Chen Z, Song R, Fan S, Han X, Zhang C, et al. An intelligent self-propelled double-row orchard trenching and fertilizing machine: modeling, evaluation, and application. *Comput Electron Agric.* 2025;229:109818.
37. Adsule PG, Banerjee K, Jadhav VT. Nutrient requirements and management in table grape orchards. *Indian J Hortic.* 2013;70(3):401–5.
38. Liufang S, Gang Y, Xingzhao S. Design of ditching and fertilization machine special for vineyard. *Agric Mech Res.* 2012;11:22.
39. Ye Q, Xie F, Sun S, Yang G, Yang W, Li Z, et al. Development of vineyard ditcher with reversal twin rotary tillage wheels. *Trans Chin Soc Agric.* 2013;29(3):9–15.
40. L X, C L, Y W. Gas explosion sub-soiling and liquid fertilizer injection equipment for orchards. *J Agric Eng Res.* 2017;9(2):98–104.
41. Grzebisz W. Site-specific nutrient management. *Agronomy.* 2021;11(4):752. <https://doi.org/10.3390/agronomy11040752>.
42. Shamshiri RR, Kalantari F, Ting KC, et al. Advances in greenhouse automation and controlled environment agriculture: a transition to plant factories and urban agriculture. *Int J Agric Biol Eng.* 2018;11(1):1–22.
43. TNAU Agritech Portal. Horticulture fruit crops: fertilizer schedule-grapes, 2020. Available on http://agritech.tnau.ac.in/horticulture/horti_fruits_fert_grapes.html. Retrieved on June 2024
44. J C, Y Z, Y L. Design of orchard-specific organic ditching and fertilization equipment. *Int J Agric Biol Eng.* 2018;11(5):64–70.
45. Gioelli F, Balsari P, Dinuccio E, Airolidi G. Band application of slurry in orchards using a prototype spreader with an automatic rate controller. *Biosys Eng.* 2014;121:130–8.
46. Balsari P, Dinuccio E, Gioelli F, Airolidi G. Band spreader for the application of slurry solid fractions to orchards. *Biosys Eng.* 2015;136:69–76.

47. Husk B. Root zone biochar application with grapevines. Bio energy lists: biochar mailing lists, 2013. Available on <http://bioc-har.bioenergylists.org/taxonomy/term/1162>
48. Tamagnone M. Development of a combined equipment for sustainable weed control in vineyard. *J Agric Eng.* 2013;44(2):45–54.
49. Celen IH, Arin S, Durgut MR. The effect of the air blast sprayer speed on the chemical distribution in vineyard. *Pak J Biol Sci.* 2008;11:1472–6.
50. Anonymous. AICRP on FIM report on plant protection equipment, 2017. Retrieved on April 2025 from <https://aicrp.icar.gov.in/fim/salient-achievements/plant-protection-equipments/>
51. Mitraweb. www.info@mitraweb.in. Retrieved on April, 2020
52. Pergher G, Zucchiatti N. Influence of canopy development in the vineyard on spray deposition from a tunnel sprayer. *J Agri Eng.* 2018;49(801):164–73.
53. X H, A Z, Y L, J S. Precision orchard sprayer based on automatically infrared target detecting and electrostatic spraying techniques. *Int J Agric Biol Eng.* 2011;4:35–40. <https://doi.org/10.3965/jissn.1934-6344.2011.01.035-040>.
54. Salcedo R, Llop J, Campos J, Costas M, Gallart M, Ortega P, et al. Evaluation of leaf deposit quality between electrostatic and conventional multi-row sprayers in a trellised vineyard. *Crop Prot.* 2020;127:1–10.
55. Zhang Z, Wang X, Lai Q, Zhang Z. Review of variable-rate sprayer applications based on real-time sensor technologies. In: Hussmann S, editor. *Automation in agriculture: securing food supplies for future generations*. InTech; 2018. p. 53–79.
56. Gil E, Llorens J, Llop J. Variable rate sprayer. Part 2 – vineyard prototype: design, implementation, and validation. *Comput Electr Agric.* 2013;95(Supplement C):136–50. <https://doi.org/10.1016/j.compag.2013.02.010>.
57. Balsari P, Tamagnone M. An ultrasonic airblast sprayer. In: *Proceedings of Europe agricultural engineering international conference of agricultural engineering*, 1998; 585–586, Oslo, Norway.
58. Esau T, Zaman Q, Chang Y, Schumann A, Percival D, Farooque A. Spot-application of fungicide for wild blueberry using an automated prototype variable rate sprayer. *Precision Ag.* 2014;15:147–61.
59. Molto E, Martn B, Gutierrez A. Pesticide loss reduction by automatic adaptation of spraying on globular trees. *J Agric Eng Res.* 2001;78:35–41.
60. Cabre TP, Landers A. Precision spraying in the orchard and vineyard: measuring canopy density. *N Y Fruit Q.* 2014;22(4):15–7.
61. Sun Z, Zhan P, Tong H, Wang Z, Bai X, Zhao Y, et al. Design and field evaluation of a stratified variable spraying system in vineyards. *Smart Agric Technol.* 2025;12:101422. <https://doi.org/10.1016/j.jatech.2025.101422>.
62. Baltazar AR, Dos Santos FN, De Sousa ML, et al. 2D LiDAR-based system for canopy sensing in smart spraying applications. *IEEE Access.* 2023;11:1. <https://doi.org/10.1109/ACCESS.2023.3271973>.
63. Gil E, Escola A, Rosell J. Variable rate application of plant protection products in vineyard using ultrasonic sensors. *Crop Prot.* 2007;26(8):1287–97.
64. Khot LR, Ehsani R, Albrigo G, Larbi PA, Landers A, Campoy J. Air-assisted sprayer adapted for precision horticulture: spray patterns and deposition assessments in small-sized citrus canopies. *Biosyst Eng.* 2012;113:76–85.
65. Solanelles F, Escola A, Planas S. An electronic control system for pesticide application proportional to the canopy width of tree crops. *Biosyst Eng.* 2006;95(4):473–81. <https://doi.org/10.1016/j.biosystemseng.2006.08.004>.
66. Zaidner G, Shapiro A. A novel data fusion algorithm for low-cost localisation and navigation of autonomous vineyard sprayer robots. *Biosyst Eng.* 2016;146:133–48.
67. Bac CW, van Henten EJ, Hemming J, Edan Y. Harvesting robots for high-value crops: state-of-the-art review and challenges ahead. *J Field Robot.* 2014;31(6):888–911.
68. Campos J, Llop J, Gallart M, García-Ruiz F, Gras A, Salcedo R, et al. Development of canopy vigour maps using UAV for site-specific management during vineyard spraying process. *Precis Agric.* 2019;20:1136–56.
69. Tsouros DC, Bibi S, Sarigiannidis PG. A review on UAV-based applications for precision agriculture. *Information.* 2019;10(11):349.
70. Clary CD, Steinhauer RE, Frisinger JE, Pepper TE. Evaluation of machine- vs. hand-harvested Chardonnay. *Am J Enol Vitic.* 1990;41(2):176–81.
71. Pezzi F, Caprara C. Mechanical grape harvesting: investigation of the transmission of vibrations. *Biosys Eng.* 2009;103:281–6.
72. Jobbagy J, Findura P. *Mechanization of viticulture* (1st edition). Nitra: Slovak University of Agriculture in Nitra; 2013. p. 165.
73. Morris JR. Development and commercialization of a complete vineyard mechanization system. *Hort Technol.* 2007;17(4):411–20.
74. Pezzi F, Martelli R. Technical and economic evaluation of mechanical grape harvesting in flat and hill vineyards. *Trans ASABE.* 2015;58(2):297–303.
75. Vieri M, Rimediotti M, Pochi D. Mechanization in viticulture: an overview of state-of-the-art and future challenges. *J Agric Eng.* 2013;44(1):34–41.
76. Intrigliolo DS, Pérez D, García-Esparza MJ, Diago MP. Mechanical harvesting of wine grapes: effects on fruit and wine composition. *OENO One.* 2017;51(1):17–27.
77. Pezzi F. Ridurre i costi senza penalizzare la qualità del prodotto (Reduce costs without penalizing product quality). *Corriere Vinicolo (Corriere Vinicolo).* 2013;39:13–5.
78. Sun Q, Ebersole C, Wong DP, Curtis K. The impact of vineyard mechanization on grape and wine phenolics, aroma compounds, and sensory properties. *Fermentation.* 2022;8(7):318. <https://doi.org/10.3390/fermentation8070318>.
79. Novak P, Burg P. Evaluation of harvest losses within a full mechanised grape harvest. *Acta Univ Agric Silvica Mendel Brun.* 2013. <https://doi.org/10.11118/Actaun201361030751>.
80. Domingues F, Aguila JS. The cost of grape mechanical harvesting is more economical than the manual harvest? BIO web of conferences 7, 01023. In: 39th world congress of vine and wine, 2016. <https://doi.org/10.1051/bioconf/20160701023>.
81. Drenjančević M, Jukić V, Zmajčić K, Kujundžić T, Rastija V. Effects of early leaf removal on grape yield, chemical characteristics, and antioxidant activity of grape variety Cabernet Sauvignon and wine from eastern Croatia. *Acta Agric Scand B Soil Plant Sci.* 2017;67:705–11.
82. Vrochidou E, Tziridis K, Nikolaou A, Kalampokas T, Papakostas GA, Pachidis TP, et al. An autonomous grape-harvester robot: integrated system architecture. *Electronics Basel.* 2021;10(9):1056. <https://doi.org/10.3390/electronics10091056>.

83. Jiang Y, Liu J, Wang J, Li W, Peng Y, Shan H. Development of a dual-arm rapid grape-harvesting robot for horizontal trellis cultivation. *Front Plant Sci.* 2022;13:881904. <https://doi.org/10.3389/fpls.2022.881904>.
84. Lytridis C, Bazinas C, Kalathas I, Siavalas G, Tsakmakis C, Spirantis T, et al. Cooperative grape harvesting using heterogeneous autonomous robots. *Robotics Basel.* 2023;12(6):147. <https://doi.org/10.3390/robotics12060147>.
85. Kurtural SK, Fidelibus MW. Mechanization of pruning, canopy management, and harvest in winegrape vineyards. *Catalyst: discovery into practice.* Am J Enol Vitic. 2021;5(1):29–44. <https://doi.org/10.5344/catalyst.2021.20011>.
86. Poni S, Sabbatini P, Palliotti A. Facing spring frost damage in grapevine: recent developments and the role of delayed winter pruning - a review. *Am J Enol Vitic.* 2022;73(4):211–26. <https://doi.org/10.5344/ajev.2022.22011>.
87. Yazar Coskun. Current approaches in viticulture mechanization. Tekirdag Viticulture Research Institute, 2023.
88. Brito PSD, Oliveira AS, Rodrigues LF. Energy valorization of solid vines pruning by thermal gasification in a pilot plant. *Waste Biomass Valor.* 2014;5:181–7. <https://doi.org/10.1007/s12649-013-9246-7>.
89. Manzone M, Paravidino E, Bonifacino G, Balsari P. Biomass availability and quality produced by vineyard management during a period of 15 years. *Renew Energy.* 2016;99:465–71. <https://doi.org/10.1016/j.renene.2016.07.031>.
90. Adamchuk V, Bulgakov V, Skorikov N, Yezekyan T, Olt J. Developing a new design of wood chopper for grape vine and fruit tree pruning and the results of field testing. *Agron Res.* 2016;14(5):1519–29.
91. Pisciotto A, Di Lorenzo R, Novara A, Laudicina VA, Barone E, Santoro A, et al. Cover crop and pruning residue management to reduce nitrogen mineral fertilization in Mediterranean vineyards. *Agronomy Basel.* 2021;11(1):164. <https://doi.org/10.3390/Agronomy11010164>.
92. Abbaz A, de Oliveira Sousa M, Bouziane K, Soares A, and Rouboa A. Analysis of vineyard pruning residues potential as a function of syngas quality indices. *AIP Conference Proceedings* 1 September, 2023; 2849 (1): 450045. <https://doi.org/10.1063/5.0164383>.
93. Los Santos-Ortega J, Mendivil-Giro MA, Fraile-García E, Ferreiro-Cabello J. Revalorisation of vine pruning waste through the production of zero CO2 emission charcoal. *Appl Sci Basel.* 2024;14(24):11527. <https://doi.org/10.3390/app142411527>.
94. Marian G, Alexiou Ivanova T, Gudima A, Nazar B, Malai L, Marian T, et al. Biomass resources from vineyard residues for the production of densified solid biofuels in the Republic of Moldova. *Agronomy Basel.* 2024;14(10):2183. <https://doi.org/10.3390/agronomy14102183>.
95. Pizzi A, Foppa-Pedretti E, Duca D, Rossini G, Mengarelli C, Ilari A, et al. Emissions of heating appliances fuelled with agropellet produced from vine pruning residues and environmental aspects. *Renew Energy.* 2018;121:513–20. <https://doi.org/10.1016/j.renene.2018.01.064>.
96. Spinelli R, Nati C, Pari L, Mescalchin E, Magagnotti N. Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. *Appl Energy.* 2012;89(1):374–9. <https://doi.org/10.1016/j.apenergy.2011.07.049>.
97. KUHN-Agricultural Machineries. Vineyard and orchard shredder broucher, 2019. [http://www.kuhngroup.org/internet/prospectus.nsf/0/C52AB8D541B78036C1258400002DA7FB/\\$File/920749GB%20final.pdf](http://www.kuhngroup.org/internet/prospectus.nsf/0/C52AB8D541B78036C1258400002DA7FB/$File/920749GB%20final.pdf). Retrieved on May 2025.
98. Ongoren N, Sessiz A. Determination of fuel and power requirement of a branch shredder for different vineyard pruning wastes. *Int J Agric Environ Food Sci.* 2023;7(4):847–52. <https://doi.org/10.31015/jaefs.2023.4.15>.
99. Zanon Macchine Agricole. Broucher- TLK Reversible blades mulcher heavy duty with hydraulically powered pick-up roller, 2020; 1–2. Accessed on 10th May 2020 at <http://www.zanon.it/wp-content/uploads/2018/02/tlk.pdf>
100. Pari L, Suardi A, Giudice DA, Scarfone A, Santangelo E. Influence of chipping system on chipper performance and wood chip particle size obtained from peach prunings. *Biomass Bioenergy.* 2018;112:121–7. <https://doi.org/10.1016/j.biombioe.2018.01.002>.
101. Toscano G, Alfano V, Scarfone A, Pari L. Pelleting vineyard pruning at low cost with a mobile technology. *Energies.* 2018;11:2477. <https://doi.org/10.3390/en11092477>.
102. Fernandez-Puratich H, Hernandez D, Tenreiro C. Analysis of energetic performance of vine biomass residues as an alternative fuel for Chilean wine industry. *Renew Energy.* 2015;83:1260–7. <https://doi.org/10.1016/j.renene.2015.06.008>.
103. Yamane K, Yamashita S, Kitano S. Conversion of grapevine prunings to biochar and syngas using a downdraft gasifier. *Renew Energy.* 2022;188:648–56.
104. Cavalaglio G, Cotana S. Recovery of vineyards pruning residues in an agro-energetic chain. In: 14th European biomass conference and exhibition, Berlin, 2007. <https://pdfs.semanticscholar.org/cefd/e120682e4cdc31b6c6da8c6eff90d2643d.pdf>
105. Silvestri S, Cristoforetti A, Mescalchin E, Spinelli R. Recovery of pruning waste for energy use: agronomic, economic and ecological aspects. In: *Proceedings of the central European biomass conference*, Graz, Austria, 2011; 26–29.
106. Frąckowiak P, Adamczyk F, Wąchalowski G, Szaroleta M, Dyjakon A, Pari L, et al. A prototype machine for harvesting and baling of pruning residues in orchards: first test on apple orchard (*Malus Mill.*) in Poland. *J Res Appl Agric Eng.* 2016;61(3):88–93.
107. CAEB International. Quick power-round-baler for vineyard prunings and trimmings 2016. Retrieved from https://caebinternational.it/wlang1/files/QUICKPOWER_EN_12.2016.pdf on May 2024.
108. Bisagli C, Romano E. Utilization of vineyard prunings: a new mechanization system from residues harvest to chips production. *Biomass Bioenergy.* 2018;115:136–42. <https://doi.org/10.1016/j.biombioe.2018.04.008>.
109. Allegro G, Martelli R, Valentini G, Pastore C, Mazzoleni R, Pezzi F, et al. Effects of mechanical winter pruning on vine performances and management costs in a Trebbiano Romagnolo vineyard: a five-year study. *Horticulturae.* 2022;9(1):21. <https://doi.org/10.3390/horticulturae9010021>.
110. Xiaobo X, Ruihong Z, Xiang S, Yifu J, Jianfeng Z. Optimal design and experiment of 3SFBQ-500 type orchard gas explosion subsoiling and fertilizer injection machine. *Trans Chin Soc Agric Eng.* 2017;33(24):35–43.
111. Gioelli F, Dinuccio E, Balsari P, D'Angelo A. Performance evaluation of a slurry band applicator to reduce ammonia emissions in vineyards. *Biosyst Eng.* 2014;124:51–60.
112. Viret O, Siegfried W, Holliger E, Raisigl U. Comparison of spray deposits and efficacy against powdery mildew of aerial and ground-based spraying equipment in viticulture. *Crop Prot.* 2003;22:1023–32.
113. Fox RD, Derksen RC, Zhu H, Brazee RD, Svensson SA. A history of air-blast sprayer development and future prospects. *Trans ASABE.* 2008;51(2):405–10.
114. Pergher G, Petris R. A novel, air-assisted tunnel sprayer for vineyards: optimization of operational parameters and first assessment in the field. *J Agric Eng.* 2009;4:39–46.

115. Planas S, Solanelles F, Fillat A. Assessment of recycling tunnel sprayers in Mediterranean vineyards and apple orchards. *Biosyst Eng.* 2022;82(1):45–52.
116. Siegfried W, Holliger E. Application technology in fruit growing and viticulture. Report, 1996, Swiss federal research station, Wädenswill, Switzerland. Siegfried W., Raisigl U. Erste Erfahrungen mit dem JocoRecyclinggerät im Rebbau [Initial experience with the Joco recycling sprayer in vineyards]. *Schweizerische Zeitschrift für Obst- und Weinbau*, 1991; 127(6):154–160
117. Siegfried W, Holliger E. Application technology in fruit growing and viticulture. Report, 1996, Swiss federal research station, Wädenswill, Switzerland, 1996
118. Suardi A, Saia S, Alfano V, Rezaei N, Cetera P, Bergonzoli S, et al. Pruning harvesting with modular towed chipper: little effect of the machine setting and configuration on performance despite strong impact on wood chip quality. *PLoS ONE*. 2021;16(12):e0261810. <https://doi.org/10.1371/journal.pone.0261810>.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.