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High-Density Planting Systems Improve Mechanical Harvest Efficiency and Fruit Quality of Grapes

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Abstract High-density cultivation systems (HDPS) are widely adopted in grape cultivation with the aim of increasing yield, improving fruit quality, and better adapting to mechanical harvesting. This study mainly analyzed the physiological and agronomic responses of grapes under HDPS conditions, including how to optimize the canopy structure, enhance the photosynthetic effect, and the changes in fruit development. It evaluated the impact of this planting method on yield stability, sugar-acid ratio, anthocyanin content, and harvest efficiency, and discussed the integrated schemes of pruning methods and mechanized operations that are compatible with HDPS. This research provides theoretical support for achieving more precise and sustainable management of vineyards, and also offers practical references for addressing labor shortages and responding to climate change.
Keywords High-density planting; Grapevine; Fruit quality; Mechanical harvest; Precision viticulture

1 Introduction

Grapes are one of the most important cash crops in the world. Nowadays, the planting area is getting larger and larger, and the output is also constantly increasing (Liang, 2024). In recent years, due to the rising labor costs and the difficulty in finding workers, the grape industry has begun to accelerate the pace of mechanization. Harvesting by machine has become a key method to improve efficiency and reduce costs (Burg et al., 2021). To adapt to mechanical operations, the design and management methods of orchards are also constantly being adjusted. high-density planting (HDP) is now becoming increasingly common in the cultivation of many fruit trees. It is believed that it can make better use of the land, enable fruit trees to bear fruit earlier, improve fruit quality, and also facilitate machine operations (Tripathi et al., 2020).

In the past, traditional vineyards were usually planted at low density and mainly harvested by hand. This approach has many problems, such as insufficient land utilization, low yield, large differences in fruit quality, and high costs of manual management and picking (Burg et al., 2021; Keller and Mills, 2021). But if the density is not appropriate, it will also cause trouble. In vineyards with a high degree of mechanization, if the density is too high, the trees will grow too densely, the leaves will be severely shaded, the microclimate will deteriorate, and it will affect the development and quality of the fruits. However, if the density is too low, it will waste land resources and the output will not increase (Tripathi et al., 2020; Keller and Mills, 2021). Furthermore, under the traditional planting methods, machine harvesting is not very convenient, has low efficiency and high fruit loss. As a result, the income is not high (Burg et al., 2021).

This study explored the impact of high-density planting on mechanical grape harvesting and fruit quality, compared the harvesting efficiency and economic benefits under different planting densities, and also analyzed how density changes affect grape yield and quality. This research hopes to provide some scientific references for the design and management of vineyards and help the industry develop in an efficient and sustainable direction.

2 Concepts and Principles of High-Density Planting

2.1 Definition and classification of high-density systems

High-density planting means planting more fruit trees on the same plot of land. It achieves earlier fruiting, higher yield, better fruit quality and greater economic benefits by making better use of vertical and horizontal Spaces, while also maintaining soil nutrients (Tripathi et al., 2020; Manju et al., 2025). Generally speaking, based on the different densities of tree planting, high-density systems can be divided into common high-density (such as 800 to 3 000 trees per hectare) and ultra-high-density (more than 4 000 trees per hectare) (Ladaniya et al., 2020; Tripathi et al., 2020). The density level varies depending on the type and variety of fruit trees, the selection of rootstocks, management methods and planting purposes. In addition, there are many types of planting layouts, such as square planting, diagonal planting, single row, double row and cluster planting, etc. This can better adapt to different mechanization requirements and management methods (Tripathi et al., 2020; Das et al., 2023).

2.2 Historical evolution in viticulture practices

Over the past few decades, the costs of land and labor have been rising continuously, and the demand for high-yield and high-quality fruits has also been increasing. So fruit trees like grapes also began to adopt high-density planting. This approach has become a very important technique in modern orchard management (Tripathi et al., 2020; Manju et al., 2025). Traditional vineyards usually have relatively large plant and row spacings, resulting in low land utilization and difficulty in increasing yields. High-density planting, by reducing the row and plant spacing, selecting dwarf varieties or rootstocks, and combining with the technology of regulating plant growth, enables orchards to produce more per unit area and obtain profits earlier (Tripathi et al., 2020; Manju et al., 2025). This approach is also more suitable for mechanized operations, saving manpower, improving the utilization rate of resources, and making grape cultivation more efficient and intelligent (Tripathi et al., 2020).

2.3 Key agronomic parameters (spacing, row orientation, trellis design)

In high-density vineyards, key planting parameters such as plant spacing, planting direction, and twill structure will directly affect the growth of grapevines, light, ventilation effect, convenience of machine operation, and the quality of fruits (Tripathi et al., 2020; Keller and Mills, 2021; Manju et al., 2025). High density usually adopts a relatively compact planting method. For example, the plant spacing is between 0.91 and 2.5 meters, and the row spacing is between 2 and 3 meters. In this way, more grapevines can be planted in the same field (Ladaniya et al., 2020; Keller and Mills, 2021; Manju et al., 2025). However, too high a density also has problems. It can make the tree canopy too dense, which is not conducive to ventilation and light, thereby affecting fruit development and quality (Keller and Mills, 2021). Choosing the right row direction is also very important. For example, planting in the north-south direction can make the sunlight exposure more uniform, which is conducive to fruit ripening and sugar accumulation, and can also make the fruit color more attractive. In addition, the trellises commonly used in high-density orchards are also more suitable for machine harvesting, such as V-shaped, Y-shaped or horizontal trellises. These structures can better manage the tree canopy, control pests and diseases, and also facilitate mechanical operations (Tripathi et al., 2020; Manju et al., 2025).

3 Mechanical Harvesting in Viticulture

3.1 Types of mechanical harvesters and working principles

There are mainly two types of mechanical grape harvesting equipment: one is semi-hanging type, which requires a tractor to tow; Another type is self-propelled, with its own power system, which can move by itself in the orchard (Da Costa Neto et al., 2019). This type of machine usually vibrates or shakes the grapevines to make the fruits fall off, and then collects the fruits with the device inside the machine. Modern harvesters like the PELLENC 8090 Selective Process not only have highly efficient vibration systems but also can automatically separate fruits, suitable for the harvesting requirements of different plots and varieties (Figure 1) (Da Costa Neto et al., 2019; Burg et al., 2021).

3.2 Benefits and limitations of mechanical harvesting

The greatest advantage of mechanical harvesting is that it saves labor and time, and its efficiency is much higher than that of manual harvesting. It is particularly suitable for situations where there is a shortage of manpower or the orchard area is relatively large (Burg et al., 2021; Coşkun, 2023; Sanjay et al., 2024). In orchards with large-scale planting, such as those over 41.92 hectares, the cost of mechanical harvesting is significantly lower than that of manual harvesting (Aguila and Domingues, 2016; Strub et al., 2020). Moreover, many studies have found that the wines made from machine-picked grapes show little difference in taste and physicochemical indicators compared with those picked manually (Ebeler et al., 2016; Couto et al., 2022). However, mechanical harvesting is not without its drawbacks. The equipment is relatively expensive and requires regular maintenance. If used improperly, it may cause damage and dropping of grape berries, and even mix in some impurities. This situation is more likely to occur in plots with inadequate orchard management or complex terrain (Da Costa Neto et al., 2019). Mechanization also has requirements for terrain. For example, orchards with too steep slopes are not very suitable for mechanical harvesting. The cost will increase and the efficiency is difficult to guarantee (Strub et al., 2020; Sanjay et al., 2024).

(a) (b)

Figure 1 Field experiments and equipment used (Adopted from Burg et al., 2021)

Image caption: (a) Trial plots; (b) Tractor Same Frutteto3 100, trailed grape harvester Pellenc8090 SP and detailed picture of thresher mechanism (Adopted from Burg et al., 2021)

3.3 Interaction with vineyard architecture

To improve the effect of mechanical harvesting, the design of the orchard must be reasonable. Vineyards suitable for mechanical operations generally have relatively regular row and plant spacing, facilitating the passage and operation of machines (Da Costa Neto et al., 2019; Coşkun, 2023). The shape of the plot, row orientation, plant type and trellis height, all these factors will affect the harvesting efficiency and fruit damage rate. For example, regular plots and appropriate trellel heights can reduce fruit loss and make the harvest smoother (Da Costa Neto et al., 2019; Coşkun, 2023). In plots with steep slopes, mechanical operations are more difficult and costly. Even in some places, machines are completely unusable (Strub et al., 2020).

4 Integration of High-Density Systems with Mechanical Harvesting

4.1 Planting geometry and harvester compatibility

In high-density vineyards, the grapevines are planted relatively densely, which poses higher requirements for mechanical harvesting equipment. The design of row spacing and plant spacing should not only allow the machine to pass through smoothly, but also ensure that the grapevines have sufficient space to grow and the quality of the fruits should not be poor. Studies have found that if the plant spacing is too small, for example, only 0.91 meters, it will cause the grapevines to grow too vigorously and have too dense branches and leaves. This not only affects ventilation and light, but may also lead to fewer fruit clusters, smaller fruit grains, and even withering of fruit stems, and the harvest efficiency will also decline (Keller and Mills, 2021). Therefore, for mechanical harvesting to play a role in high-density planting, the row spacing and plant spacing must be selected appropriately, which not only increases the yield per unit area but also ensures the smooth operation of the machinery.

4.2 Row spacing and machine maneuverability

The efficiency of mechanical harvesting largely depends on the row spacing design of the vineyard. Although a narrower row spacing can produce more grapes, it also makes the machine more difficult to operate, reduces the operating space, and makes it easy to touch the vines and branches and damage the fruits (Da Costa Neto et al., 2019; Keller and Mills, 2021). A study compared row spacings of 2.44 meters and 2.74 meters and found that the former had a higher yield. However, being too narrow still brought problems of inconvenient mechanical harvesting, such as incomplete harvesting or more losses (Da Costa Neto et al., 2019). In addition, different types of harvesters (such as towed or self-propelled) perform differently at different row spacings. Therefore, when designing a vineyard, it is necessary to consider how to increase the yield by using high-density planting on the premise of ensuring the smooth operation of the machines.

4.3 Canopy management for efficient fruit detachment

Under high-density planting conditions, it is particularly important to manage the grape canopy well. If the branches and leaves are too dense, the middle leaves will die, ventilation will deteriorate, humidity will increase, which is not conducive to fruit ripening and will also affect the fruit drop efficiency at harvest (Keller and Mills, 2021). Adopting some effective canopy management methods, such as mechanical pruning and appropriate leaf removal, can improve ventilation and light conditions, help fruits mature more evenly, and also reduce fruit loss at harvest. In addition, some precision agriculture technologies can now be used, such as visualization tools or near-infrared spectroscopy, to detect the difficulty of fruit drop in advance and adjust the harvesting parameters, thereby further improving the harvesting efficiency and fruit quality (Bono et al., 2019).

5 Impact on Fruit Yield and Grape Quality

5.1 Effects on yield components

High-density planting will have a significant impact on the yield structure of grapes. Some studies have found that in the early stage of planting, if the plant spacing is relatively small, for example, only 0.91 meters, the yield per unit area will be relatively high. But over time, if the density is too high, it will instead cause the yield of each plant to decrease. The manifestations are that each fruit cluster becomes fewer, the number of fruit grains in each fruit cluster decreases, the weight of the fruit cluster reduces, and the fruit stalks are prone to damage, ultimately leading to a decrease in the total output (Brar and Bindra, 2015; Keller and Mills, 2021; Haque and Sakimin, 2022). In contrast, a moderate density, such as 2.0×2.0 meters, can ensure the yield per plant while also providing a decent yield per mu. It is a relatively ideal planting method (Brar and Bindra, 2015; Haque and Sakimin, 2022). In addition, excessive density can also easily cause grapevines to grow overly luxuriantly. The branches and leaves are too dense, which not only blocks light but also fails to ventilate, both of which will affect fruit development (Brar and Bindra, 2015; Keller and Mills, 2021).

5.2 Influence on soluble solids, acidity, and phenolic content

In terms of fruit quality, high-density cultivation has little impact on some key indicators, such as sugar content (soluble solids), total acid and color. Some studies have found that at different densities, the differences in sugar content, acidity and color of grape juice are not obvious (Brar and Bindra, 2015; Keller and Mills, 2021). However, some studies have pointed out that appropriately controlling the yield can actually increase the sugar content of the fruit, especially when the yield drops to a certain range, such as controlling the yield at around 1 000 kilograms per 667 square meters, the sugar content will be higher. Overall, excessive density is prone to reduce quality, while moderate density is more conducive to the balance of sugar-acid ratio and the accumulation of phenolic substances (Haque and Sakimin, 2022).

5.3 Post-harvest quality retention and storage behavior

High-density planting may also affect the storage capacity of grapes. Due to uneven fruit ripening and overly dense canolas, the microclimate in the orchard deteriorated, making the fruit stems more prone to spoilage and the fruits more likely to rot, resulting in a reduced storage capacity of grapes (Keller and Mills, 2021; Deng et al., 2024). Long-term high-density planting may also lead to a reduction in soil nutrients and a decrease in beneficial microorganisms, which will also affect the post-harvest quality and preservation time (Deng et al., 2024). Therefore, scientifically adjusting the planting density can not only improve the fruit quality at harvest, but also be conducive to extending the storage time and maintaining the market appearance of grapes (Haque and Sakimin, 2022; Deng et al., 2024).

6 Physiological and Morphological Adaptations

6.1 Vine vigor and canopy microclimate changes

High-density planting will significantly affect the growth of grapevines and the structure of their branches and leaves. When planted densely, the total leaf area and the exposed leaf area of each plot will increase, making the entire canopy thicker and denser, and there will also be more water evaporation (Keller and Mills, 2021; Kovaleva et al., 2022). However, the leaves and yield of individual grape plants may decrease. When the canopy structure changes, the microclimate will also be affected. Too dense a canopy will cause poor light and ventilation inside, which will affect fruit development and make the fruits more prone to diseases. Studies have found that the leaf mortality rate within the canopy will increase, which may be related to changes in nutrient distribution and the hot and humid microclimate (Keller and Mills, 2021). However, if the structure of branches and leaves is adjusted reasonably, such as allowing the branches to grow naturally or setting an appropriate rope height, water loss can be reduced, and the photosynthetic efficiency and yield in drought years can also be improved (Kovaleva et al., 2022).

6.2 Photosynthetic efficiency in dense plantings

High-density planting, due to the large number of leaves, will increase the overall photosynthetic capacity. However, the photosynthetic capacity of each grape plant itself may be affected (Keller and Mills, 2021). In years when water is relatively abundant, if vertical branches and ropes are set lower, it will help improve photosynthetic efficiency. However, in drought years, freely growing branches and moderate branch and leaf density are more conducive to maintaining photosynthetic activity (Kovaleva et al., 2022). However, if it is too dense, the light cannot enter the interior of the canopy, the photosynthetic efficiency of the leaves will decrease, and the quality of the fruit may also deteriorate, compared with problems such as if the bunches are too tight, there are few fruit grains, and the fruit stems are prone to damage (Tello and Ibáñez, 2018; Keller and Mills, 2021). Therefore, under dense planting conditions, it is very important to manage the structure of branches and leaves reasonably, so as to ensure the effectiveness of photosynthesis and the high quality of fruits.

6.3 Root competition and nutrient uptake

Dense planting will also intensify the competition for water and nutrients among grape roots, thereby affecting the morphology and function of the roots. Under dense planting conditions, the number of roots will increase and the number of fine roots will also increase, which is conducive to enhancing the ability to absorb water and nutrients and improving drought resistance (Medrano et al., 2025). However, due to fierce competition, the absorption efficiency of individual grape plants may decline, affecting the growth of the trees and fruit development (Keller and Mills, 2021). In addition, dense planting may also reduce the organic matter and nutrients in the soil, thereby affecting the nutritional status of leaves and the quality of fruits (Ladaniya et al., 2020). Therefore, in high-density planting, how to manage the root system and soil nutrition well is the key to increasing the yield and fruit quality of the vineyard.

7 Economic and Environmental Implications

7.1 Input costs and return on investment

The initial cost of high-density planting is relatively high, such as spending a considerable amount of money on seedlings, support frames and irrigation equipment, etc. But in the long run, its payback period is shorter and the risk is relatively lower. For instance, in cherry cultivation, although the high-density approach requires a large investment, due to its stable yield and quick return on investment, the final profit is actually higher than that of the medium and low-density approach (Ghelfi and Palmieri, 2022; Bai et al., 2023). Among crops such as soybeans and corn, if high-density planting is combined with an appropriate reduction in fertilizers, it is possible to reduce costs, increase profits and return on investment while ensuring that the yield does not decline (Han et al., 2020; Bai et al., 2023; Wu et al., 2024). In addition, for some crops with relatively high value, the economic benefits brought by high-density planting are more obvious than those of traditional planting. However, it should also be noted that this method consumes a large amount of resources such as land and water, and may increase environmental pressure (Figure 2) (Su et al., 2023).

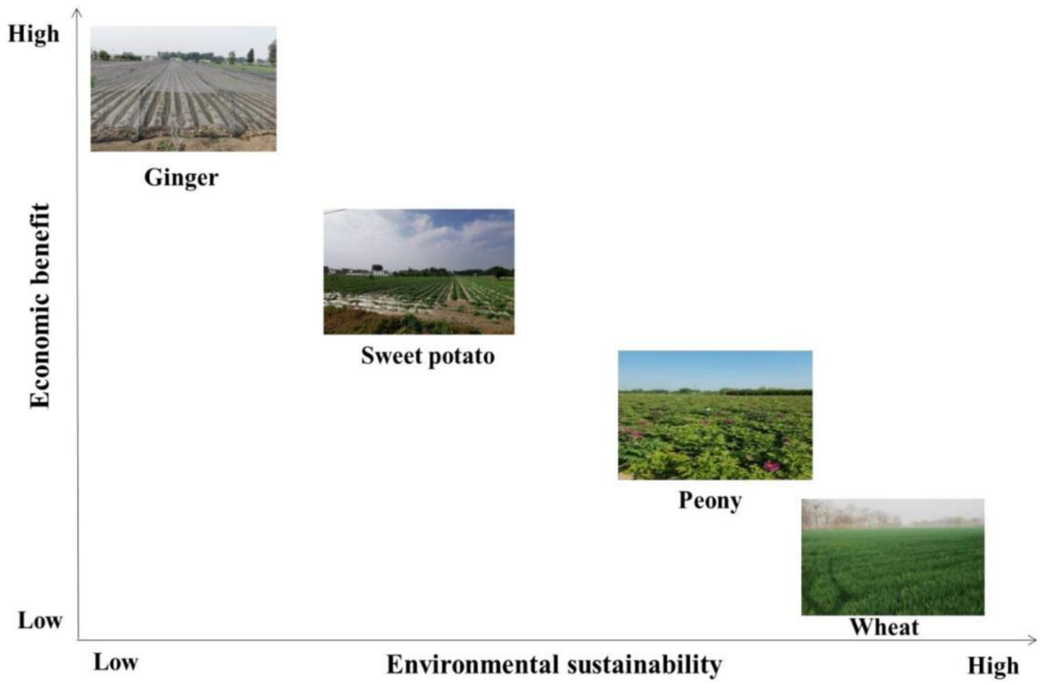

Figure 2 The conceptual trade-off of economic benefits and environmental impacts of four planting systems (Adopted from Su et al., 2023)
Image caption: The position of the four planting systems on the x-axis shows the environmental sustainability (ESI), while the y-axis shows the economic benefits of each system (Adopted from Su et al., 2023)

7.2 Labor savings and mechanization economics

High-density planting is also more suitable for achieving mechanized operation, which can significantly reduce labor costs and improve work efficiency (Parasuraman et al., 2024). Take cotton as an example. After adopting high-density planting, it is not only more suitable for machine harvesting, but also can complete the picking more quickly, save labor, and ultimately increase the income (Parasuraman et al., 2024). Regarding fruit trees, if automated equipment is added to high-density orchards, not only can the payback time be further shortened, but also the reliance on manual labor can be reduced and economic security can be enhanced (Ghelfi and Palmieri, 2022). Therefore, combining high-density planting with mechanization is an important way to improve agricultural efficiency and solve the problem of labor shortage.

7.3 Resource use efficiency and sustainability

High-density planting can also enhance the utilization efficiency of water, light and nutrients. For example, on corn and rice, appropriately increasing the planting density and reducing the input of nitrogen fertilizer not only improves the nitrogen fertilizer utilization efficiency (NUE), but also reduces nitrogen fertilizer residues, lowers environmental pollution, and achieves a balance among yield, income and environmental protection (Han et al., 2020; Li et al., 2020; Wu et al., 2024). In arid or semi-arid regions, high-density combination with water-saving irrigation technologies also helps to “determine production based on water”, making the use of water resources more rational and promoting sustainable agricultural development (Parasuraman et al., 2024; Wu et al., 2024). However, it should also be noted that if the density is too high, it may reduce ecological diversity and increase the environmental burden. This requires the development of greener and more environmentally friendly high-density planting methods through means such as optimizing the input structure and policy guidance (Guerrero-Casado et al., 2021; Su et al., 2023).

8 Case Study: Application of High-Density Planting in a Commercial Vineyard

8.1 Vineyard location and design parameters

This case occurred in the southern grassland area, where the climate and soil are both very suitable for growing grapes. The vineyard adopts two different planting densities: one is the standard density, with 2 222 plants per hectare; The other type is high density, with 4 000 plants per hectare. Generally speaking, small wine producers tend to use high-density methods, while large enterprises mostly adopt standard density. The design of row spacing and plant spacing for high-density planting is mainly to make more full use of the land and facilitate the use of small mechanical equipment.

8.2 Implementation of mechanized harvest with high-density rows

In the high-density system, the vineyard uses small machinery suitable for narrow row spacing for management and harvesting. Because it is planted relatively compactly, this structure can enhance the efficiency of mechanized operations and reduce manual intervention. Mechanical harvesting is not only fast, but also more consistent and efficient (Irish-Brown et al., 2022). The compact line spacing also makes it easier for the machine to pass through and operate, further enhancing the operational efficiency (Irish-Brown et al., 2022).

8.3 Observed changes in productivity, quality, and labor efficiency

High-density planting significantly increased the yield per hectare, with an increase ranging from 26.8% to 32.5%, and the yield-increasing effects varied among different varieties. For instance, the Aromatnyi variety yields an average of 2.5 tons per hectare, while Zahrei yields 4.0 tons per hectare more. However, high density also brings some problems, such as the rising demand for labor. The costs of labor and drivers increased by 63.1% and 50.2% respectively, and the labor intensity per unit of product also rose by 11.3% to 13.7%. Fortunately, through mechanized operations, the problem of insufficient labor has been partially alleviated, and the harvesting efficiency has also been improved (Irish-Brown et al., 2022).

In terms of fruit quality, high-density planting helps improve light conditions and space utilization, which can enhance the consistency and overall quality of the fruits (Irish-Brown et al., 2022; Manju et al., 2025). However, if the density is too high, the canopy may be overly dense, affecting the microclimate conditions around the fruit, and may even lead to problems such as fewer fruit clusters and a decrease in the number of fruit grains (Keller and Mills, 2021). Therefore, to increase both output and ensure quality, the key lies in designing a reasonable high-density system and combining it with mechanization for management (Keller and Mills, 2021; Irish-Brown et al., 2022; Manju et al., 2025).

9 Challenges and Research Gaps

9.1 Limitations in existing varieties for dense systems

High-density planting has put forward higher requirements for the adaptability of grape varieties. Some studies have found that the yield of some existing varieties decreases and the fruit quality deteriorates under dense planting conditions (for example, with a plant spacing of only 0.91 meters). Because the vines grew too vigorously and the canopy was too dense, the microclimate in the orchard became worse, eventually resulting in fewer fruit clusters, fewer fruit grains, and more prone fruit stems to damage (Keller and Mills, 2021). In addition, the economic performance of some new varieties varies at different densities. It is still necessary to continue screening out specialized varieties that are more suitable for high-density mechanized planting (Di Lorenzo et al., 2022).

9.2 Equipment compatibility in sloped or non-uniform terrain

Mechanical harvesting equipment performs well in flat vineyards, but it encounters difficulties on sloping land or in areas with irregular terrain. In emerging grape-producing areas like China, due to the complex terrain, along with the variety of equipment types and inconsistent standards, mechanical harvesting cannot be widely implemented in many places (Yang et al., 2025). Moreover, there is no clear conclusion yet on whether it is cost-effective and useful for small vineyards to use small equipment under high-density planting conditions. In orchards with complex terrain, machine operations may also make the soil more compact, affecting the long-term health of the vineyard.

9.3 Long-term effects on vineyard longevity and soil health

High-density planting combined with frequent mechanical operations may also have an impact on soil health and the sustainable development of orchards. Long-term dense planting will cause the nutrients in the soil to be consumed more quickly, the organic matter to decrease, the soil may become acidic, and salinization problems may occur. All these will affect the yield and fruit quality (Zhou et al., 2019; Deng et al., 2024). If mechanical operations are frequently carried out in humid weather, it is also easy for the soil to be compacted, the root system is not easy to grow, and air and water are not easy to enter the soil. The grapevines will not grow well and the yield will also be affected (Mattii et al., 2021). Furthermore, high-density continuous planting may also lead to a decrease in microorganisms in the soil, a reduction in beneficial bacteria and an increase in pathogenic bacteria, which will also affect the ecological balance of the vineyard (Wilson et al., 2020; Deng et al., 2024). At present, systematic research on these long-term effects is insufficient. Further research is needed on how to optimize management to enable sustainable development of high-density planting as well (Wilson et al., 2020; Mattii et al., 2021; Gonzalez-Maldonado et al., 2024).

10 Concluding Remarks

High-density planting has put forward higher requirements for the growth, stress resistance and fruit quality of grape varieties. When choosing varieties, in addition to having a compact tree shape and a moderate canopy, they should also be suitable for mechanical harvesting to reduce fruit loss and improve quality. Nowadays, by combining molecular breeding with high-throughput phenotypic analysis, key genes related to fruit quality and stress resistance can be identified more quickly, accelerating the cultivation of new varieties that are high-yielding, high-quality and suitable for mechanization. In addition, whether the combination of rootstocks and varieties is appropriate, as well as whether management methods like high-rack pruning are adopted, will also directly affect the yield and fruit quality. All these need to be considered together in breeding and cultivation.

Precision agriculture technology has provided a lot of help for the management of high-density vineyards. Through genotyping, automated phenotypic monitoring, and real-time collection of environmental and growth data, growers can dynamically understand the structure of branches and leaves, fruit development, and pest and disease conditions. They can also precisely adjust water, fertilizer, and harvest time based on these data. This not only enhances management efficiency, but also improves fruit quality and yield, avoids resource waste, and helps achieve sustainable development of high-density planting and mechanized harvesting.

Nowadays, combining high-density planting with mechanized harvesting has become an important way to increase grape yields and fruit quality. This model can make more effective use of land, water and sunlight, reduce labor input and increase the economic benefit per mu. However, if they are planted too densely, problems such as overly dense canopies, poor ventilation, and a decline in fruit quality are also likely to occur. Therefore, both the planting density and the management methods need to be scientifically designed. In the future, with the continuous upgrading of variety breeding, precision agriculture and mechanization technologies, this high-density + mechanized grape cultivation method is expected to be more widely promoted globally, driving the grape industry towards high-quality and sustainable development.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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