

Research Insight

Open Access

Statistical Analysis of Vineyard Management Factors Affecting Grape Growth and Quality

Jili He 

Zhuji Puxi Crops Professional Cooperative, Zhuji, 311800, Zhejiang, China

 Corresponding author: 1198115935@qq.comComputational Molecular Biology, 2026, Vol.16, No.5 doi: [10.5376/cmb.2026.16.0024](https://doi.org/10.5376/cmb.2026.16.0024)

Received: 13 Aug., 2026

Accepted: 19 Sep., 2026

Published: 30 Sep., 2026

Copyright © 2026 He, This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preferred citation for this article:

He J.L., 2026, Statistical analysis of vineyard management factors affecting grape growth and quality, Computational Molecular Biology, 16(5): 342-359 (doi: [10.5376/cmb.2026.16.0024](https://doi.org/10.5376/cmb.2026.16.0024))

Abstract Grape growth and fruit quality are jointly influenced by environmental conditions, soil properties, and orchard management practices, making it essential to identify and quantify the relative contributions of these factors. This paper systematically analyzes the major factors affecting grape growth, yield, and fruit quality from a statistical perspective. Key indicators, including vegetative growth, yield components, soluble solids, titratable acidity, sugar-acid ratio, fruit coloration, and physiological traits, are considered. Environmental factors such as temperature, light, water availability, humidity, and soil physicochemical properties are evaluated alongside fertilization, irrigation, pruning, crop load regulation, and cluster management. Statistical approaches, including correlation analysis, analysis of variance, multiple regression, multivariate analysis, and machine learning, are discussed for identifying key influencing factors and characterizing nonlinear relationships and interactions. A case study based on orchard management data further demonstrates the application of statistical models in evaluating grape yield and quality responses. The integrated analysis provides a quantitative basis for identifying critical management factors and developing data-driven precision orchard management strategies. These findings highlight the potential of statistical analysis and intelligent technologies to improve resource-use efficiency, stabilize yield, enhance fruit quality, and promote sustainable grape production.

Keywords Grape growth; Fruit quality; Orchard management; Statistical analysis; Precision agriculture

1 Introduction

Grapevine is one of the most widespread and economically important perennial fruit crops in the world, and viticulture has continued to expand and transform under the combined pressure of global markets, environmental change, and rising quality expectations. Global production remains economically significant, but recent long-run analyses suggest that production growth has lagged behind population growth, while competition among producing countries has become less concentrated and more technologically demanding (Kupe and Uzundumlu, 2026). At the same time, grapes are consumed as fresh fruit and processed into wine, raisins, and juice, which means that fruit quality directly shapes value across multiple supply chains rather than only determining field productivity (Khadatkar et al., 2025). In modern markets, growers are increasingly judged not only by yield, but by their ability to produce fruit with desirable appearance, sugar-acid balance, flavor, phenolic composition, and health status, because consumers are shifting toward higher-quality products and quality-differentiated markets such as geographically identified wines. This emphasis on quality improvement has also intensified because grapevine production is highly vulnerable to drought, heat, diseases, and other biotic and abiotic stresses that reduce yield, shorten vineyard lifespan, and threaten competitiveness (Butiuc-Keul and Coste, 2023). Accordingly, recent reviews argue that innovation in mechanization, precision management, artificial intelligence, and biotechnology is no longer optional, but central to improving quality, stabilizing production, and sustaining the grape industry under changing production conditions.

Against this background, orchard or vineyard management factors have become a central research focus because grape growth and fruit quality emerge from the interaction of cultivation practices with soil, climate, and vine physiology rather than from any single factor alone. Grape quality is a complex outcome that depends simultaneously on viticultural practices and natural conditions, while yield and composition are shaped across macroclimate, site, and canopy scales (Cameron et al., 2024). Studies consistently show that management

practices such as pruning, irrigation, fertilization, canopy regulation, training systems, and weed or disease control can alter shoot growth, leaf area, cluster number, berry size, ripening dynamics, and final compositional traits, although the direction and magnitude of these effects depend strongly on timing, severity, and environmental context. For example, a recent meta-analysis found that cluster thinning, leaf removal, shoot thinning, and irrigation reduction significantly reduced yield, whereas reduced pruning severity increased yield mainly through higher bud number, highlighting the classic tension between yield regulation and fruit composition management. Irrigation is especially important in water-limited systems: multi-experiment evidence indicates that cumulative irrigation is positively associated with yield components but levels off beyond a threshold, while excessive evaporative demand depresses yield and cluster weight (Ohana-Levi et al., 2024). Fertilizer management is similarly influential, because nutrient supply affects vine physiological growth, sugar and polyphenol accumulation, and overall productivity, yet poorly balanced fertilization can also disturb grape physicochemical composition. Field experiments further show that combining organic and inorganic fertilizers under drip irrigation can improve soil nutrient status, photosynthetic performance, yield, and several quality indices, with one study identifying 720 mm irrigation and a 50:50 organic-inorganic fertilizer ratio as a favorable regime. Management effects are not limited to water and fertilizer inputs: training system significantly affects economic performance, tendone systems have been associated with markedly higher total value product than vertical systems in Chilean vineyards, and organic or biodynamic systems can reduce vine growth and yield without necessarily changing basic berry quality traits such as soluble solids, acidity, and pH. Soil nutrient structure also contributes to quality formation, but because berry quality and soil fertility each contain multiple interrelated indicators, their relationship cannot be adequately represented by simple pairwise associations alone.

These characteristics make statistical analysis indispensable for grape orchard management research. Traditional one-factor analytical approaches can describe isolated responses, but they do not adequately capture the interdependence, collinearity, and nonlinear interactions that characterize vineyard systems. Recent viticulture studies therefore increasingly apply multivariate and predictive methods to integrate management, environmental, physiological, and quality variables within unified analytical frameworks. Partial least squares regression has been used to relate viticultural practices, soil, and climatic conditions to harvest quality traits such as sugar, acidity, nitrogen status, pH, and bunch rot, thereby identifying the most relevant determinants for each quality index. Similar approaches have been adopted to screen major soil nutrient factors affecting berry quality, establish multivariate regression equations, and optimize nutrient targets for local vineyard soil management. Beyond PLS, principal component analysis has been used as an effective tool for comprehensive grape quality evaluation under irrigation-fertilizer experiments, while classification and regression trees have identified decisive variables for vineyard water-stress classification and quality-related responses under heterogeneous mesoclimatic conditions. Support vector machine models have also achieved high prediction accuracy for yield, cluster number, and cluster weight using integrated datasets spanning varieties, climates, and irrigation experiments, demonstrating the value of data-driven ranking of dominant factors such as leaf area index, growing degree days, irrigation, and evapotranspiration. In related grape and wine quality research, multivariate regression, principal component regression, clustering, and linear regression have been used to predict sensory quality, classify grape raw materials, and quantify the influence of physicochemical indicators on wine quality and economic decision-making. Together, these studies show that statistical methods are not merely auxiliary tools for data description; they are essential for revealing hidden structure in complex vineyard datasets, quantifying the relative importance of management factors, and supporting precise, evidence-based decisions under increasingly variable production environments. Therefore, an introduction to the statistical analysis of vineyard management factors affecting grape growth and quality must begin from three linked premises: the grape industry increasingly depends on high-quality production, vineyard management exerts multidimensional and interacting effects on growth and fruit traits, and robust statistical modeling is necessary to convert complex field observations into actionable guidance for sustainable and competitive viticulture.

2 Major Indicators for Evaluating Grape Growth and Quality Formation

2.1 Vegetative growth and yield indicators of grapevines

Vegetative growth and yield indicators are the most direct variables for describing vineyard performance, because

they reflect both canopy development and the vine's capacity to convert assimilates into reproductive output. Common vegetative indicators include shoot length, leaf number, leaf area, trunk diameter, cane growth, pruning weight, and leaf area index, while yield is usually characterized by cluster number, cluster weight, berry weight, fruit set, and total yield per vine or per hectare. Among these, leaf area index is especially informative because it integrates canopy size with light interception and is strongly associated with vine health, yield, and management responsiveness. These indicators are valuable not only as descriptive traits but also as quantitative signals of source-sink balance. Multi-experiment evidence shows that yield is positively related to both cluster weight and cluster number, while cluster weight and cluster number often trade off against each other, indicating compensatory allocation within the crop. Canopy size must also be interpreted cautiously, because excessive leaf area can become counterproductive: leaf area shows an optimum range for yield components, and very high LAI, especially above about 1.6-1.7, tends to reduce yield by intensifying competition between vegetative and reproductive sinks.

In management studies, these indicators are also useful because they are sensitive to irrigation, shoot density, crop load, genotype, and training system. Irrigation is a primary driver of LAI expansion, and early-season LAI is more closely associated with yield, whereas later LAI better predicts pruning weight and cane growth. Likewise, lower shoot density can increase main shoot length, lateral growth, leaf area per shoot, and shoot diameter, while increasing cluster number generally raises crop yield up to a point before source limitation appears (Naor et al., 2002). Recent research also shows that vegetative and yield indicators can be monitored objectively with imaging and remote sensing, which makes them suitable for statistical analysis at both vine and field scales. RGB image classification has estimated grapevine leaf area and yield with good accuracy, with reported coefficients of determination around 0.81 for leaf area and 0.73 for yield. At the larger spatial scale, UAV-based multispectral indices correlate strongly with yield and pruning weight from early phenological stages, supporting their use for mapping vineyard vigor variability and improving management efficiency (Ferro et al., 2023).

2.2 Grape fruit quality indicators

Grape fruit quality indicators describe the market and processing value of berries and therefore form the core response variables in studies of vineyard management. The most commonly used chemical indicators are soluble solids content, titratable acidity, pH, total sugars, and the sugar-acid ratio, while phenolic indicators include anthocyanins, tannins, flavonoids, and total phenolic compounds. These variables are central because they determine ripening status, harvest timing, flavor balance, color expression, processing suitability, and final wine or table-grape acceptability. Fruit quality evaluation also includes physical and sensory-related traits. Berry weight, berry length and diameter, firmness or hardness, cluster appearance, and fruit color are frequently measured because they affect commercial grading and consumer acceptance. In colored cultivars especially, anthocyanin accumulation is a key indicator because it drives skin color development and contributes directly to the visual quality of berries (Shahab et al., 2023).

Beyond basic ripening indices, phenolic composition is increasingly treated as a major quality dimension because it links nutritional value, antioxidant activity, and processing potential. Comparative cultivar analysis identified dozens of polyphenolic compounds in grapes, including anthocyanins, flavonols, phenolic acids, flavan-3-ols, and stilbenes, and showed large differences in total polyphenol content and antioxidant activity among cultivars. Reviews further emphasize that phenolic compounds are not only bioactive metabolites but also major determinants of commercial grape quality through their effects on color, stress response, and final berry composition. Because fruit quality is multidimensional, recent studies increasingly favor rapid and nondestructive assessment methods that can quantify several indicators simultaneously. Portable NIR spectroscopy has shown strong predictive performance for soluble solids, titratable acidity, anthocyanins, and tannins in intact grapes, making it useful for vineyard screening during ripening (Rouxinol et al., 2022). Spectral reflectance indices and machine-learning approaches have also predicted soluble solids, pH, acidity, anthocyanins, tannins, phenols, berry size, and sugar-related traits with practical accuracy, indicating that these quality indicators are well suited to statistical modeling and precision harvest decisions.

2.3 Physiological indicators related to grape quality formation

Physiological indicators are essential because they reveal the internal processes through which management and environment influence grape growth and berry composition. The most widely used indicators include net photosynthetic rate, stomatal conductance, transpiration rate, intercellular CO₂ concentration, chlorophyll content, water use efficiency, and leaf or stem water potential. These metrics connect canopy function to assimilate production, water relations, and stress status, and therefore help explain why differences in yield or fruit composition emerge under different vineyard treatments (Selnekovič et al., 2026). Photosynthesis-related traits are particularly informative in grape quality formation because they reflect the vine's capacity to generate assimilates for berry growth and ripening. Experiments under different light qualities showed that blue and red light improved chlorophyll content, net photosynthetic rate, stomatal conductance, electron transport traits, and several morphological parameters, while also increasing soluble sugars and improving fruit firmness and acidity traits. Related transcriptome-metabolome evidence showed that blue and red light also increased plant height, stem diameter, leaf area, pigments, mineral uptake, and the expression of photosynthesis- and secondary-metabolism-related genes, linking physiological activity to the pathways underlying quality formation.

Water-status indicators are another core category, especially in vineyards exposed to heat and deficit irrigation. Comparative testing of physiological metrics found stomatal conductance to be among the earliest and most sensitive indicators of grapevine water stress, while stem water potential outperformed leaf water potential as an integrative indicator of vine water status. Under drought, grapevines often show reduced stomatal conductance, transpiration, and intercellular CO₂, whereas water use efficiency can increase as stomata close and vines adjust carbon gain relative to water loss. Finally, physiological evaluation increasingly extends beyond gas exchange to include fluorescence, antioxidant enzymes, pigment indices, and canopy-level spectral indicators. Studies of grapevine responses to water deficit show that photoprotection depends on photorespiration, non-photochemical energy dissipation, and stomatal sensitivity, indicating that quality-related stress responses cannot be understood from a single variable alone. Likewise, SPAD, chlorophyll a and b, NDVI, PRI, and antioxidant enzymes such as POD, SOD, and CAT have been used alongside gas-exchange traits to characterize cultivar-specific physiological status, demonstrating that grape quality formation is best evaluated through integrated physiological indicator systems rather than isolated measurements. Together, these three groups of indicators define the main measurable dimensions of grape growth and quality formation: vegetative-yield structure, berry quality composition, and physiological function. For the statistical analysis of vineyard management factors affecting grape growth and quality, these indicators provide the core dependent variables needed to identify key drivers, quantify interactions, and support precision viticulture decisions (Figure 1).

3 Orchard Environmental Factors and Their Effects on Grapevine Growth and Quality

3.1 Temperature and light conditions

Temperature and light conditions directly regulate grapevine vegetative growth, reproductive development, and berry ripening, so their effects extend from bud differentiation to harvest composition. Early controlled-environment work showed that grapevine fruitfulness increased as light intensity increased, while bud differentiation was poor at 20°C and improved progressively above that level, indicating that both adequate radiation and favorable temperature are prerequisites for reproductive potential. More recent work similarly shows that low light reduces leaf photosynthesis, carbon accumulation, and flower bud development, whereas excessive light can cause photoinhibition, so grape response depends on maintaining a suitable rather than maximal light environment (Yuan et al., 2025). During berry development, temperature and light jointly shape fruit size, softening, sugar accumulation, and coloration. High temperature causes abnormal berry softening and difficulty in coloring, while weak light slows sugar and anthocyanin metabolism, making these two stresses especially important during veraison. Climatic warming also tends to advance maturity and increase the sugar-to-acid ratio, but this compositional shift is not necessarily beneficial, because high temperature can impair antioxidant formation, reduce anthocyanin and tannin biosynthesis, and create quality problems in table grapes.

Field and protected-cultivation studies further show that the effects of radiation depend strongly on exposure level and timing. In hot climates, anthocyanins and phenolics can increase with moderate light exposure, yet decline

when cluster exposure becomes excessive or when berry temperature exceeds critical thresholds, showing that temperature can override the positive effect of light on color formation. Supplemental LED lighting in protected vineyards improved grape total soluble solids, glucose, and sugar-acid ratio, and night lighting at moderate intensity produced the best economic and yield response, indicating that optimized light duration can partly compensate for insufficient natural radiation. Temperature stress also affects growth and quality through its effects on photosynthesis and assimilate supply. Heat stress during flowering significantly reduced fruit set in ‘Kyoho’, and from veraison to maturity it reduced berry weight, berry size, and anthocyanin content while slowing soluble solids accumulation and accelerating acidity loss (Sun et al., 2025). Under climate-change simulations, drought combined with elevated temperature drastically reduced vegetative growth and bunch weight, although the magnitude and quality response were cultivar dependent, confirming that heat effects must be interpreted together with water status and genotype.



Figure 1 Field measurement of major physiological indicators in grapevines, including gas exchange, chlorophyll content, and plant water status

3.2 Water availability and air humidity

Water availability is one of the strongest environmental constraints on grapevine performance, because it influences canopy expansion, stomatal regulation, photosynthesis, yield formation, and berry composition. Long-term field evidence shows that soil water availability largely determines leaf photosynthesis and transpiration, and moderate irrigation generally improves plant water status and yield compared with non-irrigated vines. Reviews of drought physiology likewise conclude that water availability is arguably the most important environmental factor limiting crop growth and productivity, and that grape yield is typically impaired under drought, although the magnitude of reduction varies with variety and environment. The effect of reduced water supply on grape quality is more nuanced than its effect on growth. Mild to moderate water deficit often improves berry composition by reducing berry size, increasing skin-to-pulp ratio, and enhancing the concentration of skin-based compounds such as anthocyanins and tannins. Experimental work in Greek cultivars similarly found that water deficit reduced berry size and increased soluble solids, total phenols, and, in the red cultivar, anthocyanins, although these responses were modified by vintage conditions (Alatzas et al., 2021).

Air humidity and atmospheric water demand alter vine responses even when soil water supply is unchanged, because stomatal behavior reflects the joint effects of soil and atmosphere. In Mediterranean ‘Tempranillo’,

differences in stomatal conductance and photosynthesis between irrigation treatments became more pronounced at midday and later in the day, reflecting the increase in atmospheric water demand, and stomatal closure was less severe where soil water storage capacity was higher. Broader physiological work also shows that vapor pressure deficit helps determine whether vines behave more anisohydrically or isohydrically, so hydraulic behavior cannot be predicted from genotype alone without accounting for environmental demand. Irrigation strategy therefore needs to balance yield preservation against quality goals under specific climate conditions. In Bobal under Mediterranean conditions, rainfed vines had lower vigor and production but higher soluble solids and phenolic compounds and lower pH than fully irrigated vines, while deficit irrigation produced intermediate responses that can help reduce the gap between technological and phenolic maturity. However, severe or prolonged drought combined with high temperature can reverse quality gains, since high berry temperature can degrade anthocyanins and limit the positive effects of water deficit on berry color and phenolics.

3.3 Soil physicochemical conditions

Soil physicochemical conditions influence grapevine growth both directly, through nutrient supply and root-zone chemistry, and indirectly, through water retention, aeration, and hydraulic regulation. Recent precision-viticulture research identified elevation, slope, soil texture, clay and sand content, total organic carbon, and nitrogen as significant predictors of vine vigor, supporting the use of management zones based on combined topographic and soil information (Karn et al., 2024). This broad pattern is consistent with the view that soil characteristics are a major source of within-vineyard variability and should be considered explicitly when optimizing vine growth, grape quality, and resource allocation. Among soil properties, physical traits often matter most because they regulate water availability to the vine. Comparative vineyard studies showed that soil type affected leaf gas exchange and water potential more strongly than cultivar, and that clayey soil with moderate water stress produced the highest berry sugar accumulation by maintaining photosynthesis while limiting excessive shoot growth after veraison. Reviews of grape quality also conclude that soil effects on berry composition are largely mediated through water-holding capacity, infiltration, drainage, and access to groundwater rather than through mineral supply alone, provided nutrient balance is not severely disrupted.

Soil chemical conditions still remain important, especially where nutrient deficiency, alkalinity, acidification, salinization, or long-term monoculture alter vine performance. In Cabernet Franc vineyards, soil nutrients and pH showed differentiated relationships with quality traits: total nitrogen was negatively associated with some traits such as titratable acidity and tannin but positively associated with soluble solids and flavonol, while soil pH was positively related to berry weight and yield per plant but negatively related to tannin and flavonol. In the Helan Mountains, vineyard soils were reported to be relatively deficient in several nutrients and alkaline overall, reinforcing the need for site-specific nutrient diagnosis in quality-oriented viticulture. Long-term degradation of soil condition can reduce both yield and fruit quality. Continuous grape cultivation for 7 to 12 years intensified soil acidification and secondary salinization, reduced soil and leaf nutrients, and significantly decreased yield and aroma compound contents, while also shifting the soil microbiome away from beneficial taxa. At the same time, recent work in organic vineyards suggests that higher soil moisture, clay, organic matter, phosphorus, and certain mineral oxides can favor the accumulation of phenolic compounds and antioxidant capacity in grape skin and seed, indicating that improved soil condition can enhance compositional quality as well as sustainability (Macías-Gallardo et al., 2025). Overall, orchard environmental factors affect grape growth and quality through interacting thermal, hydraulic, and edaphic pathways. For statistical analysis of vineyard management factors, temperature and light, water and atmospheric demand, and soil physicochemical properties should therefore be treated as core explanatory variables for variation in vine vigor, yield, ripening, and berry quality.

4 Orchard Cultivation and Management Factors

4.1 Fertilization and nutrient management

Fertilization and nutrient management regulate grapevine growth by altering nutrient supply, vine nitrogen status, and soil fertility, but their effects are not linear, so both deficiency and excess can reduce production efficiency and fruit quality. A large meta-analysis of 374 trials found that grape yield approached 95% of its maximum at about 30-40 kg·N·ha⁻¹, whereas the nitrogen range associated with optimal winemaking quality was lower, around

20-25 kg·N·ha⁻¹, highlighting a practical divergence between yield maximization and quality optimization (Visconti et al., 2023). This pattern is consistent with field experiments showing that nitrogen fertilization increased pruning weight, leaf area, cluster weight, and overall yield, but doubling the N rate did not further improve vegetative or productive traits.

Nutrient management also affects berry composition through both soil and plant pathways, so integrated fertilization is usually more effective than sole mineral input. In drip-irrigated vineyards, combining organic and inorganic fertilizers significantly increased available soil N, P, and K, enhanced photosynthetic activity, and raised grape yield and fruit quality relative to inorganic fertilizer alone. Reduced-N substitution with organic fertilizer further improved total sugar, sugar-acid ratio, vitamin C, photosynthetic efficiency, and economic return, with 20%-30% N reduction plus organic fertilizer performing best in Shine Muscat (Huang et al., 2026). Long-term evidence also indicates that fertilization changes yield and quality partly by modifying soil nutrients and microbial communities, with fertilization accounting for the largest share of variance in yield and nutritional traits in a 15-year trial.

4.2 Irrigation and integrated water-fertilizer management

Irrigation management strongly affects grape growth, yield, and berry composition because it controls vine water status, nutrient transport, and the balance between vegetative growth and ripening. A three-year drip fertigation study showed that both irrigation and fertilization significantly affected yield, while irrigation also changed titratable acidity and sugar-acid ratio; the best overall treatment was moderate irrigation combined with moderate fertilization, which balanced yield, quality, water-use efficiency, and fertilizer productivity. In an arid-region field experiment, integrated water-fertilizer management with mixed organic and inorganic fertilizer improved growth, yield, and fruit quality across irrigation levels, and the recommended combination was 720 mm irrigation with a 50:50 organic-inorganic fertilizer ratio. These results support the broader view that deficit and regulated irrigation are useful only when scheduled against variety, rootstock, and site conditions rather than applied uniformly (Romero et al., 2022).

The quality response to irrigation is more nuanced than the growth response, because moderate water restriction can improve maturity and phenolic accumulation, while severe stress can depress yield unless compensated by supporting practices. In Sangiovese, pre-veraison deficit irrigation reduced vegetative growth without reducing yield and produced the highest berry anthocyanin concentration together with lower titratable acidity. A table-grape study similarly found that a precision irrigation program reduced water input by 30% without reducing total yield, while increasing berry growth and maturity index (Zapata-García et al., 2025). Under stronger drought pressure, however, irrigation at 60% field capacity reduced growth and yield when used alone, whereas combining deficit irrigation with soil amendment and proline improved irrigation water-use efficiency and preserved fruit-quality traits.

4.3 Training, pruning, crop load regulation, and cluster management

Training and pruning determine canopy architecture, light distribution, bud number, and leaf area-to-fruit balance, so they are central tools for regulating both yield formation and ripening pace. A recent meta-analysis found that cluster thinning, leaf removal, shoot thinning, and irrigation reduction generally reduced yield, whereas less severe pruning increased yield mainly through higher bud number, although timing and intensity often changed the final outcome (Cameron et al., 2024). In Riesling, the semi-minimal-pruned hedge system produced substantially higher yield than vertical shoot positioning but also a narrower leaf area-to-fruit ratio and delayed ripening, while shoot thinning, biotechnological thinning, and bunch thinning all reduced yield and accelerated maturity. These findings show that canopy-load regulation is fundamentally an exercise in adjusting source-sink balance rather than simply reducing crop size.

The effectiveness of specific training and crop-load interventions remains cultivar- and objective-dependent. In California table grapes, cane and spur pruning produced no significant differences in berry physical or chemical composition in either cultivar, but cane pruning increased marketable yield in Autumn King while Scarlet Royal responded similarly to both systems (El-Kereamy and Kurtural, 2022). In the Mevlana cultivar trained on rational

pergola, girdling under both crop-load levels improved berry growth and biochemical properties, indicating that cluster-level interventions can complement broader training decisions. Under climate warming, training-system choice is also being reconsidered as an adaptation tool, with warm regions increasingly favoring systems that promote slower ripening, greater cluster shading, and reduced overheating risk rather than maximum exposure. Overall, orchard cultivation and management factors affect grape growth and quality through nutrient supply, water regulation, and canopy-crop balance. For statistical analysis of vineyard management factors affecting grape growth and quality, fertilization, irrigation strategy, and training-pruning-load regulation should therefore be treated as major explanatory variables with strong interaction effects on yield, ripening, and fruit composition.

5 Statistical Methods for Analyzing Grape Growth and Quality

5.1 Univariate statistical analysis and correlation analysis

Univariate statistical analysis and correlation analysis are the basic tools for evaluating grape growth and quality data, especially when the aim is to test treatment effects or describe direct relationships between two variables. In vineyard studies, one-way ANOVA is commonly used to test differences among cultivation treatments, while least significant difference tests are then used to compare means across groups (Abdel-Sattar et al., 2022). Correlation analysis is similarly used to evaluate relationships between measured variables such as soil nutrients, grape quality traits, and canopy or environmental indicators, and Pearson correlation remains one of the most common starting points for this purpose.

The main advantage of these methods is their clarity, but their explanatory scope is limited when grape quality is controlled by many interacting factors. Correlation analysis in the Hexi Corridor showed that titratable acidity, pH, and Brix were strongly associated with both climate and soil variables, demonstrating the usefulness of simple statistical screening for environmental effects. However, grape quality and soil nutrient systems are multivariate by nature, and simple correlations alone do not adequately explain the mechanism of action when predictors are interrelated. Work in breeding populations reaches a similar conclusion: correlation identifies associated traits, but path analysis is needed to separate direct from indirect effects, for example showing that cluster number has the strongest direct effect on yield per plant (Rodrigues et al., 2023).

5.2 Multiple regression and multifactor statistical models

Multiple regression is more suitable when grape growth or quality depends on several predictors acting simultaneously, because it quantifies the independent contribution of each factor within a single equation. In cold-climate grapes, models based on only one or two predictors were fit with ordinary least squares, whereas models with more than two factors used elastic net regression to improve variable selection and control collinearity (Schrader et al., 2020). These multifactor phenology models were much more accurate than simpler models using cultivar and growing degree days alone, with clear improvements in both fit and prediction error across budbreak, bloom, veraison, and harvest stages (Figure 2).

In fruit-quality studies, multiple linear regression has also shown strong practical value for predicting market and compositional traits from plant nutritional status or environmental measurements. For Flame Seedless grapes, multiple linear regression was used to predict cluster weight, cluster dimensions, and berry color attributes from leaf mineral composition, chlorophyll, and carotenoids, with test-set R^2 values ranging from 0.9286 to 0.9972. Similar multifactor approaches have been used to integrate viticultural practices, soil, and climate into explanatory models of harvest quality, allowing researchers to identify the most relevant management and environmental variables for sugar, acidity, nitrogen status, pH, and bunch rot. Multiple regression models are especially useful when the goal is interpretation rather than only prediction. Spatial vineyard studies showed that yield zones could be linked to soil fertility and crop nutrition characteristics, and that inverse spatial correlations between yield and some quality parameters can guide site-specific fertilizer strategies. Even so, regression models remain sensitive to multicollinearity, missing data, and model specification. In grape yield forecasting from soil and weather databases, random forest achieved the best average results, whereas PLSR was less sensitive to weather-data imputation, showing that classical regression and more flexible predictive methods each have distinct strengths depending on data quality and modeling objectives (Andrade et al., 2023).

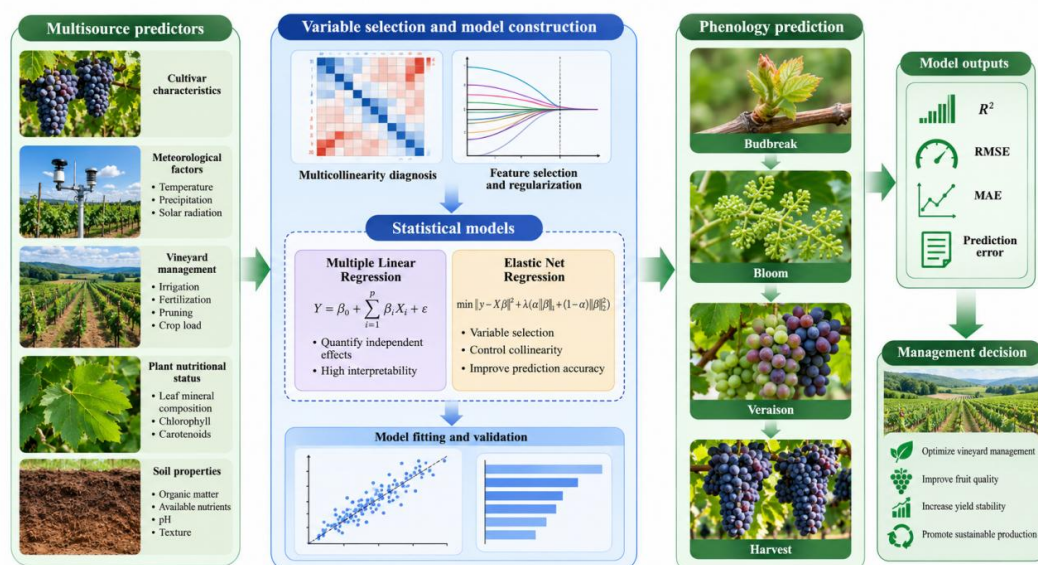


Figure 2 Conceptual framework of multifactor regression modeling for predicting grapevine phenology and growth responses

5.3 Multivariate analysis and machine learning methods

Multivariate analysis becomes necessary when grape growth and quality are represented by many correlated indicators that cannot be interpreted adequately one variable at a time. In Cabernet Franc vineyards, partial least squares regression was selected because soil nutrient indices showed multiple collinearity relationships, and this approach was used to screen the main nutrient factors affecting each quality index before constructing subsequent regression equations. Principal component analysis is also widely used for dimensionality reduction and quality evaluation: in high-altitude Cabernet Sauvignon regions, PCA explained more than 85% of total variance and clearly separated grapes from different altitudes into distinct quality groups. Multivariate methods are also effective for handling spatial and temporal heterogeneity in ripening. FTIR-based vineyard analysis showed that maturity over time was the dominant source of variability, while berry position within the vine and cluster also had significant effects; PCA-based multivariate statistical process control was then used to identify samples matching the optimal harvest state (Schorn-García et al., 2023). Structural equation modeling extends this logic by estimating causal networks among environmental and quality variables, and in high-altitude vineyards it showed that temperature and extreme air temperature had stronger direct effects on key quality indices than light.

Machine learning methods are increasingly used when the objective is accurate prediction from high-dimensional, nonlinear, or multimodal vineyard datasets. In multimodal grapevine sensing, hyperspectral vegetation indices, thermal indices, and canopy state variables were combined with machine-learning workflows that included correlation screening, preprocessing, feature selection, 10-fold cross-validation, and predictor-importance analysis (Jewan et al., 2024). In that study, gradient boosting performed best for most berry-composition traits and several yield components, while random forest performed best for total yield and titratable acidity. Broader machine-learning work in grape and wine systems shows a similar pattern: ensemble models often outperform simpler algorithms, but feature selection and validation are critical to avoid overfitting. Random forest and XGBoost were the most accurate models in wine-quality classification after feature selection, and cluster analysis was used to reduce collinearity without sacrificing predictive accuracy. Likewise, gradient boosting regressor outperformed ridge regression, support vector machines, and neural networks in one wine-quality study, whereas a PCA plus optimized K-means framework provided reproducible grading of wine grapes into quality tiers based on more than 30 biochemical markers. Overall, statistical analysis of grape growth and quality follows a clear progression from simple description to integrated prediction. Univariate and correlation methods are suitable for preliminary screening, multiple regression is more effective for interpreting joint effects of several factors, and multivariate or machine-learning methods are better suited to high-dimensional, nonlinear, and spatially variable vineyard systems.

6 Statistical Responses of Grape Growth and Quality to Different Management Factors

6.1 Relationships between environmental factors and grape growth and quality

Environmental factors show clear statistical relationships with grape growth and quality, but the strength and direction of these relationships vary by trait and phenological stage. Climate and soil significantly affected table-grape yield and most tested quality traits in a three-year commercial vineyard study, and those effects differed across growth stages (Anastasiou et al., 2022). A terroir-oriented variance analysis similarly showed that vine development and phenology were driven mainly by climate, whereas yield parameters were jointly shaped by climate and soil, with cluster number more climate-sensitive and cluster weight more soil-sensitive. Statistical work in the Hexi Corridor further found that titratable acidity was negatively correlated with warmer temperatures and growing degree days but positively correlated with rainfall and soil available potassium, confirming that fruit composition responds to both meteorological and edaphic gradients.

Quality traits are also differentiated by the specific environmental variables included in the model. In the same Hexi Corridor analysis, juice pH was negatively correlated with annual rainfall and soil available potassium, but positively correlated with temperature-related indices and soil total nitrogen. High-altitude modeling using PCA and structural equation modeling showed strong spatial separation in grape quality, and the direct effects of temperature and extreme air temperature were greater than those of light, with major contributions from soil temperature and day-night temperature difference (Zhang et al., 2024). Postharvest table-grape quality also tracked climatic indices statistically, with Box-Cox-transformed Pearson correlations linking hydrothermic conditions in early and mid-season stages to traits such as pH, Brix, grape volume, and pedicel detachment force.

6.2 Relationships between cultivation practices and grape quality formation

Cultivation practices alter grape quality formation through measurable effects on yield components, berry composition, and vine physiological status. A recent meta-analysis found that cluster thinning, leaf removal, shoot thinning, and irrigation reduction significantly reduced yield, while less severe pruning increased yield mainly through higher bud number (Cameron et al., 2024). A companion meta-analysis on composition showed that management effects depended on timing and severity, and that increases in anthocyanins and total phenolics were generally larger than increases in soluble solids. However, these compositional gains often came with lower productivity per hectare, because many practices increased concentration while reducing yield and total anthocyanin or sugar output per unit area.

Water and nutrient management show the clearest statistical responses because they directly affect both production and berry chemistry. In a three-year drip fertigation experiment, both irrigation and fertilization significantly affected yield, irrigation significantly altered titratable acidity and sugar-acid ratio, and the moderate water-moderate fertilizer treatment gave the best combined score for yield, quality, and resource-use efficiency. Under extremely arid conditions, combined organic-inorganic fertilization increased soil available nutrients, enhanced photosynthetic traits, and improved grape yield and fruit quality relative to sole inorganic fertilizer, with PCA identifying 720 mm irrigation and a 50:50 fertilizer ratio as the preferred regime. Broader evidence also indicates that nutrient effects are not purely positive: nutrient-specific programs are needed because deficiencies reduce growth and sugar or polyphenol accumulation, whereas mineral fertilization can also interfere with grape physicochemical composition if poorly balanced.

6.3 Interactions among orchard management factors

The strongest statistical signal across studies is that orchard factors interact rather than act independently. Reviews of grape quality emphasize that soil, nutrients, light, temperature, and water availability affect quality both as standalone factors and in interaction. This is reinforced by integrated modeling work showing that grape quality depends simultaneously on viticultural practices and natural conditions, and that practices should be considered as linked technical routes rather than isolated interventions. In spatially heterogeneous vineyards, site-specific management confirmed this interaction logic: leaf removal improved productivity and quality in high-vigor zones, while the benefits of added nitrogen in low-vigor zones depended strongly on water availability (Pereyra et al., 2022).

Several studies show that interaction terms or covariates materially improve explanation of vineyard responses, even when some pairwise interaction effects are weak. In North China, irrigation-fertilization interactions were statistically significant only for fertilizer productivity, yet the integrated optimum still emerged from joint evaluation of yield, quality, water-use efficiency, and fertilizer-use efficiency. In Mediterranean organic vineyards, regression models for SPAD, stem water potential, yield, and must quality improved when detailed soil parameters were included as covariates, showing that soil variability must be accounted for when estimating practice effects (Raffa et al., 2022). Continuous cropping studies add a biological interaction layer, because declining soil nutrients and beneficial microorganisms, together with increasing pathogens, jointly shifted grape yield and quality over time. Overall, the statistical response of grape growth and quality is best understood as a combined system response to environmental conditions, cultivation measures, and their interactions. For this reason, multifactor and spatially explicit analyses are more suitable than single-factor comparisons for explaining vineyard performance and guiding precision management.

7 Case Study: Statistical Analysis of Grape Yield and Quality Based on Orchard Management Data

7.1 Case study design and data sources

The case study should be designed as a multi-source observational analysis using vineyard blocks or experimental plots as the basic statistical units. Recent grape studies commonly combine management records with field measurements of yield components, berry composition, and environmental covariates, allowing the same dataset to support both explanatory statistics and predictive modeling (Ohana-Levi et al., 2024). A practical design is to include core response variables such as yield per vine, cluster number, cluster weight, berry weight, total soluble solids, titratable acidity, pH, anthocyanins, and tannins, because these indicators are repeatedly used to represent grape growth and fruit quality in integrated analyses. Data sources should cover four linked domains: vineyard management, orchard environment, vine state, and harvest outcomes. Management variables can include irrigation quota, fertilizer rate, training system, pruning intensity, cover-crop or soil-management practice, and mechanization, while environmental data can include weather, evapotranspiration, rainfall, soil chemistry, topography, and remote-sensing indices. To strengthen inference, the dataset should also contain vine physiological or canopy descriptors such as leaf area index, chlorophyll, stem water potential, gas exchange, or fPAR, because these variables often mediate the effect of management on yield and berry composition.

In terms of sampling structure, the strongest recent studies use either multi-year field trials or multi-site databases to capture temporal and spatial variability. Examples include four long-term irrigation experiments across different climatic regions, three-year drip-fertigation trials, and two-season multimodal sensing studies across separate vineyards, all of which improve the generality of fitted relationships. If the present paper emphasizes management diagnosis rather than only prediction, then retaining site identifiers, year effects, and management-zone information is important because vineyard heterogeneity strongly affects statistical responses. For statistical processing, the case-study dataset should be split into training and testing subsets or organized into calibration and independent validation sets when predictive models are used. Recent vineyard studies applied repeated k-fold cross-validation, 5-fold cross-validation, and independent-vineyard validation, showing that robust validation is now standard for both machine-learning and multivariate workflows. Before modeling, preprocessing should address missing values, scaling, outliers, and dimensionality reduction, with PCA, recursive feature elimination, and collinearity screening being especially useful when orchard variables are numerous and correlated (Figure 3).

7.2 Statistical relationships between management factors and grape growth and quality

The statistical relationships in orchard datasets generally show that grape yield is jointly controlled by vegetative state, irrigation, and thermal demand. In a multi-experiment database, yield was positively related to cluster weight and cluster number, while cluster weight and cluster number were negatively related to each other, indicating compensatory behavior among yield components (Ohana-Levi et al., 2024). The same study found that cumulative leaf area index, growing degree days, cumulative irrigation, and evapotranspiration were the dominant variables affecting yield components, with irrigation showing a positive effect that leveled off above about

348-395 mm per season. Quality traits show similarly structured but more complex relationships with management and environment. Moderate irrigation and fertilization significantly altered yield and berry chemistry in North China, and the moderate water-moderate fertilizer treatment gave the best combined outcome for yield, quality, and efficiency. In extremely arid vineyards, combined organic-inorganic fertilization increased soil nutrient availability, improved photosynthesis, and raised both yield and fruit quality, supporting the inclusion of soil fertility variables and water-fertilizer interactions in the case-study analysis.

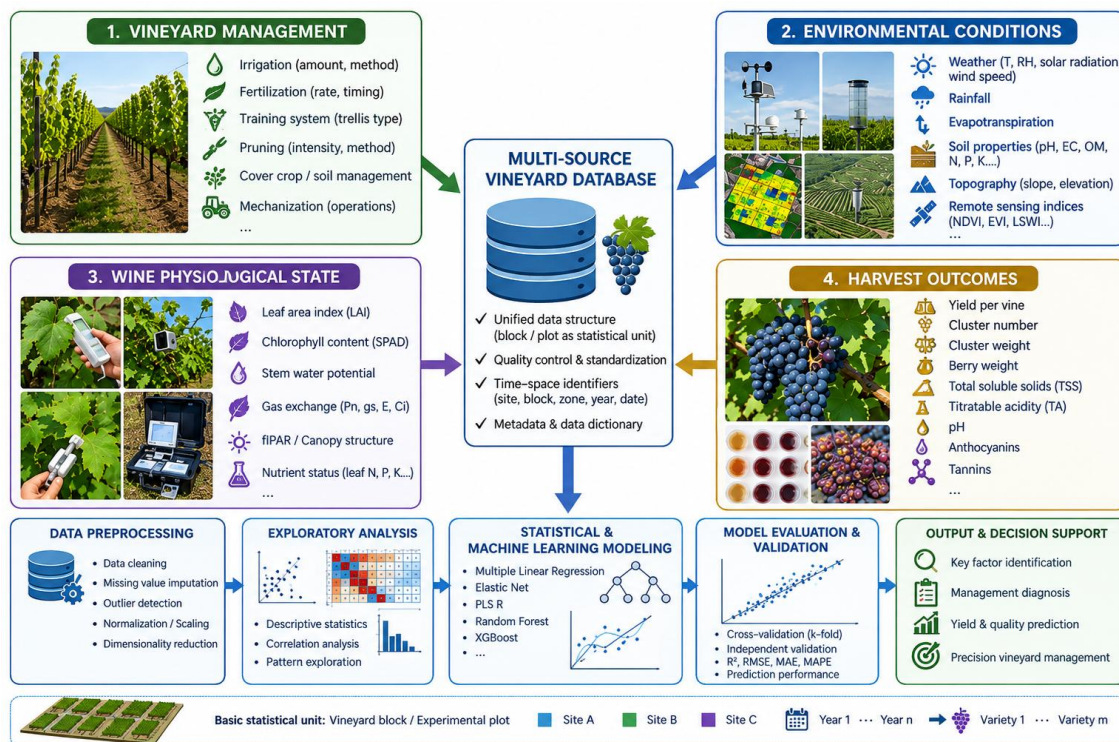


Figure 3 Multi-source data framework for observational analysis of grapevine growth and fruit quality

Relationships between soil conditions and berry quality are also statistically important and should not be treated as background noise. In Cabernet Franc vineyards, soil nutrient indices showed complex and correlated associations with quality, and partial least squares regression was needed to screen the main nutrient factors before building multilinear models. Likewise, soil variability improved regression performance in Mediterranean vineyards when represented by detailed covariates rather than only proximal sensor summaries, which shows that edaphic heterogeneity can materially change estimated management effects. Management-system comparisons also show that not all cultivation factors influence yield and quality in the same way. Organic and biodynamic management reduced vine growth and yield relative to integrated management, while fruit quality remained largely unchanged, implying that some management effects operate mainly through vigor, disease pressure, and physiological performance rather than direct changes in berry composition. At the farm-economic scale, training system had a stronger effect on total value product than irrigation method or harvest mechanization, which suggests that structural management variables should be modeled alongside seasonal inputs in orchard case studies (Bopp et al., 2022).

7.3 Identification of key influencing factors and model evaluation

Key influencing factors should be identified by combining variable-screening methods with models that can rank predictor importance. PCA-based minimum data set selection, partial least squares screening, and correlation preselection have all been used to reduce redundancy before final modeling, especially when predictors include soil, weather, physiology, and sensor-derived variables together. This step is essential because vineyard datasets often contain multicollinearity, and unfiltered predictors can weaken interpretation even when overall predictive accuracy appears high. Across recent case studies, the most repeatedly identified influential factors include weather, irrigation, canopy structure, and plant-status variables. Weather-only models often outperformed

soil-only models for yield prediction, and important predictors included plant age, plot identity, May temperature, soil pH, and exchangeable Zn, Cu, K, and Mn (Andrade et al., 2023). In multimodal quality modeling, top predictors included canopy temperature depression, leaf chlorophyll content, fiPAR, stem water potential, stomatal conductance, and net photosynthesis, indicating that physiological state variables are especially informative bridges between management actions and berry outcomes.

Model evaluation should rely on both goodness-of-fit and error-based metrics, with final judgment based on independent validation rather than training performance alone. Recent vineyard studies used R^2 , RMSE, MAE, MAPE, and sometimes ELPD, and they repeatedly showed that ensemble or tree-based models often outperform single linear models for yield or quality prediction (Canicatti et al., 2025). For example, weighted ensemble learning improved yield prediction over individual base learners, and gradient boosting or random forest frequently gave the best performance for yield components and berry composition traits. Even so, model choice should depend on the study objective. If the goal is causal interpretation or management recommendation, multivariate linear regression, log-log regression, or partial least squares models remain useful because their coefficients are directly interpretable. If the goal is field-scale forecasting or precision intervention, then random forest, gradient boosting, AutoML, Bayesian hierarchical mapping, or stacked ensembles are more suitable because they better capture nonlinear responses, spatial heterogeneity, and uncertainty (Canicatti et al., 2025). Overall, the case study should treat grape yield and quality as multifactor responses to orchard management, environmental conditions, and vine physiological status. A well-designed dataset, combined with validated multivariate or machine-learning models, can identify the main controlling factors and provide a statistically sound basis for precision vineyard management.

8 Integrated Discussion and Optimization of Orchard Management

8.1 Key management factors and their underlying mechanisms

The key management factors are water supply, nutrient management, canopy-load regulation, and soil management because these variables directly control vine vigor, fruit set, berry growth, ripening, and composition. Soil and climate jointly determine vine water and nitrogen supply, which then regulate vegetative and reproductive development. Meta-analysis further shows that the effects of irrigation, leaf removal, shoot thinning, cluster thinning, and pruning severity depend on timing, intensity, environment, and cultivar, so the same practice can improve one trait while reducing another (Cameron et al., 2024). The underlying mechanisms are increasingly clear from recent experimental work. Moderate drip fertigation improved the balance among yield, berry quality, water-use efficiency, and fertilizer productivity in North China, indicating that optimized water and nutrient synchrony is more effective than maximizing either input alone. In extremely arid vineyards, combining organic and inorganic fertilizer increased soil available nutrients, enhanced photosynthesis, and improved grape growth, yield, and quality, which supports the view that nutrient effects operate through both soil fertility and vine physiological status.

Canopy and crop-load management act mainly through source-sink balance and cluster microclimate. Yield-focused meta-analysis showed that reduced irrigation lowered all yield components, while less severe pruning increased yield by increasing bud number, confirming that structural and seasonal practices shift production through different physiological pathways. Composition-focused meta-analysis found that many practices increased anthocyanins and total phenolics more strongly than sugars, but these gains often came with lower production per hectare, so quality improvement cannot be evaluated independently of output and economic return. Soil management adds a longer-term mechanism that links orchard practices to sustainability. In Mediterranean organic vineyards, groundcovers significantly influenced must quality, anthocyanins, polyphenols, and yeast assimilable nitrogen, showing that inter-row management alters both water and nitrogen dynamics. Long-term continuous cropping, by contrast, reduced soil nutrients and beneficial microorganisms while increasing pathogens, and these shifts were associated with declines in yield and aroma quality, indicating that biological soil degradation should be treated as a core management constraint rather than a background condition.

8.2 Data-driven precision orchard management strategies

Data-driven precision orchard management should be built on management zones, covariate-adjusted models, and repeated in-season monitoring rather than plot-wide uniform decisions. Commercial vineyard evidence shows that the combined effect of weather and soil on spatiotemporal variability in table-grape quantity and quality is essential information for modern precision viticulture (Anastasiou et al., 2022). Site-specific work in heterogeneous vineyards similarly showed that differential irrigation, fertilization, and leaf removal by vigor zone can optimize production and quality while increasing input-use efficiency. The best precision strategies therefore start with zone delineation and then adapt management within each zone. Terrain-based studies showed that topographic wetness index can delineate irrigation management zones and that understanding the links among soil water availability, vine vigor, and water stress improves irrigation decisions. Remote and field measurements used together are especially useful because they combine high spatial coverage with physiological accuracy across the season.

Statistical modeling then converts heterogeneous vineyard data into decision rules. Multivariate PLS models integrating viticultural practices, soil, and climate quantified which variables matter most for each harvest-quality criterion, and they identified plant density, dryness index, and nitrogen fertilization among the major explanatory factors. In another organic-vineyard study, regression models for vine status, yield, and must quality improved when detailed soil parameters were included as covariates, which shows that precision models are stronger when they explicitly account for edaphic variability. Precision management should also include predictive tools that match the complexity of the target problem. Climatic indices combined with Box-Cox-transformed correlations successfully predicted several postharvest table-grape traits and revealed management-zone-specific dependencies (Anastasiou et al., 2022). PCA and SEM applied to high-altitude vineyards separated quality classes and showed that temperature variables had stronger direct effects than light, demonstrating how multivariate tools can move from description to mechanism-based management adjustment.

8.3 Applications of statistical analysis in sustainable grape production

In sustainable grape production, statistical analysis is most useful when it supports simultaneous evaluation of yield, quality, resource efficiency, and environmental effects. Reviews of Mediterranean irrigation strategies conclude that deficit irrigation combined with agroecological practices such as cover crops, mulching, composting, and reduced tillage can improve productive water-use efficiency and resilience under climate change. This broader framework aligns with vineyard studies showing that management should target not only fruit composition, but also soil health and system stability over time. Recent fertigation studies illustrate how statistical analysis can identify practical sustainability optima. Under drip fertigation, a 25% irrigation reduction combined with an intermediate fertilizer rate maintained vine vigor while balancing yield and environmental benefits, and global warming potential was driven mainly by SPAD, water-filled pore space, and residual soil nutrients (Peng et al., 2024). This result complements production-oriented optimization in wine grape, where moderate water and fertilizer rates gave the highest integrated performance score across yield, quality, and input-use efficiency.

Statistical analysis also supports sustainability by revealing when management effects depend on interactions that would be missed in simple comparisons. In a high-heterogeneity vineyard, the benefits of additional nitrogen in low-vigor zones depended strongly on water availability, while leaf removal in high-vigor zones was the most efficient way to improve productivity and quality. A recent three-year study of tillage and organic fertilization likewise found complex treatment-by-year interactions in grape mineral, hormonal, and enzymatic traits, reinforcing the need for multiyear models before generalizing management recommendations (Kaya et al., 2025). Finally, sustainable optimization should include economic as well as agronomic criteria. A Chilean case study using log-log regression found that training system had the largest effect on total value product, while pressurized irrigation and mechanized harvest showed no significant effect in that dataset, indicating that structural management choices can outweigh some seasonal technologies in economic performance. Overall, statistical analysis supports sustainable grape production most effectively when it integrates biophysical, environmental, and economic responses into one management framework.

9 Conclusions

Grape growth and quality are shaped by a multifactor system rather than by any single management input. Environmental conditions, especially temperature, water status, radiation, and soil properties, repeatedly emerge as dominant controls on yield components and berry composition. Across vineyards, cumulative leaf area index, growing degree days, irrigation amount, and evapotranspiration explain much of the variation in yield, cluster number, and cluster weight, while water effects are often nonlinear and tend to plateau beyond moderate irrigation thresholds. Soil nutrient supply is similarly complex, because berry quality responds to multiple correlated nutrient indices rather than to isolated elements, making simple one-factor interpretation inadequate. At the cultivation level, pruning, thinning, irrigation reduction, and canopy operations can improve particular quality traits but often reduce yield, confirming that vineyard management is fundamentally an exercise in balancing quantity, composition, and profitability. The strongest practical conclusion is that optimized combinations of water, fertilizer, and canopy regulation generally outperform maximization of any one input. In drip-fertigated wine grape, moderate irrigation with moderate fertilization provided the best combined balance of yield, berry quality, and input-use efficiency. In extremely arid vineyards, a 50:50 organic-inorganic fertilizer ratio combined with 720 mm irrigation improved soil nutrients, photosynthesis, yield, and fruit quality, showing that water and fertility must be managed jointly. Groundcover and soil-management treatments also altered must quality, anthocyanins, polyphenols, and nitrogen status, and their effects became clearer when soil variability was explicitly included in the analysis. Structural management choices matter as well: training system strongly affected vineyard economic performance in Chile, while pruning intensity and mycorrhizal biofertilization significantly changed soluble solids, sugars, anthocyanins, acidity, and yield traits in recent field work.

Statistical analysis contributes most by converting diverse vineyard observations into interpretable relationships, predictive tools, and management thresholds. Correlation analysis and basic regression remain useful for screening links among climate, soil, vine status, and berry traits, but multivariate methods are needed once predictors become numerous and collinear. Partial least squares regression, multilinear regression, and linear programming have already been used to move from diagnosis to optimization by identifying major soil-nutrient drivers of berry quality and estimating target nutrient ranges for improved fruit composition. Meta-analysis adds another level of contribution by synthesizing management effects across experiments, showing where practices such as irrigation reduction, thinning, or pruning have consistent yield consequences and where their effects depend on timing or severity. More recent work shows that machine learning and spatial modeling substantially extend these capabilities when vineyard data are nonlinear, high-dimensional, or spatially heterogeneous. Gradient boosting and random forest often outperform simpler models for predicting yield components and berry composition from multimodal sensing and physiological data, while ensemble learning can further improve predictive stability. Bayesian yield mapping adds the important dimension of uncertainty quantification, allowing managers to identify yield-limiting zones, prioritize selective harvest, and support post-harvest fertilization planning with spatial confidence estimates rather than point predictions alone. Automated and sensor-based approaches also reduce reliance on destructive laboratory sampling by enabling non-destructive estimation of sugar content or total soluble solids across whole vineyard blocks. Taken together, these methods have shifted viticulture from descriptive assessment toward precision decision-making that can target variability within blocks and across seasons.

Future research should focus first on longer and broader datasets that better capture year effects, genotype differences, and site-specific responses. Several studies indicate that perennial carryover effects, year-to-year climatic variation, and interactions among treatment, site, and season complicate causal interpretation, so short trials are often insufficient for general recommendations. Multi-season and multi-vineyard datasets are therefore needed to improve model generalization, reduce prediction uncertainty, and capture responses across cultivars, training systems, and pedoclimatic regions. Water-management research should also move beyond universal prescriptions by incorporating vine age, planting density, and variety, because these factors modify the balance between yield, water productivity, and quality. Similarly, future nutrient studies should combine site-specific quantitative trials with explicit tests of multi-factor interactions and quality-response mechanisms rather than

relying only on observational nutrient correlations. A second priority is tighter integration of omics, sensing, and decision models for sustainable vineyard management. Reviews of grape quality point to new scions and rootstocks, transcriptomics, and metabolomics as promising tools for understanding how cultivar quality can be maintained under changing environments and management regimes. At the same time, remote and proximal sensing need to be linked more directly with physiological indicators, disease monitoring, and management actions so that prediction pipelines extend from vineyard condition to final grape and wine quality. Methodologically, future work should emphasize standardized monitoring protocols, better uncertainty reporting, and models that jointly evaluate agronomic, environmental, and economic outcomes. Overall, future progress in statistical analysis of vineyard management factors will depend on building integrated, interpretable, and scalable frameworks that support both precision intervention and long-term sustainability. In conclusion, the evidence shows that grape growth and quality depend on interacting management and environmental controls, and that statistical analysis is essential for identifying those controls, quantifying their tradeoffs, and guiding more precise and sustainable vineyard management.

Acknowledgments

I extend my sincere gratitude to the anonymous reviewers for their valuable and insightful comments, which have greatly strengthened this paper.

Conflict of Interest Disclosure

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

Reference

- Abdel-Sattar M., Al-Saif A.M., Aboukarima A.M., Eshra D.H., and Sas-Paszt L., 2022, Quality attributes prediction of Flame Seedless grape clusters based on nutritional status employing multiple linear regression technique, *Agriculture*, 12(9): 1303.
<https://doi.org/10.3390/agriculture12091303>.
- Alatzas A., Theocharis S., Miliordos D.E., Leontaridou K., Kanellis A.K., Kotseridis Y., Hatzopoulos P., and Koundouras S., 2021, The effect of water deficit on two Greek *Vitis vinifera* L. cultivars: physiology, grape composition and gene expression during berry development, *Plants*, 10(9): 1947.
<https://doi.org/10.3390/plants10091947>.
- Anastasiou E., Templalexis C.G., Lentzou D., Biniari K., Xanthopoulos G., and Fountas S., 2023, Do soil and climatic parameters affect yield and quality on table grapes?, *Smart Agricultural Technology*, 3: 100088.
<https://doi.org/10.1016/j.atech.2022.100088>.
- Andrade C.B., Moura-Bueno J.M., Comin J.J., and Brunetto G., 2023, Grape yield prediction models: Approaching different machine learning algorithms, *Horticulturae*, 9(12): 1294.
<https://doi.org/10.3390/horticulturae9121294>.
- Bopp C., Jara-Rojas R., Engler A., and Araya-Alman M., 2022, How are vineyards management strategies and climate-related conditions affecting economic performance ? a case study of Chilean wine grape growers, *Wine Economics and Policy*, 11(2): 61-73.
<https://doi.org/10.36253/wep-12739>.
- Butiuc-Keul A., and Coste A., 2023, Biotechnologies and strategies for grapevine improvement, *Horticulturae*, 9(1): 62.
<https://doi.org/10.3390/horticulturae9010062>.
- Cameron W., Petrie P.R., and Bonada M., 2024, Effects of vineyard management practices on winegrape yield components, a review using meta-analysis, *American Journal of Enology and Viticulture*, 75(1): 0750007.
<https://doi.org/10.5344/ajev.2024.23046>.
- Canicatti M., Ferro M.V., Vallone M., Orlando S., and Catania P., 2025, Bayesian yield mapping and uncertainty analysis in vineyards using remote sensing data and grape harvester tracking, *Precision Agriculture*, 26(4): 63.
<https://doi.org/10.1007/s11119-025-10258-w>.
- El-Kereamy A., and Kurtural S.K., 2022, Yield and physiological response of Autumn King and Scarlet Royal table grapes to cane and spur pruning systems, *Horticulturae*, 8(9): 802.
<https://doi.org/10.3390/horticulturae8090802>.
- Ferro M.V., Catania P., Miccichè D., Pisciotta A., Vallone M., and Orlando S., 2023, Assessment of vineyard vigour and yield spatio-temporal variability based on UAV high resolution multispectral images, *Biosystems Engineering*, 231: 36-56.
<https://doi.org/10.1016/j.biosystemseng.2023.06.001>.
- Huang Y., Sun X., Xu M., Zhou X., Zhong X., Luo G., Yang G., and Peng J., 2026, Organic fertilizer substitution improves grape yield and quality by regulating soil nutrient availability and berry morphological traits: a two-year field study, *Agriculture*, 16(8): 862.
<https://doi.org/10.3390/agriculture16080862>.

- Jewan S.Y.Y., Gautam D., Sparkes D., Singh A., Billa L., Cogato A., Murchie E.H., and Pagay V., 2024, Integrating hyperspectral, thermal, and ground data with machine learning algorithms enhances the prediction of grapevine yield and berry composition, *Remote Sensing*, 16(23): 4539.
<https://doi.org/10.3390/rs16234539>
- Karn R., Hillin D., Helwi P., Scheiner J., and Guo W., 2024, Assessing grapevine vigor as affected by soil physicochemical properties and topographic attributes for precision vineyard management, *Scientia Horticulturae*, 328: 112857.
<https://doi.org/10.1016/j.scienta.2024.112857>
- Kaya O., Karakus S., Ates F., Daler S., and Hatterman-Valenti H., 2025, Enhancing Royal grape quality through a three-year investigation of soil management practices and organic amendments on berry biochemistry, *Chemical and Biological Technologies in Agriculture*, 12(1): 17.
<https://doi.org/10.1186/s40538-025-00733-x>
- Khadatkar A., Sawant C.P., Thorat D., Gupta A., Jadhav S.K., Gawande D., and Magar A.P., 2025, A comprehensive review on grapes (*Vitis* spp.) cultivation and its crop management, *Discover Agriculture*, 3(1): 9.
<https://doi.org/10.1007/s44279-025-00162-2>
- Krishankumar S., Hunter J.J., Alyafei M., Hamed F., Subramaniam S., Ramlal A., Kurup S.S., and Amiri K.M.A., 2025, Physiological, biochemical and elemental responses of grafted grapevines under drought stress: insights into tolerance mechanisms, *BMC Plant Biology*, 25(1): 385.
<https://doi.org/10.1186/s12870-025-06374-4>
- Kupe M., Uzundumlu A.S., and Govez E., 2026, Trends in global grape production over six decades: Leading countries, market concentration, and future projections based on ARIMA modeling, *Horticulturae*, 12(6): 658.
<https://doi.org/10.3390/horticulturae12060658>
- Macías-Gallardo F., Quiñones-Muñoz T.A., Miranda-Avilés R., Ramírez-Santoyo L.F., Zano G.A., and Ozuna C., 2025, Impact of organic agriculture on the quality of grapes (Syrah and Tempranillo) harvested in Guanajuato, Mexico: Relationship between soil elemental profile and grape bioactive properties, *Agriculture*, 15(2): 169.
<https://doi.org/10.3390/agriculture15020169>
- Naor A., Gal Y., and Bravdo B., 2002, Shoot and cluster thinning influence vegetative growth, fruit yield, and wine quality of 'Sauvignon blanc' grapevines, *Journal of the American Society for Horticultural Science*, 127(4): 628-634.
<https://doi.org/10.21273/jashs.127.4.628>
- Ohana-Levi N., Cohen Y., Munitz S., Michaelovsky R., Ferman Mintz D., Hagag N., Getz Y., and Netzer Y., 2024, The response of yield, number of clusters, and cluster weight to meteorological factors and irrigation practices in grapevines: A multi-experiment study, *Scientia Horticulturae*, 326: 112761.
<https://doi.org/10.1016/j.scienta.2023.112761>
- Peng X., Chen D., Zhen J., Wang Y., and Hu X., 2024, Greenhouse gas emissions and drivers of the global warming potential of vineyards under different irrigation and fertilizer management practices, *Science of the Total Environment*, 950: 175447.
<https://doi.org/10.1016/j.scitotenv.2024.175447>
- Pereyra G., Pellegrino A., Gaudin R., and Ferrer M., 2022, Evaluation of site-specific management to optimise *Vitis vinifera* L. (cv. Tannat) production in a vineyard with high heterogeneity, *OENO One*, 56(3): 397-412.
<https://doi.org/10.20870/oeno-one.2022.56.3.5485>
- Raffa D.W., Antichi D., Carlesi S., Puig-Sirera À., Rallo G., and Bàrberi P., 2022, Ground vegetation covers increase grape yield and must quality in Mediterranean organic vineyards despite variable effects on vine water deficit and nitrogen status, *European Journal of Agronomy*, 136: 126483.
<https://doi.org/10.1016/j.eja.2022.126483>
- Rodrigues C.S., Moura M.F., Oliveira G.L., Silva M.P., Tecchio M.A., and Leão P.C.S., 2024, Best linear unbiased prediction in combination with path analysis in processing grapes, *Scientia Agricola*, 81: e20220218.
<https://doi.org/10.1590/1678-992X-2022-0218>
- Romero P., Navarro J.M., and Ordaz P.B., 2022, Towards a sustainable viticulture: The combination of deficit irrigation strategies and agroecological practices in Mediterranean vineyards: a review and update, *Agricultural Water Management*, 259: 107216.
<https://doi.org/10.1016/j.agwat.2021.107216>
- Rouxinol M.I., Martins M.R., Murta G.C., Mota Barroso J., and Rato A.E., 2022, Quality assessment of red wine grapes through NIR spectroscopy, *Agronomy*, 12(3): 637.
<https://doi.org/10.3390/agronomy12030637>
- Schorn-García D., Giussani B., García-Casas M.J., Rico D., Martín-Diana A.B., Aceña L., Busto O., Boqué R., and Mestres M., 2023, Assessment of variability sources in grape ripening parameters by using FTIR and multivariate modelling, *Foods*, 12(5): 962.
<https://doi.org/10.3390/foods12050962>
- Schrader J.A., Domoto P.A., Nonnecke G.R., and Cochran D.R., 2020, Multifactor models for improved prediction of phenological timing in cold-climate wine grapes, *HortScience*, 55(12): 1912-1925.
<https://doi.org/10.21273/hortsci15367-20>
- Selnekovič A., Mezey J., Janás M., Kollárová I., Vician T., and Ernst D., 2026, Application of plant stimulants to Slovak grape varieties (*Vitis vinifera* L.) and their effect on selected physiological indicators, *Agriculture*, 16(7): 812.
<https://doi.org/10.3390/agriculture16070812>
- Shahab M., Roberto S., Adnan M., Fahad S., Koyama R., Saleem M., Nasar J., Saud S., Hassan S., and Nawaz T., 2023, Phenolic compounds as a quality determinant of grapes: a critical review, *Journal of Plant Growth Regulation*, 42(9): 5325-5331.
<https://doi.org/10.1007/s00344-023-10953-w>

- Sun Y., Sun S., Zahid M.S., Qiu Q., Wang L., and Wang S., 2025, Root-applied brassinosteroid and salicylic acid enhance thermotolerance and fruit quality in heat-stressed 'Kyoho' grapevines, *Frontiers in Plant Science*, 16: 1563270.
<https://doi.org/10.3389/fpls.2025.1563270>
- Visconti F., Intrigliolo D.S., and Mirás-Avalos J.M., 2023, Effects of the annual nitrogen fertilization rate on vine performance and grape quality for winemaking: Insights from a meta-analysis, *Australian Journal of Grape and Wine Research*, 2023(1): 7989254.
<https://doi.org/10.1155/2023/7989254>
- Yuan Y., Liu S., Xie Y., Nie J., Yang X., and Huang R., 2025, The effects of light duration and intensity with supplemental light-emitting diode lights on grape photosynthesis, yield, and fruit quality, *Agronomy*, 15(3): 518.
<https://doi.org/10.3390/agronomy15030518>
- Zapata-García S., Berrios P., Temnani A., Espinosa P.J., Monllor C., and Pérez-Pastor A., 2025, Combined use of biostimulation and deficit irrigation improved the fruit quality in table grape, *Plants*, 14(3): 485.
<https://doi.org/10.3390/plants14030485>
- Zhang K., Cao J., Yin H., Wang J., Wang X., Yang Y., and Xi Z., 2024, Microclimate diversity drives grape quality difference at high-altitude: Observation using PCA analysis and structural equation modeling (SEM), *Food Research International*, 191: 114644.
<https://doi.org/10.1016/j.foodres.2024.114644>

Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.