Meteorological Conditions for Cabernet Sauvignon Quality Formation and Rating Methods in the Eastern Foothills of Helan Mountain (Postprint)

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Abstract

Grape quality largely determines wine quality and is closely related to meteorological conditions. Under normal management and agricultural technology levels, the method for measuring whether meteorological conditions during grape growth are suitable for quality formation is referred to as meteorological evaluation technology for wine grape quality. Research on meteorological rating techniques and meteorological indicators for wine grape quality formation can provide a climatic reference basis for wine commercial rating, vintage identification, and cellaring. Using data from 51 samples of Cabernet Sauvignon collected and analyzed from multiple sites at the eastern foothill of Helan Mountain from 2003-2011, including total sugar, total acid, sugar-acid ratio, pH, and tannin, significant meteorological factors with biological significance were identified through correlation screening. Weight models for the five quality indicators were established based on the coefficient of determination of each factor, and a comprehensive quality meteorological evaluation model was constructed through the contribution of individual quality indicators to overall quality. Referencing previous research on wine quality and wine grape quality and four standards, thresholds for each quality indicator of Cabernet Sauvignon were determined based on the total sugar, total acid, sugar-acid ratio, pH, and tannin required for wine production. Meteorological factor thresholds corresponding to wine quality and meteorological classification standards for Cabernet Sauvignon quality were derived inversely using the model. Back-substitution tests showed that all five quality indicators passed the R-test and F-test at the 0.001 significance level, being close to measured values and showing consistent trends. The simulation effects for total sugar, total acid, sugar-acid ratio, and tannin were favorable, with R 0.59 and relatively small RMSE, but the error for pH was relatively large. The quality grade of Cabernet Sauvignon was estimated using

50 samples that did not participate in model construction. Total sugar and total acid were close to measured values. For individual samples, the errors in sugar-acid ratio and tannin were relatively large, but the variation trends were consistent with measured values. The pH of samples was within the suitable range and relatively stable. In terms of comprehensive scores and grades, 28 samples matched the actual grade, 18 samples had errors within one grade, and only 4 samples differed by two grades, accurately reflecting the quality of raw materials. The meteorological evaluation indicators and model for Cabernet Sauvignon quality provide a feasible method for evaluating wine grape quality at the eastern foothill of Helan Mountain.

Full Text

Preamble

Meteorological Conditions and Rating Method for Quality Formation of Cabernet Sauvignon in the Eastern Foothills of Helan Mountain*

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Abstract: Grape quality largely determines wine quality and is closely related to meteorological conditions during the growing season. Under normal management and agricultural technology levels, methods for evaluating whether meteorological conditions are suitable for fruit quality formation are referred to as wine grape quality meteorological evaluation techniques. Research on meteorological rating techniques and indices for wine grape quality formation can provide climatic references for wine commercial grading, vintage identification, and cellaring. Using data from 51 samples of Cabernet Sauvignon collected and analyzed between 2003-2011 from multiple sites in the eastern foothills of Helan Mountain, we identified significant meteorological factors with biological meaning through correlation screening. Weight models for five quality indicators were established based on the coefficient of determination for each factor, and a comprehensive quality meteorological evaluation model was constructed based on the contribution of individual quality indicators to overall quality. Referencing previous research on wine and grape quality and four established standards, we determined thresholds for each Cabernet Sauvignon quality indicator according to the total sugar, total acid, sugar-acid ratio, pH, and tannin content required for winemaking. Using the models, we derived meteorological factor thresholds corresponding to wine quality and established a meteorological classification standard for Cabernet Sauvignon quality. Back-substitution tests showed that all five quality indicators passed R and F tests at the 0.001 significance level, with estimated values close to measured values and consistent trends. Total sugar, total acid, sugar-acid ratio, and tannin showed good simulation effects (R 0.59) with small RMSE, while pH errors were relatively larger. Using 50 samples not involved in model construction, we estimated Cabernet Sauvignon quality grades. Total sugar and total acid estimates were close to measured values. While errors in sugar-acid ratio and tannin were relatively large for individual samples, the trends were consistent with measured values. Sample pH values were all within suitable ranges and relatively stable. In terms of comprehensive scores and grades, 28 samples matched actual grades, 18 samples differed by one grade, and only 4 samples differed by two grades, accurately reflecting raw material quality. The meteorological evaluation indices and models for Cabernet Sauvignon quality provide a feasible method for evaluating wine grape quality in the eastern foothills of Helan Mountain.

Keywords: Eastern Foothills of Helan Mountain; Cabernet Sauvignon; Wine Grape; Meteorological Quality; Grade

Introduction

The eastern foothills of Helan Mountain enjoy abundant sunlight and heat, with dry and rain-free conditions, and are recognized by the industry as one of the world' s premier wine grape production regions. Wines from this area have won numerous domestic and international awards, and the region received "National Geographical Indication Product" protection certification for wine in 2003 [1]. The industry widely acknowledges that high-quality wine depends primarily on variety, soil, and meteorological conditions [2], with meteorological conditions being the key determinant of raw material quality [3]. High-quality vintage wines exhibit high concentration and abundant levels of tannins, pigments, phenolic substances, minerals, and vitamins [4]. Developing meteorological evaluation methods for wine grape quality can provide important references for wine grading, value-added enhancement, and market recognition.

Research on wine grape quality must first identify the key compositional indicators that determine wine quality. Li Jiming [5] proposed that wine quality depends on grape total sugar, total acid, sugar-acid ratio, pH, and tannin content. Total sugar determines alcohol content and flavor, with levels above 170 g · L 1 required to produce high-quality wine [6]. Total sugar is related to maturity; Wang Hua et al. [7] used the hydrothermal coefficient to reflect grape maturity. Vršič et al. [8] and Neumann et al. [9] found that rising temperatures increase grape total sugar while decreasing total acid. Mao Ruzhi et al. [10] attributed the higher total sugar and tannin content of Merlot grapes in Yunnan compared to Shandong to higher temperatures, while Webb et al. [11-12] found that Cabernet Sauvignon and Pinot Noir quality in Australia declined with increasing temperature. Total acid affects taste; Li Hua et al. [13] determined that suitable acidity for wine grapes is 6–10 g · L ^{1}, with insufficient acid resulting in bland, flat wine and excessive acid causing harshness. Zhai Heng et al. [14] suggested that total acid depends on photosynthesis and respiration, berry dilution during expansion, and metabolic conversion of sugars, aldehydes, and acids. The sugar-acid ratio is relatively stable; Liu Yulan et al. [15-16] found it closely related to the hydrothermal coefficient 35 days before harvest, with an optimal ratio around 32, as values too high or too low make quality wine production difficult. Chen Xiaoqian et al. [17] considered pH a quality indicator, with Li Jiming [6] recommending 3.0–3.6 for high-quality wine, as higher pH increases microbial activity, reduces anthocyanin color expression and free SO effectiveness, and shortens aging potential. Zhang Xiaoyu et al. [18] found pH closely related to maximum temperature from flowering to maturity. Yue Junbo et al. [19] noted that tannins can precipitate proteins, enhance structure, stabilize pigments, and provide antioxidant, free radical scavenging, and antimicrobial properties that prevent reduction off-flavors.

Grape quality is also soil-related. Zhou Tao et al. [20] found that soil texture affects wine grape quality in the Helan Mountain eastern foothills. Zhao Lei et al. [21] attributed the higher aroma compounds in Cabernet Sauvignon and Merlot from Helan Mountain compared to Shacheng, Hebei to climate and soil differences. Wang Xiuqin et al. [22] related regional climate and soil differences to anthocyanins, sugar, pH, titratable acid, skin and seed polyphenols, and wine alcohol content, malic acid, total phenols, color intensity, color stability, and mouthfeel. Pircalabu et al. [23] and Jones et al. [24] found that climate variability causes significant interannual differences in grape flavor. Other components also affect wine quality and flavor; Cheng et al. [25] found that more days 35°C and less precipitation in Xinjiang increase anthocyanin concentration. Zhang Juan et al. [26] and Zhou Shuzhen et al. [27] found that meteorological conditions affect wine total phenol content. Yang Xiaofan et al. [28] related accumulated temperature to aroma compound accumulation. Fang Yulin et al. [29] demonstrated that water deficit affects wine grape growth and quality. Some countries have attempted climate-based vintage evaluation, such as Webb et al. [11-12] who established climate sensitivity models for premium wine varieties, Gouveia et al. [30] who developed Portuguese vintage climate prediction models using spring-summer maximum temperature, precipitation, and frost days, and Zhang Xiaoyu et al. [18,31] who constructed comprehensive quality weight models for Helan Mountain wine grapes using harmonic weighting methods.

In summary, numerous domestic and international studies have examined relationships between grape quality and meteorological/soil conditions, with some countries establishing climate models for vintage evaluation, but China has not yet established meteorological evaluation models for wine grape quality. Wine quality is 70% determined by raw materials and 30% by processing technology and equipment. Building on previous research, this study conducted correlation screening between meteorological elements (temperature, accumulated temperature, maximum/minimum temperature, precipitation, sunshine hours) from different growth periods and total sugar, total acid, sugar-acid ratio, pH, and tannin content. We selected significant meteorological factors with clear biological meaning and synthesized optimal simulation equations based on their contribution weights. Referencing relevant standards [32-35] and research by Li Jiming et al. [5-6], combined with winemaker experience, we established grading indicators for Cabernet Sauvignon total sugar, total acid, sugar-acid ratio, pH, and tannin, along with threshold ranges for key meteorological factors, constructing a meteorological evaluation model and indices for Cabernet Sauvignon comprehensive quality. This service can evaluate the quality grade that raw materials should achieve under given meteorological conditions, providing references for producing high-quality wine and commercial grading.

Materials and Methods

1.1 Data Sources

Data consisted of 101 samples of Cabernet Sauvignon chemical analysis and phenological observations from grape bases and wineries in 7 cities and counties in the Helan Mountain eastern foothills from 2003–2011. Phenological stages included flowering, veraison, and harvest, with quality analysis indicators including soluble solids, total sugar, total acid, sugar-acid ratio, pH, and tannin content. Total sugar was measured using the Fehling reagent titration method, total acid (as tartaric acid) by NaOH titration, and tannin by the sulfuric acid-phenol method. Fifty-one samples were selected for model development, with the remaining 50 used for validation. Meteorological data comprised daily temperature and precipitation from automatic weather stations corresponding to sampling years and locations, with sunshine hours obtained from county-level meteorological stations (Table 1).

1.2 Expanded Correlation Screening Between Cabernet Sauvignon Quality Indicators and Meteorological Factors

Using chemical analysis results for Cabernet Sauvignon soluble solids, total sugar, total acid, sugar-acid ratio, pH, and tannin, we conducted expanded correlation screening with various meteorological factors during different growth stages, including average temperature, maximum/minimum temperature, 10°C accumulated temperature, cumulative precipitation, average daily precipitation, and cumulative sunshine hours. Periods were divided into flowering to harvest, veraison to harvest, and 10–40 days before harvest at 5-day intervals to expand factor screening and preliminarily select meteorological factors passing significance tests.

1.3 Relationship Models Between Cabernet Sauvignon Quality Components and Meteorological Factors

We examined linear and nonlinear relationships between soluble solids, total sugar, total acid, sugar-acid ratio, pH, and tannin with highly significant meteorological factors. Factors passing R-tests with biological significance for quality formation were selected to establish relationship models for different quality indicators. Comprehensive weight simulation equations for individual wine grape quality components were developed based on the weight of the coefficient of determination for selected meteorological factors.

1.4 Individual Quality Component Grading Indicators and Comprehensive Quality Meteorological Grade Model

Referencing four wine and grape quality evaluation standards, the International Plant Genetic Resources Board (BPGR) grape quality grading standards [32-35], and relevant literature [5-6], combined with grading experience from winemakers at Yuquanying and Lilan wineries, we established grading indicators for evaluating wine grape total sugar, total acid, sugar-acid ratio, pH, and tannin quality. Each indicator was divided into five grades: excellent (Grade 5), very good (Grade 4), good (Grade 3), medium (Grade 2), and poor (Grade 1). Threshold ranges for significant meteorological factors were derived inversely. Considering the contribution of these five quality components to overall wine grape quality, we integrated a comprehensive quality meteorological grade model using the R^2 of each component’ s meteorological factor simulation equation as weights. The comprehensive quality grade was also divided into five levels following the same method. For evaluation, relevant meteorological factors are substituted into each quality meteorological simulation model to obtain estimated values and corresponding grades for total sugar, total acid, sugar-acid ratio, pH, and tannin, which are then input into the comprehensive quality grade model to evaluate overall wine grape quality grade.

1.5 Validation of Quality Meteorological Evaluation Models

To test the applicability of the method, we used Cabernet Sauvignon chemical samples from Yongning, Qingtongxia, and Luhuatai grape bases from 2003–2011. Back-substitution error testing was performed using the 51 modeling samples, while the remaining 50 samples were used for validation testing. Both estimated and measured values were classified into quality grades according to classification thresholds and compared to calculate accuracy rates for individual quality indicator scores and comprehensive scores.

Results

2.1 Expanded Correlation Screening Between Cabernet Sauvignon Quality and Meteorological Factors

Expanded correlation screening (Table 2) revealed that soluble solids, total sugar content, and sugar-acid ratio were significantly negatively correlated with average temperature and maximum temperature from flowering to harvest, and significantly positively correlated with 10°C accumulated temperature and sunshine hours. Correlations were stronger during the veraison to harvest period, indicating that adverse meteorological conditions frequently occur after veraison, affecting total sugar and soluble solids accumulation and sugar-acid conversion. Total acid content was significantly positively correlated with average temperature and negatively correlated with sunshine hours from flowering to harvest (both passing 0.001 R-tests), while correlations were weaker during veraison to harvest, suggesting that total acid accumulates mainly during the early to mid-fruit development stage, with post-veraison conditions primarily affecting sugar-acid conversion. pH value showed only extremely significant correlations (0.005 level) with sunshine hours from veraison to harvest and precipitation 30 days before harvest. Tannin content was positively correlated with accumulated temperature and sunshine hours from veraison to harvest, negatively correlated with average and minimum temperature after veraison, and more significantly negatively correlated with minimum temperature and precipitation 10–30 days before harvest. These results indicate that lower temperatures and less sunshine after veraison increase tannin content; longer veraison-harvest intervals with more accumulated temperature and sunshine represent more sunny days with greater diurnal temperature ranges, increasing tannin content, while more precipitation during this period decreases tannin content.

2.2.1 Total Sugar

Meteorological factors highly significantly correlated with total sugar were selected to establish linear or nonlinear models (Table 3). Total sugar showed extremely significant positive correlations with 10°C accumulated temperature and sunshine hours from flowering to harvest; later harvest and better maturity resulted in higher total sugar content. Total sugar exhibited quadratic relationships with minimum temperature, 10°C accumulated temperature, and sunshine hours during veraison to harvest. Higher minimum temperature 30 days before harvest indicated earlier harvest, poorer maturity, and lower sugar content. For every 10 mm increase in precipitation 30 days before harvest, total sugar decreased by 9.7 g·L ¹, similar to the 8.2 g·L ¹ reduction reported by Liu Yulan et al. [17] and Xiu Deren et al. [36].

Referencing BPGR grape quality grading standards [32-35], combined with Smith' s [37] grading indicators for Cabernet Sauvignon and other varieties and Li Jiming's [5-6] requirements for premium and ultra-premium wine production, Cabernet Sauvignon total sugar was divided into five grades: excellent (210 g·

L ^{1}), very good (195.1–210 g · L ^{1}), good (170.1–195 g · L ^{1}), medium (155.1–170 g · L ^{1}), and poor (<155 g · L ^{1}). Meteorological factor threshold ranges were derived inversely from the total sugar-meteorological factor relationships (Table 3). High-quality wine production requires average temperature 22.6°C during flowering to harvest, 10°C accumulated temperature 2,189°C · d, and sunshine 867 h. Specifically, from veraison to harvest: average temperature 21.7°C, average minimum temperature 16.6°C, 10°C accumulated temperature 789.6°C · d, and sunshine 303 h; 30 days before harvest: minimum temperature 16.1°C and precipitation 49.1 mm. In practice, total sugar content can be estimated using the equations and indicators in Table 3 to determine optimal harvest timing for premium grade.

2.2.2 Total Acid

Grape total acid content showed a quadratic relationship with average temperature from flowering to harvest; high temperatures accelerate acid decomposition, reducing total acid content. Total acid was linearly positively correlated with average daily precipitation during veraison to harvest; more precipitation after veraison increased total acid. Total acid showed logarithmic relationships with cumulative sunshine hours from both flowering to harvest and veraison to harvest; more sunshine decreased total acid content. Maximum temperature 10 days before harvest showed a quadratic relationship with total acid; higher temperatures indicated earlier harvest with insufficient sugar-acid conversion, resulting in higher total acid content (Table 4).

According to wine quality requirements, Cabernet Sauvignon total acid content was divided into: excellent (8.0–9.4 g · L ^{1}), very good (9.5–10.5 g · L ^{1}), good (10.6–12.0 g · L ^{1}), medium (12.1–13.5 g · L ^{1}), and poor (>13.5 g · L ^{1}). Meteorological factor thresholds for different total acid levels were derived inversely. Premium wine production requires average temperature 22.2°C during flowering to harvest and cumulative sunshine >930 h. During veraison to harvest: 10°C accumulated temperature 946°C · d, average daily precipitation 1.4 mm, cumulative sunshine 357.5 h, and average maximum temperature 10 days before harvest 25.7°C.

2.2.3 Sugar-Acid Ratio

As average temperature from flowering to harvest increased, sugar-acid ratio decreased by 4.3 per 1°C increase. Later harvest with lower average temperature, more 10°C accumulated temperature, and more cumulative sunshine increased sugar-acid ratio. For every 100°C · d increase in 10°C accumulated temperature, sugar-acid ratio increased by 1.2; for every 100 h increase in sunshine, it increased by 2.8. Similar relationships existed for meteorological factors during veraison to harvest. Precipitation 30 days before harvest showed a negative exponential relationship with sugar-acid ratio; as precipitation increased from 20–70 mm, sugar-acid ratio decreased. Average minimum temperature 30 days before harvest was negatively correlated with sugar-acid ratio; low temperatures promoted sugar-acid conversion, while early harvest resulted in low ratios.

Wang Hua et al. [40] used sugar-acid ratio to measure grape maturity, dividing it into: excellent (27-30), very good (24-26.9 or 30.1-33.0), good (19.0-23.9 or 33.1-36.0), medium (14.0-18.9 or 36.1-40.0), and poor (<14.0 or >40.0). Based on equations in Table 5 , ideal sugar-acid ratios for premium wine require: average temperature 19.1-21.2°C, 10°C accumulated temperature 2,654°C · d, and sunshine 1,068 h from flowering to harvest; average temperature 15.9-19.4°C, 10°C accumulated temperature 1,238.9-1,953.2°C · d, and sunshine 501.1-813.6 h from veraison to harvest; precipitation 21.8 mm and average minimum temperature 5.6-12.0°C 30 days before harvest. Most historical samples fell within premium ranges, indicating that Helan Mountain eastern foothills are suitable for developing the sugar-acid ratios needed for premium wine.

2.2.4 pH Value

Wine grape pH was positively correlated with accumulated temperature and sunshine from both flowering to harvest and veraison to harvest; more accumulated temperature and sunshine drove pH toward less acidic values (Table 6). pH decreased with increasing precipitation 30 days before harvest. Sample pH values ranged from 2.9-3.6, essentially matching Li Jiming' s [6] optimal range for premium wine, indicating that Helan Mountain eastern foothills' meteorological conditions are suitable for producing grapes with appropriate pH for high-quality wine, with limited meteorological influence on pH variation.

Premium wine grapes have pH 3.0-3.6, divided into: excellent (3.2-3.4), very good (3.41-3.5 or 3.1-3.19), good (3.51-3.6 or 3.0-3.09), medium (3.61-3.7 or 2.9-2.99), and poor (>3.7 or <2.9). Since all samples fell within 2.9-3.6, mostly in premium grades, some meteorological factors could not be used to derive classification grades. For premium wine pH classification, the following conditions are needed: 10°C accumulated temperature 1,671-2,671°C · d and average daily sunshine <12.5 $h \cdot d^{1}$ from flowering to harvest; 10°C accumulated temperature 500-1,360.8°C · d and sunshine 203.5-525.0 h from veraison to harvest; and precipitation <79.4 mm 30 days before harvest.

2.2.5 Tannin

Tannin content showed quadratic relationships with average minimum temperature during both flowering to harvest and veraison to harvest, with optimal values of 15.2°C and 13.3°C respectively, with greater impact after veraison. For every 100 h increase in sunshine from veraison to harvest, tannin increased by 2.6 $mmol \cdot kg^{1}$. Average minimum temperature 30 days before harvest and precipitation 20 days before harvest affected tannin content; every 10 mm increase in precipitation 20 days before harvest decreased tannin by 1.2 $mmol \cdot kg^{1}$. Diurnal temperature range 10 days before harvest of 10-13°C resulted in higher tannin content, with decreases at smaller or larger ranges (Table 7).

According to winemaking quality requirements, tannin was divided into: excellent (>30.1 mmol · kg ^{1}), very good (25.1-30 mmol · kg ^{1}), good (20.1-25 mmol · kg ^{1}), medium (15.1-20 mmol · kg ^{1}), and poor (<15.0 mmol · kg ^{1}). Premium wine production requires average daily minimum temperatures of 15.0-17.3°C (flowering to harvest) and 13.5-17.1°C (veraison to harvest), sunshine 430.6-633.1 h from veraison to harvest, average minimum temperature 9.6-17.4°C 30 days before harvest, precipitation 59.5 mm 20 days before harvest, and average diurnal temperature range 9.9°C 10 days before harvest.

2.3 Comprehensive Meteorological Simulation Model for Cabernet Sauvignon Quality

Based on relationship models between wine grape quality components and meteorological factors in Section 2.2, we constructed comprehensive evaluation models for five quality components using significant and independent factors weighted by their coefficients of determination (Table 8). Multiple correlation coefficients improved substantially, allowing regional quality prediction based on actual meteorological conditions.

Table 8 The optimal relation model between the quality indicators and meteorological factors of Cabernet Sauvignon (n=51)

Quality indicator	Comprehensive weight model
Total sugar content (CS)	CS = 0.068Sfh - 0.332Tn30^{2} + 5.921Tn30 - 15.678lnR30 + 185.982
Total acid content (CA)	CA = 0.2224Tfh^{2} - 9.1635Tfh - 1.0387ln(Sch) + 0.0132Tm10^{2} - 0.4904Tm10 + 114.225
Sugar/acid (RS/A)	RS/A = 0.01315Sfh + 22.48914R30 · ^{3} - 0.56417Tn30 + 10.1225
pH	pH = -0.01873Sdfh + 0.000139ATsch - 0.00148R30 + 3.3156
Tannin content (CTan)	CTan = -0.3199Tnch^{2} + 8.4991Tnch - 2.0556R20 - 0.2256Td10^{2} + 6.0513Td10 - 57.821

Sfh, Sdfh: Sunshine hours (h) and average daily sunshine hours (h · d ^{1}) from flowering to harvest; Tfh: Average temperature (°C) from flowering to harvest; ATsch: 10°C accumulated temperature (°C · d) from veraison to harvest; Tnch: Average minimum temperature (°C) from veraison to harvest; Sch: Sunshine hours (h) from veraison to harvest; Tn30: Average minimum temperature (°C) 30 days before harvest; R30, R20: Precipitation (mm) 30 and 20 days before harvest; Tm10, Td10: Average maximum temperature and diurnal temperature range (°C) 10 days before harvest.

2.4 Comprehensive Discriminant Model and Indices for Cabernet Sauvignon Quality Grading

Referencing Li Jiming [5] and Zhang Xiaoyu et al. [31], combined with winemaker recommendations, we weighted each quality component according to its contribution to wine quality:

$$Gp = 0.54PSc + 0.10PAc + 0.21PS/A + 0.10PTan + 0.05PpH \quad (1)$$

Where *Gp* is the comprehensive meteorological quality of Cabernet Sauvignon; *PSc*, *PAc*, *PS/A*, *PTan*, and *PpH* represent quality grades for total sugar, total acid, sugar-acid ratio, tannin, and pH value respectively, each divided into five grades: excellent (Grade 5), very good (Grade 4), good (Grade 3), medium (Grade 2), and poor (Grade 1). These are classified according to Tables 3-6, yielding comprehensive meteorological quality grading indices for Cabernet Sauvignon (Table 9).

Table 9 Comprehensive index of meteorological quality of Cabernet Sauvignon

Comprehensive meteorological quality grade	Evaluation index standard
5 (Excellent)	3.2–4.2
4 (Very good)	2.2–3.1
3 (Good)	1.2–2.1
2 (Medium)	0.2–1.1
1 (Poor)	<0.2

2.5 Model Validation

Using the 51 modeling samples for back-substitution testing (Fig. 1 [Figure 1: see original paper]), all five quality component meteorological models passed R and F tests at the 0.001 significance level. Total sugar, total acid, sugar-acid ratio, and tannin showed good simulation effects with R 0.59 and small RMSE. pH simulation showed relatively large dispersion, likely because sample pH values themselves varied little and meteorological factors had limited influence.

To test model predictive effects, we used 50 Cabernet Sauvignon chemical samples from Yongning, Qingtongxia, and Luhuatai bases (2003-2011) that were not used in model development. Quality components were estimated using optimal models and arranged by increasing total sugar (Fig. 2 [Figure 2: see original paper]). Results showed that estimated total sugar and total acid were close to measured values with consistent trends. Sugar-acid ratio estimates had large errors for 2005 and 2011 samples but were otherwise accurate. Individual tannin samples showed errors approaching 10 mmol·kg ^{1}, relatively large but with consistent trends. pH estimates were stable and did not reflect sample differences. Overall, measured and estimated values increased and decreased synchronously with consistent trends.

Based on individual quality classification thresholds, estimated values were classified into five grades. Both measured and estimated values were used to calculate comprehensive scores using equation (1) and classified according to Table 9. Among the 50 validation samples, 4 samples were estimated as Grade 5 when actual was Grade 3, while the rest differed by 0–1 grade, with 28 samples matching actual grades exactly (Fig. 3 [Figure 3: see original paper]).

Discussion

3.1 Light and Heat Conditions Primarily Affect Grape Maturity, and Models Can Predict Optimal Harvest Timing

Wine grape quality relates to maturity [8]; fully mature grapes have high sugar content, complete sugar-acid conversion, low total acid, appropriate sugar-acid ratio, and rich aromatic substances and tannins in seeds and skins. Simulations showed that days from flowering to harvest were extremely significantly positively correlated with total sugar, sugar-acid ratio, and tannin, and negatively correlated with total acid. Total sugar, sugar-acid ratio, and tannin increased with delayed harvest, while total acid decreased, indicating that longer fruit development improves maturity and quality. Wang Hua et al. [38] identified temperature and light as primary factors affecting various effective components, with significant correlations between accumulated temperature, cumulative sunshine, and these substance contents during flowering to harvest, veraison to harvest, and the month before harvest, reflecting relationships between meteorological conditions and maturity and indicating that insufficient late-season light and heat affect grape maturity. Since meteorological conditions vary greatly across regions and fruit development days differ significantly between warm and cool years, growers cannot readily measure numerous quality components and often rely on experience to determine harvest timing. Using meteorological factors like accumulated temperature and cumulative sunshine to estimate substance content objectively reflects grape maturity and can provide objective basis for determining optimal harvest timing.

3.2 Post-Veraison Meteorological Conditions Have Greater Impact on Wine Grape Quality

Light and heat conditions primarily affect grape total sugar and total acid accumulation and conversion, thereby influencing sugar-acid ratio and pH. Cabernet Sauvignon total sugar and sugar-acid ratio had more extremely significant meteorological factors during veraison to harvest and 30 days before harvest than during flowering to harvest, indicating greater late-season influence and showing that insufficient late-season light/heat and excessive moisture affect total sugar accumulation and conversion. Total acid correlations with meteorological factors from flowering to harvest were stronger than post-veraison, indicating that total acid accumulation relates closely to early-mid fruit development conditions.

pH correlations with post-veraison sunshine and precipitation 30 days before harvest suggest that insufficient heat and rainy weather after veraison affect pH. More meteorological factors were significantly correlated with tannin after veraison, indicating that post-veraison temperature decline and excessive precipitation affect tannin content. Earlier harvest resulted in less tannin, while more late-season light/heat and less precipitation increased tannin content. These findings align with Deng Haoliang [39] and Li Tao et al. [40], who found that moderate water deficit from fruit coloring to maturity increased anthocyanins, reducing sugars, tannins, and total phenols while effectively suppressing titratable acid accumulation.

3.3 Wine Grape Quality Meteorological Grading References Winemaking Standards with Good Validation Results

Quality meteorological grading referenced foreign grape quality grading standards [41], five-grade standards for *Vitis amurensis*, and four published standards. Based on winemaking requirements for total sugar, total acid, sugar-acid ratio, pH, and tannin content, five grades were established, and meteorological factor thresholds and quality meteorological grades were determined accordingly. Therefore, meteorological model estimates correspond with chemical analysis results, objectively reflecting quality grades that should form under given meteorological conditions, rather than relative quality grades based on quality fluctuation ranges, providing some assistance for wine quality evaluation and prediction.

Back-substitution results showed accurate simulation for total sugar, total acid, sugar-acid ratio, and tannin, while pH showed weaker relationships with meteorological factors, suggesting that Helan Mountain eastern foothills' meteorological conditions are not the main factor limiting pH variation. Validation with non-modeling samples showed estimated total sugar and total acid close to measured values, sugar-acid ratio basically accurate, relatively large tannin errors, and pH estimates not reflecting sample differences. Comprehensive grade scores matched actual grades in 56% of samples, differed by one grade in 36%, and by two grades in 8%. Overall, the method and indices objectively reflect Cabernet Sauvignon quality grades with good comprehensive grading performance.

3.4 Model Limitations and Uncertainties

Besides raw material quality, wine quality also depends heavily on winemaking technology; meteorological conditions are only one important aspect affecting wine grape quality. The quality components analyzed were limited to the five indicators above, particularly lacking data on aromatic hydrocarbons and numerous other quality components, making comprehensive meteorological quality difficult to fully reflect wine color, aroma, flavor, and smoothness. Therefore, this method can serve as objective reference for vintage quality evaluation but cannot be equated completely with wine quality. Second, meteorological factor simulation accuracy depends on factors remaining within the normal range of sampling; accuracy is affected if meteorological factors exceed modeling ranges. Third, some statistical relationships used quadratic curves for rising or falling segments, but actual meteorological data sometimes exceeded modeling ranges (e.g., maximum precipitation 30 days before harvest was only 60 mm in modeling data but has historically exceeded 100 mm). Applications must ensure factor values remain within modeling sample ranges to avoid erroneous conclusions. Additionally, quality analysis data were limited to Ningxia, giving results certain limitations requiring cautious application and local validation in other Chinese regions. Future work could establish quality component and meteorological quality models based on sampling data from nationwide regions, add other necessary quality indicators according to winemaking requirements, increase climate variation, and expand model applicability. Similar methods could also develop quality meteorological evaluation models for other grape varieties to create a systematic, objective, and quantitative series for wine grape climate quality evaluation and authentication.

Conclusion

Wine quality depends primarily on premium raw materials and relates to variety, soil, and meteorological conditions. Under normal water and fertilizer management, meteorological conditions are the main cause of interannual quality variation. This study examined relationships between five Cabernet Sauvignon quality components and meteorological factors, constructed optimal individual quality component meteorological evaluation models, selected factors with clear biological significance, and developed integrated weighted models and meteorological factor grade thresholds for five quality components. Drawing on previous research, standards, and winemaker input, we constructed a weighted model and grading standard for Cabernet Sauvignon comprehensive quality evaluation. Validation with non-modeling samples showed the model accurately reflected comprehensive quality grades for Cabernet Sauvignon in the Helan Mountain eastern foothills. The methods and grading indices can provide reference for vintage wine rating, helping establish China' s premium wine grape production regions, implement high-end brand strategies, and enhance brand recognition.

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