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Effects of environmental factors in different producing areas of Hexi Corridor on the fruit quality of ' Italian Riesling ' grapes

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Abstract

Background

Wine grape quality is profoundly influenced by environmental conditions, yet systematic evaluations of how regional climatic and soil factors differentially shape berry composition in arid production areas remain limited. This study aimed to elucidate the effects of environmental factors on the fruit quality of 'Italian Riesling' wine grapes across three ecologically distinct production regions (Jiayuguan, Zhangye, and Wuwei) within the Hexi Corridor of northwestern China. Berry quality attributes—including soluble sugars, organic acids, total phenols, tannins, and volatile compounds—were comprehensively evaluated over three consecutive vintages (2018–2020). Concurrently, meteorological parameters and soil physicochemical properties (organic matter, pH, nitrogen, phosphorus, potassium, calcium, iron, manganese, and copper at four soil depths: 0–20, 20–40, 40–60, and 60–80 cm) were measured. Correlation analyses and principal component analysis (PCA) were performed to identify key environmental drivers of berry quality. Regional disparities in berry quality were substantial.

Result

Zhangye consistently exhibited the highest soluble sugar content (21.03% in 2018) and glucose content across all three years, while Wuwei showed the highest total phenol content (28.56 mg·g⁻¹ in 2019).A total of 46 aroma compounds were identified, with aldehydes being the most abundant fraction; Jiayuguan recorded the highest total aroma content (4,972.97 μg·kg⁻¹ in 2019). Correlation analysis revealed that soil organic matter (in the 60–80 cm soil layer) and calcium (in the 20–40 cm soil layer) were significantly positively correlated with fruit alcohol content, while soil pH (60–80 cm) showed a significant positive correlation with soluble sugar content. PCA demonstrated that accumulated temperature from April to September was the primary factor discriminating Jiayuguan from Zhangye and Wuwei, with the former exhibiting a distinct compositional profile.

Conclusion

The marked differences in berry quality among the three regions were predominantly driven by variations in thermal conditions and depth-specific soil nutrients. These findings underscore the critical role of site-specific environmental factors in shaping wine grape composition and provide a theoretical foundation for precision viticulture and regional cultivar selection in arid viticultural zones.

Introduction

The Hexi Corridor in Gansu Province, located west of the Yellow River and between the Qilian Mountains and the Badain Jaran Desert in northwestern China, possesses distinctive geographical advantages and a continental arid climate characterized by low precipitation, long sunshine hours, and large diurnal temperature fluctuations[1]. These conditions support a long history of wine grape cultivation. Among the major grape-producing areas within this region, Jiayuguan, Zhangye, and Wuwei are key wine grape production zones in the Hexi Corridor.

'Italian Riesling' (*Vitis vinifera L.*), introduced from Italy into China in 1982, is a prominent white wine grape variety. Wines produced from this variety are typically light yellow, crystal-clear and bright, with a pleasant aroma, making it an excellent choice for producing high-quality white wine. However, the oenological potential of this variety is strongly modulated by growing conditions, and its performance in the distinct environments of the Hexi Corridor remains poorly understood.

Wine grape quality is influenced by a complex interplay of genetic, environmental, and viticultural factors, among which climate and soil have particularly pronounced effects[2]. Climate is a primary determinant of grapevine's geographic distribution and directly influences yield and berry composition[3]. Light availability, for instance, significantly affects berry development; cluster shading has been shown to reduce berry size and individual berry weight, delay ripening, and decrease the accumulation of anthocyanins, phenols, and tannins, while suppressing key volatile compounds such as geranial, phenylacetaldehyde, nerolidol, and ethyl acetate[4]. Temperature is another critical climatic factor, affecting both the quantity and quality of wine production[5]. Higher temperatures can alter berry metabolite profiles, thereby modifying wine polyphenol concentrations and color intensity[6]. Moreover, high summer temperatures coupled with large diurnal temperature ranges have been reported to reduce fruit firmness while increasing soluble sugar content[7]; conversely, excessive heat can inhibit grape growth, diminish berry size[8], accelerate malic acid degradation[9], and suppress the accumulation of aroma volatiles[10].

Beyond climate, soil conditions fundamentally influence vine development and berry quality by modulating nutrient availability and nutrient uptake. Vadivel et al. demonstrated that amending native soil with black soil not only improved fruit quality but also increased yield[11]. Similarly, Ha et al. found that increasing soil organic matter, nitrogen, potassium, calcium, and micronutrients enhanced tomato plant growth, fruit size, yield, and sugar content[12]. These findings underscore the critical role of soil physicochemical properties in determining fruit compositional quality.

Viticultural practices—including irrigation, fertilization, and canopy management—also modulate fruit quality. Over-irrigation has been shown to increase citrus fruit size, whereas deficit irrigation reduces size but elevates sugar content[13]. Optimized N, P and K fertilization at key phenological stages can enhance fruit dimensions, single-fruit weight, and anthocyanin and soluble protein contents[14]. Furthermore, fruit bagging has been reported to improve surface finish and firmness in persimmons, affecting external quality attributes[15].

Aroma compounds have become key indicators of fruit quality, and their composition is highly sensitive to growing conditions and orchard management. Fruit variety, harvest timing[16], and environmental factors all significantly influence aroma profiles[17]. Moderate soil moisture (70–80% field capacity) has

been shown to improve fruit nutritional quality[18], while increased soil N, P and K availability promotes sugar accumulation and overall vine productivity[19]. Notably, soil pH and mineral composition—particularly phosphorus and manganese—are among the most influential factors affecting grape berry nutrition and quality[20].

Given the profound impact of environmental conditions on grape composition, and wine grape quality directly determines wine quality, understanding the region-specific drivers of berry quality is of both scientific and practical importance. Jiayuguan, Zhangye, and Wuwei represent three ecologically distinct wine grape production areas within the Hexi Corridor, yet a systematic comparative assessment of how local environmental factors influence 'Italian Riesling' berry quality across these regions is lacking.

To address this gap, the present study measured environmental variables (meteorological parameters and soil physicochemical properties at multiple depths) and comprehensively evaluated berry quality attributes—including sugars, organic acids, phenolic compounds, and volatile profiles—over three consecutive vintages (2018–2020) in the three production areas. The objectives were to: (1) characterize the regional variability in berry quality and aroma composition; (2) elucidate the relationships between environmental factors and key quality traits; and (3) identify the primary environmental drivers differentiating the three regions. The findings are expected to provide a scientific basis for site-specific viticultural management and contribute to the sustainable development of the wine grape industry in arid regions of China.

Materials and Methods

Experimental site and materials

The test variety is perennial Italian Riesling (*Vitis vinifera L. subsp. vinifera 'Italian Riesling'*), the germplasm resources of this cultivar are preserved in IAT360 (Vitis International Variety Catalogue, VIVC, variety number, 13217).

The test sites were Jiayuguan Zixuan Vineyard, Zhangye Qilian Wine Gaotai Vineyard and Wuwei Mogao Wine Vineyard. Jiayuguan City is located at 98°17' E longitude and 39°47' N latitude, with a temperate continental desert climate, with the average annual temperature is around 6℃, the average annual sunshine hours are 3,000 h, and the evaporation is 2,149 mm. Gaotai County in Zhangye City is located between 99°38' to 99°47' E longitude and 39°17' to 39°20' N latitude, with a temperate continental arid climate, average annual precipitation is 112.30 mm, evaporation is 1,923.40 mm, and groundwater resources are abundant. Liangzhou District of Wuwei City is located between 102°02' to 103°23'E longitude and 37°23' to 38°14'N latitude, with 2,830.30 h of sunshine hours, an annual average of 147 d of frost-free period, an annual average of 262.90 mm of precipitation, and 1,996.60 mm of evaporation, with a temperate continental desert climate.

Meteorological information

Meteorological information was obtained from the small meteorological stations of Gansu Zixuan Wine Industry Corporation, Gansu Qilian Wine Industry Corporation, and Gansu Mogao Industrial Development Corporation.

Soil samples and collection methods

In 2020, soil samples were collected from the 'Italian Riesling' vineyards of Gansu Zixuan Wine Industry Corporation, Gansu Qilian Wine Industry Corporation, and Gansu Mogao Industrial Development Corporation. The soil sampling was conducted using the 'S'-shaped method, with 15 sampling points established to collect soil from the 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm layers in their undisturbed state. The samples were then brought back to the laboratory, mixed, and air-dried for the determination of physicochemical properties.

Species and management

The experimental materials were 9 to 10-year-old 'Italian Riesling' grapevines, trained to a single hedgerow system with multiple main vines in a fan-shaped configuration. Irrigation and fertilization were carried out according to the management system established by the enterprise. The fruit harvest periods from 2018 to 2020 all fell between September 15 and September 18. In each orchard, 30 clusters were sampled from different locations, with every 10 clusters constituting one replicate (3 replicates total). From each cluster, 30 berries were picked from different positions, resulting in 300 berries per replicate. These samples were used for indicator measurements, while subsamples for volatile compound analysis were quick-frozen in liquid nitrogen and stored at –80°C for later use.

Experimental Methods

Measurement of basic berry quality

Soluble solids in grape juice were measured using a handheld digital refractometer (PAL-1, Atago, Japan). pH was measured using a pH meter. Titratable acid content was determined by NaOH titration[21]. Soluble sugar content was measured by the anthrone reagent method[22]. Total phenol content was determined by the Folin-phenol method[23]. Tannin content was determined by the Folin-Denis method[24]. Each experiment was repeated three times.

Determination of berry sugar and acid fractions

Sugar fractions and contents were determined using high performance liquid chromatography (HPLC, Waters Acquity Arc, USA). The chromatographic conditions were as follows: a column (4.6 mm × 150 mm, 2.5 μm), a mobile phase consisting of 75% acetonitrile, 0.2% triethylamine, and 24.8% ultrapure water, a flow rate of 0.8 mL·min⁻¹, an injection volume of 10 μL, a detection wavelength of 254 nm, and a column temperature of 40°C. The mobile phase was filtered through a 0.22 μm organic filter membrane and degassed by ultrasonication before use.

Organic acid components and content were determined using high performance liquid chromatography (HPLC, Waters Acquity Arc, USA)[25]. The method used a column (4.6 mm × 150 mm, 3 μm) and a mobile phase of 20 mmol·L⁻¹ NaH_2PO_4. Chromatographic conditions were as follows: flow rate 0.5 mL·min⁻¹, injection volume 20 μL, detection wavelength 210 nm, and column temperature 30°C. The mobile phase was filtered through a 0.45 μm aqueous filter membrane and degassed by ultrasonication before use.

Determination of volatile substances in grape berries

Determination was performed with reference to the method of Wang et al. [26]. Washed and dried grape berries (100 g) were ground with liquid nitrogen. PVPP (1 g) and D-gluconolactone (0.5 g) were added, and the mixture was extracted by ultrasonication (30 min, 4°C), followed by centrifugation (8 000 r·min⁻¹, 10 min). The supernatant (grape juice) was collected. Grape juice (10 mL) was transferred to a 20 mL injection vial, followed by the sequential addition of 2.4 g of NaCl and 50 μL of the internal standard 2-octanol (88.2 mg·L⁻¹). Place an extraction needle containing a 2-cm-long, 50/30-micron divinylbenzene - carboxylic acid - polydimethylsiloxane fiber (DVB/CAR/PDMS, Supelco, Bellefonte, Pennsylvania, USA) into the vial. Perform extraction at 40°C and 500 rpm for 30 min. After the extraction is completed, insert the extraction needle into the injection port of the gas chromatograph, and conduct thermal desorption at 240°C in the splitless mode for 8 min to complete the collection of volatile substances. After the collection is finished, continue to incinerate the needle at this temperature for 20 min to minimize substance residues. After extraction, the sample was analyzed by GC-MS injection (3 replicates per sample).

The chromatographic conditions were as follows: OV-1701 column (60 m × 0.25 mm × 0.5 μm), inlet temperature 250°C, injection volume 1.0 μL, and carrier gas helium at a flow rate of 0.80 mL·min⁻¹. The temperature program was: 40°C held for 5 min, raised to 60°C at 10°C·min⁻¹ and held for 5 min, then raised to 140°C at 4°C·min⁻¹ and held for 10 min, and finally raised to 220°C at 15°C·min⁻¹ and held for 10 min. The electron energy was 70 eV, ion source temperature 230°C, and mass scan range 35–350 m/z.

Volatile compounds were analyzed using an Agilent 7890A gas chromatograph coupled to an Agilent 5975C mass-selective detector (Agilent Technologies, Santa Clara, CA, USA). Separation was performed on a DB-17MS capillary column (30 m × 0.25 mm i.d. × 0.25 μm film thickness; Agilent J&W). The oven temperature was initially maintained at 40°C for 5 min, increased to 180°C at 3.5°C/min, and then held at 180°C for 15 min. High-purity helium (≥ 99.999%) was used as the carrier gas at a constant flow rate of 1.0 mL/min. The injector temperature was 240°C, and injections were performed in splitless mode.

Peaks were integrated using the automated integration algorithm of the instrument software, and the mass spectrum of each separated compound was compared with spectra in the NIST 2014 mass-spectral library.

Content of each component of the aroma ($\mu g \cdot g^{-1}$) = [peak area of each component/peak area of the internal standard × concentration of the internal standard ($mg \cdot L^{-1}$) × 50 μL]/volume of sample (g).

Soil nutrient determination

Nitrogen in soil was determined using the Kjeldahl method[27], and iron (Fe), manganese (Mn), copper (Cu), and calcium (Ca) in soil were determined using DTPA-TEA extraction and flame/graphite furnace atomic absorption spectrometry (900T AAS, PerkinElmer Inc., Waltham, MA, USA)[21]. Soil organic matter was determined using the Walkley-Black method[29], and soil pH was measured using a pH meter (pHS-3C). Soil samples (0.50 g) were placed in 150 mL conical flasks. Ultrapure water (1 mL) was added to moisten the soil, followed by concentrated sulfuric acid (5 mL), and the mixture was shaken thoroughly and allowed to stand for 6 h. Hydrogen peroxide (4 mL) was then added to the flask. After the reaction was complete, the flask was placed on an electric hotplate and slowly heated. The temperature was raised when the concentrated sulfuric acid decomposed and emitted large amounts of white smoke. The flask was removed when the solution became uniformly brownish-black. After cooling slightly, 10 drops of 30% hydrogen peroxide were added with continuous shaking, and the flask was reheated for 5–10 min. After removal and slight cooling, 30% hydrogen peroxide was added dropwise (5–10 drops) with constant shaking, and the solution was boiled (repeat 3–5 times). The amount of hydrogen peroxide added was gradually reduced, and boiling continued until the solution became colorless or clear. The flask was then heated for 5–10 min to remove excess hydrogen peroxide, removed, and allowed to cool. The digested solution was quantitatively transferred into a 50 mL volumetric flask with ultrapure water, made up to volume, shaken, and used for elemental determination.

Data handling

Statistical analysis of the experimental data was performed using Excel 2023, and one-way ANOVA was conducted using SPSS 24.0. Correlation analysis between environmental factors and fruit quality was carried out using Origin 2022. Cluster analysis is carried out using the hierarchical clustering method, perform principal component analysis using the ggplot2 package in R language. All indicators were subjected to three biological replicates, and the results are expressed as mean ± standard deviation.

Results and Analysis

Analysis of meteorological data in different regions

Meteorological data for Jiayuguan, Zhangye, and Wuwei are shown in Table 1. After consecutive years of experimentation in these three production areas, the data were obtained from the small meteorological stations of Gansu Zixuan Wine Industry Corporation, Gansu Qilian Wine Industry Corporation, and Gansu Mogao Industrial Development Corporation.

Table 1
Meteorological data for different production areas

Area	Yeas	MT Apr-Sep(℃)	ATT Apr-Sep(℃)	MDT Apr r-Sep(℃)	Jul-Sep rainfall(mm)
Jiayuguan	2018	20.09	3384.00	12.78	267.30
	2019	20.08	3380.00	11.71	131.30
	2020	19.42	3251.00	12.10	182.36
Zhangye	2018	19.47	3724.88	14.34	387.10
	2019	19.29	3694.00	14.07	270.8
	2020	18.71	3458.00	14.36	314.28
Wuwei	2018	18.76	3536.00	12.27	631.10
	2019	18.80	3310.00	11.62	415.40
	2020	17.87	3239.00	12.46	450.60
Coefficient (%)		3.62	4.64	9.44	45.21

Analysis of soil nutrients in different regions

Soil nutrient and trace element contents in the three regions of Jiayuguan, Zhangye, and Wuwei are shown in Table 2. Among them, Wuwei had the highest soil organic matter content, with a mean value of 1.35% and a coefficient of variation of 22.55%; its nitrogen content was 46.6% higher than that of Jiayuguan and 57.14% higher than that of Zhangye, with a coefficient of variation of 25.64%. Zhangye had the lowest soil pH (7.81), which was 7.81% lower than that of Jiayuguan and 2.94% lower than that of Wuwei; it also had the lowest calcium (2.87 g·kg⁻¹) and copper (7.11 mg·kg⁻¹) contents, and the highest manganese content (543.81 mg·kg⁻¹). Jiayuguan soil had a phosphorus content of 0.16% with a coefficient of variation of 7.87%, a potassium content higher than those of Zhangye and Wuwei, and the highest iron content of 19.96 g·kg⁻¹ with a coefficient of variation of 2.09%.

Table 2
Soil nutrient and trace element contents in different production areas

Areas	Soil depth (cm)	Organic matter (%)	pH	N (%)	P (%)	K (%)	Ca ($g \cdot kg^{-1}$)	Cu ($mg \cdot kg^{-1}$)	Fe ($g \cdot kg^{-1}$)	Mn ($mg \cdot kg^{-1}$)
Jiayuguan	0 ~ 20 cm	1.44	8.01	0.17	0.16	2.17	4.18	18.47	20.01	410.47
	20 ~ 40 cm	1.37	8.03	0.13	0.16	2.48	4.87	11.20	19.44	602.73
	40 ~ 60 cm	1.15	8.05	0.15	0.16	3.18	4.76	9.80	20.39	459.56
	60 ~ 80 cm	1.06	8.04	0.15	0.16	2.56	4.71	7.93	20.00	485.77
	average	1.26	8.03	0.15	0.16	2.60	4.63	11.85	19.96	489.63
Zhangye	0 ~ 20 cm	1.39	7.26	0.18	0.15	2.30	3.11	4.80	18.89	492.44
	20 ~ 40 cm	0.87	7.88	0.13	0.13	1.95	2.90	6.93	18.88	551.74
	40 ~ 60 cm	0.72	7.96	0.11	0.14	2.18	2.44	12.17	19.48	569.95
	60 ~ 80 cm	0.45	8.13	0.15	0.14	3.02	3.03	4.53	19.40	561.10
	average	0.86	7.81	0.14	0.14	2.36	2.87	7.11	19.16	543.81
Wuwei	0 ~ 20 cm	1.93	7.76	0.37	0.15	1.79	5.04	18.30	20.16	399.29
	20 ~ 40 cm	1.41	7.78	0.23	0.14	1.98	4.06	14.90	19.31	371.03
	40 ~ 60 cm	1.22	7.92	0.13	0.14	2.36	3.10	8.70	19.40	635.35
	60 ~ 80 cm	0.83	8.04	0.13	0.13	2.46	3.54	8.43	19.96	557.38
	average	1.35	7.88	0.22	0.14	2.15	3.94	12.58	19.71	490.76
Coefficient(%)		22.55	1.42	25.64	7.87	9.50	23.26	28.25	2.09	6.09

Analysis of basic quality and fruit sugar-acid content of wine grapes in different regions

Table 3 presents the basic fruit quality of 'Italian Riesling' wine grapes from the three regions of Jiayuguan, Zhangye, and Wuwei during 2018–2020. The soluble sugar content in Zhangye was higher than that in Jiayuguan and Wuwei in all three years, with significant differences from the latter two; the coefficients of variation were 29.70%, 12.97%, and 19.78%, respectively. In 2018, the coefficient of variation for titratable acid was 11.35%. In 2019, the total phenol content was 28.56 mg·g⁻¹ in Zhangye, 26.62 mg·g⁻¹ in Wuwei, and 19.03 mg·g⁻¹ in Jiayuguan, with a coefficient of variation of 20.36%. The tannin content differed significantly among the three regions in 2018 and 2020, with coefficients of variation of 28.89% and 24.58%, respectively; the highest values were 6.04 mg·g⁻¹ in Zhangye in 2018 and 4.95 mg·g⁻¹ in Jiayuguan in 2020. Regarding soluble solids content, the Zhangye region was generally higher than the other two regions in 2018 and 2019, at 25.14% and 27.67%, respectively, while Jiayuguan had the highest value in 2020 at 24.36%. Over the three-year period, the variability among the three regions was lower in 2020 than in 2018 and 2019, with coefficients of variation of 8.48% for Zhangye, 11.91% for Wuwei, and 11.89% for Jiayuguan.

Table 3
Basic quality of wine grapes by region

Years	**2018**				**2019**				**2020**			
Areas	Jiayuguan	Zhangye	Wuwei	Coefficient (%)	Jiayuguan	Zhangye	Wuwei	Coefficient (%)	Jiayuguan	Zhangye	Wuwei	Co
Soluble sugar (%)	12.99 ± 0.30b	21.03 ± 0.64a	12.96 ± 0.04b	29.70	19.55 ± 0.71b	25.19 ± 0.67a	21.51 ± 0.62b	12.97	15.97 ± 0.92b	22.27 ± 0.60a	16.15 ± 1.53b	19
Titratable acid (%)	0.88 ± 0.03c	0.93 ± 0.02b	1.09 ± 0.03a	11.35	1.08 ± 0.08b	1.13 ± 0.03a	1.05 ± 0.05b	3.72	0.87 ± 0.02a	0.64 ± 0.08b	0.68 ± 0.11b	16
Total phenols ($mg·g^{-1}$)	11.65 ± 0.72b	13.72 ± 0.15a	14.29 ± 0.16a	10.51	19.03 ± 0.16c	26.62 ± 1.46b	28.56 ± 1.48a	20.36	16.39 ± 0.13b	17.61 ± 1.74b	21.93 ± 0.53a	15
Tannin($mg·g^{-1}$)	3.46 ± 0.02c	6.04 ± 0.12a	4.24 ± 0.13b	28.89	3.54 ± 0.09c	4.62 ± 0.03b	5.25 ± 0.05a	19.35	4.95 ± 0.08a	3.04 ± 0.23b	4.71 ± 0.02a	24
soluble solid (%)	19.91 ± 0.14c	25.14 ± 0.19a	21.75 ± 0.54b	11.91	21.90 ± 0.67c	27.67 ± 0.47a	24.03 ± 0.34b	11.89	24.36 ± 0.33a	23.5 ± 1.04a	20.66 ± 0.50b	8.4

Note: Values are expressed as mean ± standard deviation, and lowercase letters indicate that there are significant differences in the same indicator among d regions in the same year ($P < 0.05$, Duncan's method was used for multiple comparisons).

Table 4 presents the sugar-acid contents of 'Italian Riesling' wine grape berries from three different regions during 2018–2020. Glucose content in Zhangye was significantly higher than that in Jiayuguan and Wuwei, with three-year coefficients of variation of 30.95%, 17.00%, and 20.77% for the respective regions. The corresponding glucose contents were 76.15, 59.67, and 78.30 mg·g⁻¹, respectively. In 2018, fructose content in Zhangye was the highest at 85.97 mg·g⁻¹, which was 80.2% higher than that in Jiayuguan and 32.9% higher than that in Wuwei. Across all three years, sucrose content in Jiayuguan remained the lowest (0.93 mg·g⁻¹), while the contents in the other two regions were both 1.83 mg·g⁻¹. Inter-regional differences in sucrose content were significant, with coefficients of variation of 41.07%, 20.27%, and 60.94% for the three region.

Table 4

Content of 'Italian Riesling' suga acid in different producing areas(mg·g^{-1})

Years	Areas	Glucose	Fructose	Sucrose	Tartaric Acid	Malic Acid	Oxalic Acid	Citric Acid	Ascorbate Acid
2018	Jiayuguan	41.74 ± 2.56b	47.71 ± 1.21c	0.93 ± 0.12b	4.57 ± 0.26b	2.53 ± 0.14a	0.45 ± 0.01b	0.27 ± 0.02b	0.11 ± 0.02a
	Zhangye	76.15 ± 4.78a	85.97 ± 3.25a	1.95 ± 0.25a	5.90 ± 0.46b	2.31 ± 0.33b	0.09 ± 0.01c	0.46 ± 0.04a	0.11 ± 0.02a
	Wuwei	52.60 ± 3.22b	64.69 ± 4.53b	2.29 ± 0.36a	6.52 ± 0.92a	2.15 ± 0.28c	0.61 ± 0.11a	0.18 ± 0.01b	0.14 ± 0.01a
	Coefficient of variation(CV,%)	30.95	28.99	41.07	17.59	8.19	69.48	47.12	14.43
2019	Jiayuguan	43.87 ± 4.56b	50.61 ± 4.12b	1.83 ± 0.15b	6.46 ± 0.78ab	2.53 ± 0.21a	0.27 ± 0.01b	0.34 ± 0.05a	0.62 ± 0.09b
	Zhangye	59.67 ± 1.58a	68.58 ± 3.98a	2.53 ± 0.19a	7.25 ± 0.56a	2.30 ± 0.23b	0.34 ± 0.02b	0.32 ± 0.01a	0.75 ± 0.04b
	Wuwei	46.36 ± 2.36b	65.88 ± 2.36a	2.75 ± 0.22a	5.86 ± 0.42b	2.14 ± 0.15c	0.61 ± 0.04a	0.46 ± 0.04a	1.01 ± 0.11a
	Coefficient of variation(CV,%)	17.00	15.71	20.27	10.69	8.44	44.15	20.28	25.03
2020	Jiayuguan	52.06 ± 1.88b	41.72 ± 1.25b	1.83 ± 0.15c	2.63 ± 0.36a	3.30 ± 0.19a	0.32 ± 0.02a	1.58 ± 0.15a	0.15 ± 0.02a
	Zhangye	78.30 ± 5.22a	73.3 ± 4.25a	6.37 ± 0.19a	2.99 ± 0.08a	0.74 ± 0.08b	0.04 ± 0.01a	1.38 ± 0.17a	0.14 ± 0.01a
	Wuwei	74.53 ± 6.10a	73.71 ± 4.86a	3.24 ± 0.23b	2.38 ± 0.15a	1.14 ± 0.11b	0.08 ± 0.01a	0.89 ± 0.11a	0.13 ± 0.01a
	Coefficient of variation(CV,%)	20.77	29.17	60.94	11.50	79.76	103.25	27.66	7.14

Note: Values are expressed as mean ± standard deviation, and lowercase letters indicate that there are significant differences in the same indicator among different regions in the same year ($P < 0.05$, Duncan's method was used for multiple comparisons).

Tartaric acid and malic acid were the predominant organic acids in the acid fraction. In 2020, the contents of both acids were generally lower in all three regions than in 2018 and 2019. Over the three-year period, the coefficients of variation for tartaric acid content among the three regions were 17.59%, 10.69%, and 11.50%, respectively. Malic acid content showed less variation in 2018 and 2019, but exhibited significant variability in 2020, with coefficients of variation of 8.19%, 8.44%, and 79.76% for Zhangye, Jiayuguan, and Wuwei, respectively.

Citric acid content in all three regions peaked in 2020, with values of 1.58, 1.38, and 0.89 mg·g⁻¹, respectively, and the differences among regions were not significant. In 2018, the citric acid content in Zhangye (0.46 mg·g⁻¹) was significantly higher than that in Jiayuguan and Wuwei, while in 2019, no significant differences were observed among the three regions. For citric acid, the coefficient of variation among regions was highest in 2018 (47.12%), followed by 2020 (27.66%) and 2019 (20.28%).

Oxalic acid content showed greater inter-regional variability across the three years, with coefficients of variation of 69.48%, 44.15%, and 79.76% for 2018, 2019, and 2020, respectively. In contrast, ascorbic acid content in 2020 showed less variability among the three regions, with a coefficient of variation of 7.14% (Table 4).

Analysis of aroma substances of 'Italian Riesling' grapes from different regions

Table 5 presents the types and concentrations of aroma compounds in 'Italian Riesling' grapes from three different regions of the Hexi Corridor during 2018–2020. A total of 46 aroma compounds were detected, comprising 14 aldehydes, 14 alcohols, 2ketones, 2 esters, and 12 other compounds. Among the aldehydes, hexanal and 2-hexenal were present at high levels, with hexanal reaching its maximum content of 1901.35 μg·kg⁻¹ in 2019 in one of the regions. Among the alcohol compounds, n-nonanol also showed high contents; Jiayuguan exhibited the highest levels among the three regions, with detected concentrations of 76.25 μg·kg⁻¹ in 2018 and 66.36 μg·kg⁻¹ in 2019.

Table 5

The variety and content of aroma substances in different producing areas of 'Italian Riesling' xiang grape(μg·kg^{-1})

compound	Jiayuguan			Zhangye			Wuwei		
Years	2018	2019	2020	2018	2019	2020	2018	2019	2020
Hexanal	575.80 ± 24.02	1901.35 ± 83.47	552.80 ± 83.77	187.23 ± 31.99	302.54 ± 25.99	226.35 ± 35.16	180.97 ± 2.42	308.95 ± 15.31	70.74 ± 25.95
3-hexenal	-	156.43 ± 39.68	25.70 ± 10.12	4.52 ± 1.24	11.25 ± 4.17	22.34 ± 7.35	6.41 ± 2.26	11.63 ± 3.48	-
pentadecanal	-	3.61 ± 2.42	-	24.65 ± 2.56	23.44 ± 3.18	15.24 ± 5.00	10.24 ± 3.26	3.42 ± 0.88	4.04 ± 1.77
2-hexenal	886.80 ± 38.91	-	925.80 ± 128.34	334.02 ± 41.67	447.26 ± 26.04	336.24 ± 43.98	104.31 ± 13.87	336.22 ± 38.49	884.00 ± 156.24
(E,E)-2, 4-hexdienal	12.10 ± 8.49	68.03 ± 6.99	52.60 ± 14.25	55.65 ± 21.15	62.15 ± 11.73	162.35 ± 79.52	14.54 ± 3.52	555.22 ± 86.59	-
(E,E)-2, 4-heptanedienal	-	4.18 ± 0.23	-	24.63 ± 4.35	32.54 ± 2.93	44.36 ± 6.01	14.11 ± 1.92	52.21 ± 5.66	11.78 ± 8.08
Benzaldehyde	12.77 ± 2.71	-	7.26 ± 2.40	68.72 ± 12.06	26.34 ± 7.86	11.43 ± 4.62	58.09 ± 5.68	3.21 ± 1.33	8.57 ± 3.89
(E)-2-Nonenal	8.24 ± 1.98	15.84 ± 1.81	17.40 ± 3.29	-	-	-	9.19 ± 2.98	82.14 ± 4.55	-
(2E,6Z)-nona-2,6-dienal	-	6.85 ± 1.32	-	33.24 ± 3.16	11.28 ± 3.11	23.56 ± 6.21	-	-	8.54 ± 3.27
2-Methylbenzaldehyde	136.40 ± 3.74	15.29 ± 1.65	-	225.34 ± 44.26	222.64 ± 20.73	352.47 ± 33.46	105.26 ± 3.95	9.95 ± 1.57	169.98 ± 74.34
p-Tolualdehyde	13.50 ± 2.34	195.01 ± 17.16	-	268.74 ± 28.64	315.42 ± 42.01	253.65 ± 113.07	78.76 ± 1.52	-	158.79 ± 36.04
2, 4-dimethylbenzaldehyde	-	208.13 ± 45.23	362.80 ± 66.79	196.87 ± 8.60	185.24 ± 18.63	215.21 ± 26.34	475.27 ± 25.05	6.21 ± 1.96	77.93 ± 10.53
phenylacetaldehyde	-	172.63 ± 24.24	-	76.32 ± 8.21	96.41 ± 9.05	57.26 ± 6.99	25.89 ± 2.96	107.8 ± 6.79	66.32 ± 11.64
Nonanal	52.63 ± 7.64	-	25.89 ± 4.24	-	-	35.24 ± 9.19	35.62 ± 4.83	22.95 ± 1.20	-
(Z)-2-Hexenol	106.30 ± 5.97	1592.12 ± 149.08	147.58 ± 33.57	115.24 ± 15.60	154.26 ± 8.03	152.37 ± 16.27	342.77 ± 15.41	125.41 ± 18.19	80.98 ± 12.72
Trans − 2-hexene-1-ol	21.31 ± 3.96	82.26 ± 7.27	44.35 ± 9.47	102.54 ± 5.27	-	102.43 ± 30.31	186.24 ± 6.25	45.23 ± 4.44	237.94 ± 104.61
5-Indanol	25.24 ± 1.90	69.67 ± 21.28	32.10 ± 7.11	33.24 ± 3.73	11.25 ± 1.06	11.26 ± 3.29	24.25 ± 1.60	6.92 ± 1.02	-
Geraniol	67.64 ± 4.30	102.34 ± 15.19	52.40 ± 8.85	68.22 ± 4.61	88.26 ± 11.98	7.24 ± 2.42	94.23 ± 8.29	8.13 ± 2.25	52.74 ± 10.51
Phenethyl alcohol	20.70 ± 3.62	75.13 ± 7.05	17.26 ± 7.76	34.25 ± 2.53	32.45 ± 3.43	25.36 ± 5.61	-	18.72 ± 2.37	-
Nerol	50.60 ± 2.48	42.36 ± 13.36	32.66 ± 4.14	11.25 ± 2.21	-	35.24 ± 4.69	-	7.24 ± 1.39	-
1-octylne-3-ol	19.60 ± 1.08	32.58 ± 5.54	25.80 ± 8.10	44.25 ± 3.82	77.54 ± 2.21	-	-	40.61 ± 2.98	9.85 ± 1.16
linalool	22.88 ± 1.65	46.32 ± 4.02	-	2.81 ± 0.56	5.62 ± 2.95	-	-	6.62 ± 0.96	4.39 ± 1.15
2-ethyl hexanol	44.20 ± 1.39	55.16 ± 4.67	33.20 ± 4.40	5.42 ± 0.75	-	3.08 ± 1.21	25.34 ± 2.45	17.36 ± 3.31	17.26 ± 4.15
Isopulegol	46.28 ± 5.05	63.28 ± 6.53	-	-	26.32 ± 4.55	15.39 ± 6.70	16.33 ± 0.35	6.51 ± 0.64	-
Cis-3-hexene-1-ol	33.62 ± 3.17	77.24 ± 3.17	45.68 ± 11.48	35.24 ± 2.40	44.23 ± 3.80	16.27 ± 1.86	52.11 ± 1.89	11.26 ± 1.70	24.23 ± 3.41
1-Nonanol	76.25 ± 10.45	66.32 ± 11.05	-	-	21.56 ± 3.15	15.82 ± 4.17	18.22 ± 1.95	-	35.64 ± 5.39

Note: The values represent the contents of volatile compounds in different regions in different years (μg·kg^{-1}), and the results are expressed as mean ± standard deviation. "-"Indicates not detected(ND, below the detection limit of GC-MS).

compound	Jiayuguan			Zhangye			Wuwei		
2-cyclohexenol	71.28 ± 6.54	73.68 ± 5.98	56.34 ± 7.56	28.62 ± 2.05	-	-	15.23 ± 2.89	33.24 ± 2.53	-
Methyl benzyl alcohol	44.56 ± 2.31	52.18 ± 3.73	33.25 ± 3.04	21.34 ± 1.47	-	-	16.28 ± 1.46	10.26 ± 2.00	-
β-Damascone	25.81 ± 2.42	381.11 ± 24.74	33.62 ± 3.86	18.26 ± 2.44	11.24 ± 1.78	17.43 ± 2.85	7.95 ± 1.34	13.21 ± 2.65	22.38 ± 2.86
β-damascenone	-	21.40 ± 2.15	6.31 ± 2.76	11.63 ± 1.83	-	-	15.26 ± 1.22	22.63 ± 3.89	-
8-Cyclohexadecen-1-one	-	9.15 ± 2.81	13.62 ± 1.30	-	8.54 ± 1.27	7.23 ± 2.52	-	-	6.42 ± 1.13
Geranylacetonee	11.25 ± 2.14	-	15.73 ± 33.24	31.22 ± 3.12	27.37 ± 3.14	22.11 ± 1.32	19.14 ± 1.61	4.41 ± 0.67	-
Tridecane	75.88 ± 4.81	446.13 ± 13.04	102.33 ± 28.50	15.28 ± 0.91	26.72 ± 4.76	-	6.70 ± 0.98	2.26 ± 1.32	-
Octane	484.23 ± 6.12	54.62 ± 14.99	-	151.24 ± 8.81	-	155.36 ± 8.34	23.21 ± 5.57	54.90 ± 9.63	76.27 ± 10.67
n-heptadecane	62.61 ± 3.14	-	74.44 ± 25.52	26.33 ± 1.90	293.55 ± 13.42	112.38 ± 23.38	13.28 ± 3.22	6.63 ± 2.00	60.68 ± 12.24
1, 2-epoxy hexadecane	-	35.22 ± 9.03	3.82 ± 0.39	46.25 ± 3.65	27.50 ± 5.08	45.72 ± 13.41	91.89 ± 7.79	-	-
Hentriacontane	51.28 ± 3.60	2.23 ± 1.46	125.64 ± 14.50	121.25 ± 3.90	204.26 ± 40.66	144.32 ± 5.29	166.23 ± 9.02	264.44 ± 9.63	165.12 ± 7.82
Dotriacontane	28.49 ± 2.84	-	21.22 ± 2.93	33.24 ± 2.46	43.85 ± 4.78	12.33 ± 3.55	46.01 ± 3.53	33.72 ± 3.02	33.65 ± 2.86
n-Octadecane	62.26 ± 5.70	152.44 ± 5.09	134.77 ± 24.23	21.66 ± 3.33	37.11 ± 5.63	77.55 ± 8.00	-	255.26 ± 12.26	-
2-ethyl furan	-	46.32 ± 6.98	-	151.91 ± 6.02	-	-	-	72.45 ± 6.97	-

Note: The values represent the contents of volatile compounds in different regions in different years ($\mu g \cdot kg^{-1}$), and the results are expressed as mean ± standard deviation. "-"Indicates not detected(ND, below the detection limit of GC-MS).

The total number of aroma compounds detected in different regions and years is shown in Fig. 1. In 2018, Zhangye had the highest total with 41 compounds, whereas both Jiayuguan and Wuwei had 36. In 2019, Zhangye recorded the lowest number with 34 compounds, and in 2020, Wuwei had the fewest with 27. Among the measured aroma substances, aldehydes and alcohols were the predominant classes, accounting for more than 50% of the total.

The differences in aroma compound accumulation patterns among the three regions in the Hexi Corridor from 2018 to 2020 were analyzed by clustering, as shown in Fig. 2. The cluster heatmap analysis revealed significant differences in aroma compounds among the regions, which were categorized into four clusters. Cluster 1 compounds were highest in Wuwei in 2019, lowest in Jiayuguan in 2018, and moderate in the other years and regions. Cluster 2 compounds were highest in Zhangye in both 2018 and 2019, and lowest in Wuwei and Jiayuguan in 2019. Cluster 3 compounds were highest in Jiayuguan in 2018 and lower in other years and regions. Cluster 4 compounds were highest in Jiayuguan in 2019, followed by those in Jiayuguan in 2018, which ranked second.

There were obvious differences in aroma substances among the different production areas. A total of five clusters were identified: Cluster 1 included samples from Jiayuguan in 2018 and 2020; Cluster 2 included samples from Zhangye during 2018–2020; Cluster 3 included samples from Wuwei in 2018 and 2020; Cluster 4 included samples from Wuwei in 2019; and Cluster 5 included samples from Jiayuguan in 2019. The cluster analysis revealed that the differences in aroma substances among the three years in the Zhangye production area were small. In contrast, the aroma substance contents in the Wuwei and Jiayuguan production areas in 2019 differed greatly from those in the other two years. This may be attributed to the fact that both the Wuwei and Jiayuguan production areas received lower rainfall from July to September in 2019 than they did in the other two years.

Correlation analysis of meteorological factors, soil nutrients and berries quality of 'Italian Riesling' in three areas

The correlation between meteorological factors and fruit quality is shown in Fig. 3(A). The effect of meteorological factors on fruit quality is relatively small. Mean air temperature and effective cumulative temperature from April to September were significantly and negatively correlated with fruit tannin, malic acid, and citric acid contents ($P < 0.05$). The day-night temperature difference from April to September and rainfall from July to September were significantly negatively correlated with fruit total phenol content, and significantly positively correlated with oxalic acid content.

The correlation between meteorological factors and fruit aroma substances is shown in Fig. 3(B). Air temperature from April to September was positively correlated with the contents of most fruit aroma substances, with the exception of ketones, phenols, aldehydes, and alcohols ($P < 0.05$). Rainfall from July to September was significantly negatively correlated with the content of phenols, aldehydes, and other aroma compounds.

Correlation analysis between soil nutrients and basic quality and aroma substances of 'Italian Riesling' berries in different regions

The correlation between soil nutrients and fruit quality is shown in Fig. 4. Soil organic matter and soil pH at the 60–80 cm depth were significantly and negatively correlated with fruit sucrose content, while pH at the same depth was significantly and positively correlated with soluble sugar content. Soil phosphorus content at the 0–20 cm and 40–60 cm depths was significantly and negatively correlated with fructose content. Soil potassium at the 40–60 cm depth was significantly and positively correlated with fruit titratable acid, malic acid, and oxalic acid contents, and significantly and negatively correlated with glucose content. Surface soil calcium and soil copper at the 20–40 cm depth were significantly and negatively correlated with fruit tartaric acid content. Additionally, surface soil copper content was significantly negatively correlated with fruit soluble sugar content. Soil iron at the 60–80 cm depth was significantly negatively correlated with fruit soluble sugar content and positively correlated with tannin content. Soil iron at the 40–60 cm depth was significantly and negatively correlated with fruit fructose content, while soil manganese at the 60–80 cm depth was significantly and positively correlated with fructose content. Soil manganese at the 20–40 cm depth was significantly negatively correlated with total fruit phenol content, and positively correlated with soluble solids and citric acid contents.

The correlation between soil nutrients and fruit aroma substances is shown in Fig. 5. Soil organic matter in the 60–80 cm layer and soil calcium in the 20–40 cm layer were significantly and positively correlated with alcohols in fruit aroma substances. Soil pH in the 20–40 cm layer was significantly and positively correlated with ketones, and soil Fe in the same layer was significantly and positively correlated with phenolics. Soil N in the 0–40 cm layer was significantly and negatively correlated with the content of other aroma substances (excluding alcohols, ketones, and phenolics), while soil N in the 60–80 cm layer was significantly and positively correlated with those compounds.

Principal component analysis of "Italian Riesling" in different regions from 2018 to 2020

Principal component analysis was conducted on various indicators in different regions over three years. The results showed (as shown in Fig. 6A-C below) that the variance contribution rates of PC1 and PC2 for each indicator over the three-year period all exceeded 99%, and PC1 was over 90% across all years, indicating that PC1 can serve as the main factor for distinguishing the grape quality characteristics of the three regions. The indicators of Wuwei and Zhangye regions are highly similar, and they are both located in the positive direction of PC1 and PC2, while Jiayuguan lies in the opposite direction, indicating that there are significant differences in chemical indicators between Jiayuguan and the other two regions. Additionall, there is an obvious negative correlation between accumulated temperature and compounds such as hexanal and hexenal. Specifically, aldehydes such as hexanal and hexenal are strongly correlated with the Jiayuguan region and weakly correlated with the Wuwei and Zhangye regions.

Discussion

The present study revealed substantial regional differences in the primary metabolite profiles of 'Italian Riesling' grapes, with Zhangye consistently exhibiting the highest soluble sugar and glucose contents over the three-year period. This pattern is most plausibly attributed to the higher effective cumulative temperature and larger diurnal temperature amplitude recorded in Zhangye during the growing season (April-September). Diurnal temperature fluctuation enhances photosynthetic carbon fixation during daytime while reducing respiratory consumption at night, thereby promoting net carbohydrate accumulation in berries[7, 22]. This physiological interpretation is supported by our correlation analysis, which demonstrated a significant positive relationship between April-September diurnal temperature range and glucose content. Similar thermal effects on sugar accumulation have been documented in apple[7] and grape[8] studies, reinforcing the notion that temperature is a primary modulator of source-sink carbohydrate partitioning.

Conversely, the higher total phenol content observed in Wuwei grapes (28.56 $mg \cdot g^{-1}$ in 2019) may be linked to the greater July-September rainfall in this region. Moderate water stress is known to stimulate secondary metabolism, particularly the phenylpropanoid pathway, by upregulating key enzymes such as phenylalanine ammonia-lyase (PAL) and chalcone synthase[23]. However, the significant negative correlation we observed between July-September rainfall and fruit total phenol content appears counterintuitive. This discrepancy may reflect a nonlinear response: while moderate drought stress promotes phenolic accumulation, excessive rainfall during the ripening period-as occurred in Wuwei in 2019-could dilute phenolic compounds through increased berry water uptake or leach them from the berry skin[24]. Alternatively, reduced solar radiation associated with overcast rainy days may downregulate light-dependent flavonoid biosynthesis genes[25]. This duality underscores the complexity of water-phenolic relationships and suggests that optimal phenolic accumulation occurs under a narrow range of soil moisture conditions.

Our correlation analysis revealed that soil nutrient effects on berry quality were highly depth-dependent, a finding with important implications for vineyard soil management. Notably, soil organic matter at 60–80 cm depth and calcium at 20–40 cm were significantly positively correlated with fruit alcohol content, while pH at 60–80 cm showed a significant positive correlation with soluble sugar content. These depth-specific patterns may be explained by the vertical distribution of grapevine root systems. In arid regions, grapevines develop deep roots to access water and nutrients from subsurface layers[26], particularly during the critical ripening phase when surface soils often become desiccated. Thus, nutrients present in deeper horizons (60–80 cm) may be more physiologically relevant for late-season berry development than those in topsoil.

The positive association between deeper-soil organic matter and alcohol aroma compounds is particularly noteworthy. Soil organic matter enhances microbial activity and nutrient mineralization, potentially influencing the availability of nitrogen and sulfur precursors for volatile compound biosynthesis[27]. Moreover, organic matter improves soil water-holding capacity, which may moderate vine water status and indirectly affect aroma precursor accumulation[28]. The significant positive correlation between 20–40 cm calcium content and fruit alcohols further suggests that calcium-an important regulator of membrane integrity and stress signaling-may facilitate the biosynthesis or retention of volatile compounds during berry maturation[29].

Interestingly, we found that soil iron at 60–80 cm was negatively correlated with soluble sugar but positively correlated with tannin content. This contrasting pattern may reflect iron's role in oxidative metabolism: excess iron can promote reactive oxygen species (ROS) generation, potentially diverting carbon flux from sugar accumulation toward phenolic defense pathways[30]. This interpretation aligns with the well-established trade-off between primary and secondary metabolism under oxidative stress conditions[31].

A total of 46 aroma compounds were identified across all samples, with aldehydes (particularly hexanal and 2-hexenal) and alcohols constituting the dominant fractions-a profile consistent with previous reports for white grape varieties[32, 33]. The total aroma content was highest in Jiayuguan in 2019 (4,972.97 $\mu g \cdot kg^{-1}$), which may be attributed to the lower rainfall during July-September of that year in this region. Our correlation analysis supports this inference, showing a significant negative relationship between late-season rainfall and phenolic/aldehyde contents in fruit aroma. Water deficit has been shown to enhance the expression of genes involved in terpenoid and fatty-acid-derived volatile biosynthesis through abscisic acid (ABA)-mediated signaling pathways[34, 35].

The cluster analysis (Fig. 3) revealed that aroma profiles in Zhangye were relatively stable across the three vintages, whereas those in Wuwei (2019) and Jiayuguan (2019) deviated markedly from their respective multi-year patterns. This inter-annual instability in Wuwei and Jiayuguan coincided with lower rainfall from July to September in 2019 compared to the other two years, suggesting that aroma composition in these regions is more sensitive to inter-annual precipitation variability. By contrast, the greater thermal consistency in Zhangye may have buffered vintage effects, resulting in more reproducible aroma profiles. This observation carries practical implications: regions with higher thermal stability may offer more predictable wine styles across vintages, whereas regions with variable rainfall may produce more distinctive but less consistent vintages.

A comparison with previous studies is instructive. Li et al.[35] detected only 26 aroma compounds in 'Italian Riesling' grapes from the Zhangye region, considerably fewer than the 46 identified in the present work. This discrepancy likely stems from methodological differences (e.g., extraction methods, GC-MS parameters) as well as inter-annual climatic variation. Our more comprehensive detection may also reflect the use of optimized extraction conditions (DVB/CAR/PDMS fiber, 40°C extraction temperature) that improved the recovery of trace volatiles[36].

Principal component analysis clearly separated Jiayuguan from Zhangye and Wuwei, with PC1 (explaining > 90% of variance) serving as the primary discriminant axis. The loading patterns indicated that accumulated temperature from April to September was the strongest contributing factor to this separation. Jiayuguan, characterized by lower accumulated temperature, clustered separately from the other two regions, which shared higher thermal sums. This thermal divergence likely underlies the distinct compositional profiles observed: Jiayuguan grapes exhibited lower sugar but higher aldehyde contents, consistent with the recognized role of temperature in modulating both primary and secondary metabolism[5, 9].

The close clustering of Zhangye and Wuwei in PCA space, despite their differences in rainfall and certain soil nutrients, suggests that thermal conditions exert a dominant influence over berry quality in this arid region, potentially overriding the effects of other environmental variables. This finding has significant implications for viticultural zoning and cultivar selection: in the Hexi Corridor, accumulated temperature may serve as the most reliable predictor of regional suitability for specific wine grape varieties. For 'Italian Riesling', which is known to perform well in moderately warm climates[1], the higher thermal sums in Zhangye and Wuwei appear to favor the accumulation of sugars and phenolic compounds, whereas the cooler conditions in Jiayuguan may be more conducive to preserving the fresh, green aromas associated with aldehydes.

Conclusion

In summary, this study demonstrates that regional environmental factors-particularly accumulated temperature, diurnal temperature range, and depth-specific soil nutrients-exert profound and differential effects on the quality of 'Italian Riesling' grapes in the Hexi Corridor. The marked inter-regional and inter-vintage variability underscores the concept of terroir as a dynamic interplay of climate, soil, and management practices. Our findings provide a scientific basis for site-specific viticultural strategies, including tailored irrigation, targeted soil amendment, and informed cultivar selection, to optimize wine grape quality in arid production environments. Furthermore, the identification of accumulated temperature as the primary discriminant factor offers a practical metric for regional quality assessment and viticultural zoning in northwestern China.

Abbreviations

HPLC, high performance liquid chromatography; PCA, principal component analysis; SSC, soluble solids content; TA, titratable acidity; HS-SPME-GC-MS, headspace solid-phase microextraction gas chromatography-mass spectrometry; CV, coefficient of variation; SD, standard deviation; ANOVA, analysis of variance. HCA, Hierarchial clustering analysis.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

competing interest

There are no other competing financial or personal relationships that could influence this work.

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Author Contributions

Zonghuan Ma (Corresponding Author) conceptualized and designed the overall study, supervised the entire research process, acquired the funding, administered the project, provided essential resources, and reviewed and edited the final manuscript. Zhanyu Guo performed the data curation, developed the software, and wrote the original draft, as well as contributing to the review and editing of the manuscript. Xuemei Hou performed the data curation, developed the software, and wrote the original draft, as well as contributing to the review and editing of the manuscript. Huilan Qiao conducted the data curation, implemented the software, and established the methodology. Yusheng Zhang also contributed to data curation, software development, and methodology. Xintong Nan carried out the formal analysis, performed software programming, and assisted with data curation. All authors have read and approved the final version of the manuscript and agree to its submission.

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References

1. Ma Zonghuan L, Yumei L. Quality analysis of Cabernet Sauvignon grapes from different production areas in the Hexi Corridor wine region[J]. Agricultural Res Arid Areas. 2023;41(03):81–7. 10.7606/j.issn.1000-7601.2023.03.12.
2. Rustioni L, Altomare A, Shanshiashvili G, et al. Microclimate of grape bunch and sunburn of white grape berries: effect on wine quality[J/OL]. Foods. 2023;12(3):621–621. 10.3390/foods12030621.
3. Nicola Damiano C, Cirillo F, Petracca, et al. Falanghina grapevine (vitis vinifera L.) yield and berry quality under different pedoclimatic conditions in southern Italy[J/OL]. Horticulturae. 2022;8(9):829–829. 10.3390/horticulturae8090829.
4. LIU M, JI H, JIANG Q, et al. Effects of full shading of clusters from véraison to ripeness on fruit quality and volatile compounds in cabernet sauvignon grapes[J/OL]. Food Chemistry: X. 2024;21:101232–101232. 10.1016/j.fochx.2024.101232.
5. Carlo PD, Aruffo E. Brune. Precipitation intensity under a warming climate is threatening some italian premium wines[J/OL]. Sci Total Environ. 2019;685:508–13. 10.1016/j.scitotenv.2019.05.449.
6. Corrado Perin PK, Verma G, Harari, et al. Influence of late pruning practice on two red skin grapevine cultivars in a semi-desert climate[J/OL]. Front Plant Sci. 2023;14:1114696–1114696. 10.3389/fpls.2023.1114696.
7. QU Z ZHOUG. Possible impact of climate change on the quality of apples from the major producing areas of China[J/OL]. Atmosphere. 2016;7(9):113–113. 10.3390/atmos7090113.
8. Liu Chunming Z, Xudon J, Jufang. Climatic zoning for grape cultivation of dry red and dry white wines in the Hexi Corridor[J]. Agricultural Res Arid Areas, 2006(06).
9. RIENTH M, LAURENT T, GAUTIER S, et al. Temperature desynchronizes sugar and organic acid metabolism in ripening grapevine fruits and remodels their transcriptome[J/OL]. BMC Plant Biol. 2016;16(1):164–164. 10.1186/s12870-016-0850-0.
10. KELLER M. Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists[J/OL]. Aust J Grape Wine Res. 2010;16:56–69. 10.1111/j.1755-0238.2009.00077.x.
11. VADIVEL R, REDDY K S, SINGH Y, et al. Effect of pit and soil types on growth and development, nutrient content and fruit quality of pomegranate in the central deccan plateau region. india[J/OL] Sustain. 2024;16(18):8099–8099. 10.3390/su16188099.
12. Ha Ron C, Yongwei J, Wei, et al. Effects of Different Soil Improvement Techniques on Growth and Fruit Quality of Tomato[J]. North Hortic. 2024;17:43–50. 10.11937/bfyy.20240807.
13. Ali AA, Bouchaou L, Hssaisoune M, et al. Exploring the effect of different irrigation levels on fruit quality in a commercial drip irrigated clementine orchard under semi-arid climate conditions[J/OL]. Irrig Sci. 2025;43(3):533–47. 10.1007/s00271-024-00992-w.

14. GUO X, AN X. Effects of stoichiometric ratio fertilization on leaf photosynthetic characteristics and fruit quality of blueberry[J/OL]. BMC Plant Biol. 2025;25(1):334–334. 10.1186/S12870-025-06331-1.
15. Lingshuai Y, Sonfeng D, Fu Jianmin. Effects of bagging treatment on the quality traits of astringent persimmon fruits[J/OL]. Res Economic Forests. 2023;41(02):282–9. 10.14067/j.cnki.1003-8981.2023.02.029.
16. BOSS PK, BÖTTCHER C. Various influences of harvest date and fruit sugar content on different wine flavor and aroma compounds[J/OL]. Am J Enol Viticult. 2014;65(03):341–53. 10.5344/ajev.2014.13137.
17. CHITARRINI G, DORDEVIC N et al. GUERRA W,. Aroma investigation of new and standard apple varieties grown at two altitudes using gas chromatography-mass spectrometry combined with sensory analysis[J/OL]. Molecules, 2020, 25(13)[2026-05-06]. 10.3390/molecules25133007
18. AN X, LI W, LIANG Y, et al. Fruit quality components of balsam pear (momordica charantia L.) and soil respiration in response to soil moisture under two soil conditions[J/OL]. J Food Meas Charact. 2018;12(2):710–20. 10.1007/s11694-017-9684-1.
19. El-Shewy AA, Abdel-Khalek, Eman A. Vegetative growth, fruit set, yield and fruit quality of le-conte pear grown under calcareous soil conditions as affected by different levels of nitrogen, phosphorus and potassium[J]. J Adv Lab Res Biology. 2013;4(02):74–81.
20. BAMBINA P, POLLON M. Effect of soil type on some composition parameters of vitis vinifera L. cv. Nero d'avola grapes at different stages of ripening[J/OL]. Int J Food Sci Technol. 2024;59(4):2361–74. 10.1111/IJFS.16964.
21. LINDSAY W L, NORVELL W A. Development of a DTPA Soil Test for Zinc, Iron, Manganese, and Copper[J]. Soil Sci Soc Am J. 1978;42(3):421–8.
22. JING C, FENG D, ZHAO Z, et al. Effect of environmental factors on skin pigmentation and taste in three apple cultivars[J/OL]. Acta Physiol Plant. 2022;42(5):1131–4. 10.1007/s11738-020-03039-7.
23. BACELAR E, PINTO T, ANJOS R, et al. Impacts of climate change and mitigation strategies for some abiotic and biotic constraints influencing fruit growth and quality[J/OL]. Plants. 2024;13(14):1942–1942. 10.3390/plants13141942.
24. ZHAI C, LI Y, LI J, et al. Signaling mechanisms governing the environmental modulation of fruit quality development[J/OL]. Hortic Res. 2026;13(4):uhag005. 10.1093/hr/uhag005.
25. WU L, QIN M, MUNEER M A, et al. Soil pH and organic matter: key edaphic factors in sustaining optimum yield and quality of pomelo fruit[J/OL]. Sci Hort. 2024;337:113524. 10.1016/j.scienta.2024.113524.
26. Fu Xiaomeng Y, Honxia L, Chunrui et al. Review on the influence of soil pH on orchard soil quality and research on regulation technologies[J/OL]. Liaoning Agricultural Sci, 2023(4): 75–8. 10.3969/j.issn.1002-1728.2023.04.015
27. NIWAYAMA S, HIGUCHI H. Passion fruit quality under acidic soil conditions[J/OL]. Hortic J. 2019;88(1):50–6. 10.2503/hortj.OKD-169.
28. YU M, LI Y, WANG L, et al. Research on the precise regulation of korla fragrant pear quality based on sensitivity analysis and artificial neural network model[J/OL]. Agronomy. 2025;15(5):1236–1236. 10.3390/agronomy15051236.
29. AHMED N, ZHANG B, CHACHAR Z, et al. Micronutrients and their effects on horticultural crop quality, productivity and sustainability[J/OL]. Sci Hort. 2024;323:112512. 10.1016/j.scienta.2023.112512.
30. MURADOĞLU F, AKKUŞ GÜLERE. Pomegranate's (punica granatum L.) fruit quality and nutrient content are influenced by soil fraction × root architecture interaction[J/OL]. Ann Appl Biol. 2024;184(3):288–99. 10.1111/aab.12889.
31. LI Y, XIAO J, YAN Y et al. Multivariate analysis and optimization of the relationship between soil nutrients and berry quality of vitis vinifera cv. Cabernet franc vineyards in the eastern foothills of the helan mountains, china[J/OL]. Horticulturae, 2024, 10(1)[2026-05-06]. 10.3390/HORTICULTURAE10010061
32. FENOLL J, MANSO A, HELLÍN P, et al. Changes in the aromatic composition of the *vitis vinifera* grape muscat hamburg during ripening[J/OL]. Food Chem. 2009;114(2):420–8. 10.1016/j.foodchem.2008.09.060.
33. Wei T, Xiaoping T, Zhigang D, et al. Analysis of fruit aroma components of four seedless table grape varieties and their parents[J/OL]. J Fruit Sci. 2015;32(03):440–7. 10.13925/j.cnki.gsxb.20140353.
34. Schwab W, Wüst M. Understanding the constitutive and induced biosynthesis of mono- and sesquiterpenes in grapes (vitis vinifera): a key to unlocking the biochemical secrets of unique grape aroma profiles[J/OL]. J Agric Food Chem. 2015;63(49):10591–603. 10.1021/acs.jafc.5b04398.
35. Li Y, Feifei Z, Weifeng M, et al. Evaluation of fruit quality and analysis of aroma characteristics of wine grapes in the Zhangye production area of the Hexi Corridor[J/OL]. Res Economic Forests. 2020;38(02):169–76. 10.14067/j.cnki.1003-8981.2020.02.021.
36. Wang Yongmei Z, Zhengwen G, Lei et al. Effects of different fruit loads on aroma substances in the berries of Italia Riesling grapes[J]. Northwest Hortic (Comprehensive), 2017(09): 61–4.

Figures

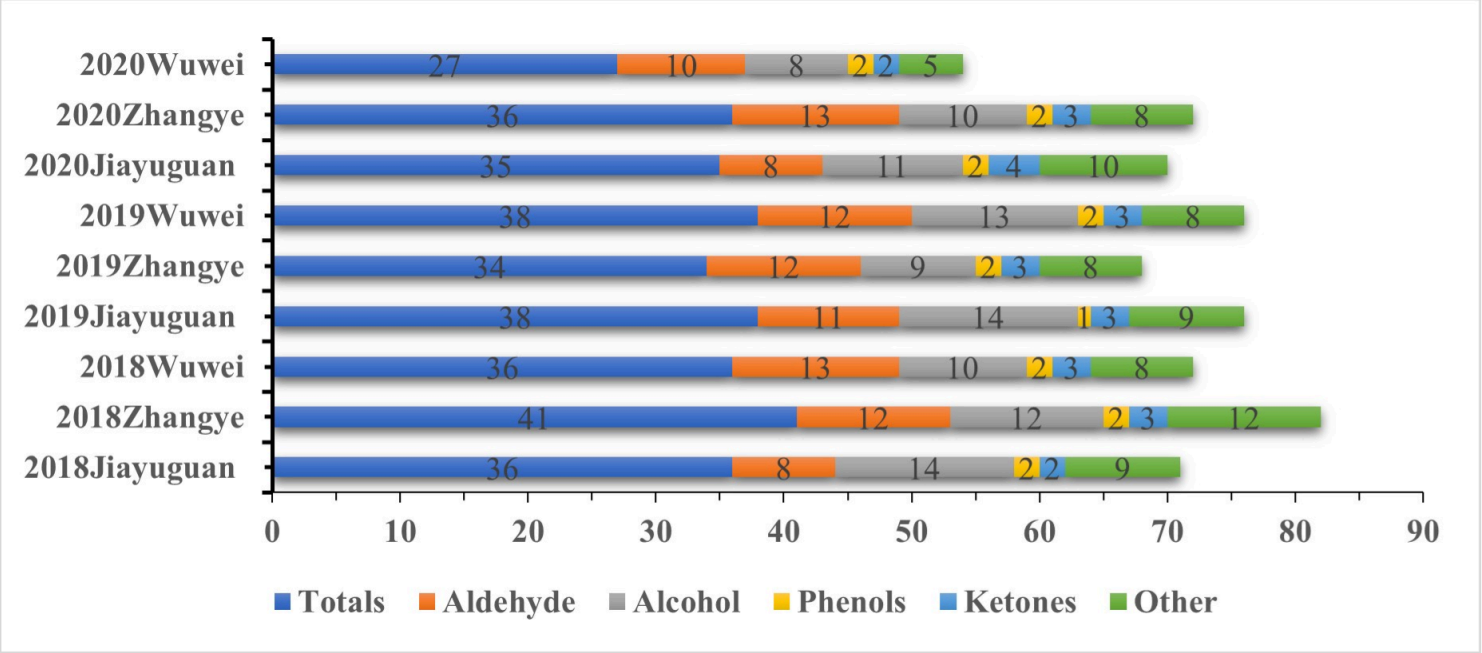


Figure 1

Diagrams of changes in volatile substance components in different regions and different years

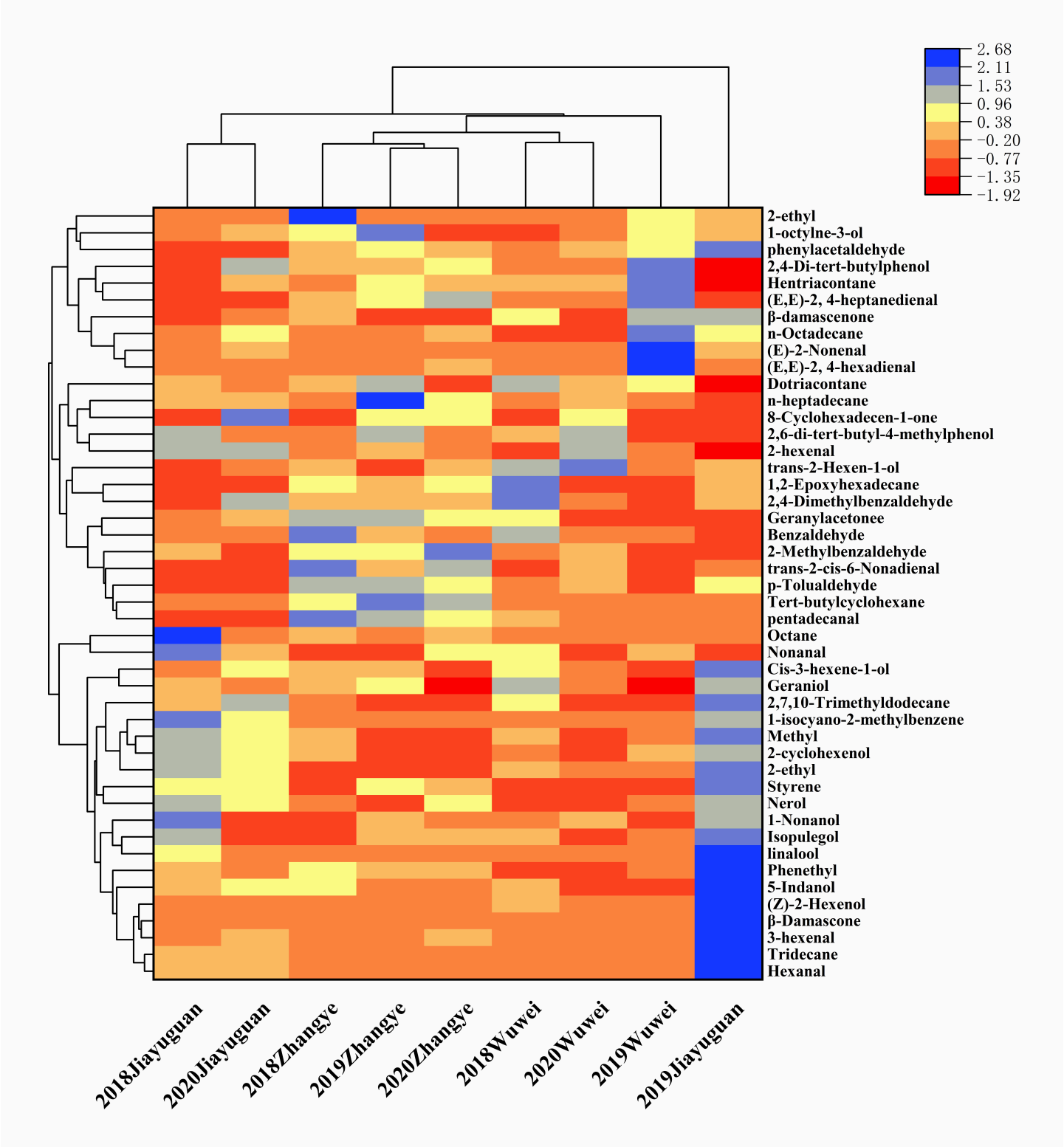


Figure 2

Cluster analysis diagrams of volatile compounds in different regions and different years

Note:Hierarchical clustering analysis of volatile compounds and accumulation patterns across three regions from 2018 to 2020. The heatmap displays the correlation between individual volatile compounds and the year of harvest. Red indicates a negative correlation, while blue indicates a positive correlation.

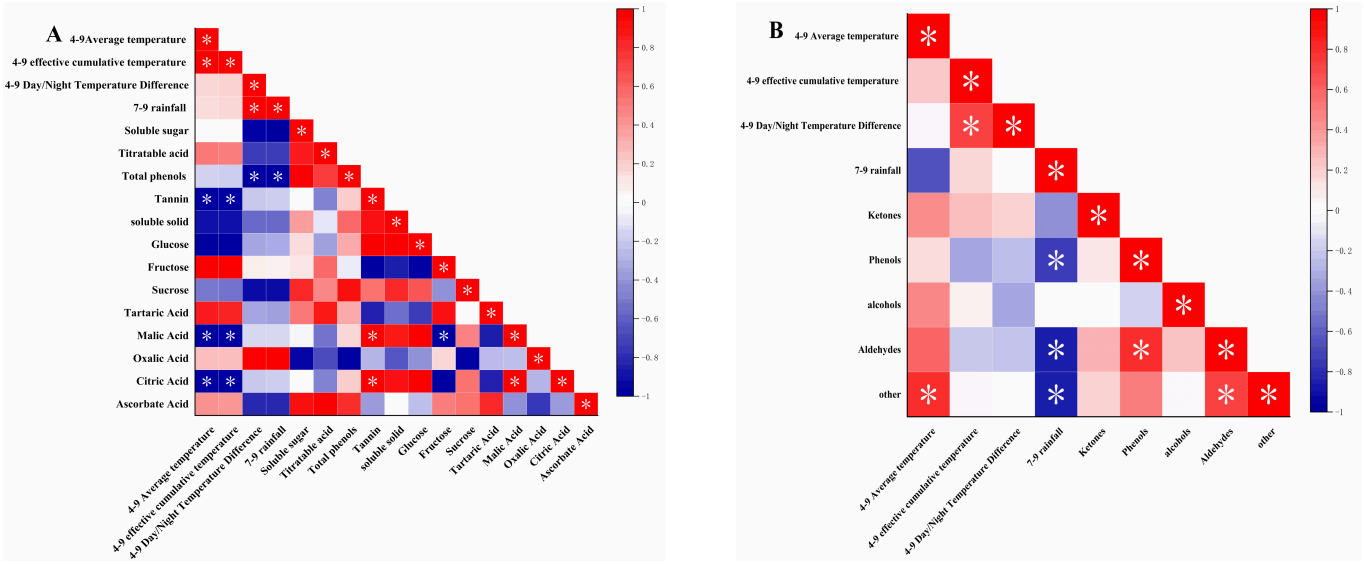


Figure 3

Correlation between meteorological factors and fruit quality

Note: (A) Pearsoncorrelation diagram between meteorological factors and fruit quality, where red indicates positive correlation and blue indicates negative correlation; (B) Pearson correlation diagram between meteorological factors and aroma compounds, where red indicates positive correlation and blue indicates negative correlation.”*”P<0.05.

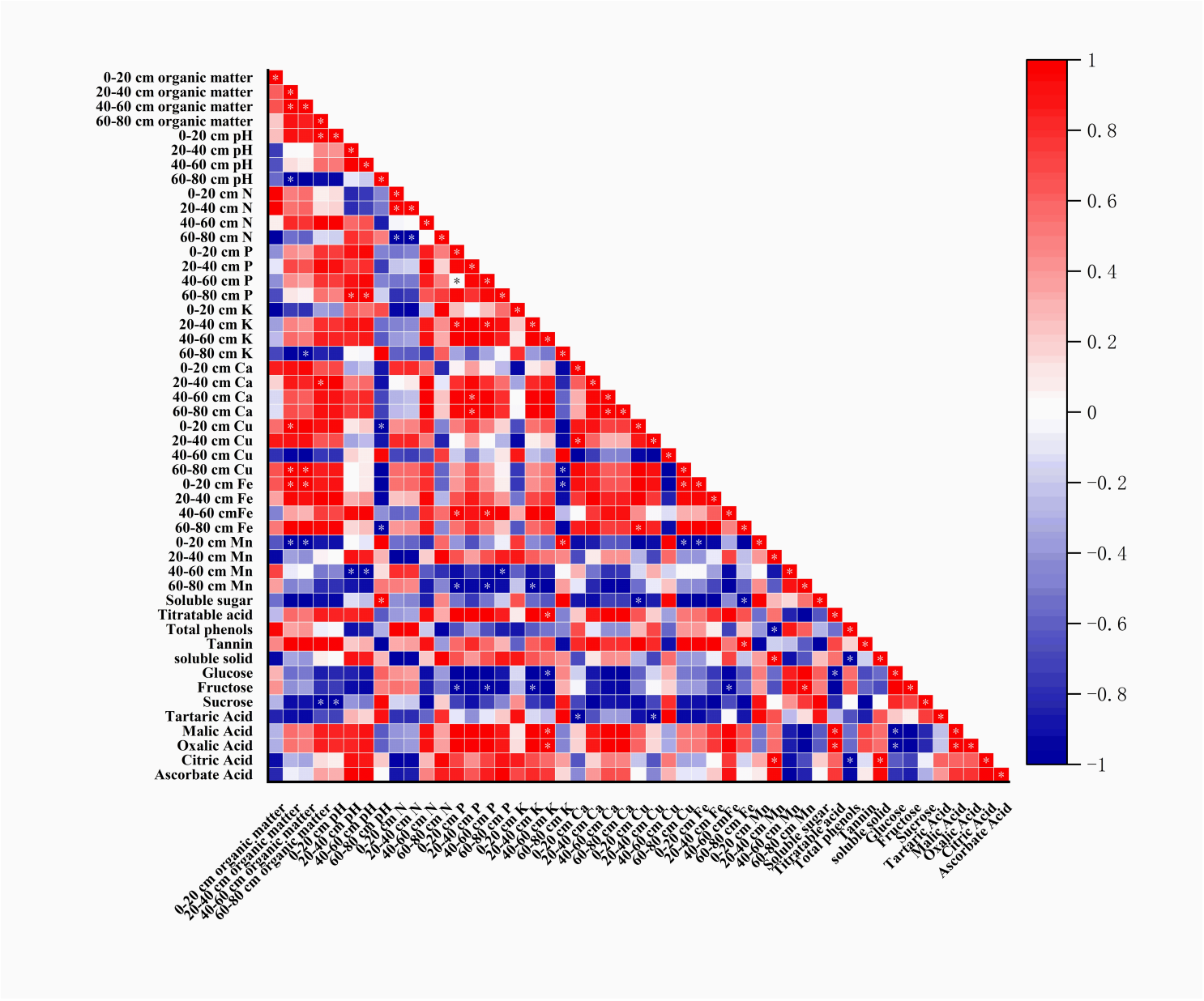


Figure 4

Analysis of the correlation between soil nutrients and fruit quality in different regions and different years

Note: Pearson correlation plots of soil nutrients and fruit quality in different regions across different years. Red indicates a positive correlation, blue indicates a negative correlation, "*"P<0.05.

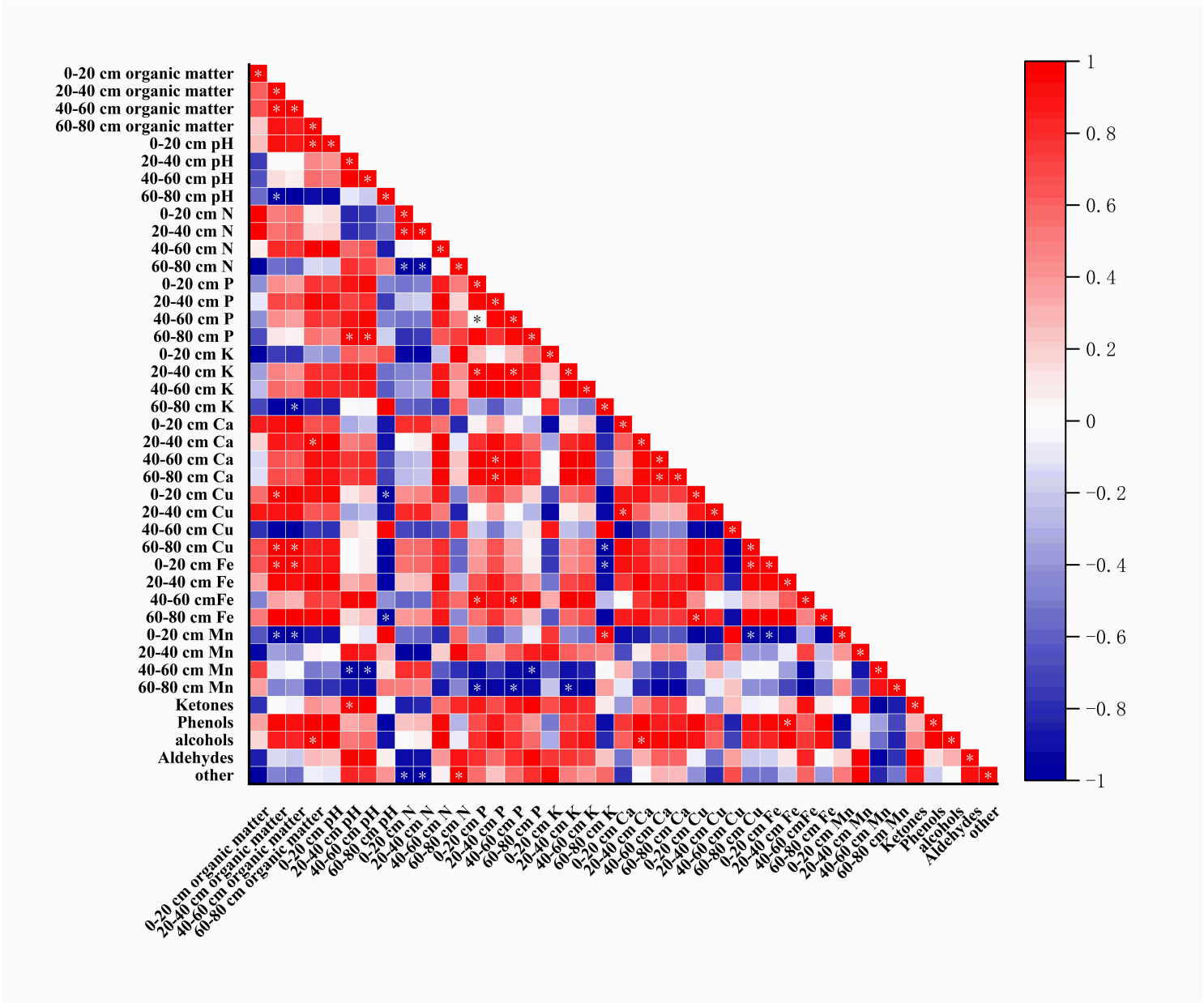


Figure 5

Correlation diagrams between soil nutrients and aroma substances in different regions and different years

Note: Pearson correlation diagram between soil nutrients and aroma substances in different regions in different years, with red indicating positive correlation and blue indicating negative correlation, "*"P<0.05.

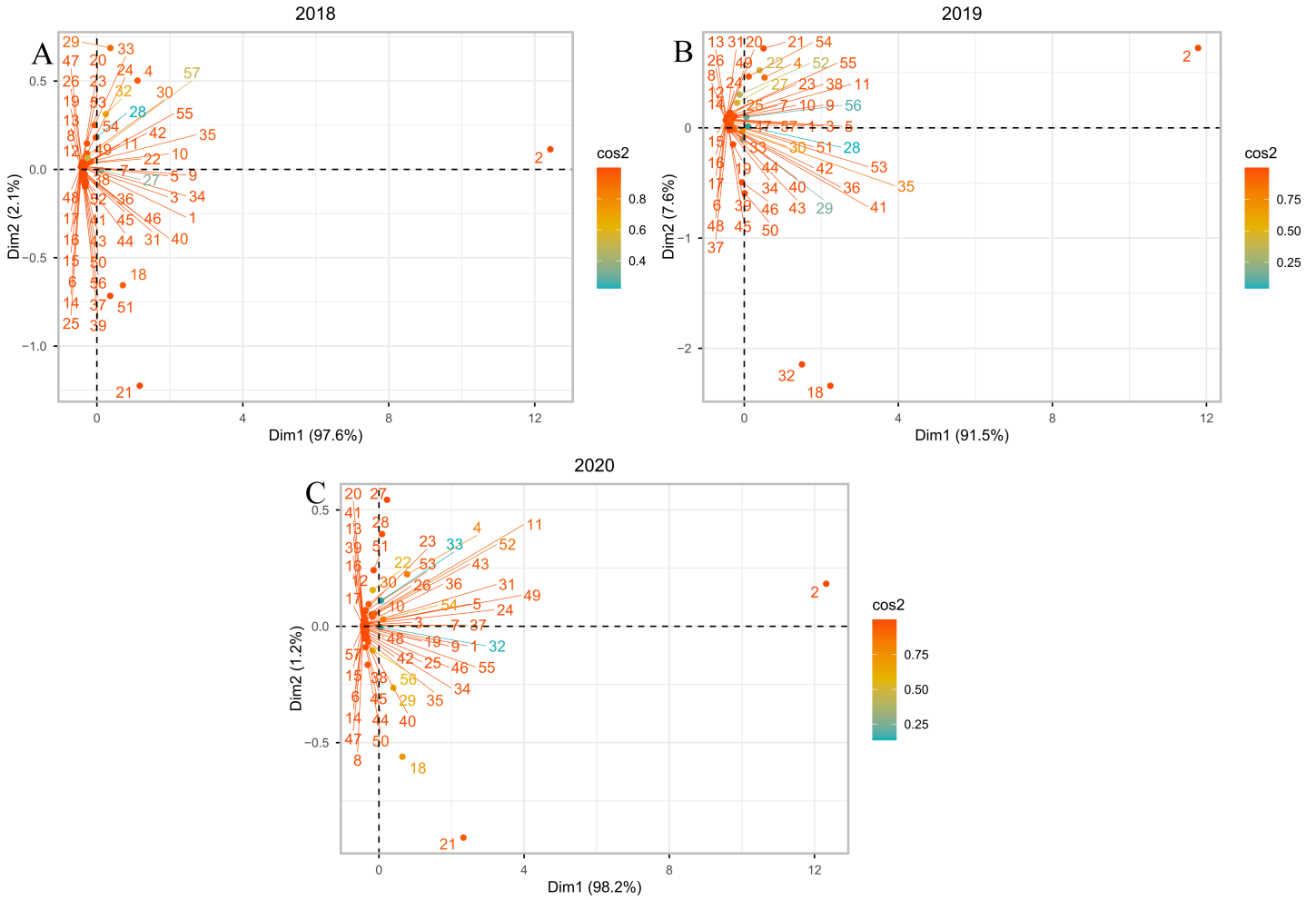


Figure 6

Principal component analysis of different regions and different years

Note: (A) Principal component analysis chart of three regions in 2018;(B) Principal component analysis chart of three regions in 2019; (C) Principal component analysis chart of three regions in 2020.1MT Apr-Sep; 2: ATT Apr-Sep; 3:MDT Apr r-Sep; 4:Jul-Sep rainfall; 5:Soluble sugar; 6: Titratable acid; 7: Total phenols; 8:Tannin; 9: Soluble solid; 10:Glucose; 11: Fructose; 12: Sucrose; 13: Tartaric Acid; 14: Malic Acid; 15: Oxalic Aci; 16: Citric Acid; 17: Ascorbate Acid; 18: Hexanal; 19: 3-Hexenal; 20: Pentadecanal; 21: 2-Hexenal; 22:(E,E)-2,4-Hexdienal; 23:(E,E)-2,4-Heptanedienal; 24: Benzaldehyde;25:(E)-2-Nonenal; 26: (2E,6Z)-nona-2,6-dienal; 27:2-Methylbenzaldehyde; 28:p-Tolualdehyde; 29: 2, 4-Dimethylbenzaldehyde; 30: Phenylacetaldehyde; 31: Nonanal; 32: (Z)-2-Hexenol; 33: Trans -2-hexene-1-ol; 34: 5-Indanol; 35: Geraniol; 36: Phenethyl alcohol; 37:Nerol; 38: 1-octylne-3-ol; 39: linalool; 40: 2-ethyl Hexanol; 41: Isopulegol; 42: Cis-3-hexene-1-ol; 43: 1-Nonanol; 44: 2-Cyclohexenol; 45: Methyl benzyl alcohol; 46: β-Damascone; 47: β-Damascenone; 48: 8-Cyclohexadecen-1-one; 49: Geranylacetonee; 50: Tridecane; 51: Octane; 52: n-Heptadecane; 53: 1,2-Epoxy hexadecane; 54: Hentriacontane; 55: Dotriacontane; 56: n-Octadecane; 57: 2-ethyl Furan.