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Quantitative Analysis of Relationship Between Fruit Quality of 'Fuji' Apple and Environmental Factors: A Case Study of the Loess Plateau Production Region

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Abstract

The objective of this study was to investigate the effect of environmental factors (soil nutrition and meteorological factors) on fruit quality traits of 'Fuji' apples. 'Fuji' apple fruits, soil samples, and meteorological data were investigated from 66 commercial orchards covering 22 counties of the Loess Plateau region in China. Partial least squares regression (PLSR) and linear programming were combined to analyze the quantitative relationship between fruit quality and environmental factors. The effect of meteorological factors (55.99%) on fruit quality was greater than that of soil nutrition factors (44.01%) in the Loess Plateau apple-producing region of China. Optimum environmental factors for high-quality 'Fuji' apples in the Loess Plateau region were: soil organic matter (13.94–17.93 g · kg^{-1}), total N (0.77–1.03 g · kg^{-1}), available N (68.39–115.87 mg · kg^{-1}), P (62.39–124.67 mg · kg^{-1}), K (324.41–468.62 mg · kg^{-1}), Ca (6.54 mg · kg^{-1}), Fe (14.97 mg · kg^{-1}), Zn (1.55–2.72 mg · kg^{-1}), B (0.37 mg · kg^{-1}), and soil pH (7.98–8.20); mean annual temperature (18 °C), total annual precipitation (431.2–713.8 mm), monthly mean temperature (19.9 °C), lowest temperature (8.03 °C), highest temperature (19.63 to 27.25 °C), temperature difference between day and night (12.41 °C), total precipitation (338.3–589.8 mm), relative humidity (56.57–82.41%), and sunshine percentage (36.96–55.87%) during the growing period (April–October).

Keywords Fruit quality traits · Soil nutrition · Meteorological factors · Model effects · Quantitative relationship

Introduction

Fruit development and quality formation are mainly determined by meteorological conditions, soil nutrition, and cultivation techniques (Mattheis and Fellman 1999). The effect of environmental factors (soil nutrition and meteorological factors) on fruit quality continues to attract much attention. Previously, most of the related works focused on the qualitative effect of environmental factors on fruit quality (e.g., Duan et al. 2014; Gao et al. 2009; Lakatos et al. 2012; Li et al. 2000; Sugiura et al. 2013; Takashi and Hisashi 2007; Wei et al. 2003; Zhang et al. 2021; Zhu et al. 2001). Some researchers reported on the correlation between soil nutrition and fruit quality in local apple orchards and optimization schemes for the production of high-quality apples, and multivariate statistical analysis was used (Xu et al. 2014; Zhang et al. 2011b, 2017; Zhou et al. 2016). However, few studies have been conducted on the quantitative relationship between apple quality and soil nutrition and meteorological factors.

The Loess Plateau in China, located at 34–40°N latitude and 103–114°E longitude, has the largest loess deposit area in the world of 630,000 km^2, where the average altitude is 1000–1500 m and the soil thickness is 50–80 m (Gan 1989). This makes it the largest apple-producing region in the world (Zhang 2019), with the apple planting area accounting for 27% of global production (Han 2015). The climate of the Loess Plateau is favorable for apple since the sunshine duration is long, the soil layer is deep and fertile, and the temperature difference between day and night is large (Ma 2006). The span of the production re-

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gion is so large that orchard conditions vary significantly. Zhang et al. (2018) found that the combination of partial least squares regression (PLSR) and linear programming is a feasible method for exploring the relationship between comprehensive meteorological factors and ‘Fuji’ fruit quality, and they obtained optimum theoretical schemes. This paper uses their method to study the effect of the specific soil–climate ecological environment on fruit quality of ‘Fuji’ apples in the Loess Plateau region. Our aim was to screen the key environmental factors that affect fruit quality and to establish an optimum scheme of soil nutrition and meteorological factors; subsequently, we aimed to obtain restrictive environmental factors for high-quality fruit production. These results will provide valuable information for ‘Fuji’ apple production in the Loess Plateau region of China.

Materials and Methods

Experiment Location and Orchard Selection

A total of 22 advantageous apple-production counties of the Loess Plateau Production region were first chosen for this study based on their geographical locations (Table 1), and then three orchards per county were determined. Each of the sampled orchards has an area of more than 0.6 ha, and the soil is loam or sandy loam type. The typical apple cultivar was ‘Fuji’ apple grafted on crabapple (*Malus pumila*), 15–20 years old, and in free-growing spindle shape or in small canopy shape. The apple yield reached 30,000–45,000 $kg \cdot ha^{-1} \cdot year^{-1}$ in the last 5 years. During production, the young fruits were covered by double-layer paper bags, and flower thinning and fruit thinning were carried out artificially.

Sampling and Testing

Six trees were chosen for testing in every orchard, and the trees were almost of the same size. In August or September of the two study years, the soil samples were collected using a drill under the six trees. A soil layer of 0–40 cm was sampled at four cardinal directions around the trunk of the tree, 50 cm inward from the canopy drip line. The soils from one tree were mixed, air-dried, and sifted with a 2-mm sieve. In the experiment, only half of each soil sample was used for testing and the other half was left as spare. The potassium dichromate volumetric external heating method, Kjeldahl method, and alkali diffusion method were employed to measure soil organic matter (SOM), soil total nitrogen (N), and soil available N, respectively; the $NaHCO_3$ extraction method, ammonium molybdate-tartaric emetic-ascorbic acid colorimetry method, NH_4OAc extraction-flame photometer

Table 1 Geographical location of the 22 sampling counties in the Loss Plateau production region of China (from Zhang et al. 2018)

Serial number	Province	County	Longitude (E)	Latitude (N)	Altitude (m, a.s.l.)
1	Shaanxi	Liquan	108°17′–108°41′	34°20′–34°50′	557
2	Shaanxi	Luochuan	109°13′–109°45′	35°26′–36°04′	1148
3	Shaanxi	Baishui	109°16′–109°45′	35°4′-35°27′	785
4	Shaanxi	Xunyi	108°08′–108°52′	34°57′-35°33′	974
5	Shaanxi	Fengxiang	107°10′–107°38′	34°20′–34°45′	782
6	Shaanxi	Ansai	108°05′–109°26′	36°30′–37°19′	1110
7	Shaanxi	Yichuan	109°41′–110°32′	35°42′–36°23′	836
8	Shaanxi	Fufeng	107°45′–108°03′	34°12′–34°37′	581
9	Shanxi	Wanrong	110°25′–110°59′	35°13′–35°31′	596
10	Shanxi	Linyi	110°17′–110°54′	34°58′–35°18′	400
11	Shanxi	Ruicheng	110°36′–110°42′	34°36′–34°48′	504
12	Shanxi	Yicheng	111°34′–112°03′	35°23′–35°52′	583
13	Shanxi	Raodu	111°05′–111°49′	35°54′–36°19′	470
14	Shanxi	Qixian	112°12′–112°39′	37°04′–37°28′	766
15	Gansu	Qin’an	105°20′–106°20′	34°44′–35°11′	1286
16	Gansu	Jingning	105°20‘–106°05’	35°01‘–35°45’	1668
17	Gansu	Jingchuan	107°15′–107°45′	35°11′-35°31′	1055
18	Gansu	Lixian	104°37′-105°36′	33°35′–34°31′	1413
19	Gansu	Qingcheng	107°16′–108°05′	35°42′–36°17′	1102
20	Gansu	Qingshui	105°45′–106°30′	34°32′–34°56′	1376
21	Gansu	Zhengning	107°56′–108°38′	35°14′–35°36′	1449
22	Gansu	Maiji	105°25′–106°43′	34°06′–34°48′	1090

method, CH_3COONa extraction-atomic absorption spectrometry method, and azomethine-H colorimetric method were used to determine the soil available phosphorus (P), soil available potassium (K), soil available calcium (Ca), and soil available boron (B), respectively (Bao 2005). The DTPA extraction-atomic absorption spectrometry method was used to test soil available iron (Fe) and zinc (Zn), and soil pH was determined using a potentiometer (Bao 2005).

The fruit samples were collected from the end of October to the beginning of November. At the fruit maturity stage, 15 apples were picked from each of the sampled trees in south–east and south–west directions, 1.5 m above the ground. There were 90 apples in total collected from each experiment orchard. The sampled apples were preserved by plastic bags, stored in a fresh-keeping storehouse or refrigerator at 4 °C within 4 h, and later transferred to our laboratory in Beijing using a refrigerator trunk. In total, 30 of the 90 apples were randomly chosen for testing. The fruit length and diameter were measured using a Vernier caliper (Harbin Measuring & Cutting Tool Group Co., Ltd., Haibin, China), and then length/diameter (L/D) was calculated. Fruit mass was weighted using a balance with a precision of 0.001 g. Fruit firmness was assessed from the two opposite sides of a fruit with a GY-1 fruit firmness tester (Mudanjiang Machinery Research Institute, China). Soluble solid content (SSC, °Brix) was measured with a digital refractometer (Atago RS-5000, Japan). Acid concentration (%) was measured by titrating the juice with 0.1 mol L^{-1} NaOH. Fruit skin color area was calculated based on a coloring index.

Meteorological Data Collection

The meteorological data of each sampled orchard were obtained from the nearby meteorological stations (National Meteorological Information Center, China) and in the study a total of 132 meteorological stations were involved. Ordinary Kriging interpolation was employed to compute the meteorological indexes at every orchard, including the mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October in 2010 and 2011.

Data Analysis

The soil nutrition factors and meteorological data and the fruit quality traits were taken as independent variables and as objective function, respectively. The PLSR (SAS 9.4 software, SAS Institute Inc., Cary, NC) was used to analyze the overall model effect weights on fruit quality, and the variable importance for projection (VIP) was used for independent variable selection. Linear regression models were fitted to identify the relationship between the selected environmental factors and fruit quality traits. The restrictions of each apple quality trait were established using the linear programming approach (LINGO 10.0 Software, Lindo System Inc., Chicago, IL), to determine the optimum environmental factors for high-quality ‘Fuji’ apples.

Results

Basic Information of Fruit Qualities and Environmental Factors

There were significant differences in apple fruit quality, soil nutrition, and meteorological factors for different apple-producing counties in the Loess Plateau region (Table 2). The differences in mean fruit weight (Y_1), SSC (Y_4), and TA content (Y_5) between different orchards were large, with the maximum being 1.53-, 1.37-, and 2.07-fold greater than the minimum values, respectively. The differences in fruit shape index (Y_2), fruit firmness (Y_3), and skin color area (Y_6) between different orchards were not as large as the difference in other factors, with the maximum being approximately 1.1-fold greater than the minimum values. The maximum of soil available P (S_4), K (S_5), and Zn (S_8) content of orchards was over 5.6-fold greater than the minimum values. The maximum of soil total N (S_2), available N (S_3), Fe (S_7), and B (S_9) content was over 3.3-fold greater than the minimum values, and the maximum of SOM (S_1) and available Ca (S_6) content was, respectively, 2.47- and 1.36-fold greater than the minimum values. The mean and the highest and lowest values of soil pH (S_{10}) were 8.20, 8.45, and 7.98, respectively, which all exceeded the most suitable pH range (6.5–7.5) for apple production. The mean and the highest and lowest values of total annual precipitation (M_2) were 565.11 mm, 713.80 mm, and 431.20 mm, respectively. The maximum of mean annual temperature (M_1) and monthly mean lowest temperature from April to October (M_4) in these orchards were, respectively, 3.27- and 2.12-fold greater than the minimum values, and for other meteorological factors (M_3, and M_5–M_9) the maximum value was more than 1.4-fold greater than the minimum values.

Table 2 Basic information of fruit qualities [a], soil nutritional status [b], and meteorological factors [c]

Measuring item	Mean	SD	Maximum	Minimum	Difference between maximum and minimum
Y_1 (g)	252.75	27.07	323.27	211.27	112.00
Y_2	0.86	0.03	0.92	0.79	0.13
Y_3 ($kg \cdot cm^{-2}$)	8.81	0.71	10.29	7.44	2.85
Y_4 (SSC, %)	13.85	1.09	16.61	12.10	4.51
Y_5 (%)	0.21	0.04	0.29	0.14	0.15
Y_6 (%)	93.40	5.29	99.00	80.40	18.60
S_1 ($g \cdot kg^{-1}$)	13.94	2.53	17.93	7.26	10.67
S_2 ($g \cdot kg^{-1}$)	0.77	0.20	1.03	0.27	0.76
S_3 ($mg \cdot kg^{-1}$)	68.39	24.10	115.87	30.73	85.14
S_4 ($mg \cdot kg^{-1}$)	62.39	31.84	124.67	18.63	106.04
S_5 ($mg \cdot kg^{-1}$)	324.41	105.68	534.67	95.07	439.60
S_6 ($mg \cdot kg^{-1}$)	5.79	0.49	6.54	4.82	1.72
S_7 ($mg \cdot kg^{-1}$)	9.27	2.65	14.97	4.44	10.53
S_8 ($mg \cdot kg^{-1}$)	1.55	0.54	2.72	0.41	2.31
S_9 ($mg \cdot kg^{-1}$)	0.37	0.16	0.90	0.20	0.70
S_{10}	8.20	0.14	8.45	7.98	0.47
M_1 (°C)	11.64	3.02	18.00	5.50	12.50
M_2 (mm)	565.11	68.03	713.80	431.20	282.60
M_3 (°C)	17.60	2.73	19.90	13.30	6.60
M_4 (°C)	13.85	2.40	17.01	8.03	8.98
M_5 (°C)	24.37	2.24	27.25	19.63	7.62
M_6 (°C)	10.52	1.18	12.41	7.31	5.10
M_7 (mm)	480.68	64.51	589.80	338.30	251.50
M_8 (%)	67.54	6.85	82.41	56.07	26.34
M_9 (%)	44.74	5.92	55.87	32.91	22.96

[a] Y_1–Y_6 denote mean fruit weight, fruit shape index, fruit firmness, soluble solid content (SSC), titratable acid (TA) content, and skin color area, respectively

[b] S_1–S_{10} denote soil organic matter (SOM), total N, available N, available P, available K, available Ca, available Fe, available Zn, available B, and pH, respectively

[c] M_1–M_9 denote mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October, respectively

SD standard deviation

Soil Nutrition and Meteorological Factor Effect Weights in the Relationship Model of "Environmental Factors–Fruit Quality Traits"

Model effect weights mainly reflect the proportion of different independent variables to overall potential effect of dependent variables (Wang et al. 2000a). In this study, the model effect weights reflected the importance of soil nutrition and meteorological factors in the formation of overall fruit quality traits in the Loess Plateau production region (Fig. 1). Six factors, including M_8, S_1, M_2, S_7, S_9, and S_2, had larger, positive effect weights on overall fruit quality traits, with their weight absolute values contributing 12.14%, 6.63%, 6.38%, 6.02%, 5.80%, and 5.79%, respectively, to fruit quality, while the factors M_9, M_5, M_4, and S_{10} showed larger, negative effect weights on overall fruit quality traits and their weight absolute values contributed 10.23%, 7.54%, 6.04%, and 5.31%, respectively, to fruit quality. Among all the environmental factors, S_{10}, M_1, M_2, M_3, M_7, and M_8 had a negative effect on fruit quality traits, while the others had a positive effect. The model effect weights of soil nutrition and meteorological factors on overall fruit quality traits were accumulated. The meteorological factors (M_1–M_9) accounted for 55.99% of the total weights, and the soil nutrition factors (S_1–S_{10}) only accounted for 44.01%, which indicated that meteorological factors influenced fruit quality more than soil nutrition factors did in the Loess Plateau apple-producing region.

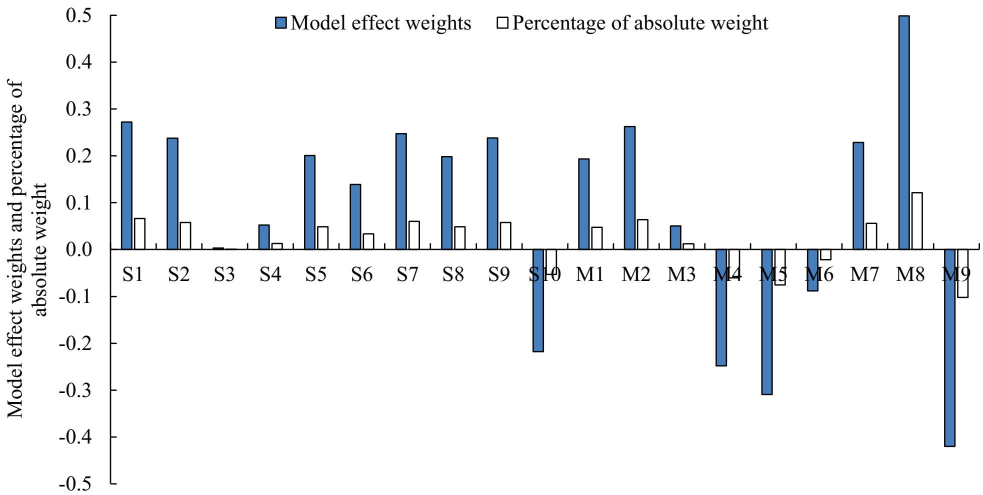

Fig. 1 Model effect weights of soil nutrition and main meteorological factors affecting fruit qualities in the Loess Plateau production region of China. S_1–S_{10} denote soil organic matter (SOM), total nitrogen, available nitrogen, available phosphorus, available potassium, available calcium, available iron, available zinc, available boron, and pH, respectively. M_1–M_9 denote mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October, respectively

Multivariate Analysis of the Relationship Between Fruit Quality and Environmental Factors

The VIP of Environmental Factors

The VIP is a variable screening method, which mainly describes the explanatory ability of related independent variables to dependent variable, and selects independent variables according to the explanatory ability. The value of VIP represents the importance of the independent variable to the dependent variable (Zhang and Feng 2012; Zhou et al. 2016). In this study, the VIP values of environmental factors on each characteristic factor of fruit quality were, respectively, calculated by taking soil nutrition factors (S_1–S_{10}) and meteorological factors (M_1–M_9) as independent variables (Table 3). The VIP value of 0.8 was set as threshold to screen the main influencing environmental factors of fruit quality traits in the Loess Plateau production region. As shown in Table 3, all environmental factors had varying degrees of influence on fruit quality traits of ‘Fuji’ apples, and different fruit quality traits were affected by different soil nutrition and meteorological factors. According to the effects, the main influencing environmental factors of mean fruit weight were sorted from large to small—$M_9 > M_8 > M_4 > M_5 > S_7 > S_1$—which indicated that sunshine, humidity, the highest temperature and lowest temperature in the growing period (April–October), and SOM had greater effects on fruit size than did other environmental factors. The order of the main environmental factors that affected fruit shape index was $S_5 > M_8 > M_1 > S_{10} > S_8 > M_2 > S_9 > M_4 > S_1 > M_6$, according to the effect from large to small. This indicated that the soil available K, available Zn, pH, mean annual temperature, and monthly mean relative humidity during the apple growing period affected fruit shape more than the other environmental factors did. The order of the main factors affecting fruit firmness was $S_3 > M_3 > S_2 > M_7 > S_5 > S_{10} > S_8 > M_1 > M_2 > S_1$, sorted by effect. This indicated that the soil available N, total N, available K, monthly mean temperature from April to October, and total precipitation from April to October had greater effects on fruit firmness. The order of the main factors affecting SSC was $M_3 > S_7 > S_2 > S_5 > M_7 > S_{10} > S_4 > S_8 > S_3 > S_1$. This indicated that the monthly mean temperature of the growing period was the foremost factor related to SSC; in addition, the total precipitation in the apple growing period, soil available Fe, total N, available K, and pH also played key roles in SSC formation. The main factors affecting TA content were ranked according to their effects, and the order was $M_9 > M_8 > S_9 > S_1 > S_2 > S_{10} > S_8 > M_7$. This indicated that the sunshine and relative humidity in apple growing period, and SOM, soil total N, available B, and soil pH had greater effects on fruit acidity than the other factors. Regarding the effect on apple skin color area, the order of the main related factors was $M_4 > M_5 > S_4 > S_6 > S_8 > S_5 > M_3 > M_8$. This indicated that temperature (highest temperature and lowest temperature) during the apple growing period was the foremost factor associated with apple skin color area, and in addition the soil available P, available K, available Ca, and available Zn also played important roles in fruit color development.

Table 3 The VIP of soil nutrition and meteorological factors affecting fruit quality traits [a]

Affecting factors [b]	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
S_1	0.84987	0.87201	0.81477	0.83023	0.90151	0.48522
S_2	0.61138	0.76002	1.28227	0.91851	0.90044	0.74149
S_3	0.63027	0.79264	1.70117	0.841	0.60375	0.71107
S_4	0.58677	0.58672	0.55886	0.87273	0.40423	1.06272
S_5	0.49318	1.12494	0.92137	0.91587	0.6068	0.94499
S_6	0.4501	0.33825	0.45169	0.20141	0.72521	1.01526
S_7	0.97217	0.6347	0.41638	0.99705	0.69971	0.308
S_8	0.64859	1.01589	0.87764	0.86275	0.87454	0.96163
S_9	0.72694	0.923	0.60965	0.51039	0.96641	0.21911
S_{10}	0.43392	1.06169	0.88407	0.89269	0.8905	0.69924
M_1	0.22584	1.06996	0.84108	0.60085	0.42575	0.67019
M_2	0.60004	0.96959	0.88301	0.62063	0.7369	0.7117
M_3	0.35751	0.48561	1.4265	1.61194	0.24628	0.8454
M_4	1.15603	0.88848	0.25062	0.74501	0.06968	1.28204
M_5	1.12459	0.67145	0.04152	0.47556	0.30103	1.25368
M_6	0.48793	0.85893	0.53856	0.72272	0.60137	0.23189
M_7	0.54925	0.79154	0.99613	0.91143	0.85533	0.50271
M_8	1.18394	1.09903	0.6011	0.73998	1.24899	0.81782
M_9	1.18347	0.57019	0.6278	0.70524	1.35646	0.20896

[a] Y_1–Y_6 denote mean fruit weight, fruit shape index, fruit firmness, soluble solid content (SSC), titratable acid (TA) content, and skin color area, respectively

[b] S_1–S_{10} denote soil organic matter (SOM), total N, available N, available P, available K, available Ca, available Fe, available Zn, available B, and pH, respectively. M_1–M_9 denote mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October, respectively

Regression Equation of Environmental Factors Affecting Fruit Quality Traits

The value of VIP can only indicate the importance of environmental factors to fruit quality but cannot reflect the positive or negative direction of their influence. To further demonstrate the positive or negative effect of environmental factors on fruit quality, regression equations for predicting the effects of these environmental factors on each characteristic factor of fruit quality were established, with major environmental factors (VIP ≥ 0.8) as independent variables and fruit quality traits as dependent variables (Table 4). The p values of these regression equations were all less than 0.05, meaning that the established regression equations were stable and reliable. The coefficients and symbols of the regression equations indicated the importance and the positive or negative direction, respectively, for the effects of different environmental factors on fruit quality traits. Results showed that the mean fruit weight was significantly positively affected by M_5 but negatively affected by M_4, which indicated that the decrease in monthly mean highest temperature or the increase in monthly mean lowest temperature during the apple growing period was not beneficial to fruit development. The fruit shape index was significantly positively affected by M_1 but negatively affected by S_{10}, indicating the decrease in mean annual temperature or the increase in soil pH was not beneficial to fruit shape improvement. The SSC was significantly positively affected by S_2 but negatively affected by S_{10}, which indicated that orchard soil with higher total N and lower pH was beneficial to sugar accumulation in fruits. In contrast to SSC, fruit firmness was significantly positively affected by S_{10} but negatively affected by S_2. The TA content was significantly positively affected by S_{10} but negatively affected by S_9, which indicated that orchard soil with higher available B and lower pH was beneficial to the decrease of fruit acidity. The skin color area of apples was significantly positively affected by S_6 but negatively affected by S_8, which indicated that orchard soil with higher available Ca and lower available Zn was beneficial to fruit color development.

Optimum Schemes of Environmental Factors for Good Fruit Quality

To quantitatively illustrate the effects of environmental factors on fruit quality traits, linear programming equations were constructed using the regression analysis in Table 4. When solving the maximum value (MaxY_n) of a certain fruit quality trait, the other fruit quality traits should be greater than the mean values of 66 orchards to ensure high-quality fruits, and the environmental factors should be limited to a certain constraint range. Due to the alkaline soil in the Loess Plateau apple-production region, the soil pH was restricted to be between 7.98 (the minimum in the 66 orchards) and 8.20 (the mean of the 66 orchards). The other soil nutrition factors (S_2–S_{10}) were limited to the range from the mean to the maximum values measured from 66 orchards, because they could be improved by some agricultural practices, such as fertilization. The restraint ranges of meteorological factors were the maximum and minimum values measured from 66 orchards, because they could represent the real climate conditions in the Loess Plateau apple-production region.

For example, the linear programming equations on the maximum mean fruit weight (MaxY_1) were as follows:

$$
\begin{aligned}
\mathrm{Max}\,Y_1 &= 266.644 - 1.3329S_1 + 3.3497S_7 - 6.3246M_4 \\
&\quad + 3.404M_5 + 0.9796M_8 - 2.0759M_9; \\
Y_2 &= 1.7374 + 0.00209S_1 - 0.00001538S_5 - 0.00412S_8 \\
&\quad - 0.02619S_9 - 0.1036S_{10} + 0.00333M_1 \\
&\quad - 0.0001255M_2 - 0.00446M_4 + 0.000412M_6 \\
&\quad + 0.0008363M_8 \geq 0.86;
\end{aligned}
$$

$$
\begin{aligned}
Y_3 &= -13.6263 - 0.04432S_1 - 0.7778S_2 + 0.01813S_3 \\
&\quad - 0.00003064S_5 + 0.1091S_8 + 2.6405S_{10} + 0.00622M_1 \\
&\quad + 0.00245M_2 + 0.00647M_3 - 0.00102M_7 \geq 8.81;
\end{aligned}
$$

$$
\begin{aligned}
Y_4 &= 32.8812 - 0.1391S_1 + 1.938S_2 - 0.00284S_3 \\
&\quad - 0.00969S_4 - 0.00522S_5 + 0.1804S_7 - 0.1107S_8 \\
&\quad - 1.9247S_{10} + 0.03243M_3 - 0.00551M_7 \geq 13.85;
\end{aligned}
$$

$$
\begin{aligned}
Y_5 &= -0.9427 + 0.0001345S_1 + 0.04186S_2 + 0.00318S_8 \\
&\quad - 0.08279S_9 + 0.1309S_{10} + 0.00007616M_7 \\
&\quad - 0.00174M_8 + 0.00299M_9 \geq 0.21;
\end{aligned}
$$

$$
\begin{aligned}
Y_6 &= 63.3856 + 0.01536S_4 + 0.0022S_5 + 15.8314S_6 \\
&\quad - 19.2775S_8 + 0.2784M_3 - 3.3131M_4 - 0.8261M_5 \\
&\quad + 0.2782M_8 \geq 93.40;
\end{aligned}
$$

Where, $13.94 \leq S_1 \leq 17.93$, $0.77 \leq S_2 \leq 1.03$, $68.39 \leq S_3 \leq 115.87$, $62.39 \leq S_4 \leq 124.67$, $324.41 \leq S_5 \leq 534.67$, $5.79 \leq S_6 \leq 6.54$, $9.27 \leq S_7 \leq 14.97$, $1.55 \leq S_8 \leq 2.72$, $0.37 \leq S_9 \leq 0.90$, $7.98 \leq S_{10} \leq 8.2$; $5.50 \leq M_1 \leq 18.00$, $431.20 \leq M_2 \leq 713.80$, $13.30 \leq M_3 \leq 19.90$, $8.03 \leq M_4 \leq 17.01$, $19.63 \leq M_5 \leq 27.25$, $7.31 \leq M_6 \leq 12.41$, $338.30 \leq M_7 \leq 589.80$, $56.07 \leq M_8 \leq 82.41$, $32.91 \leq M_9 \leq 55.87$.

Table 4 Regression equation of soil nutrition and meteorological factors affecting fruit quality traits

Objective functions [a]	Affecting factor [b]	Regression equation	p	$Pr > F$
Y_1	S_1, S_7, M_4, M_5, M_8, M_9	$Y_1 = 266.644 - 1.3329S_1 + 3.3497S_7 - 6.3246M_4 + 3.404M_5 + 0.9796M_8 - 2.0759M_9$	22.96	<0.0001
Y_2	S_1, S_5, S_8, S_9, S_{10}, M_1, M_2, M_4, M_6, M_8	$Y_2 = 1.7374 + 0.00209S_1 - 0.00001538S_5 - 0.00412S_8 - 0.02619S_9 - 0.1036S_{10} + 0.00333M_1 - 0.0001255M_2 - 0.00446M_4 + 0.000412M_6 + 0.0008363M_8$	7.06	<0.0001
Y_3	S_1, S_2, S_3, S_5, S_8, S_{10}, M_1, M_2, M_3, M_7	$Y_3 = -13.6263 - 0.04432S_1 - 0.7778S_2 + 0.01813S_3 - 0.00003064S_5 + 0.1091S_8 + 2.6405S_{10} + 0.00622M_1 + 0.00245M_2 + 0.00647M_3 - 0.00102M_7$	9.82	<0.0001
Y_4	S_1, S_2, S_3, S_4, S_5, S_7, S_8, S_{10}, M_3, M_7	$Y_4 = 32.8812 - 0.1391S_1 + 1.938S_2 - 0.00284S_3 - 0.00969S_4 - 0.00522S_5 + 0.1804S_7 - 0.1107S_8 - 1.9247S_{10} + 0.03243M_3 - 0.00551M_7$	4.76	0.0003
Y_5	S_1, S_2, S_8, S_9, S_{10}, M_7, M_8, M_9	$Y_5 = -0.9427 + 0.0001345S_1 + 0.04186S_2 + 0.00318S_8 - 0.08279S_9 + 0.1309S_{10} + 0.00007616M_7 - 0.00174M_8 + 0.00299M_9$	19.31	<0.0001
Y_6	S_4, S_5, S_6, S_8, M_3, M_4, M_5, M_8	$Y_6 = 63.3856 + 0.01536S_4 + 0.0022S_5 + 15.8314S_6 - 19.2775S_8 + 0.2784M_3 - 3.3131M_4 - 0.8261M_5 + 0.2782M_8$	8.91	<0.0001

[a] Y_1–Y_6 denote mean fruit weight, fruit shape index, fruit firmness, soluble solid content (SSC), titratable acid (TA) content, and skin color area, respectively

[b] S_1–S_{10} denote soil organic matter (SOM), total N, available N, available P, available K, available Ca, available Fe, available Zn, available B, and pH, respectively. M_1–M_9 denote mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October, respectively

Table 5 Optimum schemes of soil nutrition and meteorological factors for good quality [a]

Affecting factor [b]	Y_1 (g)	Y_2	Y_3 (kg · cm^{-2})	Y_4 (%)	Y_5 (%)	Y_6 (%)	Range of optimum affecting factors
S_1 (g · kg^{-1})	13.94	17.93	13.94	17.93	13.94	13.94	13.94–17.93
S_2 (g · kg^{-1})	1.03	1.03	0.77	1.03	1.03	1.03	0.77–1.03
S_3 (mg · kg^{-1})	68.39	115.87	115.87	68.39	68.39	68.39	68.39–115.87
S_4 (mg · kg^{-1})	124.67	62.39	62.39	62.39	62.39	124.67	62.39–124.67
S_5 (mg · kg^{-1})	329.91	324.41	324.41	324.41	324.41	468.62	324.41–468.62
S_6 (mg · kg^{-1})	6.54	6.54	6.54	6.54	6.54	6.54	6.54
S_7 (mg · kg^{-1})	14.97	14.97	14.97	14.97	14.97	14.97	14.97
S_8 (mg · kg^{-1})	2.51	1.55	2.72	1.55	2.72	1.55	1.55–2.72
S_9 (mg · kg^{-1})	0.37	0.37	0.37	0.37	0.37	0.37	0.37
S_{10}	8.2	7.98	8.2	7.98	8.2	8.2	7.98–8.2
M_1 (°C)	18	18	18	18	18	18	18
M_2 (mm)	713.8	431.2	713.8	713.8	713.8	713.8	431.2–713.8
M_3 (°C)	19.9	19.9	19.9	19.9	19.9	19.9	19.9
M_4 (°C)	8.03	8.03	8.03	8.03	8.03	8.03	8.03
M_5 (°C)	27.25	19.63	19.63	19.63	20.92	19.63	19.63–27.25
M_6 (°C)	12.41	12.41	12.41	12.41	12.41	12.41	12.41
M_7 (mm)	589.8	589.8	338.3	338.3	589.8	477.61	338.3–589.8
M_8 (%)	56.57	71.23	56.57	56.57	56.57	82.41	56.57–82.41
M_9 (%)	36.96	55.87	46.78	54.01	55.87	55.87	36.96–55.87
Objective value of fruit qualities (Y_n)	318.88	0.96	10.84	16.40	0.27	125.64	–

[a] Y_1–Y_6 denote mean fruit weight, fruit shape index, fruit firmness, soluble solid content (SSC), titratable acid (TA) content, and skin color area, respectively

[b] S_1–S_{10} denote soil organic matter (SOM), total N, available N, available P, available K, available Ca, available Fe, available Zn, available B, and pH, respectively; M_1–M_9 denote mean annual temperature, total annual precipitation, monthly mean temperature from April to October, monthly mean lowest temperature from April to October, monthly mean highest temperature from April to October, monthly mean temperature difference between day and night from April to October, total precipitation from April to October, monthly mean relative humidity from April to October, and monthly mean sunshine percentage from April to October, respectively

The same method was performed to obtain the maximum of other fruit quality traits (Y_2–Y_6) when mean Y_1 was ≥ 252.75 g, and then optimum schemes of environmental factors for the largest value of fruit quality factor were achieved (Table 5). According to theoretical optimum schemes, the proposed optimum values of S_6, S_7, M_1, M_3, and M_6 were the maximum of constraints, while those of S_9, and M_4 were the minimum of constraints. Furthermore, the upper limit of the proposed optimum value of S_{10} was the average value of measurement (8.2); the upper limit of the proposed optimum S_5 was lower than the maximum value of measurement; the lower limit of the proposed optimum value of M_9 was higher than the minimum value of measurement.

The optimum environmental factors for high-quality 'Fuji' apples in the Loess Plateau production region were: SOM, from 13.94 to 17.93 g · kg^{-1}; total N, from 0.77 to 1.03 g · kg^{-1}; available N, from 68.39 to 115.87 mg · kg^{-1}; available P, from 62.39 to 124.67 mg · kg^{-1}; available K, from 324.41 to 468.62 mg · kg^{-1}; available Ca, 6.54 mg · kg^{-1}; available Fe, 14.97 mg · kg^{-1}; available Zn, from 1.55 to 2.72 mg · kg^{-1}; available B, 0.37 mg · kg^{-1}; soil pH, from 7.98 to 8.20; mean annual temperature, 18 °C; total annual precipitation, from 431.2 to 713.8 mm; monthly mean temperature from April to October, 19.9 °C; monthly mean lowest temperature from April to October, 8.03 °C; monthly mean highest temperature from April to October, from 19.63 to 27.25 °C; monthly mean temperature difference between day and night from April to October, 12.41 °C; total precipitation from April to October, from 338.3 to 589.8 mm; monthly mean relative humidity from April to October, from 56.57 to 82.41%; and monthly mean sunshine percentage from April to October, from 36.96 to 55.87%.

Discussion

Relationship Between Fruit Quality of 'Fuji' Apple and Environmental Factors in the Loess Plateau Production Region

The growth and development of apple trees and quality formation of apple fruits are mainly determined by meteorological conditions, soil nutrition, cultivation techniques, etc. In this study, the model effect weights of environmental factors on overall fruit quality were obtained by analyzing the relationship between 19 independent variable parameters (S_1–S_{10}, and M_1–M_9) and six fruit quality factors (Y_1–Y_6). According to the results, we proposed for the first time that the effect of soil nutrition factors (55.99%) on fruit quality was greater than that of meteorological factors (44.01%) in the Loess Plateau production region of China. Thus, under similar landform types and soil textures, the difference in 'Fuji' fruit quality of vigorous apples was due to the varying meteorological factors in the Loess Plateau apple-producing region.

This study found that the mean fruit weight of vigorous apple was significantly affected by sunshine, humidity, temperature (the highest temperature and the lowest temperature), and SOM content during the growing period, and it was significantly positively affected by M_5 and negatively affected by M_4. We found that the lower maximum temperature and the higher minimum temperature in the apple-growing period were not good for fruit development, which was consistent with the results reported by Forshey (1990). A possible reason is that the temperature at the early growing stage of apples directly affected the growth of the apple tree, and then influenced the numbers of fruit cells and the distribution of photosynthetic products to fruit (Austin et al. 1999). The fruit shape index was remarkably affected by S_5, S_8, S_{10}, M_1, and M_8, of which M_1 had the largest positive effect, but this was different from the results of Warrington et al. (1999). Fruit shape index is affected by cell division at the early stage of fruit development (Goffinet et al. 1995), thus the effect of monthly or 10-day temperature factors on fruit development should be further studied. The fruit firmness was significantly affected by S_2, S_3, S_5, M_2, and M_3, with S_2 having the largest negative effect among them, from which we can speculated that the decrease in fruit firmness was due to high soil nitrogen and reduced calcium content in fruit (John et al. 2007), or was due to insufficient soil nitrogen that inhibited fruit expansion. In addition, fruit firmness was also negatively affected by soil available K, which was consistent with the results of Fallahi et al. (2010), who used integrated fertilizer and water technology to study the effect of potassium on apple fruit firmness. The factor M_3 was the most important meteorological factor related to SSC and influenced SSC positively, which was consistent with the results of Sugiura et al. (2013) and Warrington et al. (1999). This might be because the increased temperature during the apple-growing period promoted apple trees to flower and ripen early. The factor S_2 had the greatest positive effect on SSC, which might be due to the low total N content ($0.77\,g \cdot kg^{-1}$) of orchard soil in the Loess Plateau production region. But this result was contrary to the results of John et al. (2007), who based their conclusion on the long-term and large-scale application of nitrogen fertilizer on fruit quality of 'Golden Delicious' apple. The factor S_{10} had the greatest negative effect on SSC, while S_7 had the larger positive effect on SSC. In alkaline soil, soluble ferric iron is converted into insoluble ferric iron and precipitated, so that the iron cannot be utilized by the roots of fruit trees, thereby affecting tree growth and fruit quality improvement. The TA content was significantly positively affected by S_{10} but negatively affected by S_9, which indicated that the soil with high boron content and low pH was beneficial for decreasing fruit acidity in the Loess Plateau production region. This might be due to the fact that soil available boron was negatively correlated with soil pH, and the boron activity of the soil solution increased as soil pH decreased (Keren et al. 1985). In other words, the soil available boron that could be absorbed by apple trees was increased, thereby increasing fruit acidity. The temperature factors (the highest temperature and the lowest temperature) during the apple-growing period were particularly important for fruit color development, showing that there was a close relationship between apple fruit color and the day and night temperature of different months during the growing period. This result was consistent with the results reported by Lakatos et al. (2012). Besides, the fruit skin color area was significantly positively affected by S_4, S_5 and S_6, which was consistent with the results of Siddique et al. (2009), Fallahi et al. (2010), and Bizjak et al. (2013). In our study, we found that S_{10} had the greatest positive effect on fruit firmness, but it had the greatest negative effect on fruit shape index and SSC, which has not been reported to date.

Schemes of Optimum Environmental Factors for Good-Quality 'Fuji' Apple in the Loess Plateau Production Region

The combination of PLSR analysis and linear programming was used to optimize environmental factors for high-quality 'Fuji' apples in the Loess Plateau production region. The optimum SOM content (13.94–$17.93\,g \cdot kg^{-1}$) for good fruit quality production of vigorous apples was basically consistent with a previous study (Liu et al. 2006) in which SOM content in good-quality and high-yield apple orchards was above 1.5%. The lower limit value ($13.94\,g \cdot kg^{-1}$) of optimum SOM was close to the value ($14.15\,g \cdot kg^{-1}$) of well-managed apple orchards in the Circum-Bohai region (Zhang et al. 2017), but it was higher than values reported in Weibei, Shaanxi Province (Wang et al. 2007; Zhang 2012), in the Loess Plateau production region (Zhang D. et al. 2016), and in Jiaodong, Shandong Province (Wang et al. 2008). The upper limit value ($17.93\,g \cdot kg^{-1}$) was lower than the value ($20.41\,g \cdot kg^{-1}$) of well-managed orchards in Changping County of Beijing (Zhang et al. 2011a, b), and also lower than the values (3.1%, 2.0%) of apple orchards under comprehensive (IFP) and organic (OFP) management in New York State (Peck et al. 2011). The lower limit value of optimum soil total N content ($0.77\,g \cdot kg^{-1}$) in this study was higher than previous survey data in the Loess Plateau production region (Zhang et al. 2013, Zhang D. et al. 2016); the upper limit value ($1.03\,g \cdot kg^{-1}$) was lower than the survey data ($2.1\,g \cdot kg^{-1}$) in the apple orchards of Punjab region of Pakistan (Khattak and Hussain 2007), and was also lower than the average value ($1.53\,g \cdot kg^{-1}$) of a well-managed apple orchard in Changping County of Beijing (Zhang et al. 2011a, b). The soil available N content measured in the study was basically consistent with previous survey results (Wang et al. 2008; Zhang et al. 2013; Zhang D. et al. 2016), while the lower limits of soil available P and K contents were higher than previous survey results (Siddique et al. 2009; Wang et al. 2008; Zhang et al. 2013; Zhang D. et al. 2016). The optimum soil available Ca content ($6.54\,mg \cdot kg^{-1}$) was higher than previous survey results (Siddique et al. 2009; Zhang et al. 2011a, b; Zhang D. et al. 2016). The optimum soil available Fe content ($14.97\,mg \cdot kg^{-1}$) and available Zn content (1.55–$2.72\,mg \cdot kg^{-1}$) were higher than the values of 108 'Fuji' orchards in 12 dominant apple-producing counties in the Loess Plateau production region (Zhang D. et al. 2016) but were lower than the survey results of well-managed apple orchards in Changping county of Beijing (Zhang et al. 2011a, b). The optimum soil available B content ($0.37\,mg \cdot kg^{-1}$) was lower than the value ($0.734\,mg \cdot kg^{-1}$) of well-managed apple orchards of Changping county in Beijing (Zhang et al. 2011a, b).

In the present study, the optimum value (18 °C) of mean annual temperature for the production of good-quality vigorous apples in the Loess Plateau production region was higher than the values (7–14 °C) reported previously, such as those by Lu (1980), Huang (1990), Wang and Yin (1992), Zhang (1994), and Duan et al. (2014). The optimum value (19.9 °C) of monthly mean temperature from April to October was close to the upper limit of monthly mean temperature (15.5–19.7 °C) in Weibei of Loess Plateau (Qu et al. 2008) but was higher than that in other regions. For example, the mean temperature during the apple-growing period in Aksu prefecture, Xinjiang (Liu and Mao 2001) was in the range of 12–18 °C, and the monthly mean temperature from April to October in the dominant apple-producing regions of northeast China, north China, and northeast China (Qu et al. 2008), and for good fruit quality of 'Pink Lady' apple in Weibei of Loess Plateau (Gao et al. 2009) the values were 16.2–18.7 °C and 15.5 °C respectively. The optimum value (8.03 °C) of the monthly mean lowest temperature from April to October was higher than the monthly mean lowest temperature during the growing period (7.2 °C) for high-quality 'Fuji' apple production in Hebei Province, China (Li et al. 2009). The optimum value (12.41 °C) of monthly mean temperature difference between day and night from April to October met the criterion (≥ 10 °C) of high-quality apple ecological regions (Zhang 1994) but was higher than the results of other studies (e.g., Wei et al. 2003; Zhu et al. 2001). Compared with previous studies (Liu and Mao 2001; Wang et al. 2000b), this study obtained a broader range of total annual precipitation for high-quality 'Fuji' apple production in the Loess Plateau production region. However, the lower limit (431.2 mm) and the upper limit (713.8 mm) were, respectively, lower than the lower and upper limits of the total annual precipitation (501–800 mm) proposed by Li et al. (1985). The range of optimal total annual precipitation from April to October (338.3–589.8 mm) was larger than the results of Zhang (1994) and Wang et al. (2000b). The optimal monthly mean relative humidity from April to October was 56.1–82.4%. The range was wider than the optimal relative humidity of 60–70% and 65.1–73.3% reported by Zhu et al. (2001) and Duan et al. (2014), respectively, for 'Fuji' apple, and the upper limit was higher than the results ($\leq 70\%$) reported by Li et al. (2000).

Restrictive Environmental Factors and Countermeasures for High-Quality Apple Production in the Loess Plateau Production Region

The difference between the measured value and theoretical value indicated that the lower monthly mean temperature difference between day and night, lower mean annual temperature and monthly mean temperature, and higher monthly mean lowest temperature during the apple-growing period, together with the low contents of soil available Ca and Fe, the high content of soil available B, and serious soil alkalization were the restrictive environmental factors for apple production in the Loess Plateau production region. In addition, suitable sunshine percentage (36.96–55.87%) during the apple-growing period and suitable soil available K content (324.41–$468.62\,mg \cdot kg^{-1}$) also had an important effect on 'Fuji' fruit quality.

In view of the large differences of soil nutrition, meteorological factors, and apple fruit quality traits in the Loess Plateau production region, and taking into account the effect weights of soil nutrition and meteorological factors on fruit quality, as well as the restrictive soil nutrition and meteorological factors for high-quality apple through optimum schemes, 'Fuji' apple is recommended to be popularized in regions with higher mean annual temperature, and higher monthly mean temperature, larger monthly mean temperature difference between day and night, lower monthly mean lowest temperature and suitable sunshine percentage during the growing period. For orchard in non-eugenic regions, the micro-climate could be improved by certain agricultural measures to respond to restrictive meteorological factors in the Loess Plateau production region. For instance, black fabric mulching along tree rows can increase ground temperature; micro-spray mist can reduce the temperature of the orchards at night, expand the temperature difference between day and night, and weaken the respiration of fruit trees, which are beneficial to fruit organic matter accumulation and sugar conversion; reflective film mulching in the fruit-ripening stage can be used to increase the daytime temperature, reduce the nighttime temperature, and expand the temperature difference between the day and night, which is beneficial to fruit organic matter accumulation and color development. In addition, soil management measures are necessary for the production of high-quality 'Fuji' apples, such as reducing soil pH and available B content, increasing the content of soil available Ca and Fe, and adjusting soil available K content.

It should be pointed out that apple quality is the result of multiple factors such as apple lines, climate–soil ecological environment, cultivation and management measures, among others (Yu et al. 1988). This study only focused on the major environmental factors associated with 'Fuji' fruit quality of vigorous apples, and the obtained optimum schemes are only theoretical; thus, the other environmental factors and the theoretical schemes obtained need to be further explored, in particular the optimum values of soil nutrition need to be verified or adjusted in practice. And finally, we should achieve a reasonable formula fertilization.

Conclusion

The effect of meteorological factors (55.99%) on fruit quality was greater than that of soil nutrition factors (44.01%) in the Loess Plateau apple-producing region of China. 'Fuji' apple should be cultivated in regions with higher mean annual temperature and higher monthly mean temperature, larger monthly mean temperature difference between day and night, lower monthly mean temperature, and suitable sunshine percentage during the growing period. The restrictive factors of high-quality 'Fuji' apples in the Loess Plateau production region were the lower content of soil available Ca and Fe, higher content of soil available B, and serious soil alkalization in some orchards.

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