

Effects of nitrogen and selenium treatments on the texture parameters of ‘Qingcui’ plum fruit

Xieping Sun^{1*}, Min Ling¹, Junyan Wang¹, Guoqiang Han¹, Xiaoli Ma², Linling Kou^{3*}

¹School of Advanced Agriculture and Bioengineering, Yangtze Normal University, Fuling, Chongqing, China; ²Chongqing Three Gorges Academy of Agricultural Sciences, Chongqing, China; ³Agricultural Technology Station of Chongqing, Chongqing, China

***Corresponding Authors:** Xieping Sun, School of Advanced Agriculture and Bioengineering, Yangtze Normal University, Juxiandadao Road, Fuling, Chongqing 408100, China. Email: xieping444@163.com; Linling Kou, Agricultural Technology Station of Chongqing, Huangshangdadao Road, Liangjiangxinqu, Chongqing 401121, China. Email: 1553507567@qq.com

Received: 10 January 2023; Accepted: 26 June 2023; Published: 15 July 2023

© 2023 Codon Publications



RESEARCH ARTICLE

Abstract

‘Qingcui’ plum fruit becomes soft at harvesting. In this study, we assessed the effect of the following different treatments on various fruit texture parameters: three concentrations of nitrogen (NH_4NO_3 0%, 0.5% and 1%) and three forms of selenium (selenomethylcysteine [$\text{C}_5\text{H}_9\text{NO}_2\text{SSe/SeMeCys}$], sodium selenate [Na_2SeO_4] and selenomethionine [SeMet]). The fruit texture parameters evaluated were fracture, hardness, cohesiveness, springiness, gumminess, chewiness and initial modulus under 4°C. Results showed that the optimal N concentration was 1% and the optimal Se form was SeMeCys. Fruits treated with SeMeCys had similar fruit texture parameters as those of the group under cysteine treatment. We then sprayed the fruit with approximately 2 mL/fruit of the following treatments: five different combinations ratios of Se (SeMeCys; 10 mg/L) and N (NH_4NO_3 ; 1%) (2:18; 4:16; 10:10; 16:4; 18:2), after which the fruit was stored at 4°C for 13 days. The parameters of fruit texture, fruit color, and other fruit qualities were measured. Linear correlations were observed between parameters, and main sensory qualities were analyzed. We observed that a combination of Se and N in a ratio of 18:2 produced the best results in terms of fracture, first hardness and second hardness, preventing the softening of the fruit. The parameters of soluble protein, titratable acid and soluble solids had significant linear relationships with three fixture parameters. The fruit color parameters of a^* (greenness) and b^* (yellowness) also had significant linear correlations with fracture and first hardness. These findings may offer a promising strategy to prolong fruit storage and maintain fruit crispness and hardness.

Keywords: ‘Qingcui’ plum; nitrate; selenium; fruit texture; fruit color

Introduction

Plum (*Prunus salicina* L.), an adaptable and disease-resistant fruit tree, is planted globally (Qiu *et al.*, 2021). China is one of the origins and distribution centers of plums and is extremely rich in germplasm resources (Liu *et al.*, 2007). ‘Qingcui’ plum is a variety group that originated in China and is widely planted in southwest

China. The fruit of this variety is known for its green color, crisp and sweet flesh, and free nucleus (Qiu *et al.*, 2021; Zhang *et al.*, 2021). According to incomplete statistics, there are nearly 40 ‘Qingcui’ plum varieties distributed in Southwest China. In Chongqing, Sichuan, Guizhou and other provinces, one finds not only the traditional cultivars, ‘Huangla’ and ‘Maihuang’, but also the newly selected ‘Wushan’, ‘Bashan’, ‘Fengtang’ and ‘Fendai’

cultivars and other super varieties. The planting area and yield of ‘Qingcui’ plum are increasing each year; this has played an important role in poverty alleviation and rural revitalization in China.

Crisp and sweet fruit are important qualities of ‘Qingcui’ plum. Crispness is measured by a texture analyzer, and sweetness, an intrinsic quality, is quantified in terms of soluble solids. The ‘Qingcui’ plum is a typical respiration climacteric fruit. During the aging process, the color changes from green to yellow-green to yellow. Change in color is assessed using a colorimeter, with assigned values of L, a*, b*, C and H (Adhikary *et al.*, 2021; Karagiannis *et al.*, 2021). As the fruit of ‘Qingcui’ plum ripens and approaches senescence, it softens slowly, mainly because the production of ethylene changes the composition of the cell wall as well as the level of enzyme activity (Zhang *et al.*, 2021). Application of sodium selenate (Na₂SeO₄) can reduce ethylene production and effectively delay fruit ripening and senescence (Pezzarossa *et al.*, 2012). Addition of sodium selenite (Na₂SeO₃) and nano Se treatment reduce ethylene production, titratable acid, and stone cell content, and improve quality of fruit (Yuan *et al.*, 2023). However, selenomethionine (SeMet) increases the content of reactive oxygen species (ROS), inhibit auxin and promote production of ethylene (Malheiros *et al.*, 2020), which could promote fruit ripening and senescence. In terms of cell distribution, the Se delivered through nano Se and Na₂SeO₃ mainly converts to SeMet, which is distributed in the cell wall. However, in selenate-treated plants, selenate was mainly distributed in the soluble cytoplasm (Wang *et al.*, 2020). Thus, differences are observed in the solubility and cell structure distribution of different forms of Se in plants, which have significant differences in the key quality of ‘Qingcui’ plum fruits during storage.

Cysteine (Cys) delays the process of fruit senescence. Gohari *et al.* (2021) reported Cys (0.4%) to be a safe, natural, and environment-friendly treatment to preserve the nutritional quality of flat peach fruit during long-term cold storage. Wang *et al.* (2022) reported that 0.05% of Cys treatments at 4°C with 90% relative humidity significantly reduced decay ratio and weight loss in goji fruit. The derivatives of Cys also show similar functions in improving the storage quality of fruits. Li *et al.* (2018) reported that application of Cys hydrochloride delayed breakdown of the aril and maintained fruit quality of longan. Liu *et al.* (2006) reported that soaking Litchi fruit in a solution of 0.1% N-acetyl cysteine and indole-3-acetic acid (IAA) inhibits browning of the pericarp and maintains flesh quality during storage. Selenomethylcysteine (C₅H₉NO₂SSe/SeMeCys) is a seleno amino acid derivative having a potent anticancer activity in animals (Brummell *et al.*, 2011). Plants in a natural manner transform inorganic Se into organic Se, in the form of

SeMeCys, SeMet *et al.* (Heryadi, *et al.*, 2020; Huang *et al.*, 2022). SeMeCys as a Cys derivative also slows ripening process during storage, although application of SeMeCys on freshly stored fruits has not been reported.

Nitrogen (N) affects several aspects of fruit quality, namely size, shape, color, texture, flavor and composition (Maheswari *et al.*, 2017). Fruit cracking, a primary disease limiting the production of ‘Qingcui’ plum, is affected by the level of elemental nutrients. Yilmaz and Ozguven (2019) showed that the fruit peel of cracked fruit contained higher levels of N, compared to that of healthy fruit whereas Engin *et al.* (2009) determined that application of N reduces cracking in sweet cherry fruit under different levels of irrigation. In a study conducted by Engin *et al.* (2009), irrigation application of N were shown to have no great effect on fruit color in sweet cherry but influenced fruit firmness. Excess of water—via rain, soaking, or irrigation—causes fruit cracking by reducing sugar content, ascorbic acid, and titratable acidity, making the fruit more susceptible to cracking (Gibert, *et al.*, 2007; Simon 2006). Application of Se to the roots has been shown to enhance leaf N content, improve N uptake efficiency, and increase fruit yield and fruit quality (Sun *et al.*, 2020; Zhan *et al.*, 2021). However, specific interaction between Se and N during the fruit development process remains unclear.

In this study, we detected the impact of different forms of Se and N concentration on ‘Qingcui’ plum quality during cold storage (4°C in a foam box). The aim was to evaluate a number of fruit qualities, viz. texture, cracking, color, and other parameters to determine the optimal combination of Se and N to slow down the ripening process.

Materials and Methods

Experimental design

‘Qingcui’ plum fruit were harvested at a commercial orchard located in Chongqing, China, from August 2021 to September 2021, to prepare for three experiments. For each experiment, the fruits were hand-picked, selecting those of intermediate size and weight. The experimental design is shown in Figure 1. For treatment of N, 90 individual fruits in three replications, with 10 fruits per treatment, were sprayed with ammonium nitrate (NH₄NO₃) at concentrations of 0.0% (control), 0.5%, and 1.0% prepared in 10-mL reagent per treatment. After 3 h, the fruits were immersed in water for 16 h to assess changes in fruit appearance, fruit texture, and fruit cracking rate.

For Se application, the fruits were sprayed (approximately 2 mL/fruit) with 10 mg/L of Se as SeMeCys, Na₂SeO₄, and SeMet as well as water only as a control spray. In case

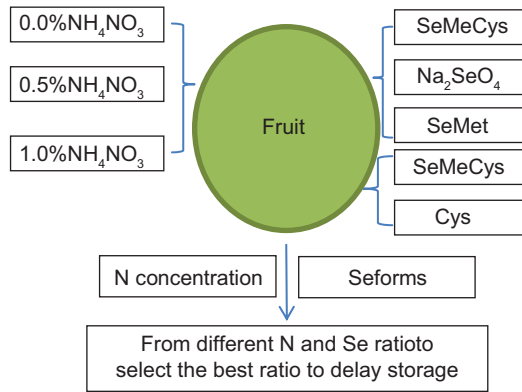


Figure 1. Experimental design.

of each treatment, 10 fruits were stored in closed foam boxes in cold storage at 4°C for 7 days, following which the fruit quality parameters were measured. In addition, 30 'Qingcui' plum fruits were used as experimental material; 15 fruits (5 fruits as a replication in three replications) were sprayed with 15-mL SeCys or Cys in 10 mg/L and stored in a closed foam box at 4°C for 7 days.

To test the effect of different combinations of N, as NH_4NO_3 (1%), and Se, as SeCys (10 mg/L), the following volumetric (mL:mL) ratios were prepared: 0:0 (control with 20-mL H_2O), 2:18, 6:14, 10:10, 14:6 and 18:2. These combinations were sprayed in volumes of 20 mL on 10 individual fruits, which were subsequently placed in a closed foam box in cold storage (4°C) for 12 days.

Analytical methods

Evaluation of fruit appearance

The transverse and longitudinal diameters of individual fruits and volume were calculated before and after the fruits were soaked in water using a Vernier caliper. Fruit weight, edible part of fresh fruit, and dry weight were measured using an electronic balance. Fruit volume was measured using the drainage method. Fruit cracking rate was measured as the number of cracked fruits divided by the total number of fruits.

Determination of fruit texture

The following texture parameters were measured: fracture, first hardness, second hardness, cohesiveness, springiness, gumminess, chewiness, and initial modulus. Half of the plum fruit was placed on the plate of a texture analyzer (TL-PRO; Food Technology Corporation, VA, USA), and the parameters were measured using a cylindrical probe P/75 with 75-mm diameter. The parameters of texture analyzer were set as follows: test speed, 60 mm/min, compression deformation of plum pulp, 60%, and triggering force, 1.5 N. The pause time was 1 s.

Determining fruit color

The surface color of the plum was determined with a colorimeter (WR-10QC; Weifu, Shenzhen, China), and the corresponding values were recorded for L (lightness), a^* (greenness), b^* (yellowness), C (chroma) ($[a^{2*} + b^{2*}]^{1/2}$), and h (hue) ($h = \tan^{-1} [b^*/a^*]$) (Adhikary *et al.*, 2021; Dobrzanski and Rybczyski, 2002). Color attributes were determined at the middle part of the outer epidermis of each fruit.

Determining fruit intrinsic quality

The water content of the edible part was calculated as follows: (fresh weight – dry weight)/fresh weight. The total soluble solid content (%) of each fruit was calculated with a refractometer (Atogo, ATC-1, Japan). The fruit titratable acid content (%) was determined using 0.1-mol/L NaOH and phenolphthalein as a pH indicator (Singh *et al.*, 2009). The soluble protein content was determined using the Coomassie brilliant blue method (Rosen, 1957), in which 5.0-g fruit was weighed, ground, and centrifuged. Then 0.3 mL of supernatant was added to 1.5 mL of Coomassie brilliant blue G-250 and mixed for 2 min before being measured at 595 nm. The ratio of soluble substance to acid was calculated as the value of soluble substance divided by titratable acid content.

Statistical analysis

The experiments were arranged in a completely randomized manner, and each treatment comprised four replicates. Data were analyzed using Origin 8.5 (OriginLab Origin Pro, MA, USA). The least significant difference (LSD) was calculated to compare significant effects at 5% level.

Results

Effect of different nitrate applications on fruit quality after soaking

Although spraying of three different concentrations of HN_4NO_3 increased transverse and longitudinal diameters of fruit, the difference between treatments was not significant (Table 1). The change in fruit volume was lowest after treating with 1.0% NH_4NO_3 and significantly lower than the other two treatments. The change in fruit weight was maximum after treating with 1.0% HN_4NO_3 , followed by 0.0% and 0.5% treatments, and the difference between these treatments was significant. However, no significant difference was observed between soluble solid content, fruit water content, and fruit cracking rate with three different N treatments. However, fruit cracking rate was increased from 0% to nearly 30% after 3 h of soaking.

All texture parameters—fracture, first hardness, and second hardness—increased with increase in HN_4NO_3

Table 1. Effect of different concentrations of HN_4NO_3 on changes in fruit diameter, weight, and volume, fruit contents of soluble solids and water, and fruit cracking rate.

Treatments	Transverse diameter change (mm)	Longitudinal diameter change (mm)	Volume change (mL)	Fruit weight change (g)	Soluble solids content (%)	Fruit water content (%)	Fruit cracking rate (%)
0.0%	0.76±0.00 ^a	1.07±0.21 ^a	1.38±0.33 ^a	0.51±0.01 ^b	11.37±0.63 ^a	88.86±0.03 ^a	28.79±0.11 ^a
0.5%	0.77±0.08 ^a	0.97±0.14 ^a	1.46±0.51 ^a	0.45±0.01 ^c	11.99±0.36 ^a	88.91±0.01 ^a	24.54±0.13 ^a
1.0%	1.17±0.38 ^a	0.71±0.30 ^a	0.65±0.31 ^b	0.66±0.02 ^a	11.94±1.20 ^a	88.50±0.00 ^a	27.91±0.15 ^a

Note: The same superscript letters indicate nonsignificant differences at the significance level of 0.05 (n = 3).

Table 2. Effect of different concentrations of HN_4NO_3 on fruit texture.

Treatments	Fracture (N)	First hardness (N)	Second hardness (N)	Cohesiveness (ratio)	Springiness (mm)	Gumminess (N)	Chewiness (mj)	Initial modulus (N/mm)
0.0%	101.86±2.23 ^a	119.43±6.10 ^a	100.21±3.55 ^a	0.09±0.01 ^a	6.44±0.20 ^a	10.19±0.82 ^a	67.83±8.40 ^a	21.04±1.08 ^a
0.5%	103.94±4.97 ^a	123.43±5.33 ^a	103.98±4.90 ^a	0.10±0.00 ^a	6.69±0.49 ^a	11.27±1.21 ^a	77.73±10.85 ^a	18.88±1.47 ^a
1.0%	112.40±8.85 ^a	127.52±3.23 ^a	109.60±7.41 ^a	0.08±0.01 ^a	6.54±0.78 ^a	10.32±1.24 ^a	71.11±14.54 ^a	20.42±0.27 ^a

Note: The same superscript letters indicate nonsignificant differences at the significance level of 0.05 (n = 3).

concentration, but without significant difference between different treatments (Table 2). No difference was observed in cohesiveness, springiness, gumminess, chewiness, and initial modulus with different N concentrations.

Effect of different Se treatments on fruit texture

In control and Na_2SeO_4 -treated fruits, similar values were obtained for fruit fracture, and these values were significantly higher than the values obtained in SeMeCys- and SeMet-treated fruits (Table 3). The highest first hardness was obtained with SeMeCys and was significantly higher than that of the control (16.7%), followed by the Na_2SeO_4 , control, and SeMet treatments. The value for second hardness was highest in the control group and significantly higher than that observed in the SeMeCys group (16.1%), followed by the SeMet, Na_2SeO_4 , and SeMeCys treatments. The parameters of cohesiveness, springiness, gumminess, and chewiness of 'Qingcui' plum fruits with SeMeCys treatment were similar to the corresponding values of the control group and higher than those obtained with the SeMet and Na_2SeO_4 treatments. The initial modulus value with SeMeCys was highest and significantly higher (19.9%) than that obtained in the control group. It was observed that SeMeCys and Na_2SeO_4 had better effect in maintaining plums' fruit texture, compared to SeMet.

There was no significant difference between SeMeCys and Cys treatments in terms of fruit fracture, first hardness,

cohesiveness, springiness, gumminess, chewiness, and initial modulus. Among these parameters, only the second hardness with Cys treatment was significantly lower than that with SeMeCys treatment. Spraying different forms of Se on the fruit surface did not produce fruit cracking.

Effect of different N and Se ratios on fruit colors

With the exception of b^* (yellowness), fruit colors with different Se and N ratios demonstrated no significant difference, compared to the control group (0:0 ratio) (Table 4). With increase in Se ratio, increase in the L (lightness) was observed, reaching the highest level with 16:4 ratio treatment, which was significantly higher (4.1%) than the result obtained with 2:18 ratio treatment. The value of L then decreased with 18:2 ratio treatment. The value of a^* also showed an increasing trend, reaching the maximum limit with 18:2 ratio treatment and significantly higher (30.7%) than that with 2:18 ratio treatment. The values of b^* and C (chroma) also showed initial increase, reaching the highest levels with 10:10 and 16:4 ratio treatments. In contrast, the value of h (hue) showed a decreasing trend and was not significantly different with different Se and N ratio treatments.

Effect of different N and Se ratios on fruit fracture

The fracture value was observed to increase with increase in Se–N ratio, but the difference was not statistically

Table 3. Effect of application of three forms of Se, i.e. SeMeCys, SeCys and Na₂SeO₄, and Cys and SeMeCys treatments on fruit texture parameters and fruit cracking rate.

Treatment	Fracture (N)	First hardness (N)	Second hardness (N)	Cohesiveness (ratio)	Springiness (mm)	Gumminess (N)	Chewiness (mj)	Initial modulus (N/mm)	Fruit cracking rate (%)
Control	120.5±27.8 ^a	121.2±16.1 ^b	57.1±4.6 ^a	0.098±0.0054 ^a	6.39±0.64 ^{ab}	12.2±1.6 ^b	75.0±12.9 ^a	17.6±4.8 ^b	0.0
SeMeCys	102.1±15.7 ^b	141.4±18.7 ^a	49.2±6.4 ^b	0.094±0.0061 ^{ab}	6.67±0.42 ^a	13.5±2.1 ^a	82.0±18.0 ^a	21.1±4.9 ^a	0.0
Na ₂ SeO ₄	120.6±13.1 ^a	127.9±10.2 ^{ab}	51.6±6.7 ^{ab}	0.088±0.013 ^{bc}	5.97±0.36 ^b	11.5±2.0 ^b	62.8±9.4 ^b	16.9±2.7 ^b	0.0
SeMet	101.6±19.6 ^b	102±21.5 ^c	56.8±6.4 ^a	0.083±0.0098 ^c	5.05±0.62 ^c	11.2±1.8 ^b	51.6±11.7 ^b	10.6±2.3 ^c	0.0
Cys	131.2±10.2 ^a	158.4±16.7 ^a	63.1±4.2 ^a	0.087±0.0005 ^a	7.52±0.41 ^a	16.4±1.2 ^a	116.2±20.1 ^a	24.1±3.1 ^a	0.0
SeMeCys	129.7±9.8 ^a	157.512.4 ^a	55.2±3.8 ^b	0.084±0.0003 ^a	7.00±0.52 ^a	16.2±0.9 ^a	107±18.7 ^a	23.7±2.5 ^a	0.0

Note: The same superscript letters indicate nonsignificant differences at the significance level of 0.05 (n = 3).

significant (Figure 2). The first hardness and the second hardness also increased, reaching the highest level at Se–N ratio of 18:2, and were significantly higher by 28.27% and 44.51%, respectively, than that of the control. The parameters of cohesiveness and springiness demonstrated a decreasing trend with increase in Se–N ratio; the values with Se–N ratios of 16:4 and 18:2 were approximately 9.56% and 1.25% higher, respectively, and statistically significant, compared to those of the control. Both gumminess and chewiness values were lowest with an Se–N ratio of 2:18, and were significantly lower than the corresponding values of the control (approximately 12.57% and 24.10%, respectively). Regarding other Se–N ratio treatments, we observed no significant differences, compared with the control. There were no significant differences in initial modulus with different Se and N ratio treatments.

Effect of different N and Se ratio treatments on intrinsic quality of fruit

The fruit water content was reduced with increase in Se–N ratio, and the highest fruit water content was obtained with an Se–N ratio of 2:18, approximately 1.16% higher than that of the control, followed by 4:16 ratio treatment, which was 1.08% higher than that of the control. The other treatments did not result in any significant differences compared to the control (Figure 3). The soluble solids content with an Se–N ratio of 2:18 resulted in the lowest value and was significantly different from the corresponding value of the control as well as that of the 18:2 ratio treatment. No significant effect was observed in titratable acid content in different Se–N ratio treatments. With increase in Se–N ratio, the soluble protein contents also increased; the levels of soluble protein content at Se–N ratios of 16:4 and 18:2 were significantly higher than the levels of the control, i.e. approximately 25.52% and 29.93% higher, respectively.

Correlation between different Se and N ratio treatments

A significant negative linear relationship was observed between L and C, a* and b*, and a* and h ($P < 0.05$) among different Se–N ratio treatments, especially, L and C showed a positive linear ($P < 0.001$) relationship (Table 5). Statistically significant linear relationships were observed for five pairs of attributes: a* and fracture, a* and first hardness, b* and fracture, b* and first hardness, and h and chewiness. Among fruit texture parameters, a positive relationship existed between fracture and first hardness and second hardness whereas a negative relationship existed between springiness, first hardness and second hardness. The initial modulus was positively correlated with chewiness and gumminess, and the

Table 4. Effects of different Se and N ratios on fruit color.

Se:N ratio	L	a*	b*	C	h
0:0	51.55±1.78 ^{a,b}	-4.32±0.91 ^{a,b}	32.22±2.45 ^a	51.72±1.78 ^{a,b}	-0.12±0.05 ^a
2:18	50.53±2.70 ^b	-4.96±1.38 ^b	31.41±2.53 ^a	50.79±2.71 ^b	-0.16±0.04 ^a
4:16	52.38±2.10 ^a	-4.68±1.45 ^{a,b}	31.82±2.16 ^a	52.60±2.11 ^a	-0.14±0.04 ^a
10:10	52.39±1.19 ^a	-4.48±2.33 ^{a,b}	32.40±1.59 ^a	52.62±1.13 ^a	-0.14±0.07 ^a
16:4	52.60±1.40 ^a	-3.53±1.94 ^{a,b}	28.73±2.04 ^b	52.75±1.40 ^a	-0.12±0.07 ^a
18:2	51.31±1.52 ^{a,b}	-3.44±1.56 ^a	28.12±2.69 ^b	51.44±1.50 ^{a,b}	-0.12±0.05 ^a

Note: The same superscript letters indicate nonsignificant differences at the significance level of 0.05 (n = 3).

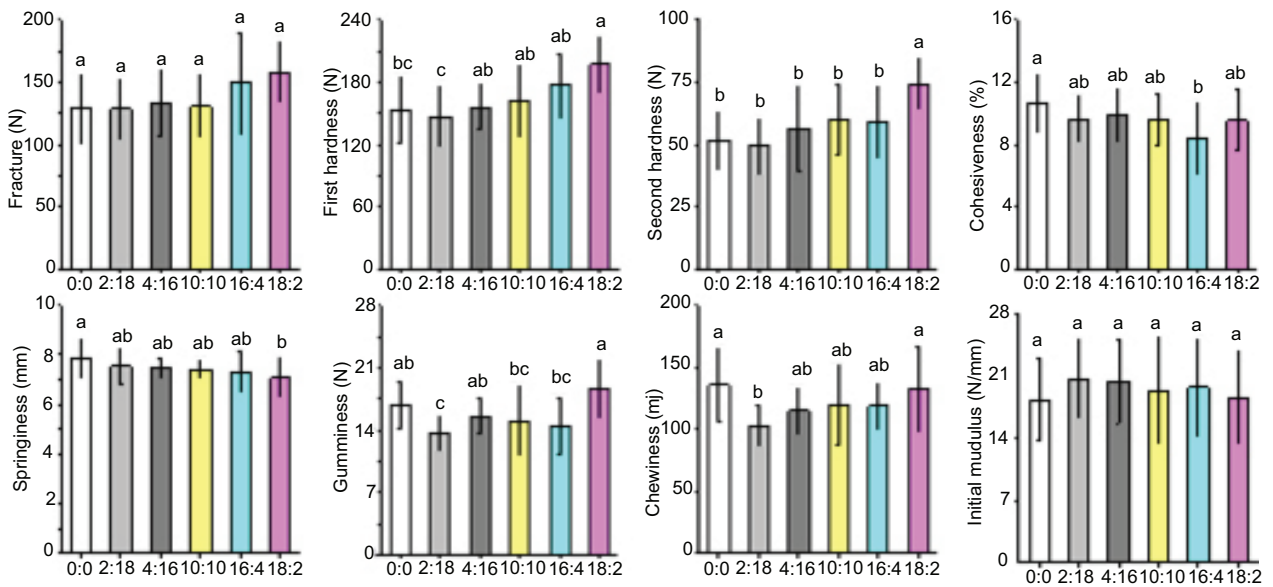


Figure 2. Effect of different N and Se ratio treatments on fruit texture.

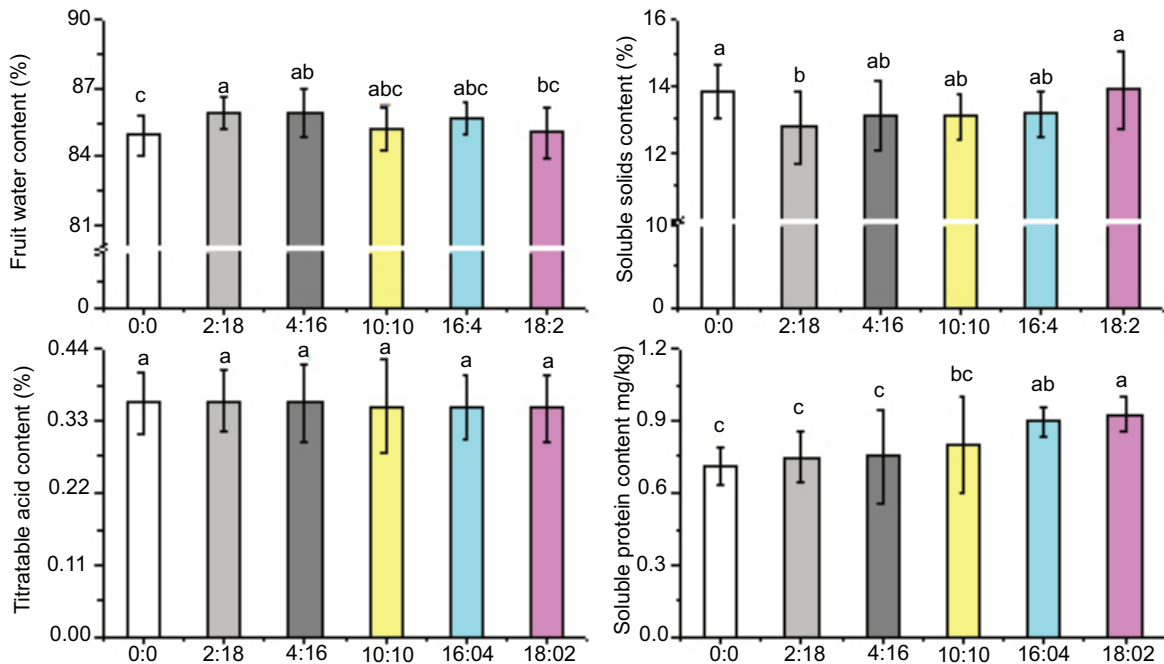


Figure 3. Effect of different N and Se ratio treatments on intrinsic quality of the fruit.

Table 5. Pearson's correlation coefficients between some selected quality parameters of plum fruit treated with different Se ratios during cold storage.

L	a*	b*	C	h	Fracture	First hardness	Second hardness	Cohesiveness	Springiness	Initial modulus	Chewiness	Gumminess	Fruit water content	Soluble protein	Titratable acid	Soluble solids content
1																
a*	1															
b*	-0.13	1														
C	-0.25	-0.69*	1													
h	0.99***	-0.19	-0.02	1												
Fracture	0.04	0.00	-0.21	0.20	1											
First hardness	0.25	0.66*	-0.91**	0.32	0.93**	1										
Second hardness	-0.25	0.75*	-0.62*	0.21	0.79*	0.93**	1									
Cohesiveness	-0.22	-0.15	-0.21	0.21	0.79*	0.93**	1									
Springiness	-0.20	0.31	0.04	-0.24	-0.08	-0.04	-0.14	1								
Initial modulus	-0.24	0.41	-0.25	-0.20	-0.53	-0.64*	-0.68*	0.31	1							
Chewiness	-0.23	-0.23	-0.11	0.68*	0.12	0.21	0.42	-0.05	-0.19	1						
Gumminess	0.03	-0.21	-0.10	0.85**	0.02	0.30	0.23	-0.22	-0.24	0.85**	1					
Fruit water content	-0.12	-0.17	0.17	0.56	-0.10	-0.07	0.03	0.09	-0.25	0.58*	0.75*	1				
Soluble protein	-0.20	-0.22	-0.17	0.52	-0.23	-0.09	0.02	-0.01	-0.24	-0.87*	0.95**	0.95**	1			
Titratable acid	-0.10	0.49	-0.25	0.04	0.94***	0.84**	0.60*	0.41	-0.88**	-0.25	-0.25	-0.21	0.24	1		
Soluble solids content	0.09	0.71*	-0.10	0.33	-0.71*	-0.78*	0.59*	0.26	0.51	0.04	-0.06	-0.10	-0.12	0.88**	1	
	0.31	0.14	-0.04	0.76*	0.67*	0.74*	0.76*	-0.11	-0.51	0.91**	-0.75*	-0.52	0.68*	0.50	-0.27	1

Note: Significant at *P < 0.05, **P < 0.01, ***P < 0.001. Minus sign (-) indicates negative relationship whereas plus sign (+) indicates positive relationship.

relationship between chewiness and gumminess was also shown to be positive.

A positive linear relationship was observed between a^* and titratable acid, and between b^* and soluble protein. Statistically significant linear correlations were also observed between fruit water content and initial modulus (negative), chewiness (positive), and gumminess (positive). The protein content was significantly passivated with fracture, first hardness and second hardness, and was negatively correlated with springiness. The titratable acid was negatively correlated with fracture and first hardness and was positively correlated with second hardness and soluble protein. A positive linear relationship was observed between soluble solids content and fracture, first hardness, second hardness, initial modulus, and fruit water content whereas a negative correlation was observed with chewiness.

Main sensory quality

Variations in crispness and sweet sensory quality of 'Qingcui' plum fruit after different Se and N ratio treatments and short-term storage are illustrated in Figure 4. Fruit treated with an Se–N ratio of 18:2 showed maximum values for first hardness, second hardness and fracture. Values of water content and the ratio of soluble substance and acid fluctuated within a narrow range with different Se–N ratio treatments.

Discussion

The application of melatonin, alginate edible coating, salicylic acid, calcium–ethylenediaminetetraacetic acid (Ca-EDTA), and other bio-regulators on plum fruit slows

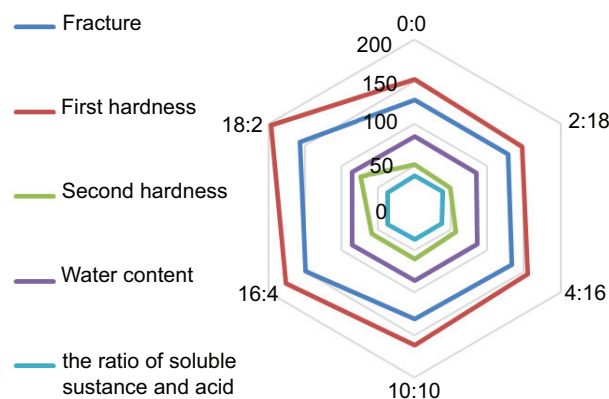


Figure 4. Effect of different N and Se ratio treatments on fracture, first hardness, second hardness, water content, and the ratio of soluble substance and acid.

ripening process during storage (Attri *et al.*, 2015; Valero *et al.*, 2013; Yan *et al.*, 2022).

Different forms and doses of Se improve the storage quality of fruits. A low concentration of Se (0.02 mg/kg) combined with chitosan prolongs the storage period and post-harvest life of guava, while high concentration of Se with chitosan has a negative effect on fruit storage conditions (Choudhary *et al.*, 2020). The application of low-concentration Se nanoparticles, synthesized using Cassia fistula L. extract and 10-mM Na_2SeO_3 solution, on post-harvest strawberry fruits increases shelf life and maintains quality attributes (Aftab *et al.*, 2022). In our study, Se with the highest content and the lowest ammonium nitrate showed the best results for preservation of fruit quality.

As a post-harvest application, N is used mainly in the form of *nitric oxide* (NO) or sodium nitroprusside (SNP) in plum, peach, and pear fruits (Singh *et al.*, 2009; Zhu *et al.*, 2006). The fruit firmness was influenced by the application of different forms of N to the roots, with application of inorganic NH_4NO_3 showing significantly prominent effects, compared to application of organic nitrogen (Fikry *et al.*, 2022). The application of NH_4NO_3 during fruit storage resulted in increased values of fracture, first hardness and second hardness (Table 2).

The weight of fruits is generally reduced during fruit ripening and senescence. The average mass loss in plum fruit is approximately 7.7% or 0.23% per day during -1°C – 0°C storage conditions (Сердюк *et al.*, 2016). In our study, the application of 1.0% NH_4NO_3 increased fruit weight significantly. The fruit water content increased with increase in N under different Se and N ratios (Table 1 and Figure 2). This result indicates that the application of NH_4NO_3 can increase fruit weight and fruit water content with Se.

Generally, fruit cracking, a physical failure of the cuticle or skin, occurs because of stress and heavy rain (Ramteke *et al.*, 2017). The maturity period of 'Qingcui' plum coincides with the rainy season. In a study, tomato plants grown in a hydroponic environment and enriched with Se (in the form of Na_2SeO_4) showed improved performance during storage and post-harvest shelf life as well as greater potential of health-promoting properties (Puccinelli *et al.*, 2019). In our study, the spray application of Na_2SeO_4 also had a beneficial effect on plum attributes during short-term storage (Table 3).

We also determined that the effectiveness of SeMetCys and Na_2SeO_4 was higher than that of SeMet treatment (Table 3). The literature has a number of reports of Cys treatment preventing fruit senescence (Gohari *et al.*, 2021; Sharma and Rao, 2013). Comparing texture

parameters under the same concentration and doses of Cys and SeMeCys, we observed that SeMeCys as well as Cys treatment could preserve fruit freshness.

The values of L, a^* and b^* increased continuously with advancement in the cold storage conditions of green pear fruit (Adhikary *et al.*, 2021). In the present study, we discovered that a 12-day application of different Se and N ratios resulted in no significant effects on a^* and L values, compared to that of control. However, the value of b^* was significantly reduced at Se–N ratios of 16:4 and 18:2 (Table 4). These results indicate that Se and N in higher ratios significantly change the color of fruit skin during storage because of the degradation of chlorophyll content. Similar changes were reported in pear fruit (Adhikary *et al.*, 2021). A significantly positive linear relationship between a^* and b^* (Table 5) indicates that greener or yellower the fruit, the higher is the N content. In the case of parameter h (hue), representing the type of pigment, the lower the angle, the greener the color. The highest level of a^* and the lowest level of b^* were determined at an Se–N ratio of 18:2 (Table 4). This result suggests that the application of N protects the pigment of fruits during storage. Our study also showed that a^* had a linear relationship with titratable acid, fracture and first hardness (Table 5), which was consistent with our knowledge. In other words, the greener the fruit, the more sour and harder it is. The value of b^* was negatively correlated with fracture and first hardness, which was consistent with the observation that the yellower the fruit, the softer it is. Karagiannis *et al.* (2021) reported that fruit firmness and, along with peel color traits (a^*), were strongly affected by Se. In our study, fruit texture parameters, as well as fruit color traits (Tables 3 and 4), were markedly influenced by Se and N ratio treatments. The L value represents black-and-white channel: 0 represents black and 100 represents white. C value reflects color saturation or purity: the greater the value of C, the brighter the fruit color. Our results demonstrated a significant and positive linear interaction between C (lightness) and L (color index) with different Se and N ratio treatments.

The longer the fruit is kept in cold storage, the more the fruit weight, titratable acid level, and phenolic content are reduced, with increase in soluble solids content (Adhikary *et al.*, 2021; Singh *et al.*, 2009; Yan *et al.*, 2022). Fruit firmness is discovered to be positively correlated with the level of titratable acid, and negatively correlated with soluble solid content (Adhikary *et al.*, 2021). In our study, we also observed linear relationships of the level of titratable acid with fracture (negative), first hardness (negative) and second hardness (positive), and a significant positive linear relationship with soluble solids and soluble protein content (Table 5). The N and Se ratio treatment increased fruit water content, and reduced soluble solid content and titratable acid, compared to the

control (0:0 ratio), to prevent fruit senescence; however, the soluble protein content was increased significantly (Figure 3).

In 'Qingcui' plums exposed to an Se–N ratio of 18:2, Se content in the edible part of the fruit was approximately 0.6 mg/fresh weight (FW), even if the fruit absorbed all the available Se. These Se-enriched fruit (ranging from 0.01 to 0.5 mg/FW in Chongqing, China) did not exhibit any signs of Se stress based on quality parameters. The addition of NH_4NO_3 had a thin impact on fruit nitrogen content, with the N content quantifying around 0.1 mg/FW, which was lower than the upper limit of N content (approximately 96 mg/FW) observed in fresh eggplant fruit in China. Overall, plums with an Se–N ratio of 18:2 exhibited higher Se content and lower N content, without any food safety concerns.

Crispness and sweetness are the most important qualities of 'Qingcui' plum, distinguishing it from other types of plums (Zhang *et al.*, 2021). 'Qingcui' plum softens more slowly than other plums (Zhang *et al.*, 2021); however, it softens quickly after harvest. This trait has a negative impact on consumer acceptability. The overall sensory quality is useful for determining fruit storage life (Adhikary *et al.*, 2021). Based on five primary sensory quality parameters, our study was capable of assessing the storage quality of fruits (Figure 4).

The fruit texture properties are examined using the concept of texture profile analysis, in which fruit is categorized as soft, moderate and hard, based on sensory textual profile analysis (Bejaei *et al.*, 2021). Storage time is inversely related to the quality of fruit texture. Appropriate ratio of N and Se improves fruit quality parameters, notably fracture, first hardness and second hardness (Figures 2 and 3). The parameters of fracture and hardness are reflected in the 'crispness' of fruit. We discovered that an Se–N ratio of 18:2 resulted in optimal values of these parameters.

Conclusion

Our results demonstrate that water is the main factor in the cracking of 'Qingcui' plum fruit. The application of N neither significantly inhibited fruit cracking of 'Qingcui' plum, nor it significantly promoted fracture and hardness. We discovered that 10-mg/L SeMeCys solution, followed by selenate treatment, could promote the short-term post-harvest quality of 'Qingcui' plum whereas SeMet had opposite effect on maintaining fruit fracture. After 12 days of treatment with different Se and N ratios, a consistent maintenance Se–N ratio of 2:18 was considered as most effective in delaying softening and maintaining fruit texture, color profiles, and intrinsic fruit quality.

Author Contributions

Xieping Sun and Linling Kou designed the study. Xieping Sun, Min Ling, Junyan Wang and Guoqiang Han developed methods and collected the data. Linling Kou, Xiaoli Ma and Min Ling selected ‘Qingcui’ plum. Xieping Sun analyzed and interpreted the data, and prepared the manuscript. All authors approved the final version of the manuscript.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant No. 31901972) and youth project of science and technology research program of Chongqing Education Commission of China (Grant No. KJQN202101408).

Conflict of Interest

The authors had no conflicts of interest to declare.

Data Availability

The data used to support the findings of this study are available from corresponding authors on reasonable request.

References

- Adhikary, T., Gill, P.P.S., Jawandha, S.K., Bhardwaj, R.D. and Anurag, R.K., 2021. Efficacy of postharvest sodium nitroprusside application to extend storability by regulating physico-chemical quality of pear fruit. *Food Chemistry* 346: 128934. <http://dio.org/10.1016/j.foodchem.2020.128934>
- Aftab, A., Ali, M., Yousaf, Z., Binjawhar, D.N., Hyder, S., Agtab, Z.H., et al. 2023. Shelf-life extension of *Fragaria × ananassa* Duch. using selenium nanoparticles synthesized from *Cassia fistula* Linn. Leaves. *Food Science and Nutrition* 11(6): 1–21. <http://dio.org/10.1002/fsn3.3336>
- Attri, B.L., Krishna, H. and Kumar, A., 2015. Effect of bio-regulators on storage life of plum (*prunus salicina*) var. santarosa at different conditions. *Indian Journal of Agricultural Sciences*, 85(5): 705–711.
- Bejaei, M., Stanich, K., Cliff and M.A., 2021. Modelling and classification of apple textural attributes using sensory. *Foods* 10(2):384. <http://dio.org/10.384.10.3390/foods10020384>
- Brummell, D.A., Watson, L.M., Pathirana, R., Joyce, N.I., West, P.J., Hunter, D.A., et al. 2011. Biofortification of tomato (*solanum lycopersicum*) fruit with the anticancer compound methylselenocysteine using a selenocysteine methyltransferase from a selenium hyperaccumulator. *Journal of Agricultural and Food Chemistry* 59(20): 10987–10994. <http://dio.org/10.1021/jf202583f>
- Сердюк, М.Е., Степаненко, А.С. and Кюрче, С.В., 2016. The study of mass loss intensity of plum fruits during storage. *Eastern-European Journal of Enterprise Technologies* 10(79): 42. <http://dio.org/10.15587/1729-4061.2016.59694>
- Choudhary, P., Kumari, N. and Jain, V., 2020. Influence of selenium and chitosan on physico-chemical properties of guava (*Psidium guajava*) under storage. *The Indian Journal of Agricultural Sciences* 90(2): 351–355. <http://dio.org/10.56093/ijas.v90i2.99021>
- Dobrzanski, B. and Rybczynski, R., 2002. Colour change of apple as a result of storage, shelf-life, and bruising. *International Agrophysics* 16(4): 261–268.
- Engin, H., Sen, F. and Gokbayrak, Z., 2009. Investigation of physiological disorders and fruit quality of sweet cherry. *European Journal of Horticultural Science* 74(3): 118–123.
- Fikry, A.M., Radhi, K.S., Abourehab, M.A.S., Sayed-Ahmed, T.A.M., Ibrahim, M. M., Mohsen, F.S., et al. 2022. Effect of inorganic and organic nitrogen sources and biofertilizer on murcott mandarin fruit quality. *Life (Base)* 12: 2120. <http://dio.org/10.3390/life12122120>
- Gibert, C., Chaduf, J., Vercambre, G. Genard, M. and Lescouret F., 2007. Cuticular cracking on nectarine fruit surface: spatial distribution and development in relation to irrigation and thinning. *Journal of the American Society for Horticultural Science*, 132(5): 583–591. <http://10.21273/JASHS.132.5.583>
- Gohari, G., Molaei, S., Kheiry, A., Ghafouri, M., Razavi, F., Lorenzo, J.M., et al. 2021. Exogenous application of proline and L-cysteine alleviates internal browning and maintains eating quality of cold stored flat “maleki” peach fruits. *Horticulturae* 7(11): 13. <http://dio.org/10.3390/horticulturae7110469>
- Heryadi, A.L., Shalihah, A., Pratiwi, R. and Mutakin, M., 2020. Selenium species in vegetables: benefits and toxicity for the body. *Journal Ilmiah Farmasi* 16(2): 155–166. <http://dio.org/10.20885/jif.vol16.iss2.art7>
- Huang, Y., Lei, N., Xiong, Y., Liu, Y., Tong, L., Wang, F., et al. 2022. Influence of selenium biofortification of soybeans on speciation and transformation during seed germination and sprouts quality. *Foods* 11(9): 1200. <http://dio.org/10.3390/foods11091200>
- Karagiannis, E., Michailidis, M., Skodra, C., Molassiotis, A. and Tanou, G., 2021. Silicon influenced ripening metabolism and improved fruit quality traits in apples. *Plant Physiology and Biochemistry* 166: 270–277. <http://dio.org/10.1016/j.plaphy.2021.05.037>
- Li, T., Wu, Q., Zhou, Y., Yun, Z., Duan, X. and Jiang, Y., 2018. L-cysteine hydrochloride delays senescence of harvested longan fruit in relation to modification of redox status. *Postharvest Biology and Technology* 143: 35–42. <http://dio.org/10.1016/j.postharvbio.2018.04.011>
- Liu, H., Shi J., Song, L., Jiang, Y. and You Y., 2006. Browning control and quality maintenance of litchi fruit treated with combination of N-acetyl cysteine and isoascorbic acid. *Journal of Food Technology* 4(2):147–151.
- Liu, W., Liu D., Zhang A., Feng C., Yang J., Yoon J., et al. 2007. Genetic diversity and phylogenetic relationships among plum

- germplasm resources in China assessed with inter-simple sequence repeat markers. *Journal of the American Society for Horticultural Science* 132(5): 619–628. <http://dio.org/10.21273/JASHS.132.5.619>
- Maheswari, M., Murthy, A. and Shanker, A.K., 2017. Nitrogen nutrition in crops and its importance in crop quality. In *The Indian Nitrogen Assessment: Sources of reactive nitrogen, environmental and climate effects, management options, and policies*, Elsevier: Amsterdam, The Netherlands, pp. 175–186. <http://dio.org/10.1016/B978-0-12-811836-8.00012-4>
- Malheiros, R.S.P., Goncalves, F.C.M., Brito, F.A.L., Zsögön, A. and Ribeiro, D.M., 2020. Selenomethionine induces oxidative stress and modifies growth in rice (*Oryza sativa* L.) seedlings through effects on hormone biosynthesis and primary metabolism. *Ecotoxicology and Environment Safety* 189: 109942. <https://doi.org/10.1016/j.ecoenv.2019.109942>
- Pezzarossa, B., Remorini, D., Gentile, M.L. and Massai, R., 2012. Effects of foliar and fruit addition of sodium selenate on selenium accumulation and fruit quality. *Journal of the Science of Food and Agriculture* 92(4): 781–786. <http://dio.org/10.1002/jsfa.4644>
- Puccinelli, M., Malorgio, F., Terry, L.A., Tosetti, R., Rosellini, I. and Pezzarossa, G., 2019. Effect of selenium enrichment on metabolism of tomato (*Solanum lycopersicum*) fruit during post-harvest ripening. *Journal of the Science of Food and Agriculture* 5(99): 2463–2472. <http://dio.org/10.1002/jsfa.9455>
- Qiu, X., Zhang, H., Zhang, H., Duan, C., Xiong, B. and Wang, Z., 2021. Fruit textural characteristics of 23 plum (*Prunus salicina* Lindl) cultivars: evaluation and cluster analysis. *Hort Science* 56(7): 816–823. <http://dio.org/10.21273/HORTSCI15828-21>
- Rosen, H., 1957. A modified ninhydrin colorfulness analysis for amino acids. *Archives Biochemistry and Biophysics* 67(1): 10–15. [http://dio.org/10.1016/0003-9861\(57\)90241-2](http://dio.org/10.1016/0003-9861(57)90241-2)
- Sharma, S. and Rao, T.R., 2013. Effect of honey and L-cysteine as antioxidants on the quality attributes of fresh-cut carambola (*Averrhoa carambola* L.) stored at two different temperatures. *International Journal of Postharvest Technology and Innovation* 24: 362–381. <http://dio.org/10.1504/IJPTI.2013.060269>
- Singh, S.P., Zora, S. and Swinny, E.E., 2009. Postharvest nitric oxide fumigation delays fruit ripening and alleviates chilling injury during cold storage of Japanese plums (*Prunus salicina* Lindell). *Postharvest Biology and Technology* 53(3): 101–108. <http://dio.org/10.1016/j.postharvbio.2009.04.007>
- Simon, G. 2006. Review on rain induced fruit cracking of sweet cherries (*Prunus avium* L.), its causes and the possibilities of prevention. *International Journal of Horticultural Science*, 12(3): 27–35. <http://dio.org/10.31421/IJHS/12/3/654>
- Sun, X., Luo, Y., Han, G., Li, H. and Tian, J., 2021. Effects of low-dose selenium on melatonin synthesis in sweet cherry. *Journal of Soil Science and Plant Nutrition* 21(4): 3309–3319. <http://dio.org/10.3864/j.issn.0578-1752.2017.22.013>
- Valero D., Diaz-Mula H.M., Zapata P.J., Guillen F., Martinez-Romero D., Castillo S., et al. 2013. Effects of alginate edible coating on preserving fruit quality in four plum cultivars during postharvest storage. *Postharvest Biology and Technology* 77(1): 1–6. <http://dio.org/10.1016/j.postharvbio.2012.10.011>
- Wang, K., Wang, Y.Q., Li, K., Wan, Y., Wang, Q., Zhuang, Z., et al. 2020. Uptake, translocation and biotransformation of selenium nanoparticles in rice seedlings (*Oryza sativa* L.). *Journal of Nanobiotechnol* 18(1): 103. <http://dio.org/10.1186/s12951-020-00659-6>
- Wang, J. Wei, L., Yan, L., Zheng, H., Liu, C. and Zheng, L., 2022. Effects of postharvest cysteine treatment on sensory quality and contents of bioactive compounds in goji fruit. *Food Chemistry* 366(5): 130546. <http://dio.org/10.1016/j.foodchem.2021.130546>
- Yan, R., Xu, Q., Dong, J., Kebbeh, M., Shen, S., Huan, C., et al. 2022. Effects of exogenous melatonin on ripening and decay incidence in plums (*Prunus salicina* L. cv. Taoxingli) during storage at room temperature. *Scientia Horticulturae* 292(20): 110655. <http://dio.org/10.1016/j.scienta.2021.110655>
- Yilmaz, C. and Ozguven A.I., 2019. Physiology of pre-harvest fruit cracking in pomegranate: mineral contents. *Acta Horticulturae* 1254: 205–211. <http://dio.org/10.17660/ActaHortic.2019.1254.31>
- Yuan, C., Bu, H., Zhao, J., Liu, J., Yuan, H. and Wang, A., 2023. Effect of Se application on selenium accumulation and fruit quality in pear (*Pyrus ussuriensis*). *Acta Physiologiae Plantarum* 45(3):45. <http://dio.org/10.1007/s11738-023-03521-y>
- Zhan, T., Hu, C., Kong, Q., Shi, G., Tang, Y., Zhou, Y., et al. 2021. Chitin combined with selenium reduced nitrogen loss in soil and improved nitrogen uptake efficiency in Guanxi pomelo orchard. *Science of the Total Environment* 799(3): 149414. <http://dio.org/10.1016/j.scitotenv.2021.149414>
- Zhang, H., Wang, H., Li, H., Zhang, H., Duan, C., Qiu, X., et al. 2021. Study on the different of EXP and PsEXP10 in ripening period of 'jinmi' plum and 'Qingcui' plum. *IOP Conference Series: Earth and Environmental Science* 792: 012036. <http://dio.org/10.1088/1755-1315/792/1/012036>
- Zhu, S., Liu, M. and Zhou, J., 2006. Inhibition by nitric oxide of ethylene biosynthesis and lipoxygenase activity in peach fruit during storage. *Postharvest Biology and Technology* 42(1): 41–48. <http://dio.org/10.1016/j.postharvbio.2006.05.004>