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STUDY OF WATER ENTRY PATHWAYS INTO *PRUNUS SALICINA* LINDL. AND THEIR RELATIONSHIP TO FRUIT CRACKING PREVENTION AND CONTROL

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ABSTRACT

In this experiment, the 'Green Crisp' plum (*Prunus salicina*) was used as a test material to investigate the mechanisms of water penetration and develop necessary measures to prevent fruit cracking due to overwatering. The results suggest that both root rain cover and fruit surface cover can reduce the occurrence of fruit cracking. However, the fruit surface is the main source of water entering the fruit, with the carpopodium being a secondary source. Water uptake from the fruit surface is more likely to cause fruit cracking than from the roots. Therefore, blocking excessive water uptake from the fruit surface is more important than from the roots. The complete cover provided by the canopy significantly reduces excessive water uptake by the roots and fruit surface, leading to a reduced incidence of fruit cracking. However, a small portion of fruits may still experience transverse cracking at the top, possibly due to nutrient imbalances. The method of preventing cracking by full canopy cover is worth popularizing, but further research into the causes and control measures under sheltered conditions is also necessary.

Key words: cracking types, fruit quality, red ink test, rain protection, water uptake

INTRODUCTION

Prunus salicina Lindl. is native to Yunnan and is widespread in the southwestern provinces of China. This plum tree has low soil requirements, is tolerant to poor soils, and is easy to cultivate. This makes it suitable for popularization in impoverished regions. It has gradually become a pillar of the industry in many poor, mountainous regions (Huang et al. 2021). However, as *P. salicina* approaches maturity, it is susceptible to cracking in rain, which significantly affects the appearance, quality, and yield of fruit, thus reducing its commercial value and weakening its market competitiveness (Sun et al. 2019). In recent years, a serious problem of fruit cracking has begun to be noticed in major production areas, which has limited the healthy development of *P. salicina*.

In undamaged fruits, three factors: skin turgor pressure, skin mechanical strength, and skin extensibility, are in equilibrium. However, when this balance is disrupted, fruit cracking occurs. There are several causes of this imbalance, including genetic factors, water, plant hormones, minerals, etc. (Cao et al. 2013; Ding et al. 2014; Ma et al. 2023). Previous studies have shown that, compared to other factors, water is the most direct and critical factor in *P. salicina* cracking. Its ripening period coincides with the rainy season, and cracking becomes significantly more severe. The longer the rainfall, the more severe the cracking. This is consistent with the results of studies by Nirala and Suresh (2022) on lychee fruit cracking, Li et al. (2019) on jujube fruit cracking, and Mesejo et al. (2016) on citrus fruit cracking. A model of moisture occurrence on fruit surfaces was developed by Tapia-Zapata et al. (2024) based on spatiotemporal temperature data from sweet cherry tree canopies.

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Water plays a key role in fruit cracking (Knoche 2015). Studying the pathway of water into the fruit is crucial for preventing excessive water absorption, which can block fruit cracking. This study combined laboratory and field experiments to analyze water absorption of easily cracking plum (*P. salicina*), widely cultivated in southwest China. In the laboratory, simulation methods were used to study the increase in fruit weight depending on the water absorption time. This allowed for analysis of the amount and rate of water absorption by the pedicel and fruit surface, as well as changes in fruit cracking rate. The goal was to determine the dominant pathway by which water enters the *P. salicina* fruit. In the field, various methods, such as fruit bagging, ground cover, and full canopy coverage, were used to block water absorption from the fruit surface, root system, and canopy. The cellulose and pectin contents associated with *P. salicina* fruit cracking and their impact on fruit quality were analyzed. This study aimed to investigate the necessary measures to prevent excessive water absorption and fruit cracking, thereby establishing a theoretical basis for the prevention and control of *P. salicina* fruit cracking.

MATERIALS AND METHODS

Sampling and field experiment were conducted in a 7-year-old *P. salicina* orchard (30.6895°N, 108.3072°E) of Xiangdanghao Agricultural Company (Lianhe, Xiangshui, Wanzhou, Chongqing, China) in the subtropical monsoon humid zone, characterized by abundant sunshine, four distinct seasons, a long frost-free period, and abundant rainfall. The average annual sunshine duration is 1484.4 hours, the average annual temperature is 17.7 °C, and the average annual rainfall is 1243 mm. The soil is red loam with deep layers. Its chemical properties are as follows: pH 5.41, available phosphorus 50.60 $mg \cdot kg^{-1}$, available potassium 63.10 $mg \cdot kg^{-1}$, available nitrogen 81.20 $mg \cdot kg^{-1}$, exchangeable calcium 3.54 $g \cdot kg^{-1}$, exchangeable magnesium 214.27 $mg \cdot kg^{-1}$, available manganese 42.20 $mg \cdot kg^{-1}$, available zinc 2.09 $mg \cdot kg^{-1}$, available copper 1.31 $mg \cdot kg^{-1}$, available iron 47.50 $mg \cdot kg^{-1}$, and available boron 0.29 $mg \cdot kg^{-1}$. The tested cultivar was the crack-prone ‘Green Crisp’, with a ripening period from late June to mid-July. Plant spacing was 2.5 m × 4.0 m, and the level of orchard management was high, with robust tree vigor.

Determination of relative water absorption and relative rate of water absorption by the fruit pedicel and surface

The experiment was conducted in July 2023 under rain-proof conditions and with consistent management. The fruit trees were at peak fruiting, with relatively stable fruit traits. Once the fruit reached maturity, 300 fruits with uniformly sized pedicels, free of pests and diseases, were selected from the periphery of the tree canopy and transported to the laboratory. Harvested fruits were divided into two groups: one with wax-sealed pedicels and the other with an unsealed control, with three replicates of 30 fruits per group. After recording the initial weight (W_0), fruits in nylon mesh bags were immersed in distilled water, and fruit weight (Wt) was measured at scheduled intervals (2–50 h), simultaneously documenting the occurrence of cracking. Relative water absorption (W) was then calculated as $W = [(Wt - W_0)/W_0] \times 100\%$, where fruit surface absorption (W_f) was equated to exclusive pericarp uptake due to pedicel blockage (W_B) from the sealed pedicel group. Pedicel absorption (W_s) was calculated as $W_A - W_B$ (W_A – total absorption from the unsealed control group). The absorption rate was determined as the rate of absorption by the fruit surface (Vw_f) = W_f/t ($\% \cdot h^{-1}$) and the rate of absorption by the pedicel (Vw_s) = W_s/t ($\% \cdot h^{-1}$), where *t* is the immersion time in hours.

Red ink tracing test

Twenty ‘Green Crisp’ plum fruits with pedicels were immersed in distilled water with added red ink, and fruit cross-sections were observed at 2, 6, 16, 28, and 42 hours to study the distribution of red ink in the fruit.

Study of the effect of rain protection on fruit cracking and fruit quality in *P. salicina*

The experiment was initiated on June 11, 2021 (one month before maturity), with four treatments and three replicates, across a total of 12 plots. Each plot covered an area of 100 m² and consisted of a row of 10 trees arranged in a randomized block design. Isolation trenches (1 m deep) were dug between adjacent plots. The treatments were as follows: (1) total rain protection in the canopy – a white, 0.14-mm-thick (14S) anti-drip polyethylene (PE) film was installed over the trees to cover the entire plot area; (2) rain protection in the root system – the entire ground of the plot was covered with 0.02-mm-thick silver-black reflective horticultural film; (3) rain protection on the fruit surface – individual fruits were packed using fruit-bagging techniques; (4) control – no rain protection – trees were left in natural conditions without any intervention. Each experimental tree was selected from the east, south, west, and north, and the total number of plums and the number of cracked fruits were recorded on the branches.

Fruit cracking rates were calculated, and cracked fruit were then collected and sent to the laboratory after each statistical analysis performed every three days. Each harvested fruit was classified into five types based on the cracking pattern: semicircular cracking – at the top or pedicel, longitudinal cracking – lengthwise, transverse cracking – horizontally, and mixed cracking – two or more of the above cracking patterns.

Sixty healthy fruits were randomly collected from each plot and packaged into three subsamples using preweighed, sealed plastic bags. This resulted in 180 fruits per treatment. Moisture content of fresh fruit was determined by drying, and plant cellulose content was determined by the gravimetry. Soluble pectin and protopectin content were determined by carbazole colorimetry. Vertical and horizontal fruit diameters were measured with a TESA-CAL IP67 digital vernier caliper. Each 10 plums were collectively weighed, and the weight of each fruit was then calculated. Soluble solids content was measured using a digital refractometer (handheld refractometer; PAL-1; AITO, Japan). Ten fruits from each plot were randomly selected as identical subsamples for two analyses. Total sugar content was determined by the phenol-sulfuric acid method (Dubois et al. 1956), and total acid content was measured by acid-base titration (AOAC 2016). The sugar-to-acid ratio was then calculated based on samples from the same sources.

Data processing and analysis

We processed the data using Microsoft Excel 2010 and generated graphs. Statistical analyses were performed using SPSS 18.0 (Statistical Package for the Social Sciences; IBM), using one-way analysis of variance (ANOVA) with Tukey’s post-hoc test ($p = 0.05$) to assess differences between groups.

RESULTS

Figure 1 shows the differences in relative water absorption between the pedicel and the fruit at different soaking times. Relative water absorption increased steadily with time. At each soaking time, the relative water absorption of the fruit surface was significantly higher than that of the pedicel. Figure 2 shows the relative ratio of water absorption of the pedicel to the fruit surface at different soaking times. The fruit surface consistently absorbed more than 50% of the total water absorbed by the whole fruit. This ratio increased with time. After 50 hours of soaking, the fruit surface absorbed 74.31% of the total water absorbed by the whole fruit.

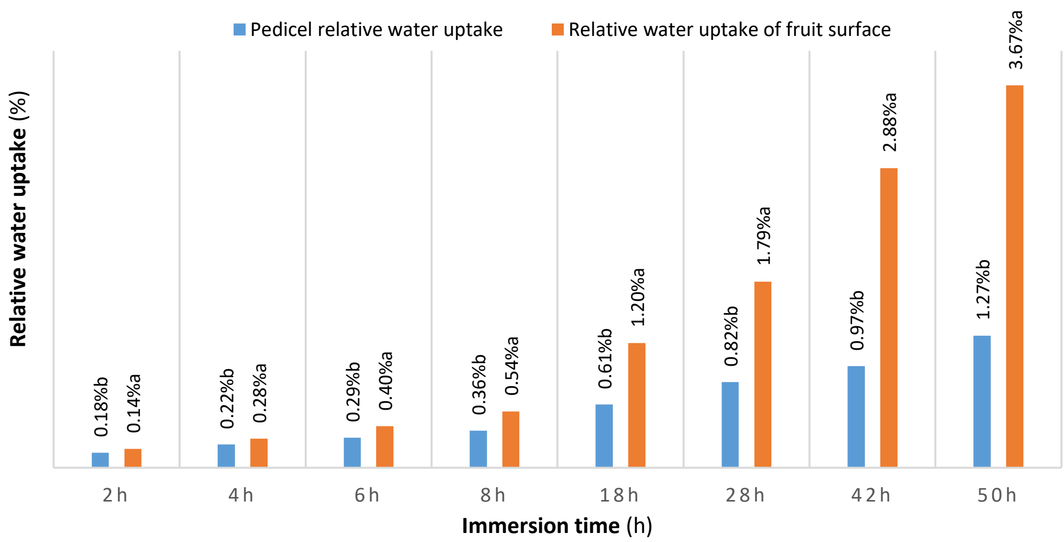

Figure 1. Effect of water soaking time on relative water absorption by the fruit pedicel and fruit surface area
Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

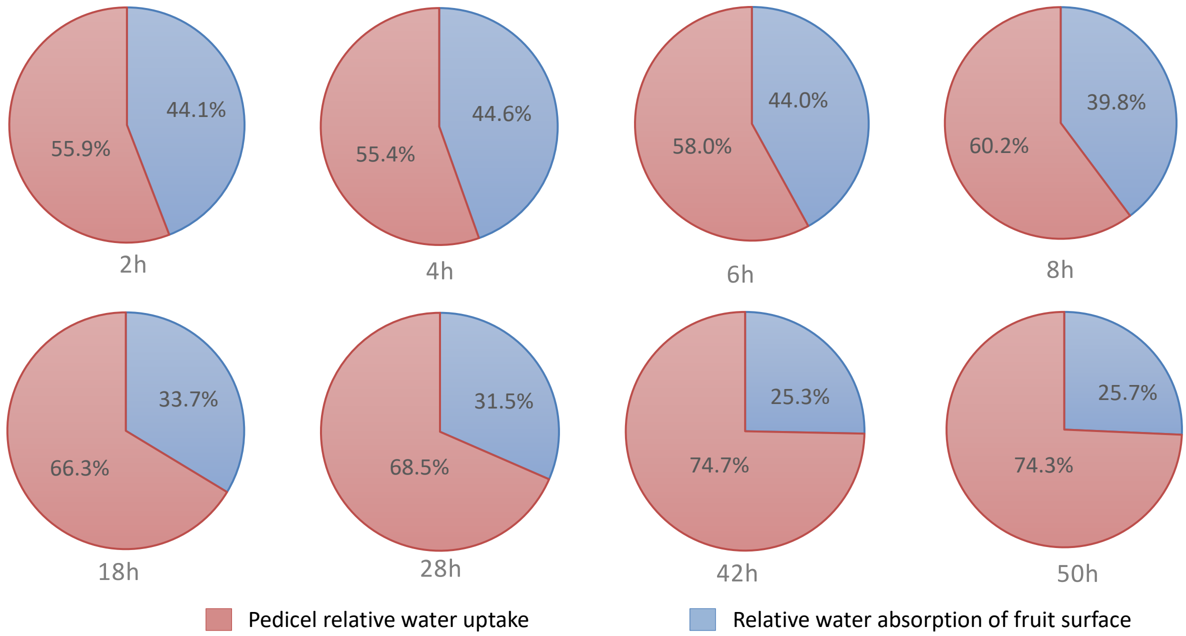

Figure 2. Effect of water absorption time on the ratio of relative water absorption by fruit pedicel and by the surface after different times

As shown in Figure 3, the differences in the relative water absorption rates between the pedicel and the fruit surface at different soaking times are depicted. It can be seen that the relative water absorption rate of the fruit surface is significantly higher than that of the pedicel at different soaking times. This indicates a clear difference in water absorption between the two parts of the fruit. As the soaking time increases, the relative water absorption rate of the pedicel gradually decreases. In contrast, the relative water absorption rate of the fruit surface decreases slightly after 2–4 hours of soaking but remains relatively stable at 0.064–0.073% per hour thereafter.

Figure 4 shows a cross-section of a fruit soaked in red ink for different times. The red color indicates that water enters the fruit mainly through the pedicel at 4 and 6 hours. As soaking time increases, water gradually enters the fruit through the skin, causing cracks. As a result, cracks become the primary route for a large amount of water to enter the fruit.

Figure 5 shows the differences in the cracking rate of *P. salicina* fruits under different soaking times when the whole fruit and the surface (wax-protected pedicel) absorb water. It can be seen that with increasing soaking time, the cracking rate of *P. salicina* fruits, both under conditions of water absorption by the whole fruit and by the surface, gradually increases. However, the cracking rate of wax-sealed fruit pedicels is lower than that of fruit pedicels and surfaces when the fruit surface absorbs water. The difference in cracking rate between whole fruit and surface water absorption after 2 and 4 hours is not significant. However, from 6 hours onward, the cracking rate of *P. salicina* increases significantly. Whole fruit water absorption is significantly higher than surface water absorption. After 50 hours of soaking, the cracking rate exceeds 90% for whole fruit water absorption, but for surface water absorption, the cracking rate is just over 60%.

Figure 6 shows the differences in fruit cracking of *P. salicina* under different rain protection methods. It can be seen that without rain protection, the fruit cracking rate is high, reaching 84.7%. After rain protection, the cracking rate is significantly reduced. The preventive effect is optimal when the entire canopy is protected from rain, resulting in a reduction of the cracking rate to 27.7%. Rain protection of the fruit surface is a second option, significantly better than root protection.

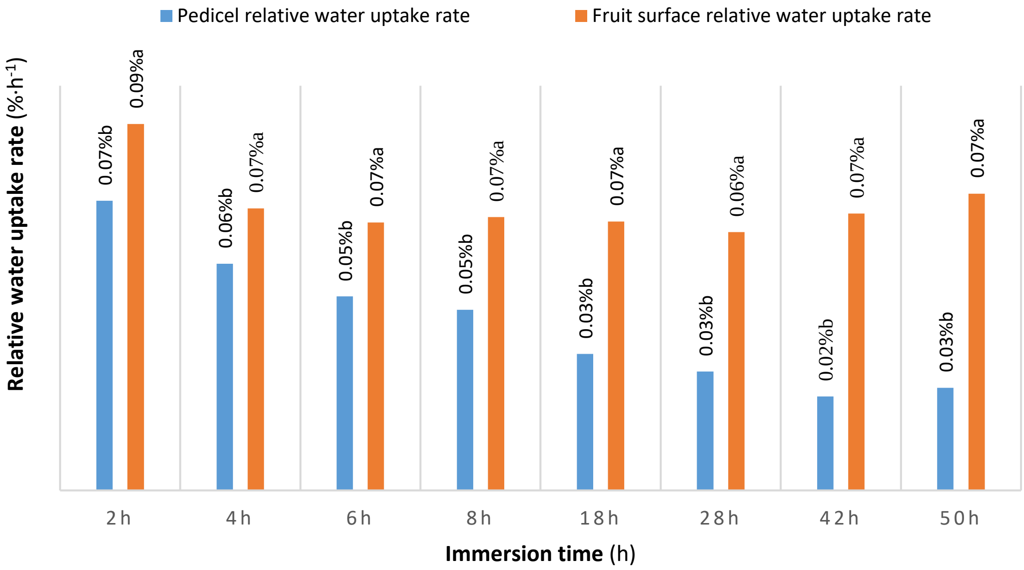

Figure 3. Differences in the water uptake rates by the pedicel and fruit surface after different immersion times
Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

4 h 6 h 16 h 28 h 42 h

Figure 4 Cross-sections of fruits with pedicels soaked in red ink for different times

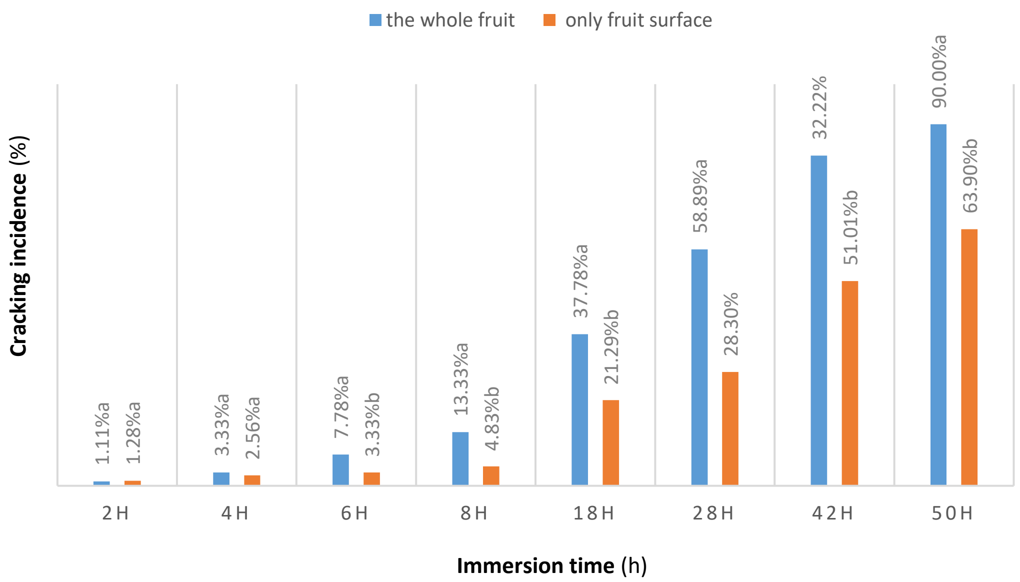

Figure 5. Differences in the rate of plum cracking at different soaking times when the whole fruit and its surface absorbed water
Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

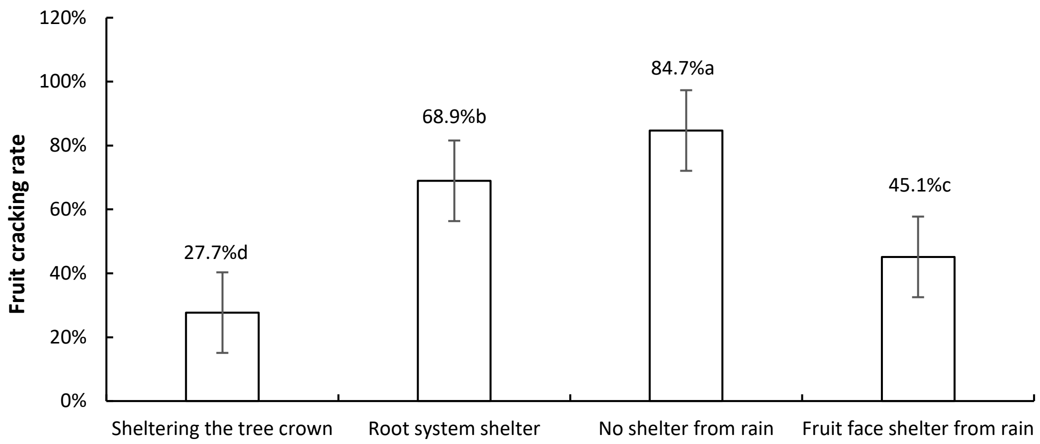

Figure 6. Effect of rain protection method on the rate of cracking of *P. salicina* fruit
Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

Table 1 shows the differences in the location and pattern of cracking of *P. salicina* fruit under different rain protection conditions. It can be seen that when the entire canopy is protected from rain, the most common type of cracking is transverse cracking at the top of the fruit, followed by longitudinal cracking in the pedicel cavity and lower part of the fruit, and relatively few semicircular cracks. In contrast, the most common cracking pattern for *P. salicina* under rain protection of the roots and fruit surface and without rain protection is a semicircular crack in the pedicel cavity, followed by a combination of longitudinal and semicircular cracks in the lower part of the fruit and pedicel cavity, while transverse cracks at the top of the fruit are the rarest.

Table 2 shows the effect of rain protection on the water, cellulose, and pectin content of fruit. It can be seen that rain protection significantly affects the water content of fruit. Unprotected fruit contained 90.8% water, while protection of the whole tree and fruits reduced the water content by 1–2%. Cellulose and soluble pectin content were highest when the roots were protected, while raw and total pectin content remained unchanged.

Table 3 displays the differences in fruit size and quality of *P. salicina* under various rain protection. It can be seen that when the entire canopy, root system, and fruit were protected from rain, the vertical diameters of *P. salicina* were significantly larger compared with those without rain protection. Horizontal diameters were larger when the entire tree and fruit were protected. Individual fruit weight was highest with rain protection over the entire canopy (45.8 g) and the lowest without rain protection (33.8 g). The total sugar, acid, and soluble solids content of *P. salicina* fruit were found to be highest with rain protection over the roots, followed by full canopy cover and fruit surface rain protection, and lowest with no rain protection. It is worth noting that the sugar-to-acid ratio was higher with full canopy cover than with the other treatments.

Table 1. Differences in 'Green Crisp' plum fruit cracking between the protection of the fruit surface, the root system, and the canopy from rain

Part protected from rain	Fruit cracking area				Fruit cracking pattern				
	upper	lower	top	pedicel end cavity	semicircular	longitudinal	transverse	mixed (semicircular + longitudinal)	mixed (horizontal + vertical)
Canopy	11.1%	26.4%	34.7%	27.8%	19.6%	21.6%	45.1%	11.8%	2.0%
Root system	14.3%	33.5%	9.4%	42.9%	47.7%	22.3%	6.2%	22.3%	1.5%
Fruit	12.9%	32.3%	7.3%	47.6%	46.1%	19.7%	3.9%	29.0%	4.7%
No rain protection	14.5%	25.8%	8.1%	51.6%	55.8%	11.6%	7.0%	20.9%	4.7%

Table 2. Effect of rain protection of the fruit surface, root system, and canopy on the water and pectin content

Part protected from rain	Water (%)	Cellulose (%)	Soluble pectins (mg per g)	Raw pectins (mg per g)	Total pectins (mg per g)
Canopy	88.50c	1.07b	1.56c	5.99a	7.55a
Root system	89.56b	1.14a	2.96a	6.04a	8.70a
Fruit	88.62c	0.99c	2.33b	6.70a	9.04a
No rain protection	90.76a	1.13a	2.49b	6.51a	8.99a

Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

Table 3. Effect of the part protected from rain on fruit, root system, and canopy quality

Part protected from rain	Longitudinal diameter (mm)	Horizontal diameter (mm)	Single fruit weight (g)	Total acid (g per 100 ml)	Total sugars (g per 100 ml)	Sugar-to-acid ratio	Soluble solids (%)
Canopy	40.80a	45.49a	45.82a	0.55c	4.70b	8.60a	8.28b
Root system	40.27a	43.63ab	42.34c	0.63a	5.20a	8.25b	9.70a
Fruit	40.59a	44.95a	44.00b	0.59b	4.47c	7.57c	8.28b
No rain protection	38.37b	42.12b	33.80d	0.59b	4.53c	7.64c	8.24b

Different letters indicate statistically significant differences ($p < 0.05$) determined by Duncan's multiple range test (DMRT) and post-hoc analysis following one-way ANOVA with homogeneous subsets ($p = 0.05$)

DISCUSSION

In this experiment, the primary way for water to enter the fruit is through the surface and the pedicel. The red ink tracing experiment showed that water penetrated through the pedicel at the early stage of soaking, but as soaking time increased, the fruit surface became the main route for water entry and diffusion. This finding is consistent with Li et al. (2019), who found that water absorption by the jujube surface is an important factor leading to fruit cracking. However, this finding is in contradiction with the research of Baba et al. (2015), who suggested that water absorption through the skin of blueberry fruit is much lower than that through the pedicel connection and hypothesized that the moisture pathway leading to fruit cracking is through the pedicel connection.

Field studies have shown that implementing rain protection for the root system can significantly reduce the occurrence of fruit cracking. This suggests that excessive root water absorption may contribute to fruit cracking, and preventing this excessive absorption may reduce the occurrence of fruit cracking. These findings contradict Liu et al. (2012), who observed that root water absorption did not result in fruit cracking after bagging and irrigation. Chen et al. (2013) concluded that root water absorption can transport water to the fruit, but its effect on cracking is limited.

At the same time, the rate of cracking of *P. salicina* after protection of the fruit surface from rain was found to be significantly lower than after protection of the roots from rain. This indicates that water absorption through the fruit surface may cause fruit cracking more than water absorption through the root system. Therefore, it is more important to prevent excessive water absorption through the fruit surface than through the root system. The consensus among most scholars in recent years is that cracking is primarily caused by water absorption through the fruit surface. The authors believe that cracking is caused by the combined effects of water absorption by the upper part of the fruit and water absorption by the underground part, with the upper part playing the dominant role and the underground part merely supplementing it. This experiment showed that when the tree canopy is completely protected from rain, the fruit cracking occurs mainly in a transverse pattern at the top of the fruit, with the fewest semicircular cracks. However, when the root system or fruit surface is protected from rain, or when there is no rain protection at all, the semicircular cracks occur most frequently in the pedicel cavity, with the fewest transverse cracks at the top of the fruit. It is speculated that the cause of top cracking in some plums when the tree canopy is completely protected from rain may not be excessive water absorption, but rather other physiological causes, such as mineral imbalance, root or fruit surface protection, or lack of protection (Mucha-Pelzer et al. 2006). The main cause of the semicircular cracking of the pedicel cavity in ‘Green Crisp’ plums under protected conditions may be excessive water absorption, which increases the likelihood of such cracking. There are few comparative studies on different types of fruit cracking (Song et al. 2018; Wang et al. 2019), and further research is necessary to understand the causes of different types and locations of fruit cracking, which will allow for targeted cultivation when different fruit cracking patterns are observed in the field.

The plant cell wall is a complex network composed of pectin, cellulose, and structural proteins. Wang et al. (2013) found that protopectin and cellulose content decreased during fruit growth in easily cracked jujubes, while water-soluble pectin content increased. This experiment showed that cellulose content in fruits was high both with and without root protection from rain. At the same time, it was lower with full canopy protection from rain and with fruit protection from rain. This discrepancy may be due to the fact that different rain protection methods do not affect cracking rates by changing cellulose content but rather by affecting water content.

In this experiment, the plum tree whose canopy was fully protected from rain had the largest longitudinal and transverse diameters and the highest individual fruit weight. This was followed by fruit surface rain protection and root rain protection, with the lowest results obtained without rain protection. The rate of fruit cracking was consistent with these findings, likely due to the elimination of large fruits in the absence of rain protection. The soluble solids and total sugar contents of *P. salicina* under root system rain protection were much higher than those under other treatments, which may be due to the use of silver-black reflective film.

CONCLUSION

Protecting the roots and fruit surfaces from rain can reduce the incidence of fruit cracking in *P. salicina* 'Green Crisp'. Water enters the fruit primarily through the fruit surface and also through the pedicel. Water absorption through the fruit surface is more likely to cause fruit cracking than through the roots. Completely protecting the tree canopy from rain significantly reduces excessive root water absorption and water absorption through the fruit surface, thereby reducing the rate of fruit cracking. However, a small portion of fruits still cracks transversely at the top of the fruit, likely due to a nutrient imbalance. The method of preventing fruit cracking by completely protecting the tree canopy from rain is recommendable. However, further research is needed to investigate the causes and preventive measures for fruit cracking under rain protection.

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