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Critical Periods of Fruit Cracking and Field Management in Satsuma Mandarin (*Citrus unshiu*)

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Abstract Fruit cracking in Satsuma mandarin (*Citrus unshiu*) is an important physiological disorder that adversely affects the proportion of marketable fruit, yield stability, and orchard profitability. This study follows the progression of fruit development and changes in cracking risk, and summarizes the stage-specific characteristics of susceptibility formation during early fruit development, key management windows after full bloom, the rapid fruit enlargement stage, and the main cracking period. Major influencing factors, including soil moisture and rainfall, temperature, fruit growth and peel load-bearing capacity, tree nutrition, crop load, and orchard conditions, are also analyzed. The periods of 50~60 and 80~90 days after full bloom (DAFB) can be regarded as important reference management windows, while fruit cracking in 'Miyagawa Wase' Satsuma mandarin occurs mainly during 110~150 DAFB. However, these periods should be adjusted according to cultivar, year, and production region. Field management should shift from reactive treatment after cracking occurs to early intervention during critical periods, with emphasis on coordinated irrigation and drainage, stable soil moisture, balanced nutrition, appropriate crop load, and tree vigor management. Family farms can establish low-cost management systems through fixed monitoring trees, weather forecasting, simple soil-moisture assessment, and annual record keeping. Future research should further refine region-specific critical periods, thresholds for water and nutrient management, and practical early-warning tools to improve the operability of fruit-cracking prevention and management.

Keywords Satsuma mandarin (*Citrus unshiu*); Fruit cracking; Critical periods; Fruit enlargement; Water management; Field management; Family farm

1 Introduction

Satsuma mandarin (*Citrus unshiu*) is an important type of loose-skinned citrus in East Asia, with a long history of cultivation in China, Japan, and neighboring regions, and it also represents an important genetic resource for citrus production and germplasm improvement. Recent genomic studies have further clarified the genetic origin of Satsuma mandarin and the varietal characteristics formed through long-term clonal propagation, highlighting its importance in the genetic improvement and commercial production of loose-skinned citrus (Liu et al., 2025). In commercial production, however, fruit cracking remains an important physiological disorder that reduces the proportion of marketable fruit, compromises yield stability, and lowers orchard profitability. Preharvest fruit cracking can occur in various citrus types, including mandarins, sweet oranges, and citrus hybrids, and its severity is influenced by cultivar characteristics, fruit developmental status, and growing conditions (Krajewski et al., 2022).

Fruit cracking results from the long-term interaction among fruit growth, changes in peel structure, and external environmental conditions. As fruit enlargement continues, the pulp and juice sacs increase in volume, while peel extensibility and mechanical load-bearing capacity gradually become limiting factors. When the internal growth rate of the fruit exceeds the capacity of the peel to accommodate expansion, pre-existing structurally weak regions or microcracks may continue to propagate. Crack-susceptible fruit are often characterized by increased water-soluble pectin, decreases in some structural cell-wall components, and rapid accumulation of soluble substances in the pulp, suggesting that reduced peel load-bearing capacity and enhanced internal water uptake and expansion may jointly contribute to fruit cracking (Huang et al., 2024). Therefore, cracking risk should not be assessed only after visible cracks appear; susceptible stages should instead be identified in advance during fruit development.

Compared with individual factors, the combined effects of fruit developmental stage and changes in weather and water availability are of greater practical importance in orchard production. Once fruit enters the rapid enlargement stage, prolonged soil drying followed by concentrated rainfall or heavy irrigation may cause rapid water uptake within a short period, further increasing the imbalance between internal turgor pressure and the load-bearing capacity of the peel (La Spada et al., 2024). Considerable differences in cracking severity also occur among cultivars, years, and orchard environments, indicating that periods of high cracking risk are not fixed dates and that management practices cannot simply be transferred across regions, years, or orchards without adjustment (Abekasis et al., 2024).

Based on these considerations, this study takes fruit developmental progression and changes in cracking risk in Satsuma mandarin as its main framework. It focuses on the stage-specific characteristics of susceptibility formation during early fruit development, key management windows after full bloom, the rapid fruit enlargement stage, and the main high-risk cracking period, while also examining major field factors including soil moisture and rainfall, temperature variation, fruit growth and peel load-bearing capacity, tree nutrition, cultivar characteristics, and orchard conditions. On this basis, the major management priorities at different developmental stages are further summarized. From the perspective of commercial orchards and family farms, risk monitoring, irrigation and drainage management, water and nutrient regulation, and tree vigor and crop-load management are integrated with critical developmental periods to establish a fruit-cracking management strategy centered on early risk identification and stage-specific intervention. Remaining challenges, including regional calibration of critical periods, thresholds for water and nutrient management, weather-based risk warning, and low-cost orchard management systems, are also discussed, with the aim of supporting a transition from reactive treatment after cracking occurs to early intervention and continuous management during critical periods in Satsuma mandarin production.

2 Critical Periods of Fruit Cracking and Stage-Specific Risk Progression in Satsuma Mandarin

2.1 Early fruit development and the establishment of cracking susceptibility

Fruit cracking in Satsuma mandarin (*Citrus unshiu*) usually becomes visible during the middle to late stages of fruit enlargement, but the ability of the peel to withstand subsequent expansion pressure is closely related to the structural foundation established during early post-bloom development. Lu et al. (2017) investigated peel development in Satsuma mandarin and found that normal fruit development could generally be divided into three stages: 0~60 days after full bloom (DAFB), dominated by cell division and tissue formation; 60~140 DAFB, dominated by cell expansion; and 140-170 DAFB, characterized by gradual fruit maturation. When heavy fruit thinning was used to create low-crop-load trees, the remaining fruit showed enhanced individual fruit growth from approximately 30 DAFB onward, accompanied by changes in fruit size, epidermal and cortical cell status, and the overall developmental trajectory of the peel. These results demonstrate that crop load and fruit growth rate during early fruit development can markedly influence subsequent peel development.

The young-fruit stage is therefore more appropriately regarded as the period during which the basis of cracking susceptibility is established, rather than as the stage when cracking itself occurs. At this time, the peel still retains a strong capacity for tissue formation, and visible cracks are generally absent in the orchard. However, crop load, individual fruit growth rate, and the early developmental coordination between the peel and pulp are already being established. In particular, on vigorous trees with relatively low fruit loads, the remaining fruit may receive greater supplies of water and assimilates, potentially altering the normal growth pattern of individual fruit.

2.2 First critical management period after full bloom

The period of 50~60 DAFB currently represents the first critical window with the clearest direct evidence from studies of fruit cracking in Satsuma mandarin. Li et al. (2025) continuously monitored fruit development during the 2022 and 2023 growing seasons using 15~20-year-old ‘Miyagawa Wase’ Satsuma mandarin trees in Linhai, Zhejiang Province. Peel thickness initially increased during early fruit development and then declined, reaching a maximum of approximately 0.52 cm at around 40 DAFB and becoming noticeably thinner after 50 DAFB. At the

same time, the initially compactly arranged cells of the albedo gradually developed larger intercellular spaces. By 50-60 DAFB, fruit development began to shift from the young-fruit stage toward the enlargement stage, accompanied by changes in the growth relationship between transverse and longitudinal fruit diameters. This period was therefore identified as the first critical point for fruit-cracking management.

The importance of this stage does not lie in the occurrence of large numbers of visibly cracked fruit in the orchard, but rather in the changing way in which the peel accommodates continued fruit enlargement. During early development, the peel can provide substantial structural buffering through active cell division and tissue thickening. As cell division slows, however, continued fruit enlargement increasingly depends on the extensibility of pre-existing tissues. Thus, 50~60 DAFB is more appropriately defined as a structural early-warning period marking the transition from peel formation to increasing peel load.

2.3 Second critical management period after full bloom

As fruit development continues, approximately 80~90 DAFB represents a second important management window. Continuous histological observations of 'Miyagawa Wase' showed that after approximately 80 DAFB, changes in fruit growth rate and peel thickness slowed. By around 90 DAFB, previously formed intercellular spaces within the albedo had continued to enlarge, distinct cavities had developed in some regions, and partial cell rupture and weakened tissue connections could be observed (Li et al., 2025). Although the external peel surface may still appear intact at this stage, the spongy buffering tissue responsible for accommodating continued pulp expansion has already become structurally looser. Compared with the first critical period, 80~90 DAFB therefore represents a stage at which the safety margin of peel load-bearing capacity becomes further reduced and cracking risk begins to accumulate.

Hu et al. (2021) also investigated 'Miyagawa Wase' Satsuma mandarin in Linhai, Zhejiang Province, and continuously evaluated fruit development at 60, 90, 120, 150, and 180 DAFB. Total soluble solids increased relatively slowly between 60 and 150 DAFB, with a much more pronounced increase occurring mainly between 150 and 180 DAFB; sucrose accumulation was likewise concentrated primarily during the later stages of maturation. Therefore, the importance of the 80~90 DAFB period should be interpreted mainly in terms of declining buffering capacity of peel tissues and the accumulation of risk associated with subsequent fruit enlargement.

2.4 Rapid fruit enlargement and amplification of cracking risk

After the second critical window, fruit gradually enters the stage during which cracking risk is substantially amplified. Two consecutive years of observations of 'Miyagawa Wase' showed that fruit cracking occurred mainly at approximately 110~150 DAFB. During this period, the fruit continued to enlarge, whereas peel thickness had already declined markedly compared with that during early fruit development, reaching approximately 0.17 cm by 150 DAFB (Li et al., 2025). More important than peel thinning alone is the mechanical relationship between transverse fruit enlargement and peel load-bearing capacity. During the middle and late stages of fruit development, transverse diameter increases more prominently than longitudinal diameter, and the resulting oblate fruit shape may concentrate mechanical stress at the fruit apex and other structurally weak regions. The peel rupture force of intact Satsuma mandarin fruit was approximately 20.31% higher than that of cracked fruit, indicating that the mechanical load-bearing capacity of the peel may be a more direct indicator of cracking susceptibility than fruit-shape changes alone.

Wang et al. (2024) analyzed several Satsuma mandarin cultivars, including the very early-maturing 'Inaba Wase' and 'Ichifumi Wase' and the early-maturing 'Okitsu Wase', and found that their fruit were distinctly oblate, with fruit shape indices of approximately 0.651, 0.630, and 0.762, respectively. When the fruit shape index was below 1, expansion stress at the fruit apex exceeded that in some directions at the equatorial region, making cracks more likely to develop at the apex of early-maturing Satsuma mandarins. The key feature of the rapid enlargement stage is therefore the simultaneous occurrence of continued fruit expansion, redistribution of mechanical stress associated with fruit shape, and declining peel load-bearing capacity, through which susceptibility established at earlier stages begins to develop into actual cracking risk.

2.5 Main cracking period and its seasonal and orchard-specific variation

When Satsuma mandarin fruit enters the middle to late stages of enlargement, previously accumulated structural weaknesses in the peel and the mechanical pressure generated by continued fruit expansion begin to become more apparent. The orchard therefore shifts gradually from occasional cracking to a stage with a greater number of visibly cracked fruit. In 'Miyagawa Wase', cracking occurs mainly during 110~150 DAFB, making this period an important reference range for understanding the main cracking stage in Satsuma mandarin. However, this result was obtained from specific orchards, trees of a particular age, and only two growing seasons, 2022 and 2023, in Linhai, Zhejiang Province.

Among different Satsuma mandarin cultivars, tree ages, and orchard conditions, the date of full bloom, fruit enlargement rate, fruit shape, soil water-holding capacity, and the temperature and rainfall patterns of a given year may all influence when visible cracking begins. At present, 50-60 DAFB and 80-90 DAFB can be used as the first and second reference early-warning windows, respectively, whereas 110-150 DAFB can be regarded as the main cracking period for 'Miyagawa Wase'. In practical orchard management, however, these periods should still be adjusted according to the actual date of full bloom and the developmental status of the fruit in each growing season.

Taken together, the progression of fruit development and cracking occurrence indicates that cracking risk in Satsuma mandarin does not arise suddenly when visible cracks first appear. Instead, it develops through a continuous sequence involving establishment of the structural basis during early fruit development, formation and accumulation of susceptibility during critical windows, amplification of risk during rapid fruit enlargement, and concentrated expression during the main cracking period. Accordingly, management objectives should also change across developmental stages, progressing from maintaining stable fruit development, early warning, and preventive intervention toward stronger water-risk management and reduction of cracking-related losses. The stage-specific progression of fruit-cracking risk and the corresponding management priorities in Satsuma mandarin are summarized in Figure 1.

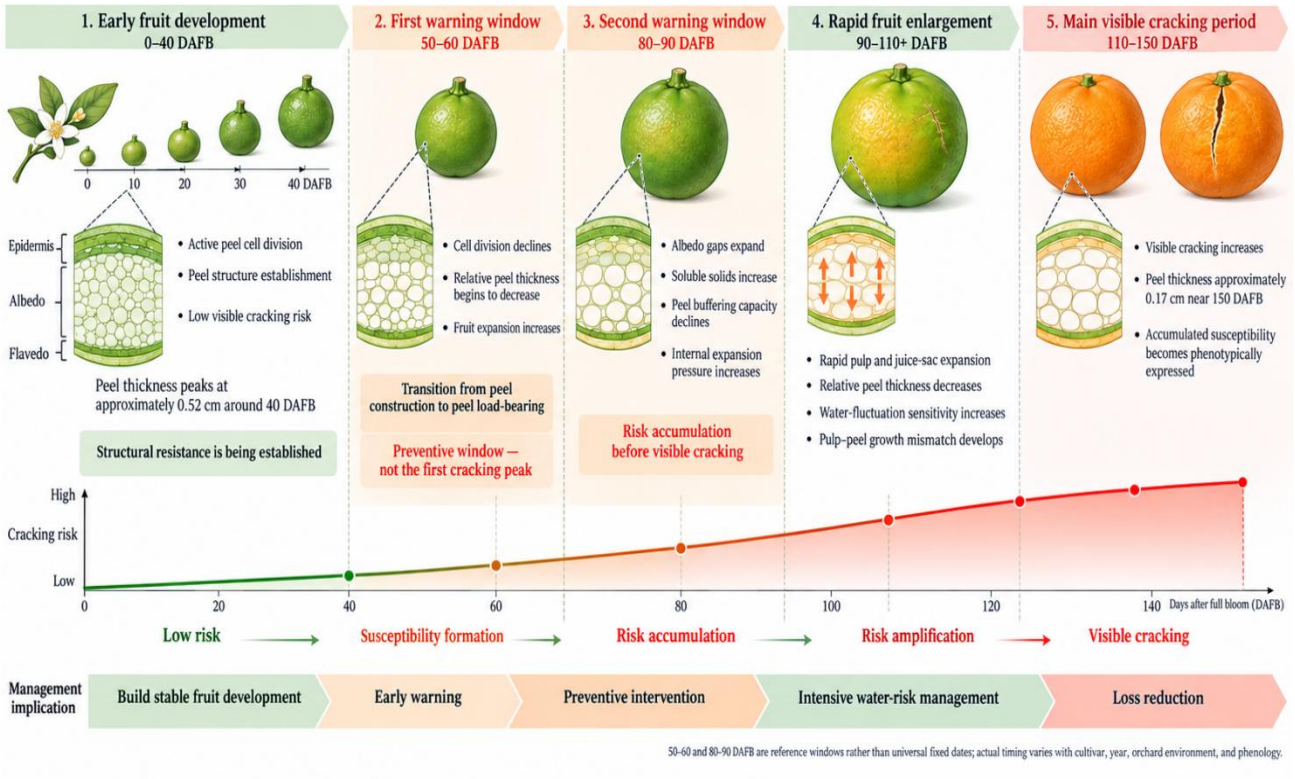


Figure 1 Stage-specific evolution of fruit-cracking risk and key management windows in Satsuma mandarin

3 Major Field Factors Affecting Fruit Cracking in Satsuma Mandarin and Their Underlying Basis

3.1 Soil moisture and rainfall fluctuations

Among the field factors associated with fruit cracking in Satsuma mandarin, water availability should be understood primarily in terms of dynamic changes rather than a single soil moisture level. Prolonged water deficit can alter tree water status, fruit enlargement, and peel tissue condition, whereas rewatering may rapidly restore fruit water relations. Hu et al. (2025) subjected 'Miyagawa Wase' Satsuma mandarin trees to drought stress and found that when relative soil water content decreased to 35%, the incidence of peel creasing increased by 28% compared with the well-watered treatment. At the same time, peel cellulose, hemicellulose, and protopectin contents decreased by 44.6%, 31.7%, and 33.1%, respectively, whereas water-soluble pectin increased by 36.3%. This study focused directly on peel creasing rather than fruit cracking; therefore, the 35% value cannot be regarded as a cracking threshold for Satsuma mandarin. Nevertheless, the results demonstrate that prolonged drought can markedly alter peel cell-wall structure and leave the peel in a more vulnerable condition when subsequent changes in water availability occur.

Rewatering studies in Satsuma mandarin further indicate that the rate of transition from dry to wet conditions is particularly important. Han et al. (2014) conducted porous-sheet mulching and drip-irrigation experiments using 35-year-old Satsuma mandarin trees. Under drought conditions induced by mulching, leaf water potential decreased to approximately -1.5~-2.5 MPa, while juice sac water potential and osmotic potential also declined. After irrigation was resumed, these parameters increased again, accompanied by a recovery in fruit growth. A field study of 'Okitsu-wase' Satsuma mandarin in Japan during 2022~2023 likewise found a clear relationship between fruit growth and water stress, with measured fruit diameter explaining approximately 0.73 of the variation in water stress. Heavy rainfall associated with a typhoon in August 2023 rapidly reduced previously distinct differences in tree water stress (Komiya et al., 2025). For Satsuma mandarin, therefore, greater attention should be given not simply to the amount of rainfall, but to whether the orchard has experienced prolonged water loss beforehand, whether the fruit is undergoing rapid enlargement, and whether tree water status recovers too rapidly after rainfall or irrigation.

3.2 Temperature and sudden weather changes

The effect of temperature on fruit cracking in Satsuma mandarin should not be simplified as "the higher the temperature, the greater the cracking risk," because an independent high-temperature threshold specifically for cracking has not yet been established. High temperatures can, however, directly alter the physiological condition of the peel and fruit. Kim et al. (2022) investigated fruit sunburn in 'Nichinan 1 gou' Satsuma mandarin and found that damage to the peel surface and oil-gland tissues became progressively more severe with increasing sunburn intensity. In laboratory and field heat-tolerance tests, obvious heat injury to the peel occurred above 47 ℃. This temperature represents a threshold for sunburn and peel heat injury rather than for fruit cracking, but it nevertheless demonstrates that intense summer radiation and high fruit-surface temperatures can impair normal peel structure and physiological function.

The influence of temperature on fruit growth also varies with developmental stage. Yano et al. (2014) reported that fruit growth in protected Satsuma mandarin cultivation was closely related to temperature during the young-fruit stage. A daytime temperature of approximately 25 ℃ favored fruit growth, whereas growth was suppressed when daytime temperature approached 30 ℃. During the middle and later developmental stages, however, the relationship between fruit growth and air temperature became weaker, while water potential became more important in explaining fruit quality. temperature should therefore be regarded as an amplifying background factor rather than an independent trigger of cracking. prolonged high temperatures first increase evapotranspiration and accelerate root-zone drying and may also impose heat stress on the peel. if concentrated rainfall or heavy irrigation subsequently occurs, trees may then experience a sequence of high temperature-drought-rapid rehydration, thereby increasing cracking risk.

3.3 Fruit growth, peel load-bearing capacity, and crop load

Whether external changes in water availability ultimately result in fruit cracking also depends on the morphological and mechanical characteristics of Satsuma mandarin fruit. Wang et al. (2024), in a study of citrus fruit shape and cracking patterns, specifically included the very early-maturing Satsuma mandarin cultivars 'Inaba' and 'Ichifumi' and the early-maturing cultivar 'Okitsu'. Their fruit shape indices were approximately 0.651, 0.630, and 0.762, respectively, indicating distinctly oblate fruit. When the fruit shape index is below 1, expansion stress at the fruit apex is greater than meridional and circumferential stresses in parts of the equatorial region. Consequently, peel cracks in early-maturing Satsuma mandarins are more likely to concentrate near the fruit apex; transverse apical cracking was also observed under field conditions. For fruit cracking in Satsuma mandarin, particular attention should therefore be given to uneven stress distribution resulting from continued transverse fruit expansion. When orchard water status increases suddenly, internal turgor pressure is exerted more strongly on regions already experiencing greater mechanical stress, allowing pre-existing microcracks to propagate more readily.

Crop load indirectly influences this mechanical basis by altering individual fruit growth and peel development. Xu et al. (2021) compared a normal crop load of 120 fruit per tree with low crop loads of 20 and 30 fruit per tree in 'Oita wase' Satsuma mandarin. Low crop load markedly altered sugar and acid metabolism and peel tissue characteristics and significantly aggravated peel puffing. Changes in peel tissue structure and antioxidant status under low crop load were associated with reduced coordination between the peel and pulp. Crop load can redistribute assimilates within the tree and alter the developmental trajectory of individual fruit. From the perspective of cracking risk, the value of maintaining an appropriate crop load lies not simply in reducing the burden on the tree, but in preventing a small number of fruit from gaining excessive growth advantage and in maintaining a continuous and coordinated relationship between fruit enlargement and changes in peel structure.

3.4 Tree nutrition and orchard management conditions

In Satsuma mandarin, tree nutrition is more appropriately regarded as a regulatory factor affecting fruit growth rate and peel condition. A study of 'Owari' Satsuma mandarin evaluated nitrogen application rates ranging from 112 to 280 kg N ha^{-1} and fertilizer application frequencies of three, five, or seven applications. Total nitrogen input had only limited effects on some physical fruit traits, whereas application frequency significantly affected fruit weight, peel weight, and fruit diameter, with seven split applications generally producing larger fruit (Basar et al., 2026). These results indicate that individual fruit size and growth patterns in Satsuma mandarin can be modified by fertilization strategy, suggesting that nutrient management may indirectly influence cracking risk by altering the balance between fruit growth rate and peel load-bearing capacity.

For practical orchard management, avoiding abnormal tree vigor and fruit growth caused by nutrient imbalance is particularly important. Excessive or highly concentrated nitrogen supply may alter the allocation between vegetative growth and fruit development, whereas excessively dry, compacted, or poorly drained root zones may prevent stable nutrient uptake even when additional fertilizer is applied. Current research on nutrition-related cracking in Satsuma mandarin therefore needs to establish a more direct relationship between tree nutritional diagnostic values and actual cracking risk.

3.5 Variation among satsuma mandarin cultivars, rootstocks, and orchard conditions

Even within Satsuma mandarin, substantial variation exists among cultivars and production regions. Li et al. (2021) compared 'Miyagawa' and 'Owari' Satsuma mandarins from three representative production regions in Zhejiang, Hubei, and Hunan Provinces, China, and found that both cultivar and production region significantly affected physicochemical and nutritional fruit traits. Principal component analysis clearly distinguished samples from different cultivars and regions, with juice content, titratable acidity, total soluble solids, and several nutritional components showing particularly strong regional effects. Thus, even within the same species, *Citrus unshiu*, cultivar and environment can create different backgrounds of fruit development and quality.

Rootstock can likewise alter fruit size and overall tree performance. Mazzotti et al. (2022) compared 'Okitsu' Satsuma mandarin grafted onto Carrizo citrange, Swingle citrumelo, and trifoliate orange. Mean fruit weights

were approximately 182, 168, and 153 g, respectively, while transverse fruit diameters were approximately 75.36, 73.90, and 71.28 mm. Fruit on trifoliate orange rootstock also had higher titratable acidity than fruit on the other two rootstocks. These findings confirm that rootstock can modify fruit size, tree nutritional status, and water-use characteristics that may be relevant to cracking susceptibility. The background risk of fruit cracking in Satsuma mandarin is therefore likely to be jointly influenced by cultivar, rootstock, soil texture, drainage conditions, and tree status. However, determining which of these factors independently alters cracking incidence will require dedicated comparisons conducted under the same site, tree age, and management conditions.

Taken together, these field factors indicate that fruit cracking in Satsuma mandarin is better understood as the combined outcome of intrinsic fruit susceptibility, abrupt changes in water availability, and orchard-specific background conditions rather than as the result of any single factor. Once fruit enters a sensitive developmental stage, prolonged drought may reduce root-zone water supply, while subsequent concentrated rainfall or irrigation can induce rapid rehydration and create a pronounced water shock. High temperature and enhanced evapotranspiration may further accelerate soil drying and amplify the effects of subsequent rainfall. At the same time, peel load-bearing capacity, individual fruit growth rate, tree vigor, crop load, cultivar, rootstock, and orchard conditions determine the underlying level of susceptibility among orchards. The interactions among these factors are summarized in the multifactor framework shown in Figure 2.

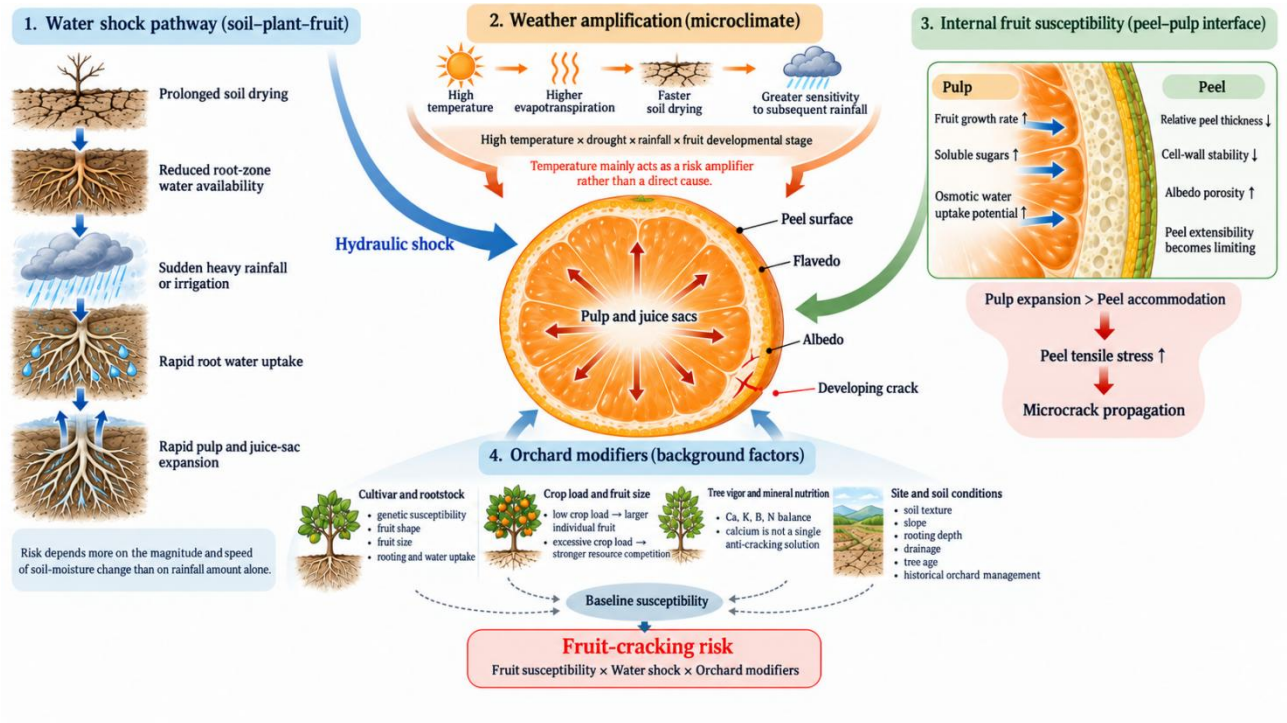


Figure 2 Integrated multifactor framework underlying fruit cracking in Satsuma mandarin

4 Field Management during Critical Developmental Stages of Satsuma Mandarin

4.1 From full bloom to early fruit development: establishing a stable basis for tree and fruit growth

From full bloom through the early fruit-development stage, Satsuma mandarin has not yet entered the period of visible fruit cracking. However, crop load, individual fruit growth rate, and the pattern of nutrient allocation within the tree are already being established during this period. Therefore, the primary management objective should be to maintain stable tree growth, fruit development, and overall growth balance rather than prematurely applying multiple anti-cracking treatments. Nakamura et al. (2010) studied two-year-old ‘Miyagawa Wase’ Satsuma mandarin trees under crop loads ranging from 0 to 6 fruit per plant and found that increasing fruit load progressively suppressed total tree growth. Fine roots were particularly affected, while summer and autumn shoot growth also declined as crop load increased. These findings indicate that crop load can redistribute assimilates and mineral nutrients within the tree. During early fruit development, excessive thinning in pursuit of larger fruit

should therefore be avoided, while excessive fruit retention that creates an obvious crop overload should also be prevented. Instead, an appropriate crop load should be gradually established according to tree vigor and fruit set.

Vigorous trees with relatively low fruit set should not be subjected to excessive shoot promotion or heavy topdressing, whereas trees carrying excessive fruit loads and showing weak vigor should have their crop load gradually adjusted to avoid prolonged suppression of root and shoot growth. In terms of water management, the basic principle should be to avoid both marked water deficit and prolonged waterlogging. This is particularly important in hilly orchards, shallow-soil orchards, and low-lying orchards in Zhejiang, where irrigation facilities and drainage ditches should be maintained in advance.

4.2 First critical period: targeting the direct fruit-cracking management window at 50–60 DAFB

The period of 50~60 days after full bloom (DAFB) is currently the first management stage for which direct experimental evidence of fruit-cracking control is available in Satsuma mandarin. Li et al. (2025) conducted two consecutive years of observations on 15~20-year-old 'Miyagawa Wase' trees in Linhai, Zhejiang Province, and carried out canopy-spray treatments in 2023 in an orchard with a history of severe fruit cracking. Treatments were applied during two critical periods, 50~60 and 80~90 DAFB. Among them, the combined application of 0.5% calcium superphosphate, 0.006% EDTA-Fe, and 10 ppm GA_3 increased peel rupture strength and reduced fruit cracking by 35.87%, without causing marked adverse effects on internal or external fruit quality.

In practical production, however, higher concentrations of GA_3 may exert more pronounced effects on quality traits such as sugar and acid accumulation and peel coloration. For commercial orchards, a more practical sequence of management during the first critical period is to first assess crop load and tree vigor, then determine whether the root zone has remained excessively dry for an extended period, and finally review whether nutrient supply during the preceding stage has been unbalanced. Targeted nutritional or growth-regulating treatments should be applied only when there is a clear need.

4.3 Second critical period: increasing the intensity of water monitoring and risk identification

After approximately 80~90 DAFB, fruit development has shifted from the earlier stage of tissue formation toward more pronounced enlargement and increasing peel load. Therefore, management during the second critical period should move beyond simply maintaining stability and place greater emphasis on increasing the frequency of risk monitoring. Suzaki et al. (2011) reported that, in mulched Satsuma mandarin orchards in Japan, fruit firmness measured in the previous afternoon could be used to estimate the maximum leaf water potential of the following morning. They further developed silicone model fruits with different levels of firmness so that growers could use simple tactile assessment to assist in evaluating tree water deficit. Consecutive trials conducted in 2008 and 2009 showed that this method, when used to guide irrigation management during July and August, could help maintain both fruit quality and productivity.

Once Satsuma mandarin enters a high-risk developmental stage, water deficit should not be judged solely by whether leaves are visibly wilted. In practical orchards, simpler alternatives can be used: several fixed monitoring trees and representative fruit can be selected, and fruit diameter, fruit firmness by touch, root-zone moisture, and recent weather conditions can be recorded every few days. If fruit remains in a rapid growth phase after a prolonged period of hot and dry weather and substantial rainfall is forecast, the orchard risk level should be raised in advance.

4.4 Rapid fruit enlargement stage: maintaining continuous and controllable root-zone water supply

During the rapid fruit enlargement stage, water management again becomes the primary concern, with emphasis placed on the continuity of water supply rather than simply increasing irrigation volume. Kang et al. (2024) compared open-field cultivation, mulching, and mulching plus drip irrigation in approximately 20-year-old 'Miyagawa Wase' Satsuma mandarin trees. Their results showed that changes in soil moisture were rapidly reflected in leaf and juice-sac water potential. In September, leaf water potential under mulching alone was approximately −2.5 to −2.7 MPa, compared with approximately −2.2 to −2.3 MPa under mulching plus drip irrigation. During a prolonged dry period in October, leaf water potential under mulching alone even declined

below −4.0 MPa, whereas the mulching plus drip-irrigation treatment maintained a value of approximately −2.64 MPa. Juice-sac water potential showed a similar pattern. These results indicate that fruit enlargement and maturation in Satsuma mandarin respond rapidly to changes in root-zone water availability.

From a production perspective, the Marudori system summarized by Shimazaki and Nesumi (2016) combines plastic-sheet mulching with drip fertigation and uses controllable water supply to buffer year-to-year variation in rainfall in Japan. Its main purpose is not to impose prolonged severe drought, but to retain the ability to provide water whenever necessary while regulating tree water status and fruit quality. For fruit-cracking management in Satsuma mandarin, the practical implications are to avoid prolonged and severe root-zone drying during periods of sustained high temperature, determine whether serious water deficit should be alleviated before forecast rainfall according to actual soil moisture conditions, maintain effective drainage during heavy rainfall, and prevent prolonged waterlogging after rain.

4.5 High-risk cracking period: reducing immediate losses and avoiding blind late-season remedial treatments

When visible fruit cracks begin to occur repeatedly in Satsuma mandarin, it indicates that peel structural susceptibility, fruit enlargement, and external water fluctuations have already been interacting for some time. At this stage, attempting to “cure” cracking with a single fertilizer spray or growth regulator is unlikely to be highly effective. Management objectives should instead shift toward three priorities. First, low-lying areas, trees with a history of severe cracking, and trees bearing obviously oversized fruit should be inspected carefully before and after heavy rainfall. Second, excess water should be drained as quickly as possible to prevent prolonged high soil moisture in the root zone. Third, fruit with large cracks, visible decay, or little remaining market value should be removed promptly to reduce fungal infection and the accumulation of rotten fruit. During the later cracking period, cracked fruit are less likely to abscise rapidly in the same manner as fruit lost during early physiological drop and are therefore more susceptible to fungal invasion and subsequent decay.

For late-season nutrient applications and plant growth regulators, caution should be emphasized rather than continued treatment intensification. Sen et al. (2013) applied preharvest GA_3 and Ca treatments to ‘Owari’ Satsuma mandarin and found that 10 ppm GA_3 improved some peel characteristics and reduced fruit drop during delayed on-tree storage, but it also delayed peel coloration; Ca applied alone showed no pronounced effect. Once fruit enters the coloration and maturation stages, any growth-regulator treatment may simultaneously affect the ripening process and commercial appearance. Management during the high-risk cracking period should therefore focus on weather response, drainage, orchard inspection, protection of marketable fruit, and recording cracking events during the current season, with identified problems fed back into earlier critical management periods in the following year.

5 Integrated Management of Fruit Cracking in Satsuma Mandarin for Orchards and Family Farms

5.1 Cracking-risk monitoring and orchard classification

Fruit cracking in Satsuma mandarin varies markedly among orchards. Even within the same production region, or between adjacent plots exposed to similar weather conditions, cracking severity may differ substantially. Therefore, integrated management should not begin with uniform fertilization or the blanket application of a particular anti-cracking product. Instead, the first step should be to determine which parts of the orchard are most prone to cracking and which types of trees are at greatest risk. Soil texture, mineral status such as Ca, K, and Mg, and orchard conditions can all influence cracking severity, and orchards with different underlying constraints may respond differently to the same management practices (Shi et al., 2025). From a production perspective, orchards can be broadly classified into drought-prone sloping sites, waterlogging-prone low-lying sites, rapidly drying sandy soils, poorly drained heavy soils, and orchards with abnormal tree vigor or crop load. These classifications can then be combined with the locations where cracking occurred in previous years to identify priority areas and trees for management. Farms do not need to establish a complex zoning system. Instead, several representative

trees can be fixed in each type of plot, and full-bloom date, changes in fruit diameter, crop load, tree vigor, and the date of first cracking can be recorded continuously to gradually develop an orchard-specific cracking-risk map.

Risk assessment should also shift from the static question of "whether a plot is inherently good or poor" to the dynamic question of "when the orchard becomes risky in a given year." Fruit cracking results from the combined effects of fruit development, weather changes, root-zone water status, and tree condition, and reliance on a single indicator can therefore lead to misjudgment. Information on cultivar, temperature, humidity, solar radiation, and orchard environment has shown predictive value for citrus fruit cracking (Abekasis et al., 2024). For practical orchard use, complex prediction models can be simplified into several indicators that are easy to observe over time: the current fruit developmental stage, whether fruit diameter has recently increased rapidly, whether the soil has remained dry for an extended period, whether concentrated rainfall is forecast in the coming days, and whether tree vigor, crop load, or individual fruit size is abnormal. When several risk factors occur simultaneously, the plot should be assigned a higher risk level and irrigation, drainage, and orchard inspection should be arranged in advance.

5.2 Coordinated management of irrigation, rainfall, and drainage

The main objective of water management for fruit-cracking prevention in Satsuma mandarin is to minimize abrupt transitions in the root zone from excessively dry to excessively wet conditions. Once fruit enters the rapid enlargement stage, prolonged soil water deficit may temporarily restrict tree and fruit growth. If this is followed by concentrated rainfall or a large single irrigation event, water uptake and fruit expansion may increase rapidly, while peel extensibility cannot increase at the same rate, thereby increasing cracking risk. Irrigation should therefore be scheduled continuously according to weather and soil conditions, rather than allowing prolonged drought followed by one-time heavy rewatering. This is particularly important in sloping orchards, sandy soils, and shallow-soil sites, where root-zone water loss during prolonged hot weather and periods without effective rainfall should be closely monitored. Small and repeated irrigation events are preferable for maintaining a relatively stable water supply before severe drought develops.

A further feature of citrus production in Zhejiang and surrounding southern regions is that summer drought, the plum-rain season, typhoons, and short-duration heavy rainfall may occur alternately within the same growing season. Therefore, irrigation cannot be considered separately from rainfall and drainage. Rapid changes among rainfall, soil moisture, and temperature provide an important background for cracking risk (La Spada et al., 2024). In practice, management can follow a continuous sequence of maintaining stable water supply during drought, clearing drainage channels before rain, draining excess water during rainfall, and inspecting fruit after rain. During prolonged hot and dry periods, emphasis should be placed on preventing excessive root-zone drying. Before forecast heavy rainfall, main and secondary drainage ditches and low-lying water-accumulation points should be cleared in advance. During rainfall, the duration of root-zone waterlogging should be minimized, and after rain, rapidly enlarging fruit, oversized fruit, low-lying plots, and trees with a history of cracking should be inspected first. Management priorities should differ according to orchard type: sloping and sandy sites should focus on avoiding rapid water loss, whereas heavy soils and low-lying orchards should focus on improving drainage and reducing waterlogging.

5.3 Coordinated regulation of water, nutrition, crop load, and tree vigor

Water supply, fertilization, crop load, and tree vigor should not be managed independently because all of these factors ultimately influence fruit growth rate and the mechanical load imposed on the peel. When both water and nitrogen are abundant, shoot and fruit growth may become excessively rapid. When crop load is too low, assimilates are concentrated into fewer fruit, which can promote oversized fruit and rapid enlargement. Excessive tree vigor can also alter nutrient allocation between shoots and fruit. Therefore, orchard management should begin by evaluating overall tree status and then determining the main management priority, rather than applying Ca, K, or plant growth regulators uniformly after cracking becomes visible. Vigorous trees with low crop load and oversized fruit should not receive continued heavy nitrogen topdressing or excessive shoot and fruit stimulation. Trees with moderate vigor and appropriate crop load should be managed mainly to maintain a stable water and

nutrient supply. Trees carrying excessive crop loads and showing weak vigor should have their crop load adjusted appropriately while maintaining a reasonable yield and promoting recovery of tree growth.

Elements such as Ca and K are related to peel tissue stability, fruit water regulation, and normal fruit enlargement, but mineral supplementation cannot substitute for stable irrigation and drainage or appropriate tree-vigor management. In orchards with compacted soil, low organic matter, or prolonged root-zone waterlogging, nutrient uptake may remain limited even if foliar and soil-applied fertilizers are repeatedly increased; improvement of the root-zone environment should therefore take priority. In orchards where tree vigor is already excessive and nitrogen input is high, further growth stimulation should be restricted. Targeted Ca, K, or other nutrient supplementation should be considered only when soil tests, leaf analysis, or long-term field performance indicate an actual deficiency.

5.4 Low-cost and practical management for family farms

For family farms and small- to medium-sized orchards, the long-term feasibility of cracking management is more important than the amount of equipment purchased at any one time. Automatic weather stations, soil-moisture sensors, fruit-diameter monitoring devices, and smart irrigation systems can improve monitoring precision, but they are not prerequisites for effective management. Ordinary orchards can establish a simplified, low-cost monitoring system by selecting several representative trees in high-, medium-, and low-risk plots and repeatedly observing the diameter and peel condition of the same group of fruit during major developmental stages. Weather forecasts can be used to track upcoming high temperatures, prolonged dry periods, and heavy rainfall. Root-zone moisture can be evaluated through soil sampling, hand-feel assessment, or simple soil-moisture meters. Orchard inspection frequency should then be increased during rapid fruit enlargement and the main high-risk cracking period.

Another important feature of low-cost management is to prioritize basic orchard conditions that can be maintained over many years. Whether drainage ditches remain open, existing drip or micro-sprinkler systems function properly, soil remains continuously exposed and prone to water loss, organic matter is insufficient, or water and fertilizer are supplied too intensively are all more important for long-term management than a single application of any anti-cracking product. Farms can also establish a simple annual recording system with four categories of information: weather records for prolonged high temperatures, periods without effective rainfall, and heavy rainfall; water-management records for major irrigation events and obvious waterlogging; fruit records for changes in fruit diameter and the first date of cracking; and orchard records identifying the most severely affected plots, tree types, and final proportion of marketable fruit. After several years of continuous recording, even farms without sophisticated equipment can gradually identify orchard-specific cracking patterns and use them to adjust management before the next growing season.

5.5 A critical-period-based orchard management model for fruit cracking

Based on the developmental characteristics of Satsuma mandarin fruit and the management measures described above, integrated cracking management can be summarized as a closed-loop sequence of phenological positioning-risk identification-orchard classification-targeted intervention-post-rain inspection-annual review. Management should begin not when the first crack is observed, but when the date of full bloom is recorded and the current fruit developmental stage is identified. The periods of 50~60 and 80~90 DAFB can be used as two reference management windows supported by current research, followed by the rapid enlargement stage and the main high-risk cracking period. However, these post-bloom periods should be treated only as temporal references. In practical production, they need to be adjusted according to temperature, rainfall, fruit growth rate, root-zone moisture, tree vigor, and crop load in the current season. If flowering time, summer drought, or rainfall patterns differ markedly among years, the risk windows may also shift earlier or later, and fixed calendar dates should therefore not be used as a universal cracking-management schedule.

In practice, family farms can follow six consecutive management steps. First, record the full-bloom date and determine the current fruit developmental stage. Second, determine whether the orchard is approaching the first critical period, the second critical period, the rapid fruit enlargement stage, or the main high-risk cracking period.

Third, simultaneously assess recent weather, soil moisture, fruit diameter, crop load, and tree vigor to determine the current risk level. Fourth, prioritize interventions according to the main problem: when water fluctuations are pronounced, irrigation and drainage should be adjusted first; when nutrient imbalance is evident, targeted supplementation can then be considered; and when tree vigor or crop load is abnormal, tree management should be adjusted accordingly. Fifth, after concentrated rainfall and during the main cracking period, record the locations, tree types, and severity of cracking. Sixth, after harvest, compare cracking incidence, marketable fruit percentage, yield, major weather events, and principal management inputs among different plots, and use these results to revise the following year's management plan. Through this process of annual recording and adjustment, cracking management can gradually shift from temporary remedial action to routine orchard management centered on critical-period identification and early risk intervention.

To facilitate the translation of these principles into orchard practice, the process can be further organized into six linked steps: phenological positioning, field monitoring, risk integration, risk classification, targeted intervention, and annual feedback. Commercial orchards and family farms can follow the same decision-making logic while adopting different monitoring methods according to farm scale and available investment. The overall management framework is shown in Figure 3.

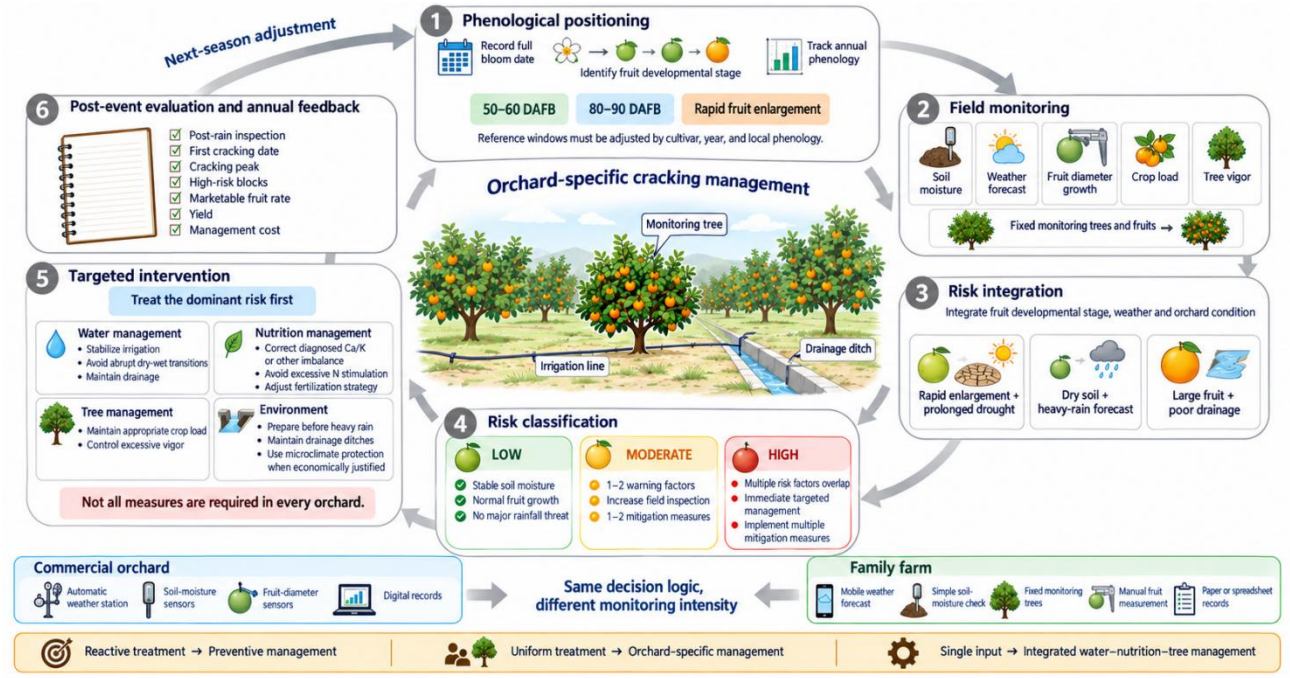


Figure 3 Stage-based risk classification and closed-loop management framework for fruit cracking in Satsuma mandarin

6 Current Limitations and Future Directions

6.1 Critical periods still need to be recalibrated across cultivars, years, and regions

Direct evidence on the critical periods of fruit cracking in Satsuma mandarin is still derived from a limited number of cultivars, production regions, and growing seasons. Therefore, the currently proposed periods of 50~60 and 80~90 days after full bloom (DAFB) are more appropriately regarded as reference management windows rather than fixed dates that can be uniformly applied to all Satsuma mandarin orchards. Cracking risk is not determined by the number of days after full bloom alone, but by the combined effects of fruit developmental progression, temperature, rainfall, soil moisture, and tree growth status in a given year. Even for the same cultivar, the onset of the high-risk stage may occur earlier or later if full bloom, the duration of summer heat, or the timing of concentrated rainfall changes among years. Future research should therefore move beyond the search for a single "optimal anti-cracking date" and instead establish practical methods for identifying critical periods under different annual and orchard conditions.

The full-bloom date can still serve as the basic temporal reference, but it should be combined with additional indicators such as the rate of fruit diameter increase, fruit enlargement status, the number of consecutive days without effective rainfall, root-zone soil moisture, and short-term rainfall forecasts. Multi-year field records are especially needed in major Satsuma mandarin production regions to compare changes in critical periods under contrasting climatic and orchard conditions. For example, hilly orchards in Zhejiang, mountainous orchards in Fujian, and other production areas in southern China differ in soil depth, soil water-holding capacity, summer temperature, and rainfall pattern. Even when the same cultivar is grown, different high-risk cracking windows may therefore develop. Future research with practical extension value should gradually shift from asking "how many days after full bloom should management begin?" to asking "which fruit, soil, and weather signals indicate that intensive management should begin?" This would improve the applicability of critical-period identification across different orchards.

6.2 Water and nutrient management still lack directly applicable thresholds

Stable water supply and balanced mineral nutrition have become two major components of citrus fruit-cracking management, but a clear gap remains between research findings and practical orchard operation. Common recommendations such as "avoid abrupt changes between dry and wet soil conditions" and "apply Ca and K appropriately" are directionally correct, but they are still too general for growers. The more practical questions are: how low should root-zone moisture fall before irrigation is required, how many consecutive dry days markedly increase risk, how much forecast rainfall should trigger preventive action, and whether these thresholds differ among soil types. Without clear operational limits, management will continue to rely heavily on experience and will be difficult to standardize.

Future work should therefore establish suitable soil-moisture ranges and risk thresholds for different orchard soils, including sandy soils, loams, and heavy clay soils. These thresholds should be integrated with the duration of periods without effective rainfall, current soil moisture status, fruit developmental stage, and forecast rainfall to provide clearer criteria for irrigation initiation and risk assessment. Nutrient management should likewise progress from simply asking "whether Ca or K should be applied" to determining "under what conditions, at which developmental stage, and to what level supplementation is required." In the future, soil testing, leaf nutrient diagnosis, tree vigor, crop load, and historical cracking severity could be combined to establish nutrient-classification standards specifically for Satsuma mandarin. Evaluation of such thresholds should not focus solely on minimizing cracking incidence, but should also consider fruit size, coloration, total soluble solids, acidity, maturity, and the proportion of marketable fruit, so that unnecessary inputs are avoided and fruit quality is not compromised in pursuit of lower cracking rates.

6.3 Cracking warning systems need to be transformed from complex models into practical orchard decision tools

Improving fruit-cracking control depends on moving management further forward in time, from intervention after visible cracking to action before symptoms appear. Information on cultivar, temperature, humidity, solar radiation, orchard conditions, and historical cracking records can provide some capacity for early prediction of citrus fruit-cracking risk. This suggests that cracking is not entirely random and that environmental and orchard information can be used for early warning. For practical orchards, however, machine-learning models, complex algorithms, and large volumes of sensor data are not the final products growers need. A useful warning system should translate complex information into risk levels that growers can readily understand and act upon.

An effective warning system for Satsuma mandarin could integrate four main types of information: fruit phenology, recent weather, root-zone water status, and fruit–tree condition. Phenological information can be used to determine whether the orchard is approaching the two reference post-bloom windows, the rapid fruit enlargement stage, or the main high-risk cracking period. Weather monitoring should focus on prolonged hot and dry conditions, forecast concentrated rainfall, and severe convective weather. Soil indicators should be used to determine whether the root zone is already under substantial water deficit or waterlogging, while fruit and tree observations should include fruit diameter increase, individual fruit size, crop load, and changes in tree vigor. Based on these indicators, complex predictions could be simplified into categories such as low risk, medium risk,

and high risk, with corresponding management actions. For example, low risk may require routine orchard inspection, medium risk may call for more frequent soil-moisture and weather checks, and high risk may require advance irrigation, drainage preparation, and intensified fruit inspection.

Future warning tools should also account for differences in farm scale and management capacity. Large commercial orchards can use automatic weather stations, soil-moisture sensors, and fruit-diameter monitoring devices to improve precision, whereas family farms can develop low-cost versions based on mobile weather forecasts, fixed monitoring trees, simple soil-moisture assessment, and manual orchard inspection. Regardless of the technical pathway, the value of a warning system should not be judged by the complexity of its model structure, but by whether it can provide a useful management signal before visible cracking occurs and whether it can clearly tell growers when closer attention is needed and what should be managed first.

6.4 Establishing low-cost integrated management systems affordable for family farms

Existing research on citrus fruit cracking has examined a wide range of practices, including irrigation, drainage, mulching, soil improvement, mineral nutrition, tree-vigor regulation, and crop-load management. However, it is neither practical nor economical for family farms to apply all available measures simultaneously. Doing so would increase both financial and labor costs, while the main constraints differ among orchards. Future integrated management should therefore move away from fixed “anti-cracking technology packages” and toward selecting measures according to the major limiting factor in each orchard. Orchards with poor drainage should first improve drainage channels and water removal; sandy sloping orchards should prioritize continuity of water supply; vigorous trees with low crop load should be managed to restrict excessive growth; and orchards with clear nutrient imbalance should receive targeted supplementation based on diagnosis. Integrated management can reduce costs and improve effectiveness only when the primary problem of each orchard is addressed first.

From the perspective of family-farm operation, fruit-cracking management can gradually be simplified into one management calendar, one annual record sheet, one basic irrigation-and-drainage system, and one annual review. The management calendar should record the full-bloom date, the 50~60 and 80~90 DAFB reference windows, the rapid enlargement stage, and the main cracking period observed in previous years. The annual record sheet can document prolonged high temperatures, heavy rainfall, irrigation events, waterlogging, changes in fruit diameter, the date of first cracking, and priority orchard plots. Basic infrastructure should ensure that irrigation can be initiated when needed and that drainage ditches can rapidly remove excess water. At the end of each growing season, cracking incidence, marketable fruit percentage, yield, and major management inputs should be compared among different plots. After several years of continuous recording, family farms can gradually develop their own maps of high-risk areas, high-risk weather combinations, and management schedules.

Future fruit-cracking control in Satsuma mandarin should therefore avoid pursuing a single standardized management formula for all production regions. Instead, region-specific calibration of critical periods, water and nutrient thresholds, weather-risk warning, and low-cost orchard management should be progressively integrated. Ultimately, whether a technology is truly suitable for practical extension can be evaluated through four simple questions: Do growers know when closer monitoring is needed? Can they determine when intervention should begin? Do they know which problem should be addressed first when several risks occur simultaneously? Can they use the results of the current season to improve management in the following year? Only when these questions can be answered clearly can research on fruit cracking be translated from experimental findings into production practices that ordinary orchards and family farms can adopt over the long term.

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