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Fruit cracking in litchi (*Litchi chinensis*): An overview

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ABSTRACT

Litchi (*Litchi chinensis* Sonn.), an arillate fruit species of China origin, possessed a unique structure comprising thin and leathery pericarp that enclosed the aril as its edible part. Fruit cracking is a serious physiological disorder in litchi that occurs during its growth and development, and causes significant loss of economic yield. Fruit cracking in litchi coincides with a period characterized by high day temperature (35-40°C) and low relative humidity (60%). It entails the implicated roles of both internal and external factors. Besides climatic effects, abnormal development of the skin during early fruit growth promotes the disorder. In this context, a concept, ball skin versus bladder effect was theorized to describe the relationship between a pre-grown skin and a growing aril. To further conceptualize the problem, Zig-zag Unfolding model was developed which decipher the role of spongy tissue in pericarp extensibility necessary for preventing pericarp cracking. Cracking occurs during the final stage of fruit growth when the aril develops and exerts pressure on the inactively growing pericarp. Thus, a balance between turgor pressure from the expanding aril and the mechanical structure and elasticity of skin is indispensable to prevent fruit cracking. Fruit cracking can be controlled by application of calcium nitrate (0.5 - 1%), borax (0.4 - 0.8%), Zn (0.4%), GA3 (10 ppm) alone or in combinations assured with timely irrigation, mulching, bagging of fruit bunches, use of shade nets and growing cracking resistant cultivars.

Key word: , Calcium, Climate, Fruit cracking, Litchi, Molecular, Pericarp, Turgor pressure

Litchi (*Litchi chinensis* Sonn.) is an important subtropical evergreen fruit crop of Sapindaceae family. The fruit is a drupe characterized by thin and leathery pericarp that encloses the aril as its edible part which in turns, covers the single brown-black seed (Menzel and Simpson 1986). It is highly specific in climatic requirements and adapted to areas characterized by warm subtropics and elevated tropics having cool dry winters and warm wet summers (Menzel and Simpson 1988). In India, although commercially predominant in the Indo-Gangetic plains of Uttar Pradesh, Bihar, Uttarakhand and West Bengal, suitable climatic conditions in the sub-tropical states of Punjab, Himachal Pradesh and Jammu and Kashmir has further expands its cultivation. The annual production of litchi in India is 528 260 metric tonnes from an area of 84 950 ha (Anon 2015) mainly restrained to Bihar (38%). Despite of unique and desirable characteristics, litchi fruit is seriously affected by fruit cracking disorder that causes significant loss of yield and commercial value (Huang *et al.* 2005).

In India, the development of litchi coincide with rising atmospheric temperature and low soil moisture and relative humidity that makes more congenial for skin to crack (Kanwar *et al.* 1972b, Yadav *et al.* 2011). Temperature higher than 38°C in combination with relative humidity lower than 60% was very favourable for cracking of litchi and causes 10-25% crop loss (Mitra *et al.* 2014). This may occur due to varietal characters, orchard soil management, inappropriate levels of water at maturity stage, light, mechanical injuries, temperature and micronutrient deficiency.

This review was prepared with the goal to unravel the underlying mechanisms behind fruit cracking in litchi. The prevailing theories on cracking mechanism have been based on the water penetrating the fruit surface causing an increase in the volume of the fruit that itself causes cracking (Christensen 1994). Some other studies indicated that the water uptake by the fruit from the root system, causing internal turgor pressure buildup, plays an important role in cracking mechanism (Yamamoto *et al.* 1990).

Problem and overview

Among the Sapindaceous fruit crops, litchi is most prone to fruit cracking as compared to rambutan and longan (Huang 2005). Cracking in litchi is most common in China (Chen and Huang 2001) and India (Mitra and Ghosh 1991), the two largest litchi producers in the world. In India, one-

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third of the crop may be lost in susceptible cultivars like Muzaffarpur and Dehra Dun (Kanwar *et al.* 1972b). Li *et al.* (2001) and Huang (2005) reviewed the problem of fruit cracking in litchi and reported that genetics of cultivars, temperature, soil and plant water status, plant growth regulators and nutrients plays a determining role. Studies on the morphology and mechanical properties of the cell walls in the skin or pericarp have further yielded valuable information about the underlying causes of cracking and suggested methods to reduce the problem.

Occurrence of the disorder in litchi: Fruit growth in litchi consists of two distinct phases: growth of the pericarp (skin) and seed, followed by growth of the aril (Kanwar *et al.* 1972a, Huang 2001). Field observations showed that, cracking occurs after colour break stage, coinciding with the initiation of rapid aril growth (Huang *et al.* 1999). Singh *et al.* (2013) observed cracking during the final stage of fruit growth when the aril develops and exerts pressure on the inactively growing pericarp. This phenomenon also occurs in other fruits during the initial stage of fruit development, mainly due to outgrowth of the seeds projecting out of the seed jacket at the apical end. Cracking injury may vary from short cracks, generally skin deep to larger ruptures extending to most of the length of the fruit. In litchi, fruit cracking may be initiated as microcracks during its growth and development on exposure to low relative humidity and hot dry winds. Microcracks formation is further triggered by the rapid expansion of the aril at the initial stage of fruit development which intensified with maturation (Underhill and Simons 1993, Huang *et al.* 2004b). Huang and Xu (1983) proposed a ball skin versus bladder effect theory which describe that cracking results from a lack of growth coordination between the 'ball skin' and the 'bladder' when stress from the 'inflating bladder' exceeds the tensile strength of the skin (Kanwar *et al.* 1972a, Li and Huang 1995).

Various studies were carried out to elucidate the mechanisms underlying fruit cracking in litchi and has focused mostly on biochemical analysis of nutrients, water (Rab and Haq 2012, Huang *et al.* 2005), hormones (Sharma and Dhillon 1986, Munish *et al.* 2003), structure and mechanical properties of the pericarp (Rab and Haq 2012), enzymes involved (Li *et al.* 2003) and girdling (Li *et al.* 1992). Although climate is one of the responsible factors in inducing fruit cracking (Kanwar and Nijjar 1984, Li *et al.* 2001), individual fruit in the same tree respond differentially under the same climatic conditions, indicating that internal factors in fruit are at play. Dry, desiccating and hot winds at the time of ripening favour the incidence of fruit cracking. Late maturing varieties suffered less from this disorder due to the onset of monsoon and availability of enough soil moisture. Apart from varietal differences, sharp diurnal temperature fluctuations coupled with sudden and heavy irrigation after dry spells contribute towards fruit cracking. This problem is also associated with some other factors including physical, anatomical, hormonal, nutritional and soil moisture availability. High water supply triggers high incidence of fruit cracking (Rab and Haq 2012) and osmotic potential favours the enhanced absorption of water by fruits and in turn leads to fruit cracking (Li *et al.* 1992). Lu and Lin (2011) found that water enters the fruit in response to decreased tissue osmotic potential.

Factors for fruit cracking

There are many factors associated with fruit cracking problem which includes morphological, genetical, environmental and physiological aspects which will be discussed in the following heads.

Fruit composition

Litchi fruit consists of a glossy and brown single seed surrounded by a sweet-acid, crispy, white to cream-colored, juicy and translucent aril. Variation in relative proportions of reducing and non-reducing sugars of pulp could be important in fruit cracking (Wang *et al.* 2006). Sucrose, fructose and glucose are found to be the major sugars in litchi (Jiang *et al.* 2006). Total sugars in physiologically mature fruit may range from 55.9 to 61.4% which is mainly represented by reducing sugar (>70%). The relative ratios between these sugars may be different in various cultivars, stage of maturity and enzyme activity. Cultivar Gola with high per cent of fruit cracking also had highest fruit weight, reducing sugars, specific gravity and TSS but the least non reducing sugars which is in contrast to that of cultivar Bedana (Haq and Rab 2012), although no correlation was reported between them. Total soluble sugar mainly affects osmotic potential while titratable acid affects cell wall softening. Both sugar and acidity may play a role in polygalactouronase enzyme signal transduction (Price *et al.* 2004).

Skin morphology

Comparatively cultivars with thick skin and fewer tubercles per unit area of skin were less susceptible to cracking (Kanwar *et al.* 1972b). Bedana and China have very thick skin as compared to Rose Scented and Shahi. Further, skin surface of Bedana is very smooth while Shahi has very distinct protuberances (Singh and Babita 2002). Huang *et al.* (1999) showed that cracking coincided with thinning of the skin during aril expansion; however, the peak of cracking did not occur at harvest when the skin was thinnest. Resistant Huaizhi had an even thinner pericarp than Nuomici at the critical period when the fruit started to turn red (Wang 1998). Therefore, differences between cultivars could not simply be attributed to the thickness of the skin.

Skin anatomy

Joubert (1986) suggested a higher ratio of tangential to radial length of the cells at the base of the epicarp in susceptible Mauritius than in resistant Brewster (Chenzi) and Haak Yip (Heiye). In Huaizhi, the spongy tissue was better developed and well organized and might be contributed to its high pericarp extensibility. Huang *et al.* (1999, 2001) found higher concentrations of cell wall materials like cellulose, hemicellulose and water-insoluble pectin in Huaizhi than in Nuomici contributed towards cracking resistance. The skin strength in litchi fruit is an important and desirable characteristic because an imbalance in cell turgidity and extensibility could lead to fruit cracking (Christensen 1994). The formation of spongy tissue was suggested to play an important role in cell rearrangement and in buffering the stress from the expanding aril, whose thickness varied among cultivars (Huang *et al.* 2004b). Pericarp strength and extensibility were higher in cracking-resistant cv. Huaizhi than in Nuomici prior to rapid aril expansion.

A deeper insight into the conceptual theory of Huang and Xu (1983) was further elaborated by Huang *et al.* (2004b) through a Zig-zag Unfolding model which described the significance of the cristate structure of the pericarp and the spongy tissue in the mesocarp. Underhill and Critchley (1993) observed that pericarp structure was initially folded and its subsequent expansion was closely associated with aril development. It is the cell rearrangement rather than cell expansion that contributes toward the extension growth of the pericarp during aril expansion (Huang *et al.* 2004a). The structure of the skin only partially explains the differences in its mechanical properties and cracking in litchi cultivars.

Turgor pressure

Cracking of fruit is basically caused by internal stresses due to turgor pressure and differential growth between the parenchymatous tissue and the skins. Bohlmann (1962) and Nobel (1983) revealed that osmotic absorption in enhancing cell swelling and tissue rigidity. It was hypothesized that a balance between turgor pressure, structure and elasticity of skin could prevent fruit cracking in litchi and that fruit cracking occurs only when aril produces more turgor pressure against the skin or reduces the structure and elasticity of the skin (Li *et al.* 2014).

Fruit growth characteristics

Fruit growth exhibited two stages in terms of the differential growth rate of pericarp and aril (Singh *et al.* 2013). The pattern of litchi fruit growth has been extensively studied in two Chinese cultivars, a cracking susceptible, Nuomici and cracking resistant, Huaizhi (Huang *et al.* 1999 Li *et al.* 2003). These two serve as the model cultivar for fruit cracking study in litchi. Stage I (slow growth phase) continues up to 52 days after anthesis (DAA), and was mainly characterized by pericarp and seed growth, while Stage II (rapid growth phase) was markedly characterized by aril growth. Fruit cracking occurred in a period of 66−80 days after anthesis. Fruit cracking of Nuomici was higher than Huaizhi, respectively, at 80 DAA. Further, at 66 DAA, the weight of the whole fruit and the aril increased abruptly in the easy-to-crack Nuomici. Although both cultivars exhibit similar changes in peel and aril weight, the ratio of pericarp to aril in Huaizhi was larger than that in Nuomici. Thus, the fruit cracking of Nuomici could be partially attributed to an abrupt and rapid growth of the aril in association with slow peel growth.

Huang *et al.* (1999) and Li *et al.* (2003) noted a much larger ratio of pericarp to aril in Huaizhi compared to Nuomici, despite of the fact that both cultivars exhibit similar changes in peel and aril weight. Incidence of cracking occurs after appearance of pulp during later growth period (Singh *et al.* 2013). This phenomenon further justify the concept, *ball skin versus bladder effect* proposed by Huang and Xu (1983) to theorize fruit cracking. The differential fruit growth pattern in which the expansion of the pericarp falls behind the growth of the aril, was an important phenomenom that provide a clearer insights towards understanding the mechanism of fruit cracking in litchi (Huang *et al.* 1999, Li *et al.* 2003).

Changes in mineral composition

The decline in pericarp Ca and B concentration prior to aril growth can be accounted for the cracking incidence (Singh *et al.* 2013). Boron and calcium contents in pericarp of uncracked fruits were significantly higher than those of cracked fruits (Li *et al.* 1995). During fruit development period, the order of the relative concentration of mineral contents follow the order of K > Ca > B (Singh *et al.* 2013).

Enzymatic activities

In litchi, changes in pectin methyl esterase (PME) and polygalacturonase (PG) activities during the early stages of fruit development act as key factors in fruit softening which in turn, could change the properties of pericarp cell wall through regulation of pectin metabolism (Peng *et al.* 2004). The activities of the wall-metabolic hydrolases, viz. PG, cellulase and PME and wall-bound peroxidase (POD) and polyphenol oxidase (PPO) was higher in the pericarp of susceptible cultivar, Nuomici (Li *et al.* 2003). Cracking resistant Huaizhi had a higher levels of structural calcium and galacturonans with lower activity of PME and ionically wall-bound POD (Huang *et al.* 2006), thus, minimizing the damage on phenolic cross-links between wall polymers, thereby maintaining cell wall extensibility.

Weather

Climatic factors such as drought, high temperatures and excessive rains play a dominant role in inducing fruit cracking (Kanwar *et al.* 1972b, Kanwar and Nijjar 1984, Li *et al.* 2001). Temperature and exposure of fruits to sunlight as well as atmospheric wind and low humidity surrounding the fruit have been considered as possible causes of cracking. However, late cultivars such as Hong Kong, had a lower incidence of cracking since aril growth starts after the main period of high temperatures ceases (Kanwar and Nijjar 1984). Continuous rain or heavy irrigation after a dry spell favours high absorption of water by fruit and aggravates the incidence of fruit cracking. In China, cracking occurs when aril expansion coincides with periods of high humidity and heavy rain (Huang 2005).

Inadequate moisture during the early fruit growth coupled with high temperature affect cell division, makes the skin hard and inelastic and it may get cracked subsequent to increased internal pressure exerted by the growing aril following irrigation (Menzel 1984). Menzel *et al.* (1995)

reported that drought increased fruit cracking by 30-40% in South Africa. Occurrences of drought during the early stages of fruit development led to abnormal skin development which in turn affects pericarp extensibility and skin elasticity that fail to accommodate the expanding aril (Li *et al.* 2001). These changes were related to the loss of calcium and boron from the pericarp and a direct inhibition of pericarp development (Li and Huang 1995, Rab and Haq 2012). Drought also increased the concentration of soluble solutes (Rab and Haq 2012) that creates an osmotic effect, which, under conditions of heavy rain, may subsequently raise the influx of water into the aril and increase turgor pressure which ultimately leads to fruit cracking (Li *et al.* 2001).

Nutritional status of soil and plant

The contents of leaf Ca, Mg and B, pericarp N/K ratio, soil N/K ratio, organic matter content and exchangable Ca of soil influence cracking. Soil nitrogen content was positively correlated with fruit cracking, but was the reverse in case of leaf nitrogen concentration (Li and Huang 1995). Cracked fruits contain higher N, P and K, but lower calcium and zinc than normal fruits (Sharma and Dhillon 1987). Low soil phosphorus and magnesium correlates with fruit cracking (Li and Huang 1995). Pericarp of normal fruits had higher contents of zinc and boron (Sanyal *et al.* 1990, Li and Huang 1995) while aril concentration of Ca, P and Mg were significantly higher in cracked fruits (Li and Huang 1995).

Exchangeable calcium when present at higher concentration in orchard soils aids in alleviating the incidence of fruit cracking (Huang 2005). Conversely, trees with lower cracking incidence have a higher calcium level (Li *et al.* 1992) and cracked fruit had lower calcium content compared to normal ones (Sanyal *et al.* 1990, Li and Huang 1995, Huang *et al.* 1999). (Huang *et al.* 2001) suggested that the lower concentration of cell wall calcium was attributed to poor remobilization rather than to a shortage of calcium.

Role of calcium in litchi fruit cracking

Calcium played a dual role in relation to litchi pericarp cracking, i.e. structurally and non-structurally *via* spongy tissue formation, a process essential for pericarp extension during aril growth (Huang *et al.* 2004b). Huang *et al.* (2001) reported that contents of the pectin-bound calcium in various parts of the pericarp were higher in the cracking resistant Huaizhi than in the cracking susceptible Nuomici. The higher capacity in binding exogenous calcium in the cell wall of pericarp suggests higher concentration of negatively charged structural component, that is, glacturonic acid residues which can be one of the material bases for cracking resistance (Zhong *et al.* 2006).

Calcium availability during early stage of fruit ontogeny is important for cracking resistance (Huang *et al.* 2005). Dilution of structural calcium during 22-52 days after anthesis leads to a decline in the level of structural calcium in litchi pericarp (Huang *et al.* 2004a) but then increase thereafter (Peng *et al.* 2004). The increase in calcium during early stages of fruit development provides a good basis of fruit pericarp development and the final increase in protopectin content in the pericarp ensures good fruit pericarp quality (Peng *et al.* 2004).

Factors hindering calcium uptake

Spraying calcium directly to fruit has long been used as a method to increase calcium availability in the fruit. There are a number of structural factors that hinders applied calcium to be an integral part of cell walls. Structural barriers, time of application and its combined anions decipher the effectiveness of the applied calcium in conferring resistance to cracking (Huang *et al.* 2005). Cuticle layer on the fruit surface act as a structural barrier thus, restricting calcium uptake to the channel of stomata. Hence, an active mechanism that drives calcium from fruit surface into the fruit tissues is indispensable. However, stomata generally occur at significantly lower density in fruit than in leaves, and are often nonfunctional. Stomata are barely observable on the epidermis of litchi pericarp (Huang *et al.* 2004a), which indicates that there is a ‘shortage’ of channels for uptake of calcium sprayed on fruit surface.

Accumulation of calcium in growing fruit depends upon the constant supply of calcium absorbed by root, and its uptake and distribution is subjected to the influence of a great number of interactions (Bangerth 1979). Thus, calcium deficiency in fruit may not be entirely a result of low calcium availability in the soil. Transportation of calcium absorbed by the root to above ground organs is almost exclusively *via* the apoplast pathways, e.g. xylem vessels and is driven by transpiration, but fruit has few xylem connections and is fed mainly *via* phloem, despite that it is an inefficient calcium-transporting pathway (White and Broadley 2003). In such a case, calcium uptake by fruit is depended upon metabolic activity of fruit and is subjected to the regulation by basipetal movement of auxin (Witney *et al.* 1990), the basis of which account for the difference in calcium uptake capability among cultivars (Huang *et al.* 2006, 2008).

Hormonal balance

Basipetal movement of auxin regulates calcium uptake by fruit at their peak metabolism period (Witney *et al.* 1990), and this might be accounted for the difference in calcium content between cultivars. An imbalance between auxins, gibberellins and cytokinins has also been reported to induce fruit cracking in litchi (Rai *et al.* 2002). Normal fruits contains higher level of gibberellins and lower level of ABA (Sharma and Dhillon 1986) and an imbalance between the two in fruit pericarp leads to fruit cracking (Li *et al.* 2014). Abscisic acid (ABA) concentrations were higher in the pericarp, seed and aril of cracked fruit than in normal fruit, while the concentrations of gibberellin (GA_3) were higher in seeds at the critical period of cracking (Sharma and Dhillon 1986).

Genetics/Cultivars

Resistance to fruit cracking is independent of calcium contents in the aril and pericarp, thus indicating the presence of a genetical link (Mandal and Mitra 2014). In India, Early Large Red, Deshi, Muzaffarpur and Elaichi (Mitra and Ghosh 1991) and the high priced Nuomici and Gwiwei cultivars of China (Chen and Huang 2001) are susceptible to cracking. Ou (1988) found that the relative order of susceptibility in China was Nuomici > Guiwei > Wai Chee in both laboratory and field experiments. Similarly, Sanyal *et al.* (1990) also presented the order of decreasing magnitude of cracking as Deshi > Early Large Red > Muzaffarpur > Nafarpal > Elachi > Bombai > McLean > Bedana, and concluded that early-ripening cultivars were more susceptible than later ones. Mandal and Mitra (2014) reported that Bedana, Bombai, Elaichi, Kasba, Nafarpal, Piazi and Seedless Late showed low amount of fruit cracking (<5%), while cultivars like China, Deshi, McLean, Early Muzaffarpur, Muzaffarpur, Purbi and Rose Scented showed higher percentages of cracked fruits (>10%).

Huang *et al.* (2004a) reported calcium content and thickness of cuticle and spongy layers as the main attribute confering resistance to fruit cracking. Despite of these facts, cultivars McLean, China and Deshi still showed higher percentages of fruit cracking irrespective of calcium and spongy tissues content (Mandal and Mitra 2014). Bedana with the lowest cracking percentage had the least calcium and boron content in the pericarp (Haq and Rab 2012). According to Mandal and Mitra (2014), it is the fruit pressure at maturity and tubercle density, rather than calcium content that determine cracking in fruits. In general, cultivars, which have relatively thin skin, few tubercles per unit area and rounded to flat in shape are less prone to crack (Kanwar *et al.* 1972a).

Molecular factors

Fruit cracking is a complex phenomenon. The interplay of multiple factors in initiation of fruit cracking further complicates the problems in assigning the contributory role to just a single factor. Consistent with this idea, researchers have stressed on the activity of cell wall loosening enzyme, xyloglucan endo-transglycosylase, XET (Goulao and Santos 2007), cell wall extending proteins, expansins (Karaaslan and Hrazdina 2010) and cell wall degrading enzymes like polygalacturonase, β-galactosidase and pectin methyl esterase (Peng *et al.* 2013), believed to possessed a close relationship with reduced pericarp elasticity. Molecular studies detected 3 genes, viz. *LcEXP1, LcEXP2 and LcXET1* associated with fruit cracking to date. Transcriptomic analysis of cracking and non-cracking fruits revealed 26 and 29 million high quality reads and identified important unigenes involved in Ca transport, water transport, GA metabolism, ABA metabolism, and in cell wall metabolism which are differentially expressed in cracked and non-cracked fruits (Lu *et al.* 2006, Wang *et al.* 2006).

Management of fruit cracking

Fruit cracking is strongly associated with drought, low concentrations of calcium and other nutritional aspects, cultivars and weather conditions (Huang 2005). Referring to the model of litchi fruit growth pattern (Wang *et al.* 2006), any management practices that prevent an abrupt increase in fruit growth rate nearing maturity, can play an indispensable role in mitigating the incidence of fruit cracking

Nutrients management

The knowledge on nutrient absorption mechanisms by above-ground plant parts has pave way for foliar spray as a means to supplement fertilization in sustainable crop production. Foliar sprays of boron, zinc and calcium were observed as the treatments of greater significance in alleviating the problem of fruit cracking. Fertigation comprising of 100% of the estimated irrigation and 137.50% of the recommended fertilizers dose minimized fruit cracking (Yadav *et al.* 2011). Rani *et al.* (2013) observed a significant reduction in cracking rate with application of vermicompost @ 75 kg/tree.

Calcium

In field experiments, reports on application of calcium salts either alone or in combination with other nutrients have so far delivered positive results. Spraying thrice with $Ca(NO_3)_2$ 100 mmol/l at full bloom, 19 and 39 days after full bloom reduced fruit cracking in Nuomici from 14.4 to 10.4% (Peng *et al.* 2001). Li *et al.* (1999) brought the cracking rate down to 17.5% from 27.7% in the same cultivar with a spray of chelated calcium solution containing 180 mmol/l calcium. However, Huang *et al.* (2008) reported that calcium chloride spray (0.2 or 0.5%) could not enhance the pericarp structural calcium in susceptible cultivar, thus inefficient to check the incidence of fruit cracking.

Boron

Boron is responsible for synthesizing pectin substances in cells, increasing the elasticity of the cell membranes and prevents the breakdown of vegetative tissues. Boron also improved the translocation of sugar and synthesis of cell wall material. Boron deficiency induced a decline in the level of calcium associated with pectin constituents, thus suggesting that boron plays an important role in calcium metabolism in the cell wall (Yamaguchi *et al.* 1986). Amongst the micronutrients, borax was most effective in reducing fruit cracking (Dixit *et al.* 2013) and foliar application of borax was found to be more effective than soil application.

Spraying borax at 1% (Rathore *et al.* 2009) and 2% (Singh 1986) during the developing stage of the fruits were highly effective in minimizing fruit cracking. Kumar *et al.* (2001) found that higher concentration (0.8%) was significantly superior to 0.4% boron in reducing fruit cracking in Shahi litchi. However, findings of different workers showed that 0.4% borax exhibited the least amount of fruit cracking (Kumar *et al.* 2001, Banyal and Rangra 2011).

Zinc

Spray of $ZnSO_4$ (1.0%) during first week of May at pit hardening stage minimized fruit cracking (19.6%) in litchi cv. Dehradun (Banyal *et al.* 2013). The positive role of zinc application in reducing fruit cracking has also been reported by several scientists (Sharma and Dhillon 1987).

Plant growth substances

The physiological effect of plant growth regulators is manifested through an influenced on hydrolytic activity and cells enlargement by increasing plasticity of cell wall. Growth regulators such as NAA (20 mg/l), gibberellic acid (40 mg/l), 2,4-D (10 mg/l), 2,4,5-T (10 mg/l) and Ethephon (10 mg/l), was beneficial in lowering the incidence of fruit cracking (Srivastava and Singh 1969).

Auxins (2,4-dichlorophenoxyacetic acid and naphthylacetic acid) at concentrations lower than 40 mg/l reduced cracking (Sharma and Dhillon 1987). Gibberellic acid is used to control fruit cracking in litchi (Sharma and Dhillon 1986) and amongst PGRs, GA_3 (20 ppm) was highly effective in checking fruit cracking (Dixit *et al.* 2013). GA_3 sprays thickened the cuticle and radial wall of epidermal cells and lowered the activity of cellulase (Peng *et al.* 2001). Spray of 20 and 40 ppm GA_3 two weeks before expected date of harvest reduced fruit cracking (Mishra *et al.* 2014). Four sprays of GA_3 (25 and 50 ppm) at biweekly intervals in cv. Dehradun were promising in reducing the intensity of cracking (Munish *et al.* 2003). Ou (1988) suggested that Gibberellin increased the critical cracking turgor and pericarp tensile strength in 'Nuomici'. However, other studies indicated that GA_3 (10-50 mg/l) was only partially effective in alleviating the extent of fruit cracking (Sharma and Dhillon 1987, Peng *et al.* 2001). Peng *et al.* (2004) reported that foliar application of brassinolide (0.5 - 1.0 g/l) before blossoming, significantly influenced the activities of cell wall degrading enzymes viz., pectin methylesterase, polygalacturonase and cellulase and increase calcium concentration of fruit pericarp, hence reduce fruit cracking in litchi.

Irrigation

Drought or deficit irrigation promotes fruit cracking in litchi (Singh 1986) while high water supply were also reported to play an equally contributing role (Rab and Haq 2012). Light but frequent irrigation that maintain a congenial microclimate within and around the plant has been found to minimize this problem. Though water requirement in litchi vary with plant age, size as well as seasons, and locations, but on an average litchi plant requires 600-800 mm water (Spohrer *et al.* 2006). Irrigation gave best result in checking fruit cracking when bearing trees are irrigated at 100% evapotranspiration replenishment (Joshi *et al.* 2012). Irrigation at 20% pan coefficient in conjunction with sprinkler irrigation or placement of dessert cooler was highly efficient in control fruit cracking (Mitra *et al.* 2014).

Mulching and bagging

Mulching, either plastic or organic mulch or alongwith three irrigations was effective in checking fruit cracking (Singh 1986). Bagging reduce the incidence of fruit cracking by altering the microenvironment for fruit development. Feizixiao litchi fruit bagged with cellophane or fabric bags from 15 days after full-bloom until harvest showed better skin colouration (Hu *et al.* 2001). Mishra *et al.* (2014) recorded positive results with 50% shade net in respect to yield and checking fruit cracking.

Integrated management of fruit cracking

Besides calcium, several compounds, viz. Zn, Cu, B and GA3 (Sharma and Dhillon 1987); were used to inhibit fruit cracking. A combination of two or more PGRs or chemicals, do not necessarily serve as a replacement for inefficacy of the sole treatment, however they proved effective in alleviating the problem of fruit cracking through their synergistic effects. Boron application promotes Calcium uptake by the fruit (Gong *et al.* 2009) or its metabolism in cell wall (Haq and Rab 2012), and that foliar Ca spray alone could not significantly prevent fruit cracking (Huang *et al.* 2008). This suggest that it might be effective to apply B and Ca together.

Micronutrients (0.8% zinc and 0.4% boron) combined with 10 ppm GA_3 was effective in reducing fruit cracking and combinations that includes Zn (0.4%), B (0.4%), and Ca (1.5%) displayed a cumulative effect in minimizing fruit cracking. In Shahi, application of ZnSO4 (1%) + Boric acid (0.4%) + SSR (20 ppm) significantly reduce fruit cracking (Jana *et al.* 2010). Peng *et al.* (2001) reported that calcium in combination with gibberellin affect the activity of cellulase, thereby maintain cell wall rigidity. Calcium nitrate (0.5 - 1%) along with borax (0.4 - 0.8%) or when combined with irrigation (100 litres) also showed a pronounced effect in controlling fruit cracking (Kumar *et al.* 2001). Joshi *et al.* (2012) reported that fertigation coupled with black mulch significantly reduce the incidence of fruit cracking. In undulating topography, Nath *et al.* (2005) suggested full moon terracing alongwith paddy straw mulching in checking fruit cracking. The integrated approach which consists of mulching the tree basins with fallen litchi leaves, spraying of different nutrient elements (B and Zn) and Kaolin, irrigating the orchard at 40% depletion of available soil moisture, sprinkler irrigation, bagging of fruit bunches and protecting the fruits with shade nets at 30 days before harvesting was effective in reducing fruit cracking (Mitra *et al.* 2010).

The problem of fruit cracking in litchi is a complex phenomenon with a large number of factors playing a contributory role. Several efforts have been tried to control fruit cracking in litchi which include irrigation, mulching, application of chemicals and PGRs and chemical which modify the growth processes. The role of an integrated orchard management which aims to minimize stress of water, nutrition and physiological factors that contribute to fruit cracking should be considered at best. There are inconsistent reports regarding factors involved in fruit cracking and the basis of fruit cracking mechanisms warrants further investigation. Attempts on analysis of the structure, expression and regulation of genes, sequencing of the genome and transcriptome of litchi should be further emphasized. As litchi fruit cracking is a results of an interplay of multiple factors, hence developing models seems to be one of the best approach to conceptualize the phenomena involved.

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