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FRUIT CRACKING IN SUB-TROPICAL FRUITS: PHYSIOLOGY AND CONTROL MEASURES

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ABSTRACT

The physiological disorder of cracking in fruits is a major problem, which results in poor productivity and reduced market value of pomegranate, litchi, citrus and mangoes. This physiological disorder is caused due to environmental, nutritional and physiological interactions. The main causes of fruit cracking include improper irrigation practices, rain following drought conditions, high temperatures, low humidity and fast changes in the soil moisture content. Physiological wise, the cracking occurs due to an excessive increase in the size of fruit pulp compared to its stretching ability, causing rupture of epidermal tissue layers. Nutritional disorder is another cause of the cracking of fruits, as the lack of calcium and nutrients such as boron, zinc and potassium causes weakening of cell walls and skin elasticity. Among these, the role of calcium is very crucial for membrane stability and reduced chances of cracking. Irrigation is the key practice that can help in keeping soil moist without any stress for fruits. Growth regulators such as GA₃ and NAA are found to be effective in minimizing fruit cracking as well. In this review, a comprehensive and critical compilation of the physiological and biochemical mechanisms underlying fruit cracking in subtropical fruits is presented on the basis of the accumulated knowledge from conventional horticultural and modern molecular science and precision agricultural approaches.

Key words : Fruit cracking, Subtropical fruits, Physiology, Plant growth regulators, Micronutrients.

Introduction

Fruits are an essential component of the human diet providing essential vitamins, minerals, fiber and antioxidants which may prevent many metabolic and degenerative diseases. Physiological disorders can damage the fruits and constitute major risks in the production of fruits in tropical and subtropical regions (Rai *et al.*, 2002 and Ram *et al.*, 1976). They can be so destructive as to wipe out an entire season's crop irrespective of pest or disease outbreaks. One of the most notorious physiological disorders is fruit cracking. Its effects are seen in litchi (*Litchi chinensis* Sonn.), pomegranate (*Punica granatum* L.), citrus species, grape (*Vitis vinifera* L.), fig (*Ficus carica* L.), bael (*Aegle marmelos* Correa) and other fruit species (Mishra

et al., 2016 and Kaur *et al.*, 2022).

Fruit cracking in subtropical orchards incurs huge economic losses. Loss of produce in affected season often varies between 50 and 85% depending on the vulnerability of cultivar, pattern of weather and quality of management practices in orchards (Misra *et al.*, 2022). Cracked fruits do not meet market standards for fresh consumption and can only be used to process them into juices or pulps which are sold at a very low price. Besides causing economic losses, cracked fruits can be easily prone to fungal invasion by *Aspergillus*, *Alternaria* and *Fusarium* species, further accelerating post-harvest decay (Misra *et al.*, 2022 and Jat *et al.*, 2021).

In fact, the problem occurs not due to a single factor but a complex interaction of multiple factors at various

stages of fruit development. In addition to environmental factors such as abrupt changes of moisture availability in terms of drought and precipitation or irrigation, the nutritional status and hormonal environment of the plant along with its inherent genetic constitution play their roles in causing fruit cracking to varying degrees. Since, it is not feasible to manage all the factors affecting cracking at a single point in time, the management of this multifaceted problem has been difficult in the past (La Spada *et al.*, 2024 and Seo *et al.*, 2022).

This review aims to bring together a comprehensive and critical overview of the mechanisms underlying fruit cracking in subtropical fruits on the basis of conventional horticultural, modern molecular science and precision agricultural approaches. Finally, new trends in technology and research priorities are analyzed.

Anatomy and Physiology of Fruit cracking

Definition and Classification of cracking patterns

It is important to have a precise definition of fruit cracking and splitting before we analyze the underlying mechanisms. Though closely related, cracking and splitting of fruits are slightly different types. Splitting of fruit refers to fracture reaching to the central part or the flesh of fruit and it appears to be more severe form compared to cracking of fruit which refer to the breaking down or collapsing of the peel or cuticle of the fruit as cracks which may not necessarily penetrate the pulp (Kaur *et al.*, 2022 and Khadivi-Khub, 2015). It is worth noting here that there exists some ambiguity in interpretation in the literature as the terms are commonly used interchangeably in popular as well as agricultural writings (Glisen *et al.*, 1995).

Different types of cracking patterns of fruits, depending on their anatomical features are described in different subtropical fruits. Concentric cracking involves the division of one fruit into several segments. Apical cracking appears in the form of minute fissures near the calyx or stylus end (Jiang *et al.*, 2010). Cavity cracking occurs in the center of the fruit even before it is visually observed on the surface. Radical cracking begins from the stem end and moves toward the center of the fruit. Lateral cracking produces multiple fractures along the sides of the fruit (Misra *et al.*, 2022 and Jat *et al.*, 2021). In citrus peel, which is multilayered, the following three types of cracking have been identified based on the structure and location: flavedo splitting, albedo splitting and interior cracking (Kaur *et al.*, 2022 and Rehman *et al.*, 2015). Penetration depth classified the fruit cracking into cuticle, micro-cracks and flesh cracks in pears (*Pyrus* spp.) by Seo *et al.* (2022). Certain location and shape of

cracking may also indicate the cause of cracking such as side cracking in litchi associated with moisture stress and subsequent rapid aril growth, and calyx-end cracking in apples linked with a shortage of gibberellin (La Spada *et al.*, 2024).

The Physiology of Internal pressure and Peel failure

Physiologically, fruit cracking can be explained as a failure of the pericarp in response to the development of internal pressure inside the pulp. Cell division in the pulp increases the amount of tissue as the fruit develops and this needs to be accommodated by the peel. Cracking occurs when expansion rate of the pulp is higher than the stretching capacity of the peel. (Kaur *et al.*, 2022). This mechanism is quite clearly elucidated in litchi where the cell division in the pericarp ceases almost 70 days after conception and the subsequent rapid expansion phase of aril (edible fleshy part) within the period 35 days after that exerts a very high turgor pressure on the peel which cannot increase in size beyond a cell-elongating limit. (Misra *et al.*, 2022). Hence, when the pericarp cell quality is degraded in terms of any causal agent like food or water stress or high temperatures during Stages I and II of fruit development, its tolerance towards that high internal turgor pressure during Stage III is reduced and cracking occurs (Reyes *et al.*, 1995).

This physiological event has been metaphorically described as the 'Bladder vs. Ballskin effect' (Huang and Xu, 1983), where a swelling bladder is forced to conform to a relatively unexpandable container or ballskin. Similar mechanisms, with varying intensities and times, apply to all subtropical fruits. The whole process of fruit cracking occurs through multiple stages, which in citrus was described by Kaur *et al.* (2022) into 5 stages starting from normal fruit development, critically vulnerable stage of peel, initial crack with burst oil gland, medium stage with gradual peeling and degradation of albedo structure, and finally late stage with indistinguishable albedo and flavedo structure; each with a specific crucial stage during which specific remedial measures are effective (Saini *et al.*, 1999; 2004).

The role of the cuticle

The first line of structural defense against cracking is the fruit cuticle, a thin, hydrophobic, extracellular membrane of polyester that forms the outer covering of the epidermis. It is composed mainly of the polyester cutin with various associated waxes and a small amount of phenolics and is responsible for regulating water and solute transport and providing mechanical support and disease resistance (La Spada *et al.*, 2024). Temperature and relative humidity, as well as other environmental

factors greatly influence its mechanical properties; Matas *et al.* (2005), La Spada *et al.* (2024) have described studies using isolated tomato cuticles showing that temperature and humidity significantly effect cuticle extensibility and fracture resistance.

A mechanical explanation for cuticle level cracking, particularly in sweet cherry fruit is provided by the zipper model described by Knoch (2019), La Spada *et al.* (2024), wherein cracks are formed by a build up of stress within the cuticle during fruit development. Cuticular wax is also an important factor affecting the cracking propensity of a fruit. It has been shown that KCS20 and KCS9 in Asian pear were shown to regulate cuticular wax metabolism (Wu *et al.*, in Seo *et al.*, 2022), which has a protective effect on cuticle extensibility during turgor-driven stress, and that cracked fruit may lack some of the wax layer present on non-cracked fruit (Seo *et al.*, 2022).

Cell Wall metabolism and Enzymatic modification

An important biochemical aspect of fruit cracking is cell wall modification and cell wall degrading enzyme activity. Cell wall hydrolases (cellulase and polygalacturonase) break down polysaccharide components of the cell wall responsible for maintaining structural integrity of the peel and in cracked fruits they exhibit an elevated activity when compared to their activity in non-cracked citrus fruits. Polygalacturonase depolymerizes pectin within the flavedo, thus reducing mechanical cohesiveness of epidermal and hypodermal cells. Degradation of pectin occurs together with loss of starch in the albedo cell walls and changes in the rind's mechanical properties, which facilitates cell wall separation and looseness of cell walls (Kaur *et al.*, 2022 and Reyes *et al.*, 1994).

Conversely cell wall oxidoreductases such as peroxidase promote lignin deposition and phenolic cross-linking, leading to stiffening and reduced extensibility of the cell wall. Therefore, fruit cracking is largely dictated by a balance between hydrolytic loosening and oxidoreductive stiffening of the cell wall that varies in a given fruit species over time depending on hormonal and environmental factors (Kaur *et al.*, 2022). The loosening activity of expansin protein which promotes cell expansion during growth under stress, is another important factor affecting fruit cracking sensitivity. Microcracks were caused by expansin gene up-regulation in *Pyrus bretschneideri* epidermis (Seo *et al.*, 2022), which represents a molecularly addressable target for breeding.

Environmental influences Driving fruit cracking Moisture Fluctuations and Rainfall

One of the best established influences on cracking of fruits in subtropical regions is moisture stress followed by an abrupt rehydration event. The physiological events associated are well documented: micro-level structural hardening, loss of elasticity and reduced ability of pericarp tissue to stretch, coupled with water loss occurs during periods of drought, while the rapid development of the pulp, presses against a peel that can no longer stretch sufficiently to accommodate the increase in volume; peel tissue fracture occurs at weakest points (Misra *et al.*, 2022 and Jat *et al.*, 2021). Pomegranates exemplify this: rainfall induced cracking, particularly on water-stressed trees, was far greater than with controlled irrigation as measured by Galindo *et al.*, (2014), in La Spada *et al.* (2024). Menzel (1984), in Misra *et al.* (2022) documented in litchi the hard and dry pericarp induced by drought that subsequently splits when rapidly growing arils begin developing after a watering event. In cherry it is not root uptake of water that induces splitting but the entry of water via the cuticle due to osmotic potential in the cherry (high sugar content). The skin then cannot expand quickly enough with a swelling fruit causing splitting (Misra *et al.*, 2022). In studies carried out in Oregon split potential was increased by 50% at 25°C than at 15°C and it is clear that it is the interaction of both temperature and moisture which induces splitting potential. Choi *et al.* (2020), in La Spada *et al.* (2024) report increased cracking on orchards undergoing transition from arid to very wet monsoon conditions; soil water fluctuations increasing the turgor pressure in the less-extensible cork and stone cells induced splitting (La Spada *et al.*, 2024).

Temperature and Humidity

High temperatures during critical growth periods influence fruit splitting in two ways; first, they hasten water loss from the pericarp leading to the dehydration hardening as described above. Hot summer winds dry out the pericarp tissue extremely quickly reducing its extensibility and hence the extent of cracking after a sudden watering in litchi pericarp in North India (Misra *et al.*, 2022). High fruit temperature increases internal gas pressure and thereby causes volumetric expansion and mechanical stress of the pulp tissue on the peel (Kaur *et al.*, 2022). Most cracking increases linearly with temperature; Simon (2006), in La Spada *et al.* (2024) demonstrated linear increases in the proportion of shattered sweet cherries with ambient temperature. Large diurnal temperature fluctuations are more stressful as they promote fatigue in peel tissue during alternate

expansion and contraction and pear cracking is increased by large temperature differentials between day and night (Seo *et al.*, 2022). Pomegranates are likewise effected by temperature fluctuation (El-Rhman, 2010, in La Spada *et al.*, 2024). The rate of water loss from the pericarp is related to evaporative requirement of the fruit surface which in turn is dependent on temperature and relative humidity. Low RH speeds pericarp water loss in dry periods, and high RH subsequent to dry periods causes rapid water entry via the cuticle. Optimal cracking for litchi occurs at above 38°C with less than 60% relative humidity (Jat *et al.*, 2021). The duration of light exposure also effects pear cracking, with low photoperiods during development inducing splitting due to influences on gene expression and metabolic activity of epidermal tissue (Choi *et al.*, 2015 and La Spada *et al.*, 2024).

Crop Load and Orchard microclimate

Crop load, or the number of fruit per tree or canopy area influences cracking propensity via a number of indirect factors; it leads to a reduction in the quality of the pericarp by virtue of increased competition for mineral nutrients and photoassimilates and it also modifies the canopy microclimate, increasing ambient humidity and reducing light penetration. It is the cultivars with the appropriate canopy structure and pruning management, inducing an unfavorable microclimate, which suffer cracking the most (Cronje, 2013, in Kaur *et al.*, 2022). It is well established that fruit cracking is linearly related to crop load and high crop loads consistently show increased cracking % compared to high/low loads (Kaur *et al.*, 2022).

Agronomic, Nutritional and Hormonal factors

Mineral nutrition and calcium

Of the agronomic factors that promote fruit cracking, the nutritional status (especially Ca deficiency) of subtropical fruit has the best documentation. Calcium has several functions to perform: It cross-links pectin molecules in the middle lamella strengthening cell wall cohesion; stabilizes phospholipid bonds within cell membranes and acts as a secondary messenger in stress signal transduction pathways (La Spada *et al.*, 2024 and Seo *et al.*, 2022). With a lack of Calcium, each of these physiological functions is hampered and cell wall structure, when subjected to turgor stress, collapses, which can result in cracking. In fact Ca deficiency has been identified as responsible for the majority of cracking in fruits of the grapevine, lemon, litchi, pomegranate, fig and many other fruit crops (La Spada *et al.*, 2024). In pears, Choi *et al.* (cited in Seo *et al.*, 2022) demonstrated increased water solubility of pectin in fruit flesh and peel

(an indication of loss of Ca-pectin cross linking) in cracked compared to intact fruit tissue. Passive uptake of Ca is predominantly driven by the transpiration stream and even in cases where soil Ca levels are sufficient, the growing fruit cannot compete with transpiring vegetative parts to satisfy the Ca requirements during a period of high rate of cell growth, so there is often need for a foliar supplementation (Sharma *et al.*, 2004).

The micro nutrient Boron (B) has a specific structural role for cell wall formation in the cross-linking of rhamnogalacturonan-II within the pectin network via the formation of borate-diol esters. Without boron, the pectin network is weaker resulting in a reduced cell wall elasticity and rigidity. Boron deficiency has been reported for cherry, pomegranate, litchi and mango cracking (Misra *et al.*, 2022). While water imbalances may be largely responsible for cracking in fully mature fruits of pomegranate, boron deficiency has been suggested to play an important role in cracking of immature fruit (Mishra *et al.*, 2016 and Sharma and Shukla, 2006).

Potassium (K) affects turgor and water relations in the pericarp by regulating the osmotic potential within cells. K deficiency has been identified as a cause for cracking in citrus, pomegranate and pear (Seo *et al.*, 2022). Zinc (Zn) is involved in the control of water uptake in roots and in controlling enzyme activity relating to carbohydrate metabolism. Water stress has been shown to reduce Zn accumulation in litchi fruit skin during the rapid expansion of the aril and foliar applied Zn significantly decreased cracking in trials (Misra *et al.*, 2022). Zinc also inhibit aquaporin activity resulting in reduced water uptake and consequently cell turgor pressure. This has a direct role in reducing fruit cracking (Seo *et al.*, 2022).

As molecular effectors in susceptibility to cracking, the role of aquaporins (integrated membrane channels for water transport across membranes) is increasingly being recognized. Breia *et al.* (cited in Seo *et al.*, 2022) reported pre-harvest calcium application to inhibit cracking, to induce expression of PaPIP1;4 a gene encoding an aquaporin and enhanced water permeability in sweet cherry fruits was mediated by aquaporins in the cracking susceptible cultivars. This finding supports a potential therapeutic, molecular link between calcium nutrition and aquaporin mediated water movement.

Hormonal regulation

Phytohormones such as gibberellins, auxins, ethylene and cytokinins have complex and sometimes species-specific roles in regulating pericarp development and the propensity for cracking. One of the most important

hormones is gibberellin (GA). High levels of endogenous GA in the fruit are correlated with a thick and elastic cuticle and reduced cracking in apples and citrus fruits (La Spada *et al.*, 2024 and Kaur *et al.*, 2022). It has been shown to enhance cell wall expansion, increase the size of the fruit and the thickness of the peel while inhibiting pectin methylesterase activity which contributes to reduced fruit splitting. External application of GA3 early in fruit development has reduced cracking in the pomegranate, litchi, pear and cherry (Mishra *et al.*, 2016 and Misra *et al.*, 2022). Ethylene plays a dual role; as the principal ripening hormone it promotes breakdown of the cell wall structure through increasing the activity of cell wall degrading enzymes, thus rendering the fruit more susceptible to cracking. In melons, the appearance of stem end cracking within 2 hr following peak ethylene evolution has been documented (Fernández-Trujillo *et al.*, 2013 as cited in La Spada *et al.*, 2024). In post-harvest treatments 1-Methylcyclopropene (1- MCP), a blocker of ethylene receptors was used to delay ripening and significantly reduce the cracking of 'Royal Gala' apples (La Spada *et al.*, 2024). Several ethylene biosynthetic genes (ACS, ACO) have been found to be differentially expressed in cracked versus intact fruits of litchi and sweet cherry suggesting that manipulating the ethylene pathway might represent a molecular target for cracking control (La Spada *et al.*, 2024). Auxins (e.g., NAA and 2,4-D) application at critical developmental stages enhanced the strength of the fruit peel in citrus, litchi and cherry by increasing the peel thickness (Misra *et al.*, 2022 and Kaur *et al.*, 2022). Application of 20–100 ppm of NAA 25–30 days prior to harvest has reduced cracking in several fruits due to increased cell set rate and improved peel strength (Misra *et al.*, 2022; Kaur *et al.*, 2022). Cytokinins, specifically 6-benzyladenine (BA), used in conjunction with GA4+7 has proven effective in reducing calyx-end cracking of apples by improving and maintaining high epidermal cell density in the developing peel of fruits (La Spada *et al.*, 2024).

Irrigation and soil moisture management

Because the principal cause of cracking in subtropical fruits is moisture stress followed by rehydration, the control of irrigation represents the most effective farming practice against cracking. Ensuring stable soil moisture levels during fruit cell enlargement and maturation will greatly reduce the potential for cracking. Rapid and wide fluctuations of soil moisture levels must be avoided (Seo *et al.*, 2022 and Jat *et al.*, 2021). Irrigation based on soil moisture sensors at soil moisture depletion levels of 30–40% would reduce cracking compared to extremes of either prolonged drought or waterlogging (Misra *et al.*,

2022). In the case of litchi, pomegranate and citrus, drip irrigation systems coupled with appropriate irrigation schedule can minimize cracking by creating stable soil moisture condition (Jat *et al.*, 2021). Sustained deficit irrigation (SDI), where the soil moisture is maintained at controlled, suboptimal levels throughout the development period has also reduced cracking in sweet cherries with no yield loss (Blanco *et al.*, 2022 as cited in La Spada *et al.*, 2024). The retention of soil moisture and regulation of root-zone temperature and reduction of sudden moisture changes following a rain event or irrigation with mulches such as straw, leaf litter or sugarcane mulch would help reduce pericarp cracking. Mulching with farm residues and three planned irrigations were found to significantly reduce pericarp cracking of litchi variety 'Shahi' (Mishra *et al.*, 2016). Cultivating border crops such as maize or sugarcane which are periodically irrigated and reduce transpiration demand in the orchard and consequently the temperature and humidity around the developing fruit (Misra *et al.*, 2022) can improve the microclimate.

Genetic and Cultivar-Level determinants

The tendency of fruit to crack is influenced greatly by genes. Cuartero *et al.* (cited in Seo *et al.*, 2022) showed that cracking susceptibility in tomatoes is genetically determined, a phenomenon that is broadly applicable to many subtropical fruit species. Different varieties or cultivars of the same species can exhibit strikingly different rates of cracking even under identical environmental conditions, and since these traits are heritable, breeding for cracking resistance represents a long-term solution to the problem.

Litchi cultivars with relatively thin skin, low density of tubercles per unit area, and flat to round fruit shapes are less susceptible to cracking than those with thick, rough skin and kidney- or heart-shaped fruit. Kidney-shaped fruits possess a deeper stem cavity, which facilitates water accumulation and increases skin absorption of water, raising susceptibility to cracking (Misra *et al.*, 2022 and Huang *et al.*, 1983). Cracking susceptibility is often greater in early-season litchi cultivars. The cracking-resistant litchi cultivar 'Swarn Roopa,' developed in Ranchi, India, is recommended for areas with severe cracking problems (Qui *et al.*, 1999).

Genetic factors that are important in cracking susceptibility of pomegranates include the thickness and nature of the rind and the elasticity of the rind; varieties with thicker rinds generally withstand greater internal pressure before cracking. Some genetically resistant cultivars include 'Francis,' 'Wonderful,' 'Sur-Anar,'

‘Shirvan’ and ‘Krasnyl,’ while ‘King’ and ‘Molar’ are more susceptible (Misra *et al.*, 2022 and Mishra *et al.*, 2016). Resistant types in cherries include ‘Sam,’ ‘Sue,’ ‘Victor,’ ‘Windsor,’ ‘Lapins’ and ‘Viscount’; firmer fleshed cultivars, like ‘Bing’ are more susceptible to cracking than softer-fleshed ones (Misra *et al.*, 2022).

Genes involved in cuticle formation, cell wall structure, aquaporin function, ethylene synthesis and expansin activity have been shown to be involved in fruit cracking traits. Expansins facilitate loosening of the cell wall during development. Li *et al.* (cited in Seo *et al.*, 2022) discovered that several aquaporin genes in litchi (LcAQP, LcPIP, LcNIP, LcSIP) were expressed differentially in cracked and uncracked fruit. Liao *et al.* (2020, cited in La Spada *et al.*, 2024) identified an ethylene-responsive transcription factor, ClERF4, in watermelon that acts as the key determinant of rind hardness, a resistance trait to cracking, suggesting that this gene would be useful for molecular breeding (Lal *et al.*, 2012).

The thickness and composition of fruit cuticle, a polygenically controlled heritable trait, is critical for the resistance of fruit to cracking. High levels of wax accumulation on the fruit surface confer resistance to cracking, as is seen in litchi, jujube, apple and pear. Genome-wide quantitative trait locus (QTL) analysis has been conducted for regions of tomato and pear chromosomes that confer cuticle thickness and composition and can be used for marker-assisted selection breeding (La Spada *et al.*, 2024 and Seo *et al.*, 2022).

Crop-specific Cracking patterns and management **Litchi (*Litchi chinensis* Sonn.)**

Although, Litchi is one of the most commercially valuable subtropical fruits, its commercial viability is severely hindered due to significant cracking, a problem that is intricately linked with the biology of the fruit. Around 10 weeks after fertilization, the cell production of the peel ceases and in the remaining 5 weeks before harvest, the peel is unable to keep up with fruit expansion without cracking (Li *et al.*, 2001). Dry periods, high temperatures and lack of nutrients that have occurred earlier in the season predispose the peel to cracking during the ripening and expanding stage. Intense heat above 38°C, low relative humidity (< 60%), dry soil conditions, and subsequent sudden influx of water, either through rain or irrigation, most consistently trigger the physiological cracking response (Queitsch *et al.*, 2016). The availability of zinc to the peel has also been demonstrated to influence cracking as its availability is likely to decrease when the

aril undergoes a rapid expansion. Applying zinc through foliage can significantly reduce cracking rates. The most efficient practices to avoid litchi cracking include consistently maintaining soil moisture by keeping it at or above 30–40%, mulching with organic materials to stabilize soil moisture and temperature, planting windbreak trees (tall and dense species such as mango and jamun at right angle to the prevailing winds), foliar spray with borax or boric acid at 2g/L after initiation of aril growth, weekly zinc sulphate sprays at 1.5% starting from early fruit development, foliar sprays with NAA at 10–20 ppm or GA3 at 40 ppm post fruit set, or combining gibberellin at 20 ppm with calcium at 2 mL/L to inhibit cellulase activity (Misra *et al.*, 2022 and Mishra *et al.*, 2016).

Mango (*Mangifera indica*)

Mango cultivation faces two major issues: excessive fruit drop and alternate bearing. Fruit drop is a common problem in mango orchards where many hermaphrodite flowers and young fruits fail to mature. In most mango varieties, less than 0.1% of hermaphrodite flowers reach maturity. One key reason is the low number of flowers that have developed and functional ovules (Davenport and Nunez-Elisea, 1997). Dahsham and Habib (1985) state that fruit drop in mango occurs in three distinct phases. The first phase happens within two months after fruit setting, the second occurs when fruits are around 60 to 75 days old, and the third happens just before harvesting. Studies on cultivars such as ‘Langra’ and ‘Dashehari’ found that the highest fruit drop takes place during the first three weeks of April, with ‘Langra’ being more vulnerable than ‘Dashehari’. Several factors affect fruit drop in mango. Nutritional deficiency among developing embryos is a major cause, as crowded fruitlets on the panicle compete for nutrients. Embryo degeneration during early development can also lead to fruit shedding. Plant hormones are crucial to this process. Ethylene encourages the formation of the abscission layer and speeds up fruit drop, while auxin helps prevent abscission (Ansari *et al.*, 2013 and Dahsham, 1985). Other hormones like gibberellins, cytokinins, abscisic acid, and polyamines may indirectly affect fruit retention by regulating ethylene and auxin activity. Self-pollination is also linked to increased fruit drop. Researchers found that spraying NAA at 20 ppm during the pea stage can effectively reduce fruit drop (Mishra *et al.*, 1973 and Shindey, 2000). Similarly, foliar sprays of GA at 10 ppm, 2,4,5-TP at 20 ppm, Ethrel at 50 ppm, and Alar at 1000 ppm at various stages of flowering and fruit development have shown positive results in minimizing fruit drop (Sharma, 2005a). Alternate bearing, or biennial bearing, is another serious issue for mango production, particularly

in northern, eastern, and central parts of India. Popular commercial varieties like Alphonso, Dashehari, Langra, and Chausa are especially susceptible. Alternate bearing occurs when mango trees produce a heavy crop one year, called the “on year,” followed by little or no crop the next season, known as the “off year.” Even varieties typically seen as regular bearers can show this pattern under certain conditions (Singh, 1990). Heavy fruiting during the “on year” exhausts the tree’s nutritional resources, reducing its ability to produce new vegetative flushes needed for flowering in the next season. This leads to a significant decline in flowering and fruit production the following year. Researchers have linked alternate bearing to several factors, including genetic makeup, physiological imbalances, environmental conditions, nutritional deficiencies, and hormonal regulation (Bhargava *et al.*, 2011).

Pomegranate (*Punica granatum* L.)

Cracking has been identified as the most damaging physiological disorders affecting pomegranates and yields of spring crop have been documented to be as low as 63% due to cracking while those of winter crop being 34%. Higher yields have been reported during rainy season due to negligible cracking losses (<10%) indicating the crucial role of seasonal conditions on cracking of fruits. Boron deficiency is generally the cause of cracking in young fruits while for mature fruits, fluctuations between day and night temperatures and irregular water availability were observed to be the triggering factors for cracking (Moriana *et al.*, 2024 and El-Kasas *et al.*, 1984). No single remedy for this disorder but a combination of methods is advocated. Choosing suitable varieties is the first step towards prevention of fruit cracking (Ram, 1976). Drip irrigation to provide water regularly and evenly during the fruiting period is advisable to avoid uneven water availability. Boron at 0.2% and calcium hydroxide at 0.1% sprayed at 14 day intervals during fruit maturation also showed promising results. Application of gibberellic acid at 15-40 ppm is a popular choice and weekly foliar sprays of magnesium sulphate and potassium nitrate at 1% solution with regular watering have also been shown to provide balanced nutrients and check the disorder (Defilippi *et al.*, 2006). Paclobutrazol and zinc sulphate soil application have also been recommended along with the application of antitranspirants, especially pinolene (5%, vapor guard), on the fruit surface to check transpiration. Recently, nano-calcium fertilizers applied through foliar sprays, show promising results (Bashira *et al.*, 2019 and Bala *et al.*, 2014).

Citrus (*Citrus* spp.)

Cracking of citrus fruit almost invariably occurs at the stylar end the point of the former flower and radiates in an approximately longitudinal or horizontal direction. Lemons and limes are the most susceptible varieties and mandarins and sweet oranges are the least so (Zong *et al.*, 1979). The cause for cracking is fairly consistent between varieties and a spell of dry weather, followed by a rapid increase in moisture availability (heavy rain or aggressive irrigation), causes swelling of the flesh that the now stiffened rind is unable to tolerate and consequently splits. High nitrogen levels further contribute if Boron and Calcium are limiting (Ladania *et al.*, 2008 and Knoche, 2019).

Controlling cracking depends on controlling the above factors. A steady flow of water is essential through the summer to keep the rind supple and prevent the problem when more water is suddenly added (Pretel *et al.*, 2005 and Zong, 1975). Amongst foliage applications, 0.5% Calcium chloride has been shown to effectively reduce cracking in lemons with no significant effect on fruit size or yield. Growth regulators, *e.g.*; 100ppm NAA or 100-120 ppm Gibberellic acid, applied during rapid fruit growth can also prevent splitting. Spraying 0.3% copper sulphate, 4% potassium sulphate or 1.0% calcium nitrate on three different occasions, at monthly intervals post fruit-set in the case of calcium nitrate, have all reduced the splitting in lemons and mandarins. Appropriate orchard management such as early harvest and thinning of fruit to promote a thicker rind may also prove effective (Kaur *et al.*, 2019; Khehra and Bal, 2014).

Grape (*Vitis vinifera* L.)

Cracking in grape berries may be attributed to the stress exerted from internal contents on the skin that it is unable to withstand. The increase in turgor pressure is mediated by movement of water through the root system, a direct absorption through the cuticle of the berry, or stem uptake. Environmental conditions influence the speed at which this increase takes place (Hall *et al.*, 2011). Humidity means lower transpiration rate so higher retention and water influx into berries increasing turgor. Temperature also has a significant effect on cracking; as temperature increase from 10°C to 40°C, rate of cracking increases, too. Diseases like powdery mildew will decrease cell elasticity and hence reduce ability to withstand internal pressure. Applications of Calcium are the most extensively researched means of controlling cracking and calcium chloride is well proven effective across various climates and varieties (Satyanarayana, 1982). Planting systems that improve airflow and

penetration of light will generally reduce humidity within canopies reducing incidence of cracking (Satyanarayana *et al.*, 1982).

Other sub tropical fruits

Fig and Bael: both cracking issues are broadly similar, being influenced strongly by atmospheric humidity, temperature changes, and levels of Boron, Zinc and Nitrogen.

Apple: Mostly due to uneven irrigation in dry periods where subsequent watering causes cells to swell at a rate the rind cannot cope with. This effect is amplified in high-sugar cultivars with a russet-type skin and fruits on the outside of canopy where they are more exposed. Stayman, Fuji and Gala appear particularly susceptible to cracking (Kasai *et al.*, 2008 and Knoche *et al.*, 2011).

Integrated Control Strategies

Site selection and orchard establishment

Controlling fruit cracking in the long term commences from the point of orchard establishment. Decisions concerning choice of site are crucial, particularly avoidance of areas where the fruits approach harvest during periods of heavy rainfall, but ensure that the soils have good enough drainage to allow some fluctuation in moisture content. In areas where dry winds cause considerable water stress, the location should offer protection (Negi, 1995). Windbreaks may be the more pragmatic, undervalued practice for controlling fruit cracking. Tall dense trees (mango, jamun, eucalyptus) planted perpendicular to the prevailing dry wind can significantly slow down the loss of water from the fruit peel (Ravindra *et al.*, 2006). Where this water loss is reduced the rind may be able to accommodate water additions from rain or irrigation. A practical method used in litchi is the practice of surrounding the orchard by maize or sugarcane grown under irrigation, which generates a cool humid microclimate to protect the growing fruits from sudden large fluctuations in humidity and temperature (Oliveira *et al.*, 2005).

Cultural practices: Irrigation, mulching and bagging

Amongst all practices the most important one for reducing fruit cracking is probably keeping the soil moisture relatively uniform during the active phase of fruit growth. Drip irrigation is well suited to this if accompanied by tensiometers; monitoring soil moisture ensures the watering reflects a true need rather than a scheduled event and therefore avoid the large swings of wetness-dryness that trigger cracking in pomegranate, litchi, citrus, etc. Organic mulching around the root-zone has a good effect by conserving moisture, reducing

temperature fluctuations, and keeping moisture levels fairly steady between watering.

Fruit bagging: This is an often-overlooked, yet effective technique to prevent cracking as it isolates the fruit from extreme heat, U.V radiation and direct contact with surface water and has proven effective in apples, pears and pomegranates.

Mineral nutrition and Foliar applications

With regard to chemical applications to prevent fruit cracking, foliar applications of Calcium, Boron, Zinc and Potassium during fruit development have received perhaps more study than any other cultural method and, for good reason, as the data from various subtropical fruits is rather compelling. Calcium has been studied the most intensely (Hoda *et al.*, 2013). Applied either as calcium chloride at 0.3-0.5%, calcium nitrate at 1.0% or calcium hydroxide at 0.1%, and reapplied on a one to two week schedule during the latter half of fruit development, the mechanism of calcium use in preventing cracking involves stabilization of cell membranes and strengthening of cell wall structure (Nirvan *et al.*, 1953). Results with pomegranate have been particularly impressive: cracking has been reduced in numerous experiments somewhere between 30% and 50% compared to fruit not receiving any supplemental Calcium spray (Gariglio *et al.*, 2003).

Boron is similar: applied at around 2 g/L as borax or boric acid, timed at the onset of aril growth in litchi and at early fruit development in pomegranate, it appears to operate by increasing the elasticity of cell walls, rendering them more able to cope with the expansive pressures placed upon them by growth. Zinc sulphate at 1.5% applied weekly to litchi from early fruit development has increased concentrations of zinc in both the peel and the leaves, enabled the plant to better cope with drought stress and reduced cracking rates. Potassium applied during cell expansion promotes thicker peel development and cell division; and Silicon enhances overall plant growth in multiple ways including boosting photosynthetic rates, encouraging cell division, and providing greater resistance to biotic and abiotic stress (Goodwin *et al.*, 2022).

A more recent research effort in this area has focused on nano-fertilizers and results have shown promise. Research has revealed that foliar application of a nano calcium formulation reduced cracking in pomegranate compared to conventional calcium products; the mechanism is hypothesized to be an increased ability to penetrate the fruit surface and reside there due to its unique nanostructure. The technology is not yet commercially prevalent, but early results indicate it may

become an important consideration in fruit cracking management in the future.

Plant Growth regulators

The use of plant growth regulators at specific times throughout the development cycle has become well-accepted in the management of fruit cracking in a number of different fruit types. The most widely studied and potentially the most effective PGR for cracking prevention, gibberellic acid, applied between 15-40ppm at the young fruit stage, has demonstrated benefits in citrus, litchi, pomegranate, cherry, and pear varieties. Its mode of action in preventing cracking appears to be its inhibition of pectin methylesterase, an enzyme that aids cell wall lysis and strengthening, and promotion of increased peel development and delayed aging. Getting timing of gibberellic acid application correct has been identified as key: research indicates that sprays after the main physiological drop of young fruit yield better results than full bloom applications (Saini *et al.*, 2004).

NAA at 10-20ppm increases peel strength and set, both of which contribute to lower cracking rates, in citrus and litchi. While applications of another synthetic auxin, 2,4-D, at a low concentration of 10ppm after fruit set has also been reported to have efficacy in reducing cracking of litchi and cherry fruits, caution is needed: higher concentrations compromise rind texture and juice content, therefore very careful concentration control is mandatory (Mishra, 1973 and Sepahi, 1986). In a related field, use of anti-transpirants has also proven successful as a practical means of preventing rapid moisture fluctuations in the developing fruit. Sprays of 5% phenol or 1% liquid paraffin to pomegranate about four to five weeks prior to harvest help conserve moisture within the fruit and maintain a more favorable micro environment around the fruit, preventing sudden shifts in moisture that can precipitate cracking (Singh *et al.*, 2003 and Sirohi *et al.*, 2005).

Genetic improvement and Precision agriculture

The most practical, economical, and long-term method of controlling fruit cracking lies with the use of naturally resistant varieties. Work in litchi, pomegranate, cherry and pear has already provided cultivars, which genuinely possess greater crack resistance; this is not through a single factor, but rather the synergistic combination of traits inherited at the genetic level including thicker peels, different cuticular composition, differing rates of water movement at the cellular level and varied hormonal balance of the fruit at different development stages (Campostrini *et al.*, 2010).

On the technology front, precision agriculture and machine learning are just beginning to shift the perspective on cracking control. In short, the aim is to move beyond pre-determined schedules and “rules of thumb” to precisely timed decisions based on current conditions both above and below ground including ambient temperature, humidity, radiation, wind speed and dew point as well as soil moisture content, multi-depth humidity and tensiometer data. This stream of data is then processed using prediction models, fine-tuned to individual varieties and specific growing conditions, to aid growers in making optimum decisions regarding irrigation timing, harvesting time and ambient environmental manipulation. Work on sweet cherry orchards has already involved RGB and thermal imaging combined with predictive modeling of specific cultivars to determine surface moisture and temperature conditions on the fruit itself.

Conclusion

Fruit cracking in subtropical crops is not an issue that is easily solved; in fact it can be economically devastating for growers due to the multitude of factors at play. After decades of research still no clear solution has emerged to prevent cracking entirely. Essentially, fruit cracking is the result of two factors: fruit flesh pushing outward and an unstable or inability of the outer skin to keep up, which is influenced by an entire cascade of environmental, cultural, nutritional and hormonal inputs, all of which play a part and interaction simultaneously throughout the entire growth period. Research has proved time and time again that irrigation will not resolve the issue, but nor will spraying with calcium, gibberellic acid or a resistance-bred variety unless all other aspects are managed accordingly (Menzel *et al.*, 2005). The most effective solution to fruit cracking is integrated management which focuses on a steady well controlled supply of moisture, applications of minerals and plant growth regulators in specific applications and doses and physical barriers against the environment such as bags, and wind breaks, along with cultivars bred for the trait. All of the above play a part that none alone can fully rectify, and therefore by combining all elements to some extent they produce the greatest degree of protection (Pandey and Sharma, 1979).

Several areas of research should be the focus of substantial investment in the coming years: better understanding of the molecular processes involved in calcium nutrition and its link to water channel proteins in relation to water transport within the pericarp of not just economically important tropical fruits but across many sub tropical species. Breeding programs targeting

cuticular properties and expression of cell wall-loosening proteins, as well as sensitivity to ethylene can lead to improved cultivars that are genetically resistant to fruit cracking (Krasnow *et al.*, 2009). The application of precision sensors and machine learning-based risk prediction systems with decision support can also turn fruit cracking management from a reaction to a proactive measure, not only enabling prediction but also proactive prevention. The use of nano-fertilizers for fruit cracking prevention is promising in initial studies, however detailed research should be carried out regarding its efficacy and safety as well as any environmental and regulatory implications (Shinde *et al.*, 2000 and Burns, 1920).

Today, there are significantly better tools available to the growers than ever before. Precision sensing and predictive modelling along with nano-fertilizers and genetically engineered resistance suggest that the next decade should provide real advances in how fruit cracking can be managed economically on a commercial level, but as always it begins with knowledge of the crop, its conditions and correct timing of the correct application (Singh, 1986 and Sharma, 2007). In a world where seasons are becoming unpredictable and demand for high quality fruit crops is only escalating, this knowledge is not just academically intriguing; it is a necessity (Singh *et al.*, 1997).

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