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EFFECT OF CHILLING ATTACHED AND DETACHED TOMATO FRUIT

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ABSTRACT

Effect of Chilling
Attached and Detached Tomato Fruit

By

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The purpose of this study was to determine the extent of field chilling injury on attached and detached tomato fruit in Southern Michigan.

Fruits of two cultivars, were harvested at weekly intervals from September 10 to October 4. Some fruits were detached a week before storage and left in paper bags in the field for comparison against others of similar maturity left on the plants. Parameters measured were decay, ripening, final color, pH, acidity, soluble solids and ascorbic acid content.

Neither cultivar tested was injured significantly by field chilling. Thus the limiting factor in tomato production in Southern Michigan was determined to be the time of the first frost rather than chilling (exposure below 13C).

Detached fruits were more prone to chilling injury than attached ones suggesting some protection provided by the plants.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES cont'd

LIST OF FIGURES

INTRODUCTION

The keeping quality of produce during storage depends on both preharvest and postharvest conditions. Since the potential quality of produce cannot be improved by even the best postharvest handling conditions, great care must be exercised during the production of crops. At harvest, produce has either attained horticultural maturity (ready to be consumed) or is capable of attaining horticultural maturity, having reached a certain physiological maturity. Ripening after harvest is often desirable but senescence, reflecting deterioration, also occurs. The goal in post-harvest produce handling is to control ripening. Often this is achieved by holding produce at low temperature levels to slow down physiological processes leading to deterioration. Any significant amount of stress during production and handling of produce will be reflected in its keeping quality. Therefore, it is important to understand the stresses to which plants and plant parts may be subjected either in the field or in storage. Temperature stresses are one of the most important types of such harmful stresses. Others include those due to water and chemicals.

Temperature stress may be due to excessively high or low temperatures both in the field and in storage. High

temperature exposure results in increased metabolism and senescence. Maintenance of low temperature serves to repress metabolism, slow down senescence and maintain freshness and nutrient content. Plants tend to assume the temperature of their environment unlike humans and other warm-blooded animals. They are thus termed 'Poikilotherms' (Levitt, 1956). Plants thus must have the ability to tolerate low temperature and there is a wide variation among plants and plant parts in their ability to, depending on their origin, water content, structure and other factors. Whether or not a plant is injured by low temperature depends on how long it is exposed to the low temperature. Low temperature injury may be due to freezing or chilling. Most plants have a freezing point slightly less than that of water (0C) due to their high water content. Frozen tissue is evident on thawing by the appearance of water-soaked areas or a total collapse of the tissue. Chilling, however, does not result in such profound manifestations. Chilling injury affects most, though not all, plant tissues. This is the result of exposure to low but non-freezing temperatures. This type of low temperature injury is less dramatic and obvious. It also varies for different plants and plant parts. The highest temperature at which chilling injury occurs also varies, generally depending on the origin of

the plant. Plants of tropical and subtropical origin are usually associated with chilling injury even though some temperate plants are also affected by chilling injury. Susceptible temperatre plants, such as asparagus and apples, are only affected after prolonged exposure to very low temperature (0 to 4 C) and are dormant during the cold season. So chilling injury depends on the species, plant tissue, temperature and duration.

The commercial tomato (Lycopersicon esculentum L. Mill) is a crop of tropical origin that is subject to chilling injury. The significant contribution of tomatoes to the diets of people throughout the world makes their susceptibility to chilling injury important. Tomatoes are subject to chilling injury at all stages of growth. Seed germination is dramatically reduced; plant growth retarded; and fruit quality is reduced by chilling injury. Tomato fruits may be chilled either in the field or in storage and during transportation. Tomato fruits which have been chilled fail to ripen properly, decay, soften excessively and may lose flavor. These symptoms are all manifestations of physiological and biochemical changes within the fruit. It is possible that these undesirable developments can be overcome with a better understanding of the various combinations of factors which influence chilling injury and how they

operate.

This study was designed to determine the extent of chilling injury to the tomato crop in Southern Michigan during the latter part of the harvest. It was also designed to determine at what storage temperature and of what duration tomatoes could be safely kept to avoid chilling injury. Finally, what, if any, effect detaching fruits in the field had on the expression of chilling injury symptoms was determined.

LITERATURE REVIEW

Chilling Injury:

Significant contributions to the understanding of chilling injury have been made in recent years. The earliest reports of chilling injury by Bierkander, Gopert and Molisch in 1778, 1830 and 1896, respectively, have been discussed by Levitt (1980). Molisch first suggested the term "chilling injury" (Erkaltung) to differentiate low temperature injury in the absence of freezing from "freezing injury" (Erfrieren). Other terms have since been used, such as "low temperature injury" (Fidler, 1968) and "low temperature breakdown" (Wilkinson, 1970); but none has gained as much general acceptance as "chilling injury". This is probably because "chilling injury" leads to least confusion with freezing injury and phenomena related to winter hardiness (Weiser, 1970). Eaks and Morris (1957) further clarified the situation by suggesting that "chilling injury" refer to the physiological damage done at low but non-freezing temperatures and "chilling" refer simply to the exposure to low but non-freezing temperatures.

Since the freezing point of most living plant materials is slightly less than OC, the lowest point of the chilling temperature range is well established at about OC - just

high enough to avoid freezing. The upper limit however is not so well defined. This varies with the origin of the plant species. Chilling injury occurs in tissues from temperate origins, such as apple fruits and asparagus stems, at about 4C. Subtropical fruits like citrus and avocado are injured at about 8C and tropical fruits, such as bananas and tomatoes around 12C (Wilkinson, 1970). Exceptional cases have been reported with cacao seeds at 14C (Boroughs and Hunter, 1963); 15C in flowering rice plants (Adir, 1968); and 15C in sugar cane (Tsunoda et al., 1968).

Generally, the lower the temperature within the chilling range, the more severe the injury. However, the relationship is not linear. Several instances have been reported where more severe symptoms appeared at slightly higher temperatures than lower ones (Ryall and Lipton, 1979; Harrington and Kihara, 1960). The relationship between the exposure time and symptom expression is also not linear, although generally the longer the time of exposure the more the injury (Christiansen, 1968; Eaks, 1965). So chilling injury is a temperature-time response but is not a simple linear response.

Physiological and Biochemical Effects:

Even though chilling injury has been known for a long time, the difficulty of recognizing its effects and

measuring them quantitatively has retarded progress in its study. Before chilling temperatures result in any visible symptoms, extensive cytologic and metabolic changes have occurred. Lyons (1973) and Lieberman et al. (1958) have discussed extensively these changes.

Lewis (1956) reported that protoplasmic streaming ceased in petiole trichomes of susceptible plants subjected to chilling temperatures. He reported a quick and irreversible cessation at lower temperatures and longer duration as against reversible and slower cessation at higher temperatures and shorter durations within the chilling range. Protoplasmic streaming continued at temperatures close to freezing after relatively long exposure in chilling resistant plant species. Several workers have reported modification of respiratory behavior in susceptible tissue subjected to chilling temperatures (Eaks, 1965; Watada and Morris, 1966; Murata, 1969). Harvested produce will normally show a gradual decline in respiration rate, except during the ripening of climacteric fruit. However, increased respiration rate with chilling has been reported for several susceptible crops (Lewis and Morris, 1956; Eaks and Morris, 1956; Ibanez, 1964). Levitt (1980) attempts to explain this abnormality as being a result of an inhibition of the aerobic phase, without any inhibition of the anaerobic phase of

respiration. Cooper et al. (1969) showed remarkable increases in the ethylene content of citrus fruits and two avocado cultivars with chilling injury. A third cultivar of avocado, which was chilling resistant did not show any significant increases in ethylene levels. This suggests that since ethylene stimulates respiration (Abeles, 1973), the increased respiration levels may be the result of increased ethylene levels.

Lieberman et al. (1958) compared isolated mitochondria from chilled and unchilled sweet potato roots. They found a gradual decline in chilled mitochondrial activity, terminating in completely inactive mitochondria. Minamikawa et al. (1961) and Uritani et al. (1971) also reported similar results; suggesting that an inactivation of mitochondria might account for the decline in respiration and final death of tissue.

Another probable cause of chilling injury is change in membrane permeability in response to low temperature exposure (Lyons, 1973). Jansen and Taylor (1961) and more recently Drew and Biddulph (1971) have found the transport of ions and water in chilling sensitive tissue to be reduced upon exposure to chilling temperatures. Hartt (1965) also reported that translocation in sugar cane ceased completely at 5C after a gradual decline. Geiger (1969)

has also provided supporting data to this concept of reduced water and mineral uptake and transport with chilling in susceptible plants. Lieberman et al. (1958) demonstrated that on removal to 20C, chilled sweet potato root tissue leaked five times as much ions as healthy tissue. Levitt (1980) recently discussed increased solute leakage quite extensively. Christiansen et al. (1970) went further and demonstrated that solute leakage could be prevented with the addition of calcium or magnesium. Other reports of increased leakage from chilled tissue include those of Katz and Reinhold (1964) in coleus; and Guinn (1971) in cotyledons.

Changes in cellular constituents and related enzyme activity with chilling injury have also been reported. Jones (1942) found a slight decrease in hydrolysis of sucrose in chilled papaya fruits, with a concomitant increase in soluble solids. However, Lorenz (1951) could not detect any significant changes in the major components of squash after chilling. Ezell and Wilcox (1952) and Ezell et al. (1952) reported a decrease in the ability of sweet potatoes injured by chilling to synthesize carotenoids as well as an accelerated loss of ascorbic acid with chilling. Other reports of increased rate of loss of ascorbic acid include those in pineapples (Miller, 1951;

Miller and Heilman, 1952) and banana (Murata and Ogata, 1966, in Lyons, 1973). However no significant losses were obtained with guava (Singh and Mathur, 1954) or tomato (Craft and Heinze, 1954; Lewis, 1956). However more recent reports utilizing improved techniques have shown significant changes in the ascorbic acid content of tomatoes with chilling (Price et al., 1976). Barnell and Barnell (1945) reported increased levels of tannins in the pulp of chilling injured bananas. Lieberman et al. (1959) obtained an increased accumulation of chlorogenic acid in sweet potato roots and Lyons (1973) suggests that this may be instrumental in the decreased activity of mitochondria observed in chilled tissue.

Other compounds involved in intermediary metabolism such as acetaldehyde and ethanol have been shown to increase with chilling injury (Murata, 1969). Taylor and others (1972) found a rapid decrease in the levels of those amino acids closely related to intermediates of the C_4-photosynthetic pathway in sensitive grass species which were chilled. This, in addition to reports of damage to chloroplast thylakoids (Garber, 1977; Melcarek and Brown, 1977) may account for the rapid decrease in photosynthetic activity with chilling injury (Levitt, 1980).

Another physiological effect of chilling temperatures which has received considerable attention is the physical phase transition of membrane lipids. Lyons et al. (1964) observed that membrane lipids from chilling sensitive plant species tended to have a higher proportion of saturated to unsaturated fatty acids than their resistant counterparts. Earlier workers had already realized that plants (as well as animals) originating from warm climates tended to have more saturated fatty acids in their lipids (Pearson and Raper, 1927, in Lyons, 1973). Canvin (1964) showed a greater proportion of unsaturated fatty acids in beans when grown in colder climates than when grown in warmer climates. Berlinger (1971) obtained similar results with oat grains. Similar results were also obtained in wheat (de la Roche et al., 1972), rye (Farkas et al., 1975), snap beans (Wilson, 1976), flax, rape and sunflower (Canvin, 1964), alfalfa (Grenier and Willemot, 1974), and (Phaseolus vulgaris) seeds (Wolk, 1980). The relationship between fatty acid composition and chilling injury sensitivity however is not exactly precise (Uritani and Yamaki, 1959; Yamaki and Uritani, 1972). Esfhani et al. (1971) have been able to show that fatty acid composition can determine the existence of a temperature induced phase transition in microorganisms. Lyons (1973) contends that this however, has been difficult

to demonstrate in higher plants. Lyons and Breidenbach (1979) recently reviewed extensively physical phase transition.

Other suggested cellular effects include protein breakdown (Levitt, 1980) and toxin accumulation (Pentzer and Heinze, 1954; Smith in Levitt, 1980).

Horticultural Symptoms of Chilling Injury

Since the physiological and biochemical effects of chilling injury are not directly observable, they are of little concern to the consumer themselves. It is those symptoms, resulting from the cellular effects, which reduce quality of the produce that are of general concern. But quality is a very difficult term to define because of its subjective nature. What may be judged as being of the best quality will depend on who is making the decision and the purpose for which it is intended. Thus quality is difficult to measure and define quantitatively. The definition of Gould (1974) will probably be best suited for this discussion; "Quality makes a product what it is: it is the combination of attributes or characteristics of a product that have significance in determining the degree of acceptability of the product to a user, and that determines its value or worth". Any deviations from the best desired by the consumer is thus a reduction in quality.

Chilling injury reduces quality of a produce by various symptoms it exhibits. Symptoms vary for different plant tissues and the degree of severity of chilling injury. The ultimate being death of the tissue involved. Symptoms are generally not expressed until the tissue has been moved from the chilling temperature to a higher temperature, for example room temperature. Ryall and Lipton (1979) list the chief symptoms as decay, discoloration, pitting and the loss of ability to ripen. Changes in texture and flavor are however often also associated with chilling injury. Any particular plant tissue may exhibit one or a combination of two or more of these symptoms. Other factors like moisture levels, sanitation and amount of bruising in handling influence the severity of symptoms. Lutz and Hardenburg (1968) present an extensive review of symptoms.

Decay:

Enhanced decay due to chilling injury is a result of tissue weakening and thus greater susceptibility to pathogen attack. For example, Alternaria, the pathogen most commonly found on chilled tomato fruits, is a weak pathogen. Alternaria will only successfully attack and infest tissue after it has been weakened by chilling injury (Hruschka et al., 1967) or wounding. McClure (1959); McColloch

(1962a, 1962b and 1966) all attest to this observation. McColloch (1966) presented a table of 26 important horticultural crops susceptible to chilling injury with their respective lowest safe storage temperatures and the symptoms expressed with chilling injury. In crops, like sweet potato, where wound healing is essential for proper storage, chilling temperatures also prevent wound healing and thus enhance decay. Harvested produce exhibiting decay with chilling injury include tomatoes, sweet potato, melons and cucumbers (McColloch, 1966).

Discoloration:

Discoloration of tissues, both internally and externally is also a common symptom of chilling injury. Some produce like avocado and cucumber are discolored only internally; while others like melons and beans are discolored only externally. Discoloration apart from its aesthetic detractions suggests that the tissue is unwholesome. Discolorations studied extensively include that in apples termed apple scald (Hulme et al., 1964; Wills and Scott, 1971) and dull gray green tips of spears in asparagus (Ryall and Lipton, 1979). Other horticulturally important crops which are discolored by chilling injury include mango, citrus, papaya, okra and plums (McColloch, 1966).

Pitting:

Surface pitting is another widespread manifestation of chilling injury. This is the result of localized collapse of subsurface cells, giving way to decay pathogens. Surface pitting in cucumbers as reported by Eaks and Morris (1957) is a good example of this disorder. Surface pitting is related to moisture loss in some commodities. The symptom develops more rapidly at lower relative humidity. Apparently, the rate of moisture loss under dry conditions cannot be compensated for by that of translocation to the tissues, so the cells collapse due to desiccation, forming pits. With excessive chilling, the pits coalesce forming large shallow depressions. Even though high humidity cannot prevent surface pitting under chilling temperature, it has been used successfully to reduce the disorder (Lyons, 1973). Produce exhibiting pitting include cucumbers, okra, melons and sweet potato (McColloch, 1966).

Abnormal Ripening:

Climacteric fruits like honeydew melons and tomatoes are harvested prior to ripening to facilitate handling and transportation. When these physiologically mature but horticulturally immature fruits are subjected to chilling temperatures, they will not attain the desired extent of ripening. In mature-green tomatoes, color development is

retarded and fruits may never attain the desired color or softness. Morris (1953) found the best color development in mature-green tomatoes to be at about 18 to 21C and injury below about 13C for mature-green and 7C for ripe fruits. He also showed that sensitivity to chilling decreased progressively as the tomato fruits ripened. Abnormal ripening has also been reported in avocado and honeydew melons (Ryall and Pentzer, 1974).

Texture Changes:

The development of "hardcore" in sweet potatoes, a symptom of chilling injury, was discussed by Daines et al. (1974). A hard mass of tissue develops and will not soften even when the roots are cooked. Exposure to 1C for only 3 days before curing at 27C caused significant amounts of hardcore when the tubers were cooked. McColloch (1966) reported that cranberries develop a rubbery texture on chilling. Oppenheimer (1960) also reported a partial non-softening of avocado fruits when chilled. Localized hard areas, which persisted even after cooking, were formed. Puffiness in citrus as a result of the separation of softened and loosened rind from the segments when chilled has also been reported (Ryall and Pentzer, 1974).

Flavor Changes:

Changes to uncharacteristic flavors, sometimes accompanied by offensive odors have been reported in avocado (Ryall and Pentzer, 1974). White potatoes when chilled often become uncharacteristically sweet (McColloch, 1966).

This great variability in symptom expression renders a generalized criterion for measuring chilling injury difficult to determine. Katz and Reinhold (1964) experimented with changes in electrical conductivity for estimating injury in coleus before external symptoms developed but this has not been acceptable as a solution to the problem.

Combatting Chilling Injury

The best way to overcome chilling injury is obviously to avoid low temperatures both in the field and in storage. However, this may not always be practical. Some success has been reported in attempts to reverse mild chilling before it becomes irreversible.

Temperature Conditioning:

Mild chilling may be reduced or reversed by exposure to warm temperature. A 1 day exposure of sweet potato to 0C or 4 days at 7C was overcome by curing at 30C for 8 days (Ryall and Lipton, 1979). Wheaton and Morris (1967)

obtained some protection against a 2 day exposure of 5 day old tomato seedlings (grown at 25C) to 1C by prior exposure to 12.5C for 48 hours. This conditioning could however not protect seedlings exposed to 1C for 7 days. Wheaton and Morris (1967) also detected a slight influence on the respiration rate of sweet potatoes of chilling, but could not reduce chilling injury symptoms. Ryall and Lipton (1979) also reported that 2 to 3 days at 20C can nullify the effects of 2 to 3 days of previous exposure to 0C. Apeland (1966) reduced the effects of exposing cucumbers to 5C for 4 or 6 days by a preconditioning temperature of 12.5C. St. John and Christiansen (1976) obtained protection against wilting due to chilling at 8C for 3 days in cotton seedlings by "hardening".

Alternating Temperatures:

Periodic fluctuations in temperature have also been shown to reduce chilling injury. Smith (1947) and Smith (1949) both obtained reductions in chilling injury by interrupting the chilling temperature with a warm (20C) period of 2 to 3 days. Lieberman et al. (1958) obtained a reversion of the characteristic reduction in ascorbic acid and increase in chlorogenic acid levels in sweet potatoes associated with chilling injury using the same principle.

Stewart and Guinn (1969) reversed a chilling induced decrease in ATP levels in cotton seedlings after 24 hours at 5C but not after 48 hours. Chilling injury symptoms in corn leaves have also been reversed after 36 hours at 0.3C by transferring them to 21C for 72 hours. Some leaves could be saved after 48 to 60 hours but not after 72 hours at 0.3C (Creencia and Bramlage, 1971). Therefore, up to a point, chilling injury can be reversed in many tissues by returning the tissue to warmer temperature.

Low pressure storage, termed hypobaric by Tolle (1969), is also reported to have reduced chilling injury in avocados, bananas, grapefruits, peppers and tomatoes (Lyons, 1973).

Controlled Atmosphere Storage:

Controlled atmospheres have also been reported to reduce chilling injury symptoms (Vakis et al., 1970; Spalding and Reeder, 1975; Wardowski et al., 1975). Such studies were prompted by the similarities between symptoms due to chilling and those due to low oxygen atmospheres (Morris and Platenius, 1938; Nelson, 1926). Miller (1946) too, noted decreases in chilling injury of citrus, but he also obtained some rind injury. Tomkins (1963), on the contrary, obtained increased chilling injury in tomatoes with increased carbon dioxide. Eaks (1956) also found that

increased carbon dioxide concentrations increased chilling injury symptoms in cucumber, while oxygen levels from zero to a hundred percent did not alter chilling injury symptoms as a result of 5C exposure for 8 days. These reports indicating a potential for controlling chilling injury with modified gas atmospheres deserve further attention.

Genetic Manipulation:

It might be possible to use genetic variability to impart chilling resistance into commercial species of, at least, some plants such as tomato and tobacco. Patterson and Graham (1977) working with Passiflora showed that species evolving in tropical lowlands were much more susceptible to chilling injury than those from cooler climates. Using electrolyte leakage as a measure of chilling injury, they ranked different species and hybrids (crosses of lines of varying susceptibility). The results obtained suggest that chilling resistance is strongly inherited in Passiflora. Patterson and Graham (1977) collected several varieties of a wild tomato (Lycopersicon hirsutum) from areas of different environmental temperatures in Peru and Ecuador. Using protoplasmic streaming of detached epidermal trichomes as indicators of chilling injury, they tested their collection for susceptibility.

Results clearly showed differences in adaptation to low temperature correlated with origin of the varieties. So utilization of genetic material from wild populations seems to be a feasible means of generating interspecies crosses more tolerant of low temperature exposure in growth and storage. Another plausible genetic manipulation is through cell-culture techniques. Some mutant tobacco and pepper lines obtained by Dix and Street (1976), using the mutagen ethylmethano sulfonate (EMS), were reported to be chilling-resistant. Using mitochondrial activity as an indicator of chilling injury, it was demonstrated that some of the Capsicum annum (pepper) lines were definitely chilling-resistant. If the rate of progress with tissue culture techniques is any indication, then this technique promises considerable advances in providing chilling-resistant cultivars.

Other Treatments:

Successes with various chemical treatments have also been reported. For example, diphenylamine in apples (Huelin and Coggiola, 1970a, b). Smock (1957) also controlled apple scald with ethoxyquin (another antioxidant). Ethanolamine was also reported to reduce chilling injury at the cytological level in tomato seedlings subjected to

5C for 3 days (Ilker et al., 1976). This response was attributed to modification of the microsomal membrane phospholipids, but not in the mitochondrial membranes (Lyons and Breidenbach, 1979). Other chemicals reported to have reduced chilling injury include IAA and vitamins (Amin, 1969); thiabendazole, (Vakis et al., 1970); butylated hyroxytoluene (Snipes et al., 1975); and sterols (Long et al., 1971).

Waxing the surface of fruits has been reported to both increase (Mack and Janer, 1942) and decrease (Morris and Platenius, 1938) chilling symptoms. The contradiction in these results is probably a result of the fact that waxing will slow desiccation and thus chilling injury; and also modify the internal atmosphere of the produce waxed. Modifying the internal atmosphere amounts to a controlled atmosphere storage with its contradictions.

Chilling Injury of Tomato Fruits:

The commercial tomato (Lycopersicon esculentum L. Mill) belongs to the nightshade family (Solanaceae). In its natural habitat, it is a herbaceous perennial, but is cultivated as an annual. It is cultivated and used as a vegetable, but botanically it is a fruit. The fruit is simple and fleshy with a skin and seeds, which fits the definition of a berry. The tomato is now grown in most

areas of the world but it is believed to have originated from the western slopes of the Andes in South America (Hobson and Davies, 1971). Being of tropical origin, it is susceptible to chilling injury at temperatures below about 12.5C (Morris, 1953).

Chilling Temperatures:

Low temperature exposure, either in the field or in storage, can cause injury. Such injury is cumulative, so that fruits subjected to any chilling before harvest need extra care during handling to avoid further chilling injury in storage (McColloch and Worthington, 1952). A yardstick on the effects of chilling in the field has been worked out for California tomatoes by Morris (1954). He used the number of hours below 15C during the final week before harvest as an indication of the amount of injury to be expected. He found no practical injury up to 95 hours below 15C. Exposure for 95 to 115 hours resulted in a slight amount of injury provided no additional chilling was experienced during postharvest handling. At 115 to 135 hours below 15C significant injury resulted, even without any further chilling after harvest. Morris (1954) found that fruits which had been exposed to more than 135 hours below 15C in the field were so seriously injured it was not

even worth harvesting them, especially the mature-green fruits. Several reports indicate that the more red color a fruit showed, the less susceptible it was to chilling injury (McColloch et al., 1968; Lutz and Hardenburg, 1968).

The USDA has established six classes of fruit color: green, breaker, turning, pink, light-red and red (USDA, 1968).

Determining When Green Fruits are Mature:

To facilitate handling, fruits are often picked green with the hope that they would have ripened by the time they reach the consumer. However, green fruits are only capable of ripening properly if they have attained a certain degree of maturity before harvest. Determining if fruits have attained this stage of maturity has been a problem for a long time. Several internal, as well as external, characteristics can be associated with mature-green fruits (Lutz, 1944). The internal characteristics are a well formed jelly-like material in the locules; and the seeds are not cut but rather displaced when fruits are sliced. The internal indicators are used in defining maturity in the USDA standards of grades (USDA, 1976). However, since these necessitate cutting and thus destroying the fruits, they cannot be used routinely by growers and packers. They have to rely more on external non-destructive criteria.

The advent of objective, non-destructive and reproducible methods is only now beginning and no generally acceptable methods have yet been established. Subjective methods are commonly based on size, shape, color, surface and stem scar. All these vary depending on cultivar but with experience in using a particular cultivar, can be quite reliable. Kader and Morris (1976) list the characteristics of mature-green as: attaining a minimum size; well rounded, not angular; whitish green or cream colored streaks at the blossom end; waxy gloss skin is not torn by scraping, reflecting more advanced cuticle formation; and the presence of brown corky tissue on the stem scar in some cultivars. Objective methods of determining maturity in the laboratory include those based on flotation (Nettles, 1959), and light transmittance (Worthington et al., 1973; Chen and Studer, 1975). These methods, however, require that the fruit first be harvested. So if used commercially they would result in a lot of loss in immature fruit being harvested and discarded.

Symptoms of Chilling Injured Fruits:

Chilling injury in tomatoes results in reduced quality of fruits in terms of color, decay, delays in ripening, flavor and nutrient reduction. One or more of these symptoms may be present in the same fruit depending on the

severity of chilling and the maturity and/or color of the fruit when it is chilled.

Color:

The best color development of tomato fruits is at about 20C (Truscott and Warner, 1967; Hall, 1974). The final color of fruits is important because it is often associated with overall quality. The customer first notices color and this provides certain preconceived notions about other quality factors such as freshness and flavor. It is thus important to make a good initial impression with a standard familiar color desired and expected by the consumer. The green color in tomato fruit is due to a mixture of chlorophylls, which perform a photosynthetic role during maturation (Boe and Salunkhe, 1967a). With ripening, yellow pigments (carotenes) are produced and become more apparent as the chlorophyll content decreases. Then the rapid accumulation of the red pigment (Lycopene) influences the fruit color, gradually becoming dominant (Hobson and Davies, 1971).

At chilling temperature, the usual biochemical process are altered, resulting in fruits with less red color (Morris, 1953; Truscott and Warner, 1967). The more red the fruit before chilling exposure, the less the reduction in the

final red color attained (Morris, 1954; McColloch, 1966). The more severe the chilling, the less red the final color (Truscott and Brubacher, 1964). Chichester and Nakayama (1965) and Edwards and Reuter (1967) provide reviews of pigment development in the tomato fruit.

Evaluation of color is traditionally done by the human eye which is capable of distinguishing small color differences by comparison (Gould, 1974). Thus, provision of a standard color chart enables the eye to make a subjective evaluation providing fairly uniform color grades. However, to make color evaluations reproducible and thus objective, not only must the human factor be eliminated but the light source also must be more stable and uniform than daylight. There are instruments available which provide such objective color evaluations (Gould, 1974; Watada and Worthington, 1976). The "Hunter Lab Color Meter" is one such instrument. It measures color on 3 scales by use of different letters. "L"-visual lightness on a scale of 0 (perfect black) to 100 (perfect white); "a"-where plus is red, zero is gray, and minus is green; and "b"-where plus is yellow, zero is gray, and minus is blue. These scales make up a three dimensional rating space providing a color cube, thus describing the color of a fruit not only objectively but also in terms of all the major color pigments

involved. Hunter (1976) discusses the principles involved in the design and use of the instrument.

The final color attained by a fruit is influenced by the amount of light it is exposed to during ripening. Shewfelt and Hoplin (1967) came to the conclusion that the quality of the light received influenced the rate of color development of harvested fruit. After a series of studies, Boe and Salunke (1967b) reported that light increased the amounts of B-carotene as well as lycopene.

Decay:

Decay caused mainly by the weak pathogen Alternaria is increased with a decrease in temperature and increased duration within the chilling range (Hall, 1961, 1964; Herregods, 1963). Fruits which have developed full red color before harvest are less susceptible to decay unless such injuries as growth cracks, blossom-end rot and sun-scald first develop. Mature-green fruits however, are much more likely to develop serious rot when chilled (McColloch and Worthington, 1952; Truscott and Warner, 1967). Typical symptoms of Alternaria rot on fruits injured by chilling are a ring of decay around the stem scar and lesions developed around skin breaks over the surface of the fruits. Such fruits are thus rendered unmarketable (Magoon, 1969). There is no objective method generally accepted for measuring

decay due to chilling injury. Consequently, subjective methods are used based on extent of damage per fruit and the percentage of fruits in a lot affected. However, it is generally acknowledged that decay due to chilling usually decreases in severity with an increase in stage of ripeness of the fruit before chilling (Kader and Morris, 1976).

Delays in Ripening:

In addition to poor final color development and increased decay, chilling injury also results in a delay in ripening. McColloch and Worthington (1952) first recorded extensive delays with ripening. They stored mature-green fruits from the same field at temperatures ranging from 0 to 20C. They kept fruits at chilling temperatures: 0, 4.5, 10, and 12.8C for 3, 6, 9 and 12 days then transferred them to 18C to ripen. The results (70 to 80% ripe) showed clearly that the fruits at chilling temperatures took longer to ripen when transferred. Also, the longer a fruit was at a particular chilling temperature, the longer it took to ripen. However, like is often the case with chilling injury, the delay in ripening did not respond linearly to temperature reductions. Similar results have since been reported by other workers, for example, Morris (1954) and Tomes (1963).

Flavor:

Flavor is composed mainly of taste and odor. Measurement of flavor has been a problem for a long time and no solution has been found yet (Moncrieff, 1967). However, there are several records of consumer complaints about the flavor of chilled tomato fruits (Stevens and Kader, 1976). The odor or aroma of the tomato is distinct but not very strong and it has been difficult to isolate the specific compounds responsible for this aroma (Gould, 1974; Kazeniac and Hall, 1970). Taste, the strongest contributor to flavor in tomatoes, is composed of four main types; sweet, sour, bitter and salt (Moncrieff, 1967).

The organic acids in tomato contribute to sourness and the sugars to sweetness and their absolute, as well as relative amounts have been shown to indicate fairly closely the taste/flavor of tomatoes in sensory evaluations (Stevens, 1972). Hobson and Davies (1971) provide an extensive review of the acids found in tomatoes. Large variations between cultivars and locations in acidity have been reported (Simandle et al., 1966; Stevens and Kader, 1976). The acid level in the fruit increases as it matures until the inception of yellow color, then it starts to decrease (Winsor et al., 1962; Dalal et al., 1965). There also seems to be a relationship between harvest date and

acidity (Massey and Winsor, 1956). Highly positive correlations have been reported between potassium content and acidity (Davies and Winsor, 1967). The hydrogen-ion concentration (expressed as pH) of the tomato fruit controls many biochemical and microbiological reactions (Gould, 1974). The juices in the fruit constitute a weak acid/strong base buffer system in which the anions are mainly citrate and malate and the cations potassium (Davies, 1965). Thus changes in acidity are not reflected in the pH which is maintained between 4.0 and 5.0. The effects of cold temperature on acidity are not well established. Hall (1974) reported that breaker fruits contained more acid when chilled than when not chilled. The duration at a given low temperature seemed to be especially important in maintaining high acidity. The results suggest that the acid level was depleted at non-chilling temperatures but remained stable at chilling temperatures.

Reducing sugars make up about 50 to 65% of the solids in tomato fruits (Winsor et al., 1962; Miladi et al., 1969) These sugars are mainly glucose and fructose with small amounts of sucrose, rarely exceeding 0.1% (Goose and Binstead, 1964). The sugar content increases with maturation and ripening (Winsor et al., 1962; Lambeth et al., 1964). At the inception of yellow color, sugar levels show a

marked increase but apparently fall if held at normal ambient temperatures of about 20 to 25C after ripening (Winsor et al., 1962). There are pronounced varietal differences in sugar content of tomatoes (Stevens and Kader, 1976). There are no reports of definite effects of chilling injury on sugar content but reports have been published of chilling injury affecting flavor. Since sugar content is related to both "sweetness" and "sourness" evaluations (Stevens and Kader, 1976), chilling injury probably affects sugar levels and/or the sugar/acid ratio. Several studies indicate that the sugar/acid ratio does, infact, relate to taste as perceived by consumers (Dennison, 1955; Stevens, 1972).

Ascorbic Acid:

Publications emphasizing the importance of tomatoes as a valuable source of vitamin C (ascorbic acid) include those by Murneek et al., (1954) and Gould (1974). Values ranging from 5 to 60 mg ascorbic acid per 100g fresh weight have been reported for U.S.A. cultivars. Stevens and Kader (1976) recently found a strong correlation between ascorbic acid and taste of tomatoes. However, it is not clear yet whether or not ascorbic acid actually has an impact on taste. A lot of the variability reported in ascorbic acid is

probably due to differences in light intensity. Fruits produced under higher light intensity contain more ascorbic acid (Crane and Zilva, 1949; Matthews, 1974). Ascorbic acid increases during maturation with either a continuing rise (Yamaguchi et al., 1960) or a slight fall (Malewski and Markakis, 1971) during the final stages of ripening. Faster ripening cultivars usually contain more ascorbic acid than the slower growing cultivars (Clutter and Miller, 1961). Matthews et al. (1973) reported that cultivars released since 1950 have consistently contained higher levels of ascorbic acid with later release date. Brown and Moser (1941) as well as Maclin and Fellers (1938) could not detect any losses in ascorbic acid at high or low temperatures. Seeling (1965) however, contends that ascorbic acid is lost at high temperatures especially under non-acid conditions by speeding up oxidation. Several researchers have reported losses of ascorbic acid in tomato products at high temperatures. Tomato products held at chilling temperatures (5 to 10C) retained 92 to 100% ascorbic acid after 2 years. Retention decreased directly with increasing temperature (Feaster et al., 1949; Guerrant et al., 1946). There are, however, no reports with fresh fruits but this suggests a possible relation.

Materials and Methods

Preliminary Greenhouse Study:

A non-replicated preliminary greenhouse study was conducted prior to doing the actual experiments. The purpose was to gain experience with the procedures which would be used in the actual field study and to help make decisions regarding the treatments and procedures to be used.

The fresh market cultivar 'Red Pak' was used. This is an early hybrid producing large, firm, slightly lobed fruits which is recommended by the Michigan State University Cooperative Extension Service (Zandstra and Price, 1979) for lower Michigan. Seed for about 100 plants was sown and seedlings were transplanted after about 5 weeks. Plants were spaced at 75 cm x 75 cm on 2 greenhouse beds - 2 rows of 11 plants each per bed. Flowers were tagged as they opened, to serve as a basis for determining when fruits matured and observing the characteristics of mature-green fruits.

Mature-green fruits and breaker fruits (fruits starting to show pink color at the blossom end) were harvested and stored. The storage treatments were: 0, 5, 10, and 15C for 3, 6, 9 and 12 days followed by a transfer to 20C; and

a lot maintained at 20C continuously. Days to ripen to "color stage 5" ("M.S.U. Tomato color chart" - Antle, 1971) was recorded for each fruit and a mean found for each lot. The number of fruits in each lot which showed signs of decay was also recorded. On the basis of this greenhouse trial, 0, 10 and 20C storage temperatures and 5 and 10 day duration were used in the field study.

Field Production:

A second cultivar - 'Jack Pot' - was used in the field study in addition to 'Red Pak'. Jack Pot is a main season hybrid producing firm but slightly smaller and smoother fruits than Red Pak. It is also recommended by the Michigan State University Agricultural Extension Service (Zandstra and Price, 1979). Seeds were sown and seedlings transplanted in the field three times at two-week intervals. Spacing was at seventy-five centimeters in rows one meter apart. Each planting (main plot) had both cultivars (sub plots) of 6 rows each containing 15 plants.

Supplemental overhead sprinkler irrigation and mechanical weed cultivation were used. Insects were controlled with "Tovel" and "Lannate" and diseases with "Bravo" and "Manzate". A 16-16-16 fertilizer mixture was applied a few days after each planting and again about two weeks later.

The first fruits for storage treatments were harvested on September 10, 1980; and subsequent harvests were on September 18 and September 26. At each harvest, based on subjective criteria of fruit size and appearance, about 250 'mature-green' and 150 'breaker' fruits were harvested for each cultivar. Then, about sixty mature-green fruits were tagged on the plants while a corresponding sixty were harvested and left in paper bags in the field for both cultivars. These were labelled as "Attached" and "Detached", respectively, and were moved into storage eight days after being tagged or detached.

Storage Treatments:

Of the approximately 250 mature-green fruits harvested 150 were selected for uniformity in appearance after washing in tap water. These 150 fruits were randomly divided into 15 lots of 10 each and each lot put into a perforated polyethylene bag. 6 bags were placed at 0C, 6 at 10C and 3 at 20C 3 bags from 0C and another 3 from 10C were moved to 20C storage after 5 days. The other 3 bags at 0C and the 3 at 10C were moved to 20C after another 5 days (10 days from day zero). The 3 bags initially put at 20C were left there throughout the storage period. The 5 storage treatments were as follows:

Treatment Number	Temperature (C)	Duration (days)
1	20	continuous
2	10	5
3	10	10
4	0	5
5	0	10

90 breakers fruits were similarly selected from the approximately 150 picked for each cultivar at each harvest. These were divided into 3 batches of 3 bags each containing 10 fruits. The 3 treatments corresponded to treatment numbers 1, 2 and 3 above with 3 replicates each.

"Attached" and "Detached" fruits were removed to a laboratory 8 days after tagging or detaching treatments. Of the approximately 60 fruits per treatment for each cultivar, 45 were selected for uniformity. These were divided into 3 replicates of 15 fruits each per bag and all 6 bags for each cultivar (3 per treatment) were stored at 20C continuously.

Records and Analysis:

All fruits in each of the three experimental lots: 'mature-green', 'breaker' and 'attached/detached' were subjected to the same records and analysis.

All fruits were observed daily in storage and inspected for any signs of decay appearing on their surfaces. Fruits which were judged to be red ripe, on the basis of a color chart (Antle, 1971) were removed from storage and recorded. The fruits were then immediately analysed for color on a Hunter Lab Color Meter (Hunter, 1976). Fruits were placed on the meter with three different areas facing the light source, rotating them about the central axis running from the pedicel to the blossom-end. L, a and b values representing relative lightness, red and yellow coloration were recorded. Fruits were then frozen and held for analysis of pH, soluble solids, total acidity and ascorbic acid content.

Fruits were thawed and then blended for three minutes in a Waring blender. pH at 20C was measured with a Beckman pH meter (Expandomatic IV) by inserting the glass electrode directly into the blended slurry.

A small portion of the slurry was filtered through a number two Whatman filter paper. The soluble solids content (degrees brix) at 20C was measured directly on the filtrate with a Bausch and Lomb refractometer (Abbe-3L).

Total acidity was measured by titration of 10g slurry with 0.1036N NaoH to an end-point of pH 8.1 at 20C, using a pH meter. Percent acid expressed as citric acid was

calculated as follows:

$$\%T.A. = \frac{(\text{ml of HaoH})\ (0.1036N\ NaOH)\ (0.09606\ g/meg)}{(10g\ slurry)} \times 100$$

The ascorbic acid content was determined by reduction of 2,6 Dichlorophenol Sodium salt (Hawk et al., 1954).

Statistical analysis of the results was based on "Principles and Procedures of Statistics" by Steele and Torrie (1980). A CDC 6500 computer was used with the aid of "Statistical Package for the Social Sciences" by Nie et al. (1975) and "Introduction to MSU Stat. System Version 4 CDC 6500" by Coston (1973).

Results and Discussion

Chilling Treatments

Ripening and Decay:

Storage of tomato fruits under chilling conditions (0 or 10C for 5 or 10 days) resulted in a delay in ripening for both mature-green and breaker fruits (Table 1). Mature-green fruits were affected more than breaker fruits. Duration of exposure at the chilling temperatures had more effect than did temperature reduction from 10 to 0C. Delays in ripening, provided final ripening quality is not affected, may be beneficial in marketing. However, chilling also reduced final fruit color quality.

Chilling treatments also resulted in more decay of both mature-green and breaker fruits (Table 1). The response of fruit by decay to low temperature was larger than the response in delay of ripening. This suggests that measurement of decay might be a better test criterion for chilling injury than ripening, at least with fruits harvested mature-green. Breaker fruits may be less sensitive to decay than to ripening delays due to chilling injury. Kader and Morris (1967) reported similar results. The results in Table 1 suggest that duration of chilling temperatures might be more important in chilling injury than the temperature reduction itself.

Table 1. Rate of ripening and percentage decay in response to chilling treatment during storage of 'Mature-Green' (MG) and 'Breaker' (Br) tomato fruits.

Temp. (C)	Time (days)	Days to Ripen[1]		Percentage Decay[2]	
		Mean Values			
		MG	BR	MG	Br
20	--	14.3	9.8	4.1	0.8
10	5	18.0	11.5	9.3	5.8
10	10	22.0	12.8	20.0	5.8
0	5	20.7	--	18.5	--
0	10	25.1	--	34.5	--
		Planned Comparisons (F Statistics)			
Control vs Expt.		89.06**	35.77*	91.68**	23.99*
10 vs 0C		18.17*	--	59.29	--
5 vs 10 days		38.07**	8.35	75.25**	1.00

* F value for comparison significant at 0.05 level

** F value for comparison significant at 0.01 level

1. Days to ripen to color stage 5 (Red) on MSU color chart (Antle, 1971).

2. Percent decay based on number of fruits in a lot that showed external decay.

There were small differences in the sensitivity of the two cultivars tested. With both ripening and decay as indicators, 'Red Pak' appears to be more resistant to chilling than 'Jack Pot' (Table 2). Both cultivars were less sensitive to chilling injury at the breaker stage than at the mature-green stage.

Later harvest dates generally resulted in more chilling injury symptoms of ripening delay and decay (Table 2). The only exception was with ripening of mature-green fruits harvested on September 18. The fruits were more delayed in ripening than those harvested on September 26. The temperatures in the field below certain levels one week prior to harvest dates (Table 3) were 84 hours below 15C for September 18 and 75 for September 26. The occurrence of a sharp increase in number of hours below 15C from September 10 to September 18, then a slight decrease for September 26 correlates closely with the ripening time for fruits harvested on these dates (Table 2). This suggests that ripening, in relation to harvest dates, of mature-green fruits is probably controlled by duration of exposure below 15C. Ripening of breaker fruits and decay of both classes of fruits, on the contrary, are probably controlled by exposure below about 12.8C or 10C. However, further evidence would be required to validate this suggestion.

Table 2. Cultivar differences and effect of harvest date on ripening and decay of 'Mature Green' (MG) and 'Breaker' (Br) fruits.

Cultivar	Days to Ripen		Percentage Decay	
	MG	Br	MG	Br
Red Pak	20.9	12.03	15.7	3.9
Jack Pot	19.2	10.7	18.8	4.4
LSD 0.05	0.43	0.36	1.83	NS
LSD 0.01	0.58	0.49	2.43	NS
Harvest date				
September 10	19.0	10.8	11.1	0.00
September 18	20.9	11.3	15.8	4.2
September 26	20.1	12.0	24.9	8.3
LSD 0.53	0.53	0.44	2.24	3.77
LSD 0.01	0.71	0.61	2.98	NS

Table 3. Temperatures prevailing during one week preceding harvest.

Harvest Date	Number of hours[1] below		
	15C	12.8C	10C
September 10	45	30	9
September 18	84	36	18
September 26	75	57	30
October 4	108	84	48

1. Number of hours below specified temperatures was obtained from 3-hourly temperature readings by the National Climatic Center (1980).

Fruits harvested on different dates responded slightly different to cold storage (Figure 1). Generally, the fruits that were exposed least in the field were the least affected. Since chilling injury is cumulative, (Lutz and Hardenburg, 1968) this could be expected. The fact that the earliest harvested fruits generally ripened fastest (least chilling injured) also can be accounted for because they received the least chilling in the field and thus would be expected to be least susceptible to chilling in storage.

Plotting days to ripen against percent decay shows a close correlation between these two symptoms (Figure 2). This indicates that both symptoms were controlled largely by the same factors - including and probably dominated by cold exposure in the field and in storage. The slope of the regression line shows that days to ripen was less influenced by chilling than was percent decay.

Final Color on L, a and b Scales:

Figure 3 is a diagram which helps in interpreting the color readings reported in Tables 4 and 5. Results obtained on the 'L' scale (lightness) indicate that chilling in storage resulted in fruits which appeared lighter in both mature-green and breaker fruits. A 5-day increase in exposure time did not make any significant difference but

a reduction in temperature from 10 to 0C resulted in a lighter shade of fruits harvested mature-green (Table 4). 'Red Pak' fruits appeared lighter than 'Jack Pot' when harvested mature-green but not when harvested after showing color changes on the plant (Table 5). Fruits which were least chilled in the field (September 10) appeared darker than those harvested after more field chilling (September 18 or 26). Breaker fruits also showed a response to increased field chilling from September 18 to 26, while mature-green fruits did not. Examining these results in conjunction with Table 3 suggests that mature-green fruits are probably controlled in their darkness/lightness by field temperatures below 15C while breaker fruits respond more to temperatures below 12.8C.

Higher values on the 'a' scale indicate more redness. Breaker fruits did not show any difference in red pigmentation while mature-green fruits did significantly - producing less red pigment with chilling (Table 4). Decreasing temperature from 10 to 0C reduced red pigment but an increase in duration from 5 to 10 days did not. These results suggest that once red color starts to appear (breaker), chilling does not significantly retard its development but cold exposure before the breaker stage retards red pigment (lycopene) development. There were no

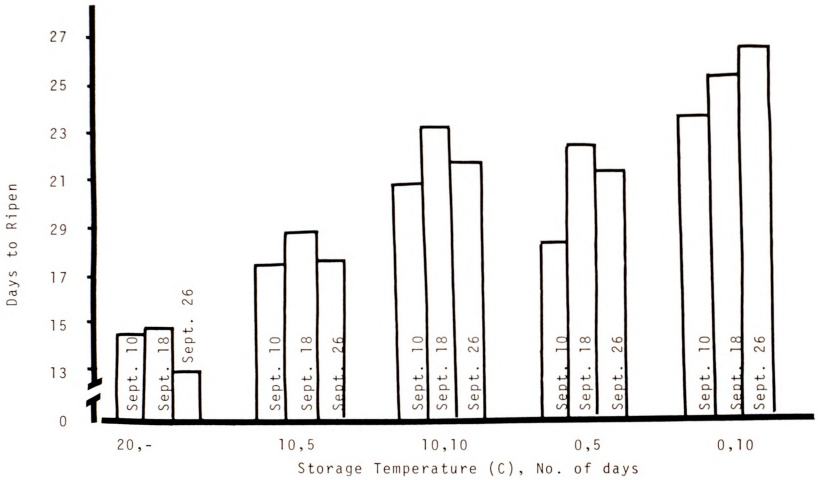

Figure 1. Difference in ripening response of fruits stored under varying conditions with regards to harvest date (F value for interaction significant at .01 level).

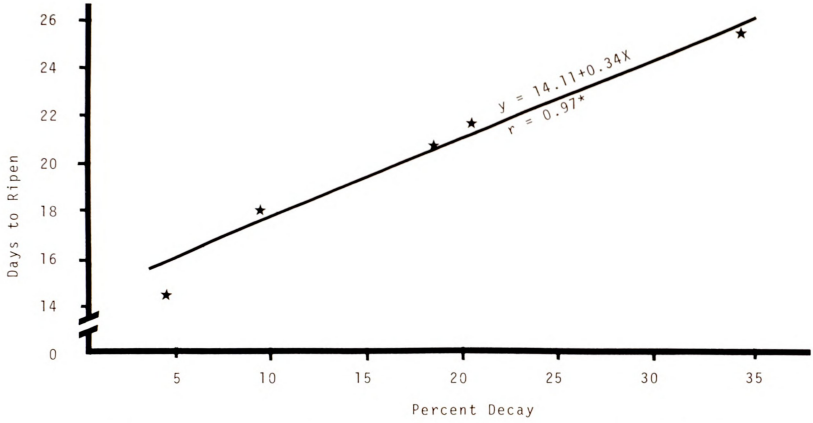

Figure 2. The relationship between percent decay and days to ripen.

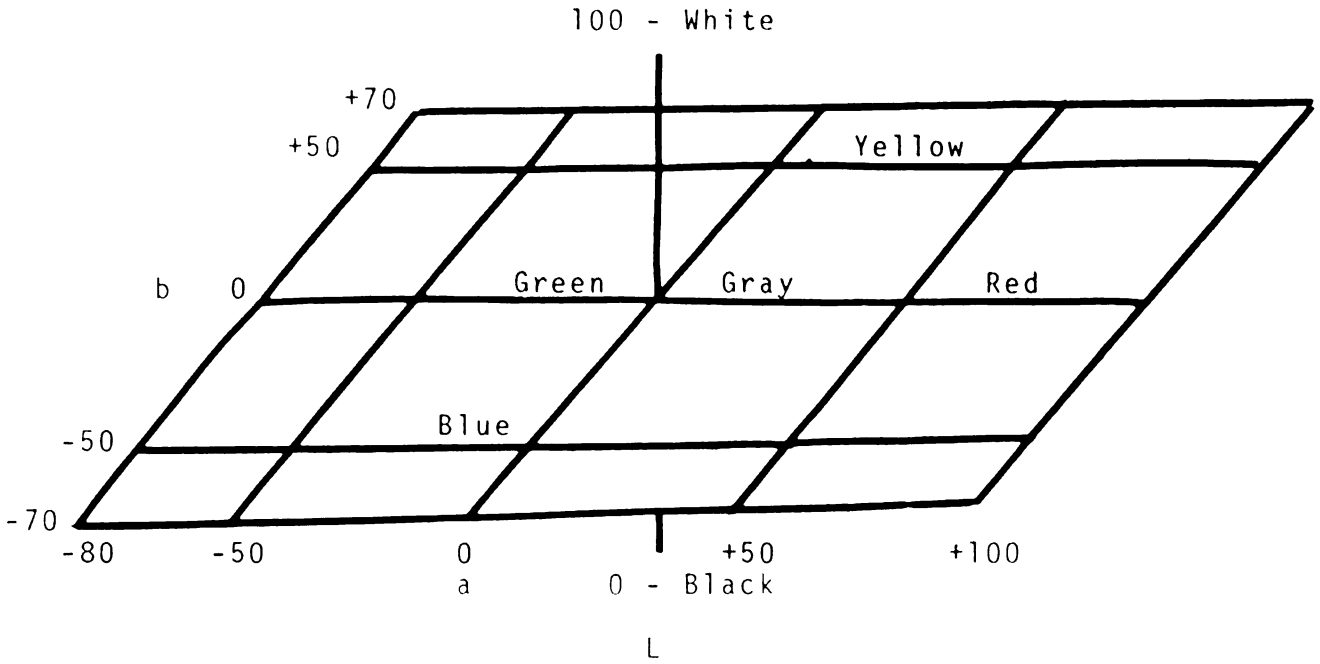

Figure 3. Dimensions of L, a, b color solid in which L measures lightness, a measures redness when + and greenness when minus, b measures yellowness when + and blueness when minus. (Diagram redrawn from Hunter [1976]).

Table 4. Final color on Hunter L, a and b scales of 'Mature-Green' (MG) and 'Breaker' (Br) tomato fruits after varying storage conditions.

Treatment Temp (C)	Time (days)	Hunter Color Scale L		a		b	
		MG	Br	MG	Br	MG	Br
20	--	37.34	36.79	30.27	28.49	16.47	15.94
10	5	38.74	38.92	29.41	27.63	17.29	17.06
10	10	38.48	39.45	29.31	27.79	16.97	17.41
0	5	39.42	--	28.29	--	17.67	--
0	10	40.01	--	27.48	--	18.10	--
		Planned Comparisons (F Statistics)					
Control vs	Expt.	30.10**	46.53**	24.69**	1.24	19.34*	14.23
10 vs	0C	13.89*	--	24.73**	--	12.02*	--
5 vs	10 days	0.30	2.48	2.37	0.13	0.05	1.14

Table 5. Cultivar differences and effect of harvest date on final color on the Hunter L, a and b scales of 'Mature-Green' (MG) and 'Breaker' (Br) fruits.

Cultivar	Hunter Color Scale L		a		b	
	MG	Br	MG	Br	MG	Br
Red Pak	39.17	38.19	29.08	28.59	17.58	16.44
Jack Pot	38.42	38.58	28.83	28.36	17.02	17.20
LSD 0.05	0.19	NS	0.24	NS	0.19	0.42
LSD 0.01	0.25	NS	NS	NS	0.25	0.57
Harvest date						
September 10	38.46	36.82	29.14	29.31	17.23	15.74
September 18	38.96	38.05	29.08	28.19	17.48	16.71
September 26	38.97	40.29	28.63	26.42	17.29	18.02
LSD 0.05	0.23	0.78	0.29	0.75	0.23	0.51
LSD 0.01	0.31	1.07	0.39	1.03	NS	0.70

significant variations in red pigmentation between the two cultivars tested (Table 5). Chilling in the field, however, reduced redness in both mature-green and breaker fruits with mature-green fruits again apparently being more sensitive to 15C and below than breaker fruits which respond instead to temperatures below 12.8C (Table 5).

The 'b' scale measures the amount of yellow color relative to blue with higher positive values corresponding to more yellow (carotene) relative to blue. Slight increases in yellow color were detected with chilling exposure in storage and 0C resulted in more yellow pigmentation relative to 10C. Duration of exposure however did not influence the appearance of yellow color (Table 4). These yellow color responses were only obtained with fruits harvested at the mature-green stage and not with breaker fruits. Visual observations recorded indicate that chilling results in less red color appearance (Truscott and Warner, 1967). So, the results in Table 4 support this view.

Generally, as fruits get lighter in color, red pigmentation decreased (Figure 4) and yellow increased (Figure 5) with mature-green harvested fruits. Also yellow pigmentation increased as red decreased (Figure 6). A review of color development by Edwards and Reuter (1967) showed a similar relationship between yellow and red color

development. Hobson and Davies (1971) also attest to the existence of such a relationship.

pH and Acidity:

Chilling treatments in storage did not have any significant effect on pH (Table 6). However, increasing chilling exposure in the field resulted in reductions in pH (Table 7). This suggests that hydrogen ion concentration in fruits is either influenced only on the plant or at stages of development earlier than the mature-green stage. 'Jack Pot' fruits had significantly higher pH levels than 'Red Pak' when harvested mature-green but showed no difference when harvested at the breaker stage (Table 7).

Acidity levels were not influenced by chilling in fruits harvested mature-green but a slight increase was recorded with breaker fruits after storage and ripening (Table 6). Hall (1976) also obtained higher levels of acidity in chilled breaker fruits than in non-chilled fruits. A higher level of acidity was obtained in mature-green 'Red Pak' fruits than in 'Jack Pot' fruits but no cultivar differences were detected with breaker fruits. Chilling exposure in the field resulted in higher acidity (Table 7). Massey and Winsor (1957) also reported increases in acidity with harvest date. Generally, fruits harvested at the

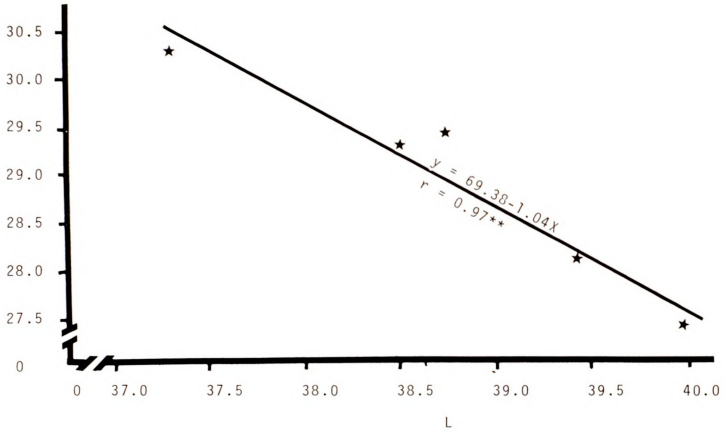

Figure 4. The relationship between lightness (L) and red (a) as measured on the Hunter color meter.

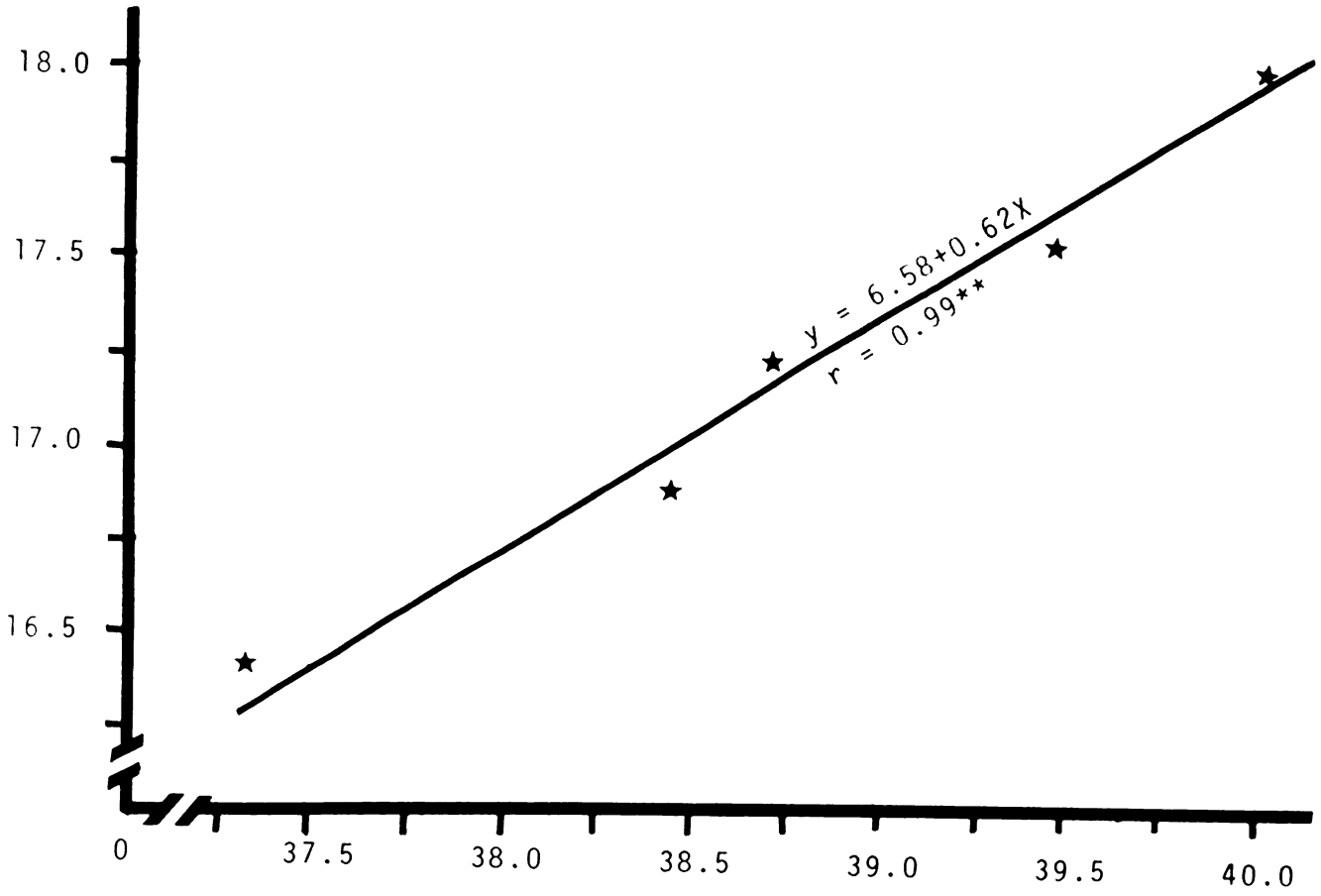

Figure 5. The relationship between lightness (L) and yellow (b) as measured on the Hunter color meter.

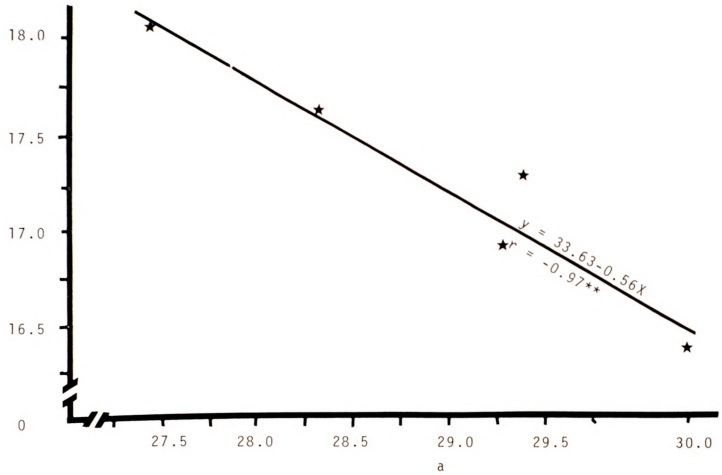

Figure 6. The relationship between red (a) and yellow (b) as measured on the Hunter color meter.

Table 6. pH and total acidity changes in response to varying storage conditions of 'Mature-Green' (MG) and 'Breaker' (Br) fruits.

Treatments Temp. (C)	Time (days)	pH		Total Acidity	
		MG	Br	MG	Br
20	--	4.65	4.64	0.579	0.517
10	5	4.54	4.56	0.598	0.577
10	10	4.54	4.56	0.600	0.620
0	5	4.43	--	0.629	--
0	10	4.47	--	0.646	--
		Planned Comparisons (F Statistics)			
Control vs	Expt.	3.98	1.97	2.93	9.25*
10 vs	0C	1.77	--	3.55	--
5 vs	10 days	0.24	1.00	0.20	1.94

Table 7. Cultivar differences and effect of harvest date on pH and total acidity of 'Mature-Green' (MG) and 'Breaker' (Br) fruits.

Cultivar		pH		Total Acidity (%)	
		MG	Br	MG	Br
Red Pak		4.50	4.58	0.618	0.587
Jack Pot		4.56	4.60	0.603	0.585
	LSD 0.05	0.04	NS	0.008	NS
	LSD 0.01	0.05	NS	NS	NS
Harvest date					
September 10		4.60	4.66	0.599	0.570
September 18		4.52	4.63	0.604	0.567
September 26		4.46	4.47	0.628	0.588
	LSD 0.05	0.05	0.06	0.010	0.018
	LSD 0.01	0.06	0.09	0.013	NS

breaker stage contained less acid than those harvested at the mature-green stage. Winsor et al. (1962) and Dalal et al. (1965) reported that tomato fruits on plants decreased in acidity after color changes begin. So, the breaker fruits probably contained less acid at harvest than mature-green fruits, thus accounting for the lower levels at ripening.

The observation that pH differences were not found while there were acidity differences may be due to the buffer system which exists in tomato fruits (Davies, 1965). The pH of 'Jack Pot' fruits was essentially not affected by chilling whereas 'Red Pak' fruits were (Figure 7). This suggests that pH responses to chilling might be cultivar dependent.

Ascorbic Acid and Soluble Solids:

Chilling conditions in storage resulted in higher ascorbic acid levels in fruits harvested mature-green but not in those harvested at the breaker stage (Table 8). This suggests that ascorbic acid retention might be better at lower temperatures and that losses after harvest may be relatively more rapid in fruits harvested mature-green than in breaker fruits. 'Red Pak' contained more ascorbic acid than 'Jack Pot' in fruits harvested at both mature-green and breaker stages (Table 9). Ascorbic acid levels

increased with successive harvest dates slightly in both mature-green and breaker fruits (Table 9). Seeling (1965) recorded losses in ascorbic acid levels of tomato fruits at high temperatures. There are also reports of higher retention of ascorbic acid at chilling temperatures (Feaster et al., 1949). Therefore, this apparent retention of ascorbic acid in chilled fruits might be expected.

Soluble solids was only slightly higher in chilled fruit than in non-chilled fruit. Exposure to 0C resulted in slightly higher levels than 10C and a 10 days exposure also resulted in slightly higher levels than a 5 day exposure (Table 8). However, these differences were only obtained with fruits harvested at the mature-green stage and not with those harvested at the breaker stage. Field chilling also resulted in more soluble solids with increasing severity of chilling and a more pronounced effect with fruits harvested mature-green than with those harvested at the breaker stage (Table 9). There were no cultivar differences in the level of soluble solids detected (Table 9). There are no records of chilling effects on soluble solids reported in the literature for comparison and since the differences detected were very small, caution will have to be exercised in making any deductions from them.

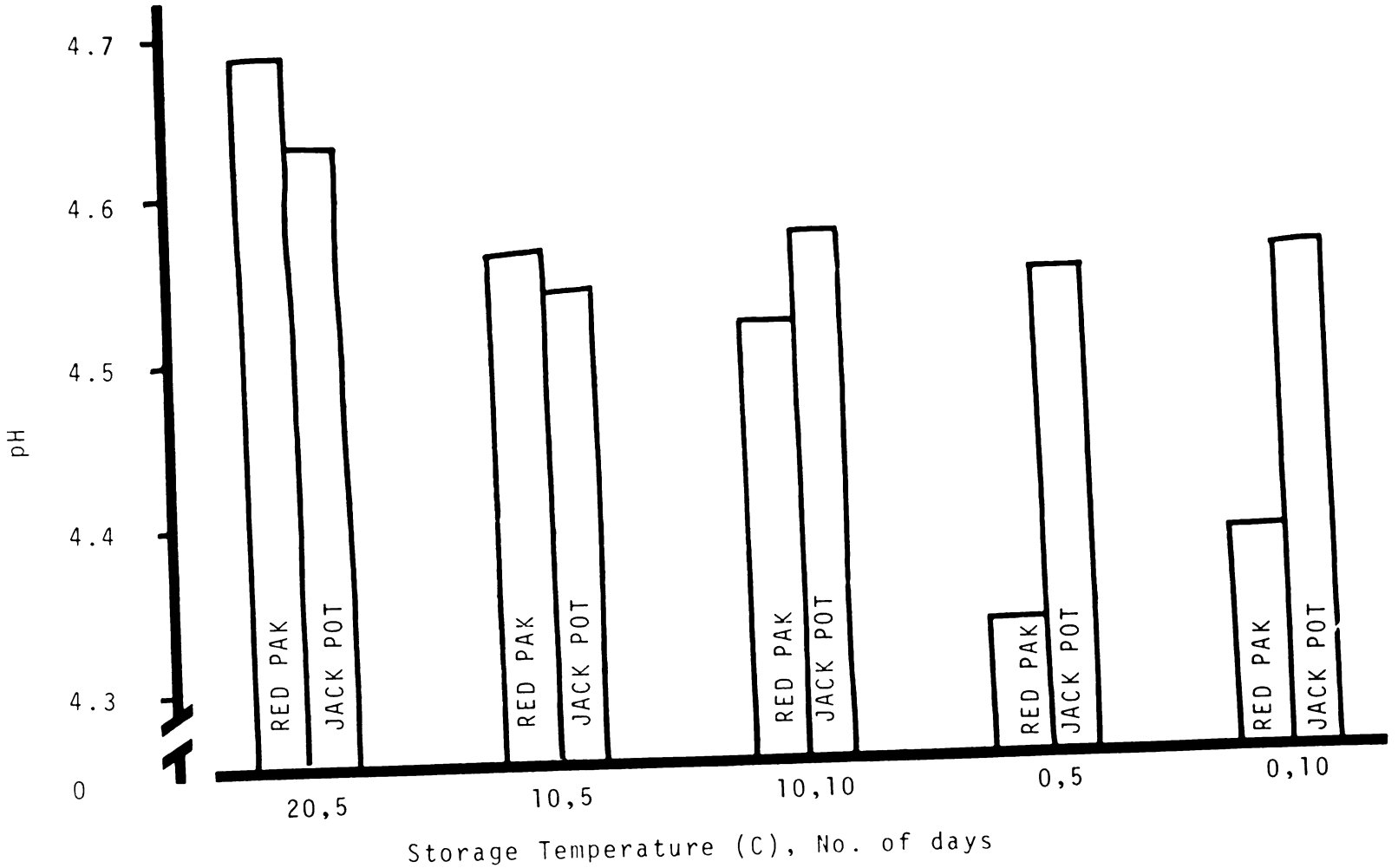

Figure 7. Differences in the effect of storage on the pH of 'Red Pak' and 'Jack Pot' fruits (F value for interaction significant at 0.01 level).

Table 8. Ascorbic acid and soluble solids levels in response to varying storage conditions of 'Mature-Green' (MG) and 'Breaker' (Br) fruits.

Treatments			Ascorbic Acid		Soluble Solids	
Temp. (C)		Time (days)	(mg per 100g fruit)		(°B)	
			MG	Br	MG	Br
20		--	25.31	25.88	1.3363	1.3362
10		5	25.81	26.21	1.3367	1.3366
10		10	26.28	26.79	1.3370	1.3372
0		5	26.94	--	1.3370	--
0		10	27.36	--	1.3379	--
			Planned Comparisons (F Statistics)			
Control	vs	Expt.	24.30**	3.30	13.71*	3.11
10	vs	0C	22.50**	--	10.00*	--
5	vs	10 days	3.83	2.22	8.14*	2.21

Table 9. Cultivar differences and effect of harvest date on ascorbic acid and solids levels of 'Mature-Green' (MG) and 'Breaker' (Br) fruits.

Cultivar	Ascorbic Acid (mg per 100g fruit)		Soluble Solids (°B)	
	MG	Br	MG	Br
Red Pak	27.01	27.03	1.3370	1.3368
Jack Pot	25.67	25.56	1.3369	1.3365
LSD 0.05	0.15	0.20	NS	NS
LSD 0.01	0.21	0.27	NS	NS
Harvest date				
September 10	26.15	25.96	1.3364	1.3365
September 18	26.41	26.54	1.3371	1.3363
September 26	26.50	26.38	1.3375	1.3369
LSD 0.05	0.19	0.24	0.0003	0.0004
LSD 0.01	0.25	0.33	0.0004	0.0006

Plotting soluble solids levels against acidity shows concurrent increases for both mature-green and breaker fruits (Figure 8). Since sugars and acids both influence taste in tomato fruits, their relative amounts are important. Stevens and Kader (1976) reported that high levels of both acids and sugars were associated with optimum flavor in tomato fruits. Since chilling temperatures resulted in the retention of sugars and concurrently acids, chilling might be beneficial to flavor even though it is definitely detrimental in terms of other factors like decay and final fruit color.

Detachment

Final Color, Decay and Ripening:

Detaching fruits did not influence lightness (L) significantly (Table 10). Redness (a) was also not influenced significantly by detachment but the amount of yellow pigment (b) was slightly reduced. The reduction in yellow color was probably due to a decrease in exposure in sunlight of detached fruits. Since the detached fruits, in this study, were placed at ground level in the rows of plants, they might have been shaded by the foliage of the plants enough to account for the differences observed. Detached fruits ripened earlier than those left on the

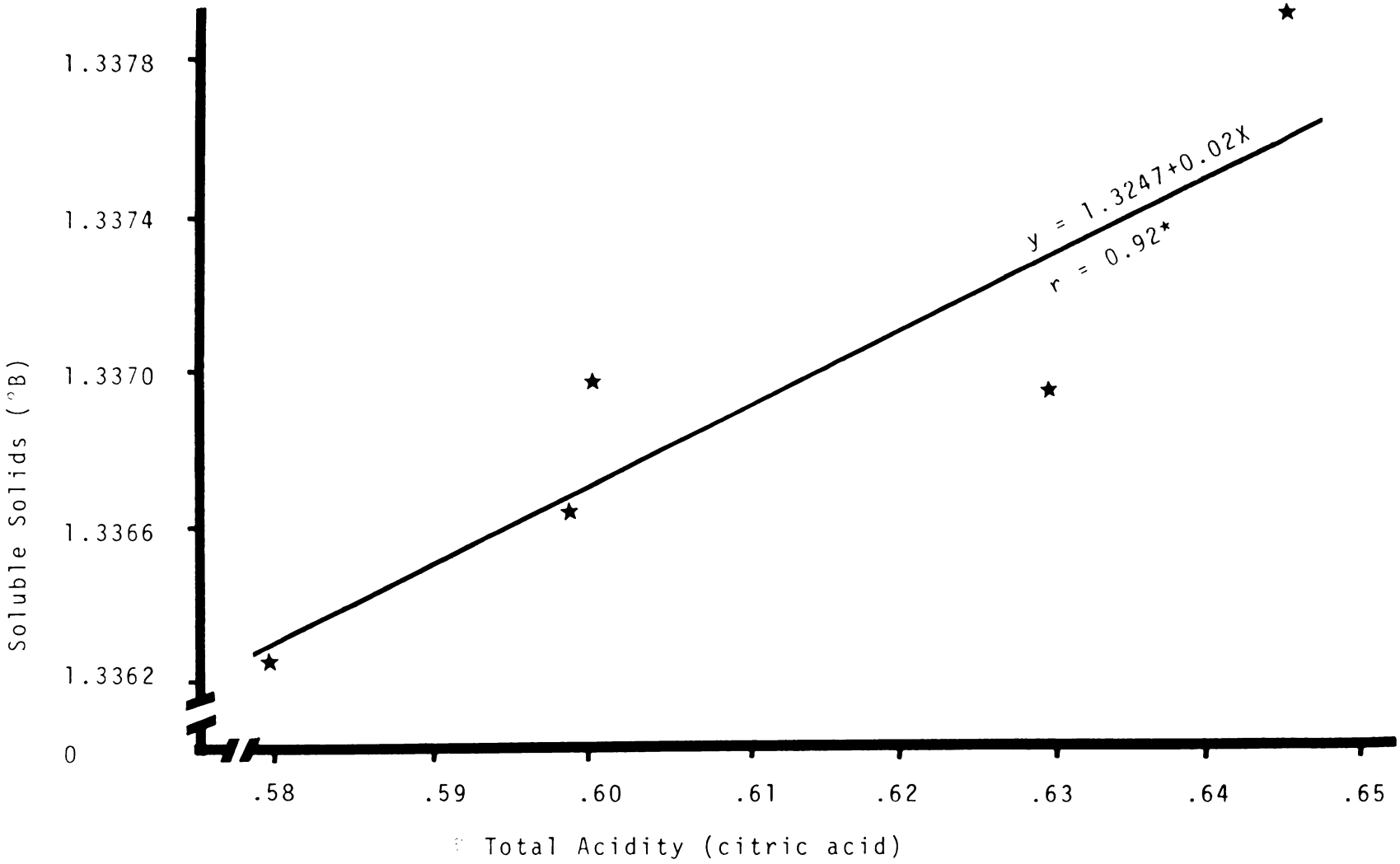

Figure 8. The relationship between acidity and soluble solids of tomato fruits.

Table 10. Effect of detaching fruits and picking date on final color on the Hunter L, a and b scales; ripening and percent decay.

Treatment	Hunter Color Scale L	a	b	Days to Ripen	Percent Decay
Attached	38.01	27.38	17.05	11.9	2.6
Detached	37.81	27.78	16.53	11.0	21.5
LSD 0.05	NS	NS	0.50	0.35	2.94
LSD 0.01	NS	NS	NS	0.48	3.99
Picking Date[1]					
September 18	38.48	27.27	17.14	9.3	5.0
September 26	37.55	28.21	16.11	11.2	12.2
October 4	37.71	27.28	17.13	13.7	18.9
LSD 0.05	0.77	0.77	0.62	1.43	3.60
LSD 0.01	NS	NS	0.84	2.59	4.89

1. Picking date is used as against harvest date to differentiate the dates for detachment records from those for chilling storage records.

plant for an extra week (Table 10). This might be due to an earlier initiation of ripening off the plant. Detached fruits were remarkably more prone to decay than attached ones (Table 10). This may be due to some protection offered by the plant against chilling injury. Probably disease organisms were more prevalent on the ground surface and thus infected the fruits in the field before they were moved into storage. However, since the fruits were in paper bags and thus not in direct contact with the ground surface they must have been, at least, partially shielded from any pathogens on the ground. The magnitude of the difference obtained suggests that other factors might be involved. Susceptibility to decay increased with chilling and some chilling occurred in the field (Table 10). This increased decay could be due to chilling injury. This indicates that tomato plants might provide some protection to fruits from chilling exposure.

The color readings (L, a and b) obtained for picking dates showed little differences but there was a consistent trend of September 26 values being significantly different from those for September 18 and October 4. An examination of Table 3 shows that this might be related to the number of hours below 15C one week before the picking dates. This suggests that 15C might be the critical temperature

for effects of low temperature exposure in the field on color measurement on the Hunter Lab color meter. Rate of ripening was slightly decreased at successive harvest dates as was, to a large extent, percent decay (Table 10). This suggests that ripening and decay are probably affected more by exposure below 12.8C than 15C. The magnitude of the values obtained with picking dates in Table 10 indicates that field chilling was not very severe until October 4. Using the results of Morris (1954) as a yardstick for field chilling, about 108 hours below 15C in the final week before harvest should cause only slight chilling injury. So the limiting factor in tomato production in Southern Michigan should be the first frost of the Fall rather than field chilling, provided not much chilling will be experienced during transportation and storage.

Percent decay of detached fruits relative to attached fruits increased with successive picking dates (Figure 9). This indicates that both detachment and picking date influence decay in tomato fruits.

pH, Acidity, Ascorbic Acid and Soluble Solids:

pH and acidity were not significantly influenced by detachment (Table 11). Ascorbic acid level, however, was markedly lower in detached than attached fruits. This may

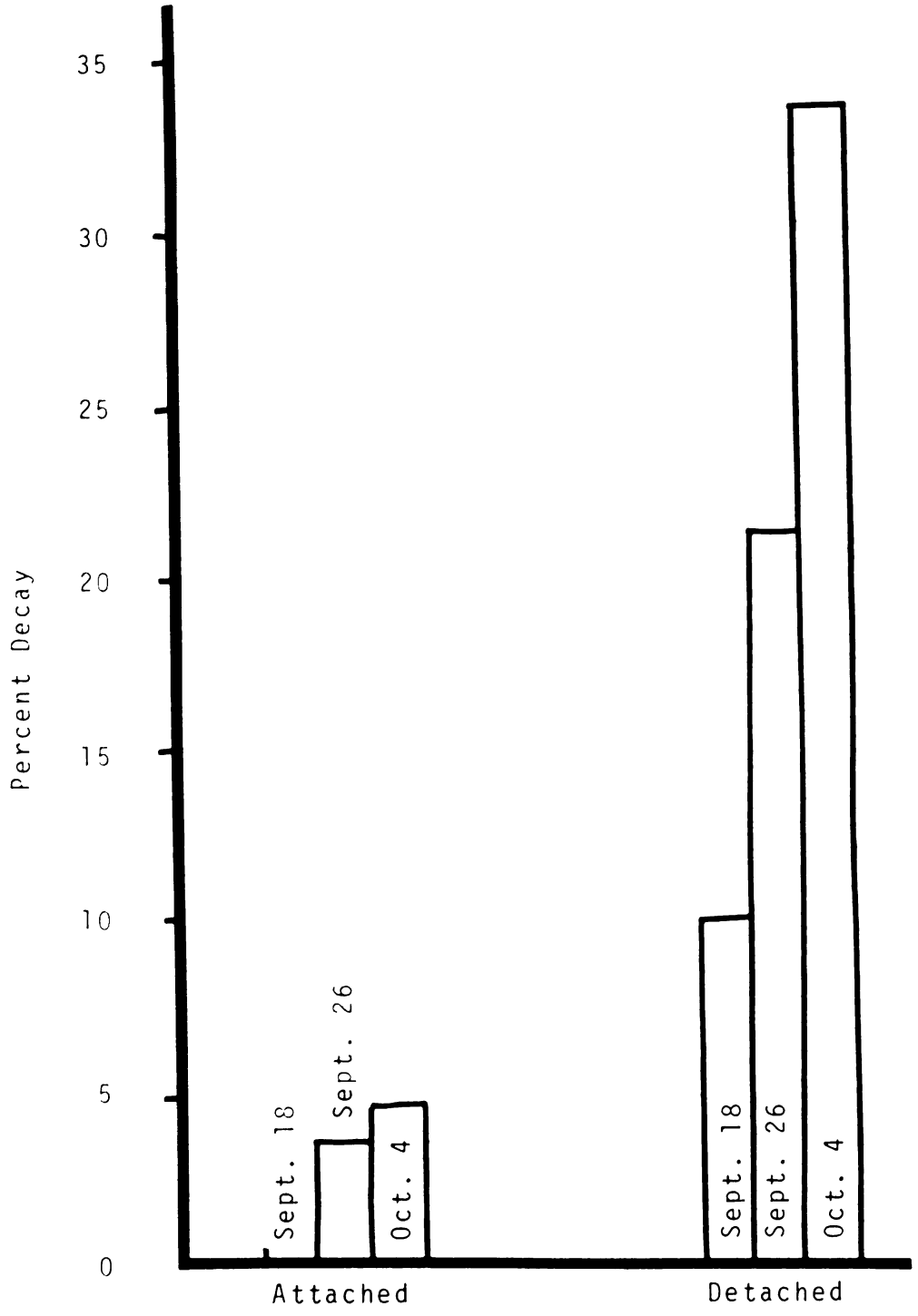

Figure 9. Differences in effect of detachment on decay of fruits picked and stored on different dates (F value for interaction significant at 0.01 level).

be due, at least partially, to less sunlight reaching the detached fruits. Light intensity has been noted to influence ascorbic acid levels to a large extent (Matthews, 1974). However, further studies would be warranted to determine if detaching fruits contributes significantly to the lowering of ascorbic acid. Soluble solids was slightly less in fruits which were detached, suggesting tomato fruits probably continue to accumulate soluble solids after the mature-green stage if left on the plant.

pH levels decreased in the last week in the field, resulting in the lowest levels in fruits picked on October 4 (Table 11). This is in agreement with the observation that field chilling reduced pH (Table 7). An increase in acidity with picking date was only observed for September 26 as compared to September 18 but not for October 4 as against September 26. This suggests that other factors must be influential in the result obtained other than the amount of chilling. Ascorbic acid level was also increased only for September 26 as against September 18; as was soluble solids too (Table 11). This apparent anomaly deserves further attention.

'Red Pak' decreased slightly in acidity due to detachment while 'Jack Pot' increased (Figure 10). Responses to detachment in terms of acidity is thus probably cultivar dependent.

Table 11. Effect of detaching fruits and picking date on pH, total acidity, ascorbic acid and soluble solids levels.

Treatment	pH	Total Acidity ( )	Ascorbic Acid (mg per 100g fruit)	Soluble Solids(°B)
Attached	4.56	0.525	26.22	1.3365
Detached	4.56	0.522	25.50	1.3362
LSD 0.05	NS	NS	0.23	0.0002
LSD 0.01	NS	NS	0.31	0.0003
Picking date				
September 18	4.59	0.498	25.21	1.3360
September 26	4.58	0.535	26.17	1.3367
October 4	4.51	0.537	26.21	1.3364
LSD 0.05	0.05	0.012	0.28	0.0004
LSD 0.01	0.07	0.016	0.38	0.0005

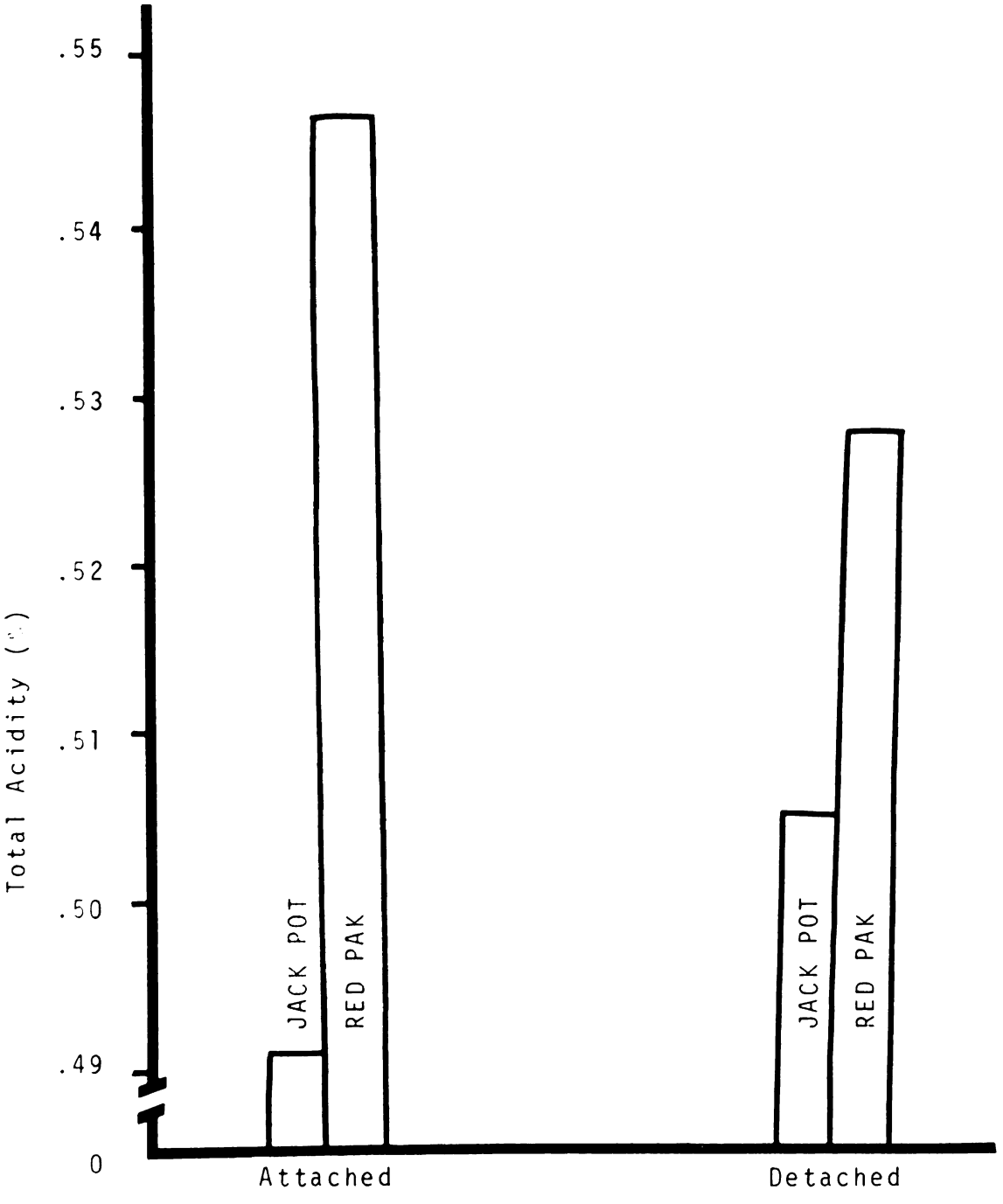

Figure 10. Differences in effect of detachment on acidity on 'Red Pak' and 'Jack Pot' (F value for interaction significant at .01 level).

SUMMARY AND CONCLUSIONS

Chilling tomatoes in storage resulted in a delay in ripening of tomato fruits. The duration of chilling temperature had a more pronounced effect than temperature reduction within the chilling range. The lower temperature (0C) resulted in longer delays than the higher (10C). Field chilling also delayed ripening but not as severely as chilling in storage. 'Jack Pot' fruits ripened faster than 'Red Pak'. Similar results were obtained with decay as the criterion for chilling injury. Generally, 'Jack Pot' was more prone to chilling injury than 'Red Pak'. A comparison of ripening delay and decay reveals a close correlation, indicating that the same factor (chilling) probably controls both. Decay was, however, more responsive to changes in chilling exposure, suggesting that it is a better criterion than ripening delay.

Chilling produced lighter colored tomato fruits with less red pigment and slightly more yellow pigment. 'Red Pak' fruits were generally lighter, more red and yellow than 'Jack Pot' fruits. Poor final color associated with chilling injury is probably due to the lightness and redness rather than the amount of yellow pigment present because the amount of yellow pigment was relatively less influenced by chilling. The relationship between these

three shades of color confirms reports by Edwards and Reuther (1967) and Hobson and Davies (1971).

Acidity and pH were not influenced much by chilling exposure. No difference in pH was recorded between cultivars but 'Red Pak' contained more acid than 'Jack Pot'. Soluble solids and ascorbic acid in chilled fruits were higher than in non-chilled fruits. This suggests that chilling enhances the retention of soluble solids and ascorbic acid. There was no cultivar difference in soluble solids but 'Red Pak' contained more ascorbic acid than 'Jack Pot'.

Detaching fruits from plants increased their susceptibility to chilling injury as measured by percent decay. This indicates that the plant offers some protection to the fruits against chilling injury, because the magnitude of the difference could not be accounted for by other factors. Detached fruits ripened earlier than attached ones but the difference was too small to be important. There were no effects of detaching on the three colors measured.

pH and acidity were not influenced by detachment and the difference in soluble solids content was too small to be of much consequence. However, detached fruits contained significantly less ascorbic acid than attached fruits.

Since chilling stabilizes ascorbic acid levels, the attached fruits which are less prone to chilling injury accumulated ascorbic acid after the stage at which they were tagged (mature-green).

There was no significant chilling injury in the field until the last week in September. Since the first frost in Southern Michigan usually occurs in late September/early October, field chilling before the first frost will not be a major factor in delaying normal ripening. Thus, the limiting factor in tomato production in Southern Michigan should be the date of the first frost.

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